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The Food and Land Use Coalition

2020 Report of the FABLE Consortium

Pathways to Sustainable Land-Use and Food Systems

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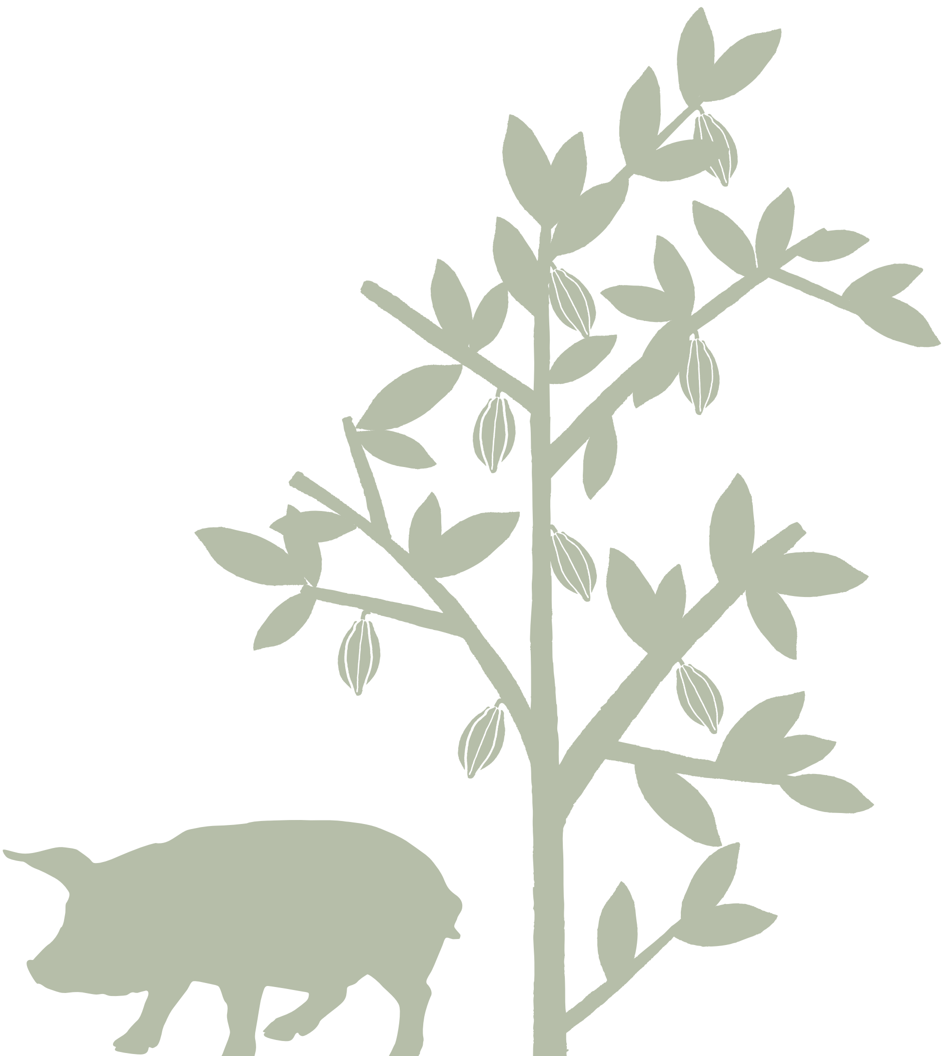
2020 Report of the FABLE Consortium

Pathways to Sustainable Land-Use and Food Systems



The Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Consortium is convened as part of the Food and Land Use Coalition (FOLU). It is led by the International Institute for Applied Systems Analysis (IIASA) and the UN Sustainable Development Solutions Network (SDSN), working closely with EAT, Bioversity International, the Potsdam Institute for Climate Impact Research (PIK), and many other institutions.

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Contents

List of Figures

Preface

This second global report of the FABLE Consortium presents thoroughly revised pathways towards sustainable land-use and food systems for 20 countries. We show that integrated strategies across food production, biodiversity, climate, and diets can meet the objectives of the Paris Agreement and the Sustainable Development Goals (SDGs). Our iterative Scenathon approach complements prevailing top-down global models, which tend to lack the granularity and local buy-in needed for policy engagement.

FABLE country teams have improved and deepened the analysis, particularly on biodiversity, climate impacts, and freshwater use. We now consider current trends pathways that describe business as usual and sustainable pathways to meet ambitious sustainability objectives. Our work is informed by consultations with governments, business, civil society organizations, and other scientists on how to align development strategies, including climate and biodiversity strategies, with the objectives of the Paris Agreement and the SDGs. The pathways described in this report will help tackle the hidden costs of today's food system described by the Food and Land Use Coalition.

In recent weeks, China, Japan, and South Korea have joined the European Union, the UK, and a growing list of countries that have committed to net-zero greenhouse gas emissions by mid-century. US President-Elect Joe Biden has also committed to decarbonization by 2050. Most of these countries have reasonably robust technical analyses for how to decarbonize their energy systems but they lack integrated analyses of land-use and food systems. Such pathways must consider climate and many other policy objectives. The FABLE pathways in this report can help fill this gap and support countries in designing integrated strategies towards sustainable land-use and food systems.

We are encouraged by efforts undertaken by the UK, as host of next year's climate COP in Glasgow, and China, the host of the 2021 biodiversity COP in Kunming, to strengthen the focus on sustainable land-use and food systems under the climate and biodiversity conventions. Both meetings must promote more ambitious targets, particularly on biodiversity, and – crucially – accelerate integrated implementation of the commitments. Our work suggests that the transformations of land-use and food systems are technically feasible, and we hope that these findings can help turn 2021 into the "super year" for land-use and food systems.

At the time of writing, some countries have controlled COVID-19, but many more are experiencing a new wave. The pandemic has underscored the vulnerabilities of the food system. As the focus shifts towards recovery, countries should consider investments in sustainable land-use and food systems to promote greater resilience and security. FABLE tools, data, and analyses can help governments and other stakeholders test different strategies for the recovery and determine their alignment with the longer-term objectives of the Paris Agreement and the SDGs.

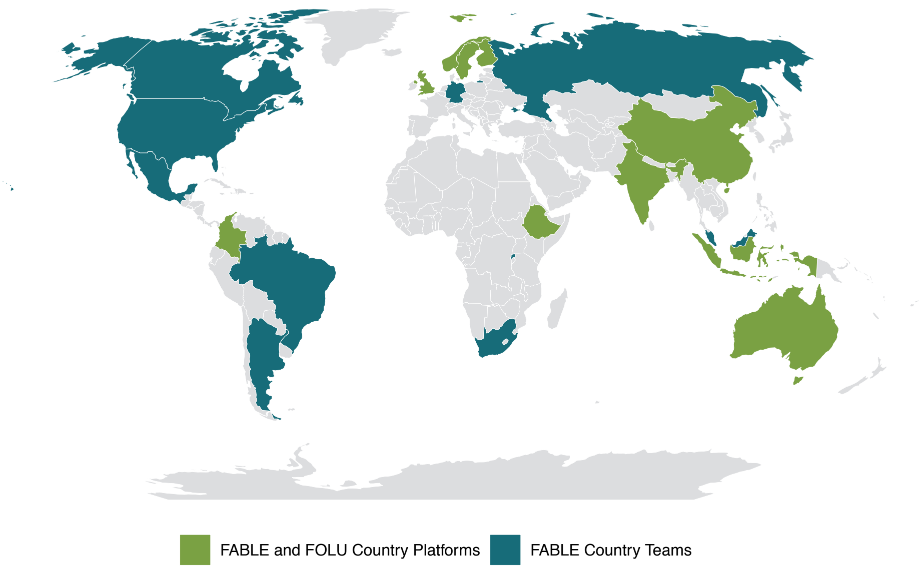
Executive Summary

In this second report of the FABLE Consortium, country teams present 20 national pathways towards sustainable land-use and food systems (Figure A). The pathways have been significantly improved since the 2019 report to show how countries can meet mid-century objectives on food security, healthy diets, greenhouse gas emissions, biodiversity, forest conservation, and freshwater use. National FABLE Pathways are consistent with the Sustainable Development Goals (SDGs) and the objectives of the Paris Agreement. They ensure consistent trade flows and can inform long-term climate strategies towards net-zero greenhouse gas emissions under the United Nations Framework Convention on Climate Change (UNFCCC) as well as biodiversity strategies under the Convention on Biological Diversity (CBD).

Towards the "super year" 2021

In 2020, the world has seen unprecedented environmental, social, and economic crises underscoring how unsustainable land-use and food systems are. Business as usual is not an option, as underscored by unprecedented forest fires, coral bleaching, heat waves, and unrelenting biodiversity loss. Deforestation rates in many parts of the Amazon are dramatically increasing. Moreover, the COVID-19 pandemic is taking lives, increasing food insecurity, causing massive economic damage, and has temporarily disrupted logistics in key food supply chains, yet the global food system has shown a surprisingly high resilience.

Figure A *Countries represented in the FABLE Consortium and the Food and Land Use Coalition*

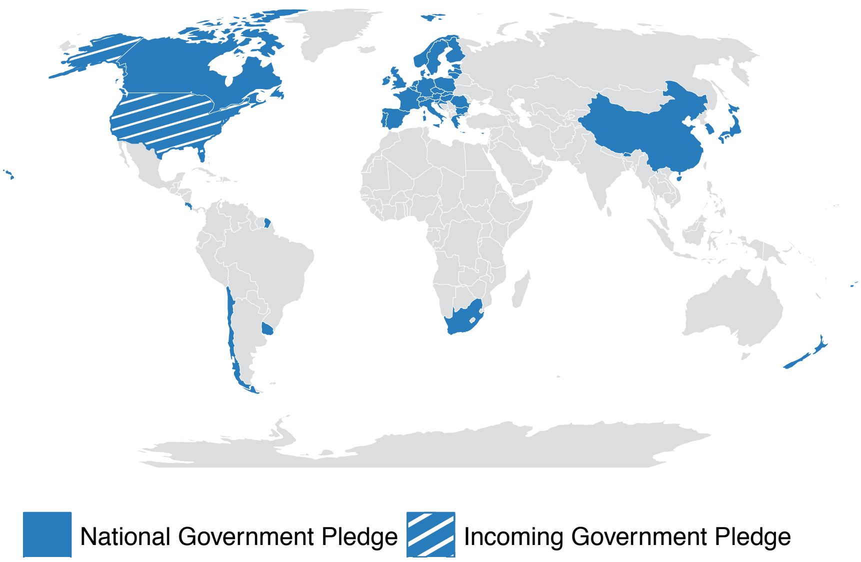


At the same time, there have been encouraging policy commitments from major economies. Indonesia has achieved the third consecutive year of falling deforestation rates. China, the European Union, Japan, South Korea, the UK, and other countries have now committed to net-zero greenhouse gas emissions around mid-century (Figure B). Leaders from 77 countries and the EU have signed the Leaders' Pledge to Nature, which commits to reversing biodiversity loss by 2030.

These pledges are highly commendable, but by and large they are not backed up by analysis and plans for meeting the targets in the land-use and food sector. Most countries do not have integrated policies and long-term strategies for sustainable land-use and food systems, as summarized by the three FABLE pillars (Figure D). This has been particularly apparent in relation to the conservation and restoration of biodiversity where ambitious targets have not been achieved. One emerging exception might be the EU, which is launching the European Green Deal with a comprehensive Farm to Fork Strategy covering the entire food and land-use system, including international spillovers. The FABLE pathways described in this report are a method for problem solving for the design and implementation of integrated, long-term strategies towards sustainable land-use and food systems.

We are heading towards a "super year" for sustainable land-use and food systems in 2021 with China hosting the CBD COP15 in Kunming, the UN hosting a Food Systems Summit in New York, and the UNFCCC COP26 in Glasgow, UK. These three major meetings provide an opportunity to increase the level of ambition, raise the profile of land-use and food systems, and – critically – accelerate the implementation of integrated strategies. Three breakthroughs are needed for the "super year":

Figure B *Countries committed to net-zero emissions around mid-century, as of November 2020*



Source. Climate Home News (2020)

1. **Governments must adopt a bold post-2020 Biodiversity Framework** that sets out ambitious goals for the protection and restoration of nature.

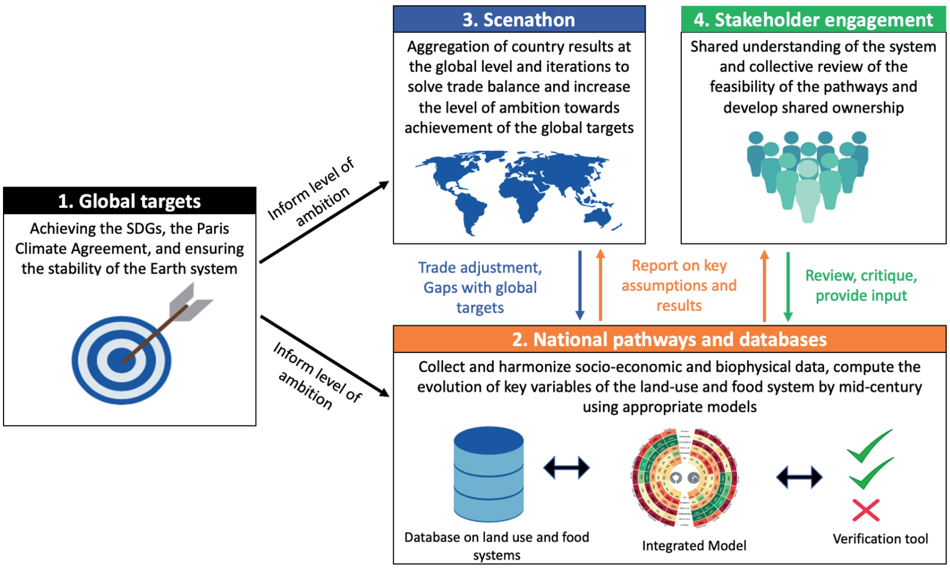
2. **All must accelerate the design and implementation of integrated strategies, particularly through more ambitious climate strategies that integrate land-use and food systems.** In particular, this will require the inclusion of biodiversity and maps for long-term land-use design in climate strategies, drawing on recent experiences in China and many other countries.

3. **Developed countries must mobilize additional finance,** for example through greater climate finance with a particular focus on nature-based solutions and biodiversity co-benefits.

The FABLE Approach

FABLE pathways for sustainable land-use and food systems are a method for problem solving. Pathways work backwards from the mid-century targets and shed light on the major transformations that are needed to achieve them. They help in three critical ways: (1) they provide a framework for engaging stakeholders (governments, businesses, civil societies and the scientific community), to review, pose questions, and suggest improvements for how to achieve the targets, which can build a societal consensus for the transformations; (2) without a long-term perspective countries risk locking themselves into unsustainable infrastructure and land-use systems, which would make achieving the mid-century targets far more costly if not impossible; (3) they help identify mid-term technology benchmarks needed to achieve the targets, such as increases in agricultural productivity or efficiency gains in livestock, which can then guide business action and innovation challenges. Long-term pathways are critical for success, and FABLE's mission is to develop the tools to prepare them.

Figure C *Step-by-step FABLE methodology*



FABLE pathways are developed by each FABLE country team in four steps (Figure C). First, country teams adopt global targets (Table A) covering the entire land-use system that are consistent with the SDGs and the Paris Agreement. Second, teams develop national pathways using locally appropriate modeling tools. To this end, the FABLE Consortium has developed a simplified FABLE Calculator to complement more complex models. Third, in an iterative process ("Scenathon") country teams adjust their assumptions and pathways to ensure balanced trade flows and to aim towards achieving the global FABLE targets. Throughout the process, country teams engage stakeholders to review assumptions, seek technical advice, and build a shared vision of how to transform land-use and food systems.

Table A *Global FABLE targets*

AREA	GLOBAL TARGET
Land and Biodiversity	**A minimum share of earth's terrestrial land supports biodiversity conservation.** *No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate.*
	A minimum share of Earth's terrestrial land is within protected areas. *At least 30% of global terrestrial area by 2030*
	Zero net deforestation. *Forest gain should at least compensate for the forest loss at the global level by 2030*
Greenhouse gas emissions from AFOLU	**Greenhouse gas emissions from crops and livestock** *compatible with keeping the rise in average global temperatures to below 1.5°C, which we interpret as below 4 $GtCO_2e$ yr^{-1} by 2050 (3.9 Gt for non-CO_2 emissions and 0.1 Gt for CO_2 emissions)*
	Greenhouse gas emissions and removals from Land-Use, Land-Use-Change, and Forestry (LULUCF) *compatible with keeping the rise in average global temperatures to below 1.5°C. Negative global greenhouse gas emissions from LULUCF by 2050*
Food security	**Zero hunger.** *Average daily energy intake per capita higher than the minimum requirement in all countries by 2030*
	Low dietary disease risk. *Diet composition to achieve premature diet related mortality below 5%*
Freshwater	**Water use in agriculture** *within the limits of internally renewable water resources, taking account of other human water uses and environmental water flows. Blue water use for irrigation <2,453 km^3yr^{-1} (global estimates in the range of 670-4,044 km^3yr^{-1}) given future possible range (61-90%) in other competing water uses*
Nitrogen	**Nitrogen release from agriculture within environmental limits.** *N use <69 Tg N yr^{-1} total Industrial and agricultural biological fixation (global estimates in the range of 52-113 Tg N yr^{-1}) and N loss from agricultural land <90 Tg N yr^{-1} (global estimates in the range of 50-146 Tg N yr^{-1}) by 2050*
Phosphorous	**Phosphorus release from agriculture within environmental limits.** *P use <16 Tg P yr^{-1} flow from fertilizers to erodible soils (global estimates in the range of 6.2-17 Tg P yr^{-1}) and P loss from agricultural soils and human excretion <8.69 Tg P yr^{-1} flow from freshwater systems into ocean by 2050*

This year, FABLE has made several improvements to the design of national pathways. First, all countries now present at least one Current Trends Pathway and one Sustainable Pathway to assess how far and how quickly improved policies can make land-use and food systems sustainable. Second, we have broadened the scope of the analysis to include freshwater, future climate-change impacts on crops, a richer discussion of biodiversity targets, and a more detailed trade analysis. Third, we have incorporated feedback on last year's pathways. As a result, we now have greater confidence in the robustness of the FABLE pathways.

Key findings and policy implications

Current Trends Pathways lead most countries towards unsustainable land-use and food systems, but through decisive action governments and other stakeholders can meet the related SDGs and objectives of the Paris Agreement. The Sustainable Pathways concurrently meet the objectives related to food security, greenhouse gas emissions, water use, and biodiversity (Table B).

Table B *Achievement of FABLE targets under the Current Trends and Sustainable Pathways*

GLOBAL FABLE TARGET	CURRENT TRENDS	SUSTAINABLE
Land and Biodiversity		
Land where natural processes predominate. No net loss by 2030 (globally) ...	*Achieved*	*Achieved*
Land where natural processes predominate. ...and an increase of at least 20% by 2050 in the area of land where natural processes predominate (globally)	*Not achieved*	*Not achieved*
Zero net deforestation globally by 2030	*Not achieved*	*Achieved*
GHG emissions from AFOLU		
Global GHG from Agriculture less than 4 $GtCO_2e\ yr^{-1}$ by 2050	*Not achieved*	*Almost achieved (4.1 $GtCO_2e\ yr^{-1}$)*
Global GHG from LULUCF less than 0 $GtCO_2e\ yr^{-1}$ by 2050	*Not achieved*	*Achieved*
Food Security		
Average calorie consumption per capita greater than the average minimum daily energy requirement in all countries by 2030	*Achieved*	*Achieved*
Freshwater Use		
Global consumptive blue water use less than 2,453 km^3yr^{-1} by 2050 (global estimates in the range of 670-4,044 km^3yr^{-1})	*Achieved* (but not achieved for the lower boundary of the literature estimates)	*Achieved* (but not achieved for the lower boundary of the literature estimates)

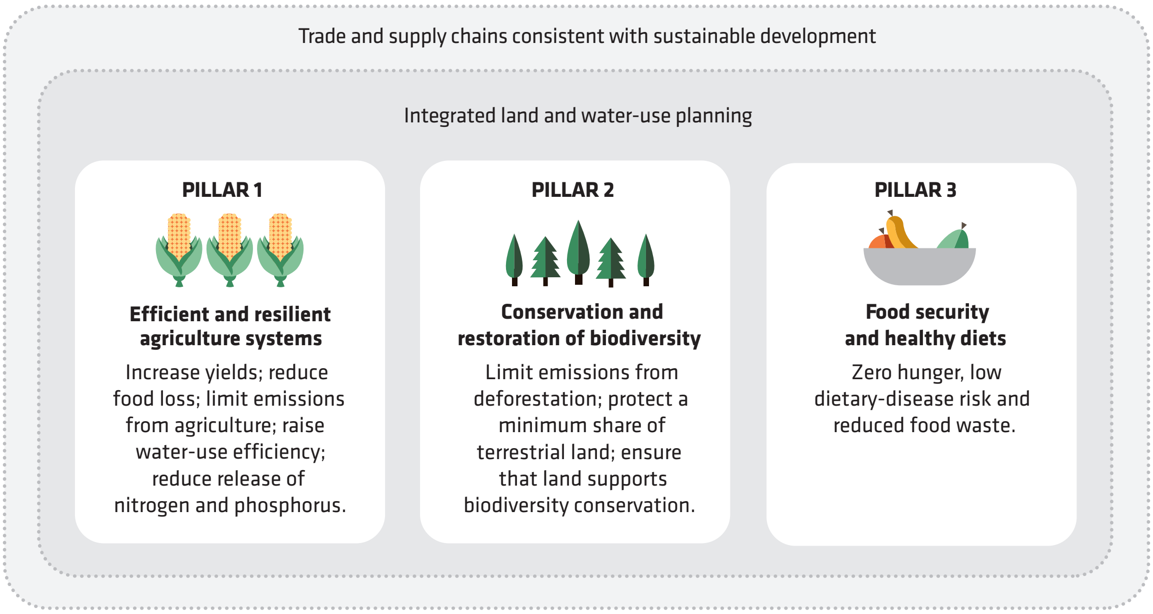
Each country faces specific challenges and solutions vary. For example, FABLE country teams adopt varying assumptions on changing diets and reducing food loss and waste. These differences often reflect deep cultural and historic preferences, agroclimatic conditions, and other factors that governments and scientists should take into account when designing strategies towards sustainable land-use and food systems. This demonstrates the importance of country-driven analyses of land-use and food systems as presented in this report.

Countries need a systems approach that covers three pillars of sustainable land-use and food systems (Figure D). These pillars cover efficient and resilient agriculture systems that ensure farmers' livelihoods, conservation and restoration of biodiversity, and food security and healthy diets – that should be embedded in integrated land-use design policies and sustainable supply chains. They contribute to many SDGs, are critical for meeting the objectives of the post-2020 Biodiversity Framework and can contribute about a third of the emission reductions to achieve the objectives of the Paris Agreement.

Countries have at least four critical levers for making land-use and food systems sustainable: (1) Dietary shifts – often towards less meat consumption and less overconsumption of food; (2) sustainable and productive agriculture; (3) improved land-use design, particularly for protecting and restoring nature; (4) rapid reductions in food loss and waste. Together, these levers can lower the demand for pasture and cropland at the global level and thereby support greater conservation and restoration of ecosystems with resultant impacts on increased carbon sequestration, biodiversity conservation and restoration. The report and the country pathways illustrate each of these levers with specific examples.

FABLE pathways provide a tool for countries to integrate biodiversity conservation and

Figure D *Three pillars for integrated land-use and food systems (Schmidt-Traub et al., 2019)*



restoration as well as food systems into their climate strategies, particularly in the run-up to the climate and biodiversity COPs. This integration does not require any new negotiations under the Conventions and can instead be advanced through operational strategies at the country level. Such strategies need to be supported by maps of desired land-use, including for food production, biodiversity conservation and restoration, ecosystem services management, and disaster risk reduction. If it is not possible to update an NDC or a long-term climate strategy ahead of the COPs, countries can announce their commitment towards this integration and spatially explicit policies. They can then complete the technical and policy work in preparation for the 2023 stock-take under the UNFCCC. The same strategies and maps could then also serve as national strategies under the Convention on Biological Diversity.

Measures to green international supply chains will make critical contributions towards sustainable land-use and food systems, but they need to be embedded into a broader transformation strategy, as outlined in FABLE Pathways. Perhaps the largest levers for most importers of food and feed to reduce their international environmental footprint is domestic demand reduction through dietary shifts, reductions in food loss and waste, and sustainable intensification of domestic agriculture. Together, these supply- and demand-side levers will reduce the need for imports. Large importers, such as the EU and China, also have an incentive to promote sustainable policies in exporting countries. This provides an added motivation for the hosts of next year's UNFCCC and CBD COPs to pursue ambitious outcomes, including greater financial support for the transformation of land-use and food systems in exporting countries.

Next steps for the FABLE Consortium

In a short period of time, our global consortium of FABLE country teams has developed major analytical capacities on land-use and food systems, pioneered new tools, and strengthened the analytical capacity in 20 countries. We plan to focus upcoming work on the following priorities:

1. As part of the Food and Land Use Coalition, we will work with interested governments to support integrated strategies, including climate and biodiversity strategies under the Conventions, that address short-term pressures on land-use and food systems and are consistent with meeting long-term goals.

2. Through the new Food, Environment, Land, and Development (FELD) Action Tracker, we will advance a deeper understanding of how countries can design, implement, and monitor better policies to transform their land-use and food systems.

3. Partnering with the Food Systems Economics Commission and the Nature Map Initiative, we want to improve modeling tools to develop pathways and model policy options for land-use and food systems. This will include better integration of economic, biophysical and geospatial analyses.

4. The FABLE Consortium members want to train the next generation of analysts and policymakers in developing long-term pathways towards sustainable land-use and food systems, so that FABLE tools can be applied by any research group or government that would like to do so.

5. And finally, we will strengthen and expand the FABLE Consortium, including by welcoming new country teams.

1. Towards sustainable land-use and food systems in 2020

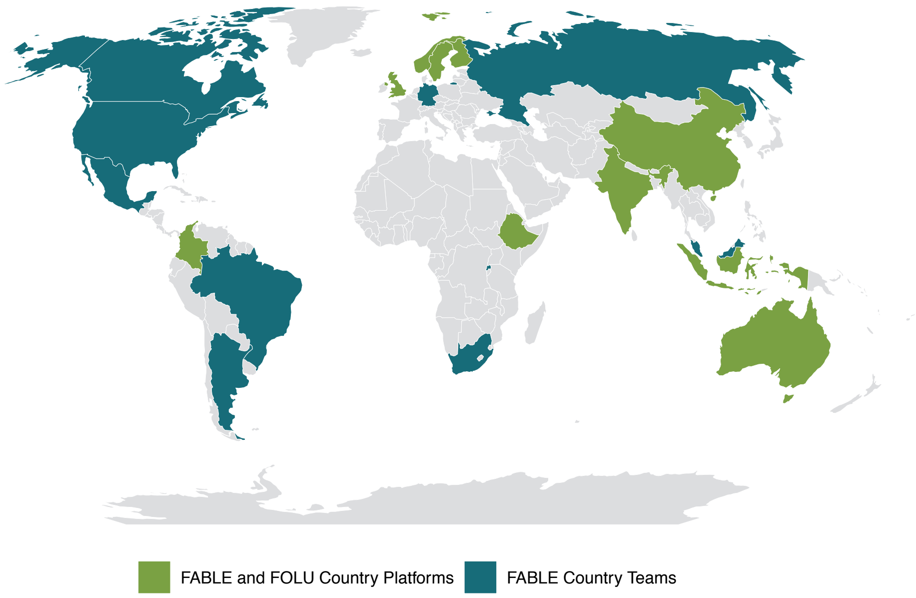
In 2020, the world has seen unprecedented environmental, social, and economic crises associated with land-use and food systems, but there have also been encouraging policy developments in major economies. Business as usual is not an option, but we are seeing the elements of possible turning points in the lead-up to 2021, which might become the "super year" for sustainable land-use and food systems. Countries need better analyses of land-use and food systems to develop policies that can meet the Sustainable Development Goals (SDGs) and the objectives of the Paris Agreement. The tools and long-term pathways developed by 20 country teams and presented in this second FABLE report support strategic approaches towards making land-use and food systems sustainable.

In this introduction we briefly review the state of land-use and food systems in 2020, including the impact of COVID-19, and describe major policy developments. We then outline the need for and use of long-term pathways towards sustainable land-use and food systems. The section concludes with an outlook on the "super year" 2021 for nature and climate.

1.1 Crises and positive momentum in 2020

The current geographic extent of land use, the large appropriation of multiple ecosystem services, and the loss of biodiversity are unprecedented in human history (Shukla et al., 2019). In 2020 the largest ever recorded wildfires swept across Australia, Siberia, the Amazon, and the western US. Another major coral bleaching event is

Figure 1 *Countries represented in the FABLE Consortium and the Food and Land Use Coalition (FOLU, Box 2)*



underway in the Pacific driven by global warming. A catastrophic locust plague has been decimating food supplies in East Africa, the Arabian Peninsula, and South Asia. In addition, the COVID-19 pandemic has not only caused massive human suffering and death, but it is also exacerbating the vulnerabilities of food systems, threatening livelihoods, undermining food security, and worsening environmental destruction (Box 1).

These crises were predicted, and they will get worse under business as usual (Díaz et al., 2019; Masson-Delmotte et al., 2018). The *Growing Better* report by the Food and Land Use Coalition (Box 2) shows that today's land-use and food systems generate large "hidden costs" in terms of poor health and malnutrition, environmental degradation, and threatened livelihoods, particularly among smallholder farmers. These hidden costs often exceed the value of all agricultural products produced in a region (FOLU, 2019). Moreover, the IPCC Special Report on Land (Arneth et al., 2019) and IPBES (Díaz et al., 2019) confirm that unsustainable land-use and food systems make countries increasingly vulnerable to environmental and social shocks. Unchecked climate change will make these shocks more severe and frequent and may – over time – lead to irreversible tipping points (Lenton et al., 2019). The Global Nutrition Report shows that for many poor and marginalized groups

Box 1 *Impact of COVID-19 on land-use and food systems*

The COVID-19 pandemic has major short-term and long-term consequences on land-use and food systems. As a result of the lockdowns and immediate consequences of COVID-19, the number of people suffering acute hunger is expected to rise significantly (WFP, 2020b). Over the medium term, the high economic cost of the disease (IMF, 2020) and falls in government spending might increase the number of extreme poor who earn less than $1.90 per day by up to half a billion people (Sumner et al., 2020). If these impacts materialize, COVID-19 would undo several decades of progress in reducing hunger and extreme poverty.

Another immediate driver of malnutrition are school closures around the world. Many children, including in some industrialized countries, depend on school meals for their caloric intake and health nutrition. The World Food Programme (WFP, 2020a) estimates that some 370 million children might have been affected during the first half of 2020. These deprivations risk irreversible damage to cognitive abilities and wellbeing (Development Initiatives, 2020) over the long term. They are compounded by expected increases in child deaths and maternal mortality rates through the direct and indirect impacts of COVID-19 (Roberton et al., 2020).

Over the short to medium term, some countries may face disruptions to food supplies owing to the impacts of lockdowns and – so far limited – trade restrictions imposed by some food exporters (Laborde et al., 2020). Livestock value chains have shown to be especially vulnerable to disruptions. Food importing countries in sub-Saharan Africa and elsewhere appear vulnerable to supply disruptions and rising prices, particularly in the face of major balance of payment crises (IMF, 2020). In parallel, the quality of diets may fall, as stretched production systems and supply chains struggle to deliver fresh vegetables and other highly perishable foods. If lockdowns persist then future planting seasons and harvests might be threatened.

In response to the economic damage wrought by COVID-19, we have seen a major loosening of environmental regulations and their enforcement in many countries. In particular, protected areas have seen sharp rises in land conversion, poaching, timber extraction, and illegal fishing, as park rangers go unpaid with declining revenues from tourism (Corlett et al., 2020). There is anecdotal evidence that some countries are trying to cushion the economic shock by accelerating the unsustainable extraction of natural resources.

Countries are deploying trillions of dollars to accelerate the economic recovery from COVID-19. So far, however, most investments in recovery are not "green", and hardly any funding has flown into nature-based solution or other green recovery programs targeting land-use and food systems (Vivid Economics & F4B, 2020). For this reason, the Food and Land Use Coalition is developing practical proposals for green recovery programs for land-use and food systems. FABLE tools described in this report can support the design of green recovery programs and ensure their alignment with long-term objectives, such as the SDGs and the Paris Agreement.

are likely to suffer even poorer nutrition, as high inequalities in today's food system are exacerbated (Development Initiatives, 2020).

Fortunately, 2020 also saw positive developments in a number of countries. They give us optimism that governments might support more ambitious policies for sustainable land-use and food systems. For example, in spite of the economic devastation caused by COVID-19, the European Union has held firm in its commitment to climate neutrality by 2050 and is in the process of increasing its ambition for 2030 through a comprehensive European Green Deal. With the Farm to Fork Strategy, this Green Deal includes a comprehensive blueprint for ensuring sustainable agricultural production through a reformed Common Agricultural Policy (CAP), the conservation and restoration of biodiversity under the Biodiversity Strategy, and sustainable and healthy diets – all governed by the Climate Law, which enshrines climate neutrality by 2050 in EU and national law. Farm to Fork emphasizes the need for sustainable agricultural trade and supply chains. While the recently enacted CAP reform does not meet high environmental standards, Farm to Fork provides an ambitious, comprehensive framework for sustainable land-use and food systems in the European Union that is fully aligned with key recommendations from the FABLE analysis (SDSN & IEEP, 2020).

In September 2020, President Xi Jinping announced in the UN General Assembly that China would achieve carbon neutrality before 2060 in line with the Paris Agreement. This is a major announcement from the largest emitter of greenhouse gas emissions. China's Minister for Ecology and Environment has subsequently made clear that this pledge also covers emissions from land-use and food systems and nature-based solutions. China is now revising its Nationally Determined Contribution and long-term climate strategy under the United Nations Framework Convention on Climate Change (UNFCCC), which presents an opportunity to put forward an integrated policy framework for climate, biodiversity, and food drawing on its strong spatial planning policies that will feature in the country's 14th Five-Year Plan (Box 3). As host of the 2021 COP15 of the Convention on Biological Diversity (CBD) in Kunming, China can of course play a critical leadership role in making land-use and food systems sustainable.

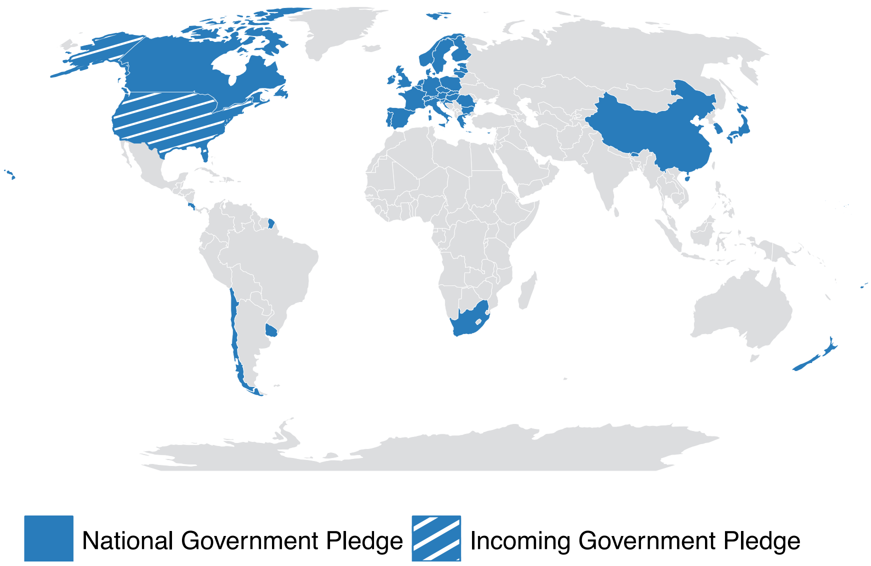
Box 2 *The Food and Land Use Coalition (FOLU)*

Established in 2017, the Food and Land Use Coalition (FOLU) is a community of organizations and individuals committed to the urgent need to transform the way we produce and consume food and use our land for people, nature, and climate. FOLU supports science-based solutions and helps build a shared understanding of the challenges and opportunities to unlock collective, ambitious action. FOLU builds on the work of the FABLE Consortium and its 20 country teams (Figure 1).

FOLU supports a growing community of country platforms, core partners, FOLU Ambassadors, and funders, connecting those who share the FOLU mission: to ensure land-use and food systems play their full role in delivering on the SDGs and the Paris Agreement to ensure the future prosperity of all people and to protect and restore our planet's vital ecosystems. FOLU brings together the public and private sectors, the research community and civil society, to harness expertise and enable systems thinking approaches.

FOLU core partners currently include Alliance for a Green Revolution in Africa (AGRA), EAT, Global Alliance for Improved Nutrition (GAIN), International Institute for Applied Systems Analysis (IIASA), Sustainable Development Solutions Network (SDSN), SYSTEMIQ, World Business Council for Sustainable Development (WBCSD), The World Farmers' Organization (WFO) and World Resources Institute (WRI). More information at www.foodandlandusecoalition.org

Figure 2 *Countries committed to net-zero emissions around mid-century, as of November 2020*



Source. Climate Home News (2020)

More recently, Japan and South Korea have also committed to full decarbonization of their energy systems by 2050. And US President-Elect Joe Biden has announced his intention to rejoin the Paris Agreement on his first day in office and to achieve zero net emissions by 2050. They all join a rapidly growing list of countries that have made similar commitments (Figure 2). All will need strategies to make their land-use and food systems sustainable, which in turn require long-term pathways as presented in this report (section 5 below).

We are encouraged by the growing commitment to net-zero greenhouse gas emissions by mid-century. These commitments force the question of how such ambitious objectives can be met in the land sector, which can deliver up to a third of the emission reductions needed for 1.5°C (Clark et al., 2020; Griscom et al., 2017) and is critical for climate change adaptation (Arneth et al., 2019).

Yet, these and other countries lack clear and robust strategies for meeting these objectives. Land-use and food systems are only poorly addressed in most national climate strategies (Fyson & Jeffery, 2019; Seddon et al., 2019), and countries do not present vital spatial information in their strategies (Khan & Schmidt-Traub, 2020). This gap must be urgently closed to turn the policy pledges into practical strategies for achieving net zero emissions and other SDGs related to sustainable land-use and food systems.

While deforestation has increased markedly in Brazil and seems on the rise in parts of Africa, other countries demonstrate that rates can be brought down. With one of the largest tropical forests, Indonesia has achieved the third consecutive year of falling deforestation rates and is on track towards achieving its ambitious climate strategy (NDC). The Government of Indonesia seeks to make the country a "Natural Capital Superpower", including by tapping into international carbon markets to finance nature conservation and restoration efforts. This commitment can set an important example for next year's CBD and UNFCCC COPs.

Building in parts on last year's IPBES report (IPBES, 2019) and the Living Planet Report (WWF, 2020), political attention to biodiversity has also risen tremendously. In September political leaders representing 77 countries and the European Union signed the Leaders Pledge for Nature, which commits to reversing biodiversity loss by 2030. More than 30 countries have come together under the High Ambition Coalition for Nature and People, which is chaired by Costa Rica and France, to support an ambitious post-2020 Biodiversity Framework.

None of these developments are a decisive breakthrough, and the data shows that the world remains off-track towards carbon neutrality by mid-century (UNEP, 2019), halting biodiversity loss (WWF, 2020) or making diets sustainable (Afshin et al., 2019). Yet, there is sufficient positive momentum now to enable breakthrough agreements next year. Success will require a shared method for problem solving.

1.2 Improvements to the FABLE method for problem solving

Countries need long-term pathways towards sustainable land-use and food systems for several reasons (FABLE, 2019). First, rigorous pathways can identify levers for action and demonstrate the feasibility of deep transformations of agriculture, biodiversity, other land-use, diets, and trade in agricultural commodities. Second, they are tools for bringing together different government ministries, private companies, civil society, indigenous peoples, and scientists to develop a shared vision of how to achieve sustainable land-use and food systems. Pathways help identify implementation challenges and unintended consequences that can be addressed by mobilizing the knowledge and experience of different expert communities and stakeholders. Finally, they help ensure that short-term policies are aligned with the long-term objectives of the SDGs and the Paris Agreement. Indeed, long-term climate and other goals can only be achieved by "back-casting" the future to identify and quantify the changes that must be made over the near term.

In this report we present first assessments of how vulnerable countries' food systems are to international supply and demand shocks such as COVID-19. We estimate the diversity of countries' trade and diversity in production using the Herfindahl-Hirschman Index (HHI). Higher concentrations suggest that countries are more vulnerable to shocks affecting individual commodities. Another measure, the Ratio of Self-Sufficiency (RSS), tracks the extent to which domestic consumption of a commodity can be satisfied through domestic production. It allows food importing countries to determine their dependency on imports.

Findings and tools presented in this report can help countries integrate land-use and food systems into national strategies. We do not provide any final answers to complex technical, political, and socio-economic questions, but our work will help articulate these questions more clearly, integrate the analysis across the full land-use and food system, consider the impacts of international trade, and determine how countries' individual approaches can deliver global sustainable development objectives. In other words, we propose a method for problem solving towards sustainable land-use and food systems. All FABLE country teams have now applied and adapted tools for modeling national and sub-national land-use and food systems that can help test different assumptions and scenarios for the future of land-use and food systems.

Since last year's report, the FABLE pathways have been thoroughly revised and improved by adding new goals, incorporating feedback from stakeholders (section 2), and considering the latest science. We are now confident that our countries can meet seemingly competing goals: food security, agricultural productivity, and environmental sustainability. Implementing the FABLE pathways will require more international cooperation to make international supply chains sustainable, improve the management of global commons, and raise the level of ambition in every country.

An important tool for integrated land-use and food systems policies is spatial design or planning that can balance competing demands on land for agriculture, nature conservation, ecosystem services, infrastructure, industry, urban development, and other needs. As one example, China is promoting land-use planning for sustainable land-use and food systems to meet ambitious biodiversity, food security, and other development objectives (Box 3). Such land-use design is necessary (but not sufficient) to make land-use and food systems sustainable, but it is rarely applied. No climate strategies under the UNFCCC contain actionable maps (Khan & Schmidt-Traub, 2020), and only 15% of national biodiversity strategies include actionable maps (Cadena et al., 2019). Of course, maps alone are not sufficient, but without them, countries' climate and biodiversity strategies cannot tackle the challenges of unsustainable land-use and food systems.

FABLE is therefore prioritizing the use and integration of maps into country pathways. This includes, for instance, land-cover and land-use maps, grid-level climate change projections, maps of low human density, key biodiversity areas, protected areas, and maps of intact forest landscapes to identify areas where natural processes currently predominate. In particular, FABLE country teams are collaborating with the Nature Map Consortium (IIASA, IIS, SDSN, UNEP-WCMC) that provides open-access global maps on biodiversity, carbon and other ecosystem services through the UN Biodiversity Lab (www.unbiodiversitylab.org). Countries can use these maps to develop and improve their own national maps, as illustrated be the case of Argentina and Mexico (section 5).

Box 3 *China's land-use planning for sustainable land-use and food systems*

With 18% of the global population and only 10% of arable land, China is highly vulnerable to loss of agricultural land and natural capital. Following major natural disasters and in view of the growing evidence of the rapid decline of biodiversity and ecosystem services (Gao, 2019; Ouyang et al., 2016) the country developed national and provincial spatial zoning plans that cover and integrate functional zones: critical ecological functions, agricultural production, and zones for industrial development and human settlements (NDRC, 2015). To strengthen coherence, these initially disparate spatial planning frameworks are now being consolidated by the Ministry for Natural Resources under a single, integrated land-use management plan for China to be incorporated into the 14th Five-Year Plan, which will take effect in 2021.

China's spatial planning frameworks include "redlines" that delineate areas for special protection or management. As one example, an agricultural redline identifies a minimum agricultural production space of 120 million hectares that must be maintained. Conversion of agricultural land within the agricultural redline is only possible if new agricultural land is brought under production elsewhere in the country.

China's Ecological Conservation Redline (ECRL) (Gao, 2019) puts about a quarter of terrestrial areas under some form of protection, based on rigorous mapping and prioritization of biodiversity and ecosystem services through a mix of top-down and bottom-up approaches (Gordon, 2019). Some of the most densely populated provinces have high proportions of land integrated into the ECRL, e.g. Beijing (26.1%) and Hebei Province (20.7%). Spatial patterns of priority ecosystem services identified through the scientific surveys also form the basis for urban master planning in many cities, such as Beijing and Guangzhou. Early lessons underscore the vital importance of consulting local populations in the land-use design (Gordon, 2019).

By coordinating the agricultural redline and the ECRL with other land-use planning frameworks, including for industry, mining, urban areas, and infrastructure, China can better identify and address land-use conflicts between economic, social, and environmental objectives. This provides the country with a comprehensive policy framework to promote nature-based solutions and make its land-use and food systems more sustainable. Lessons might be applicable to other countries grappling with the competing demands on scarce land.

Source. Adapted from Schmidt-Traub et al. (2020).

1.3 Making 2021 the "super year" for land-use and food systems

Next year will see three major international events on land-use and food systems. In September 2021, the UN Secretary-General will host the Food Systems Summit in New York. This will likely be followed in the fall by the COP15 of the CBD under Chinese Presidency in Kunming. The UK with support from Italy will host the UNFCCC COP26 in Glasgow in early November. If successful, each event can set the long-term direction and level of ambition on key dimensions of land-use and food systems.

To make 2021 the "super year" for climate and nature, breakthroughs are needed in three broad areas. First, the CBD COP15 needs to adopt a bold post-2020 Biodiversity Framework that sets out ambitious goals for the protection and restoration of nature. The zero draft (CBD, 2020) suggests that 30% of terrestrial and marine areas be placed under protection by 2030 to help bend the curve on biodiversity loss (Leclère et al., 2020). This proposed target sets out a minimum to be achieved at global levels. Similarly, the Food Systems Summit has an opportunity to build consensus around targets for healthy and sustainable nutrition, which can then help guide national dietary standards and implementation strategies.

Second, all three events must accelerate implementation of existing agreements, such as the Paris Agreement and the 2030 Agenda, including the SDGs as well as new goals. In the case of the climate convention this requires on the one hand increasing the level of ambition of NDCs (UNEP, 2019) and including land-use and food systems in climate strategies, which account for about a third of greenhouse gas emissions, but are inadequately considered in most NDCs (Fyson & Jeffery, 2019). Even if many NDCs have already been completed, there is scope for further improvements before the COPs and the critical 2023 stock-take under the Paris Agreement. On the other hand, countries should submit long-term low greenhouse gas emissions development strategies (LT-LEDS), as foreseen under Article 4.19 of the Paris Agreement, that chart out pathways towards net-zero emission by mid-century. Such LT-LEDS must cover land-use and food systems from both an adaptation and mitigation perspective.

Accelerating implementation is more complicated for the CBD. The CBD's objectives of biodiversity conservation, sustainable use, and fair benefit sharing can only be achieved by curbing the drivers of biodiversity loss, such as land-use change (chiefly through agriculture), infrastructure and urbanization, climate changes, and invasive species (Díaz et al., 2019). Yet with the exception of invasive species, all these drivers are outside the scope of the CBD and the environment ministers who attend the meetings. Moreover, the CBD lacks a robust country reporting framework along the lines of the Paris Rulebook.

For this reason, biodiversity needs to be "mainstreamed" into sector strategies. One promising way to achieve objectives under the CBD and UNFCCC, including climate change mitigation and adaptation, is to include biodiversity and nature-based solution in NDCs and LT-LEDS. In particular, this can be done by including maps for desired long-term land use into climate strategies, drawing inter alia on emerging experiences from China (Box 3). Such integration will overcome an unhelpful separation between climate and biodiversity strategies. And, critically, it can be undertaken voluntarily by countries without requiring any new negotiations. The FABLE country chapters in section 5 illustrate how maps can support this integration.

It is less clear how the Food Systems Summit can accelerate implementation towards sustainable diets, as the event does not have an intergovernmental mandate or infrastructure for country strategies and reporting. So perhaps like in the case of biodiversity, the Summit can make a major contribution by sharing best practice and urging the inclusion of healthy and sustainable diets in national biodiversity and climate strategies. Again, this FABLE report shows why this inclusion is so important and how it can be done.

Third and importantly, the 2021 conferences must mobilize additional financing and greater international solidarity in making land-use and food systems sustainable. Some developing countries need financial support to transform their existing land-use and food systems and to protect vital ecosystems. Most importantly, some countries need international support to enhance nutrition outcomes, particularly among children, to avoid crippling long-term cognitive impairment and to curb inequalities (Development Initiatives, 2020). The United Nations and other international organizations play a critical role in promoting and coordinating international solidarity at a time when many countries are inward-looking.

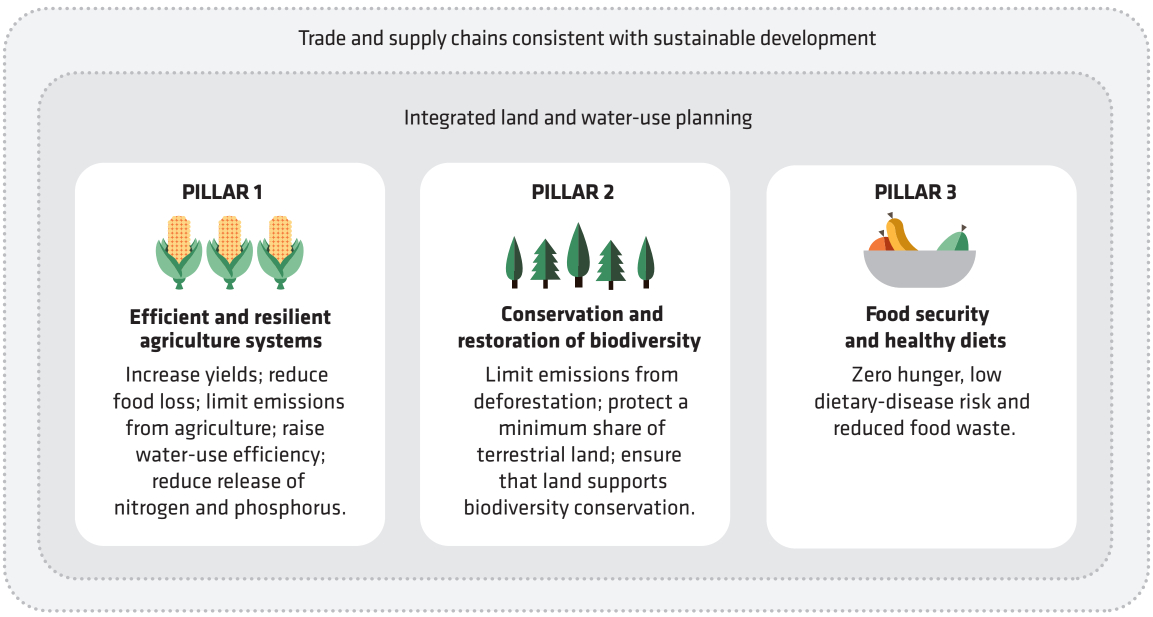
We are of course under no illusion about the difficulties in realizing these breakthroughs, but recent positive developments, particularly from the EU, China, and the US, open up a path towards breakthroughs at the international level. We also see strong demand in each of our countries for making land-use and food systems more sustainable. The motivations range from economic, social, to environmental concerns, but they all point towards the need for the same integrated pathways that we present in this report.

2. The FABLE approach to coordinated pathway design

The FABLE Consortium has identified three pillars for action to make land-use and food systems sustainable: (i) efficient and resilient agriculture systems, (ii) conservation and restoration of biodiversity, and (iii) food security and healthy diets (Schmidt-Traub et al., 2019) (Figure 3). Each pillar covers essential priorities for transforming land-use and food systems that require profound changes from business as usual practices. Each is equally important, and all are interdependent and synergistic. They must also operate over the near and long-term. Naturally, the pillars should be tailored to each country, take account of local constraints, and be complemented with local priorities.

The three pillars can guide the design of pathways and their implementation at local, national, and global scales. They are also consistent with the ten critical transitions identified in the Growing Better report by the Food and Land Use Coalition (FOLU, 2020). Pursuing them in an integrated manner will make critical contributions towards meeting the Sustainable Development Goals (SDGs) and the objectives of the Paris Agreement (Sachs et al., 2019).

Figure 3 *Three pillars for integrated land-use and food systems must be assessed in the context of integrated land-use planning and sustainable international supply chains (Schmidt-Traub et al., 2019)*



FABLE country teams have developed four steps for coordinating bottom-up national pathways to address national priorities, collectively achieve global sustainability objectives, and balance international trade in agricultural commodities (Figure 4). Our work proceeds in four steps:

1. **Global Targets** – the country teams jointly decide on global targets to be achieved collectively, and each country team applies them to its country context.

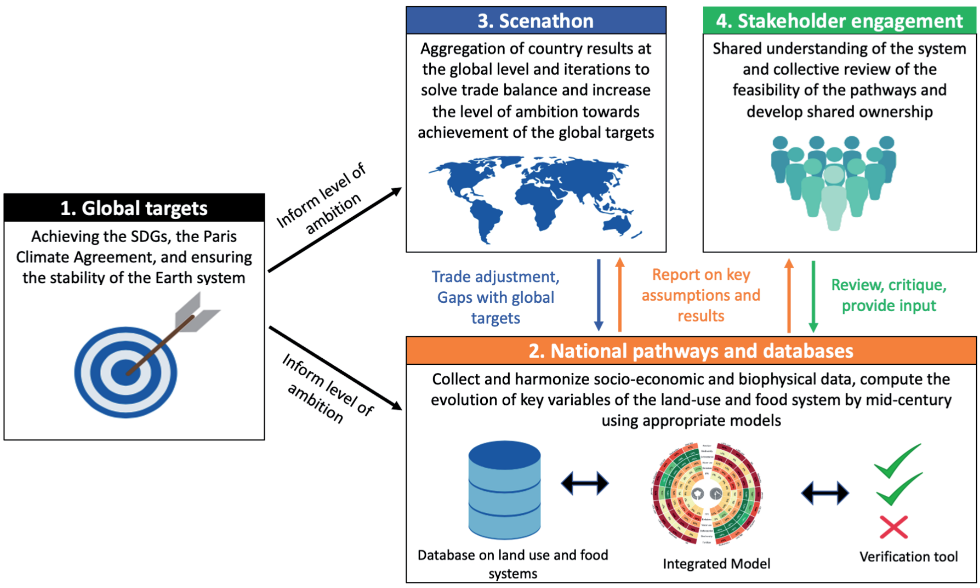
2. **National pathways and databases** – each FABLE country team integrates national data from many different sources and develops mid-century pathways towards sustainable land-use and food systems.

3. **Scenathon** – key parameters and results from the FABLE country pathways are aggregated to determine if the sum of national pathways meets the FABLE targets and to check for consistency in assumptions regarding imports and exports of agricultural commodities. Discrepancies are addressed through iterative refinements of national FABLE pathways.

4. **Stakeholder engagement** – throughout, FABLE country teams consult stakeholders to test and refine assumptions, support a shared understanding of land-use and food systems, and develop shared ownership of the results.

These four steps along with our methodological advancements since the 2019 FABLE Report (FABLE, 2019) are described in detail in the remainder of this section.

Figure 4 *Step-by-step methodology for coordinated national pathways consistent with global sustainability objectives*



2.1 Step 1: Agree on global targets

In a first step, each country team needs to set long-term targets for sustainable land-use and food systems, consistent with achieving the SDGs, meeting the objectives of the Paris Agreement, and ensuring the stability of the Earth system (Rockström, Steffen, Noone, Persson, Chapin III, et al., 2009). Such targets are critical to set the level of ambition, drive coherence, and ensure short-term policies are consistent with the long-term transformation (Sachs et al., 2019). There are many ways to apply global targets at the national level, taking account of fairness principles for burden sharing arrangements, vulnerability to environmental change, ability to finance transformations, poverty levels, and other development needs (Leach et al., 2018), as applied for greenhouse gas emissions (UNEP, 2019). Since there is no universally agreed top-down method for assigning national targets, all FABLE country teams commit to meeting the global targets jointly (Table 1), and each team sets its own national targets. These national targets can successively be aligned with global goals through an iterative process described in step 3 below.

The choice of global FABLE targets is guided by four principles. First, we propose as few targets as necessary to cover the three pillars of sustainable land-use and food systems while avoiding unnecessary complexity. Second, we focus on mid-century targets that can guide the transformation towards sustainable food systems and land use. Third, we use science-based targets drawing on the latest literature and give priority to targets that have been agreed by the international community. Finally, we frame targets in ways that enable them to guide policymaking at local, national, regional, and global levels.

2.1.1 Land and biodiversity

The SDGs contain the Aichi Targets for conservation of biodiversity and ecosystems. These include a minimum of 17% of the terrestrial surface area under protection for conservation by 2020. A new conservation target is currently under negotiation under the CBD. Following the release of the CBD's zero-draft of the post-2020 Biodiversity Framework, we have revised our biodiversity targets. Specifically, they now aim to achieve "no net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate" and ensure that "protected areas cover at least 30% of land by 2030". Moreover, as in our 2019 FABLE Report, we also aim to achieve a third target on zero-net deforestation, meaning that forest gain should at least compensate for forest loss at the global level by 2030.

FABLE supports area-based conservation targets. There is considerable debate about the dimension and effectiveness of such area-based targets and the extent to which the focus should be placed on complementary or alternative targets (Ellis, 2019; Joppa & Pfaff, 2009, 2011). While monitoring biodiversity conservation based on species extinction rates more accurately captures losses, habitat for biodiversity must be conserved to avoid further extinctions and maintain nature's capacity to provide Earth system and ecosystem functions.

We use the term "land where natural processes predominate" to more accurately reflect what the targets and associated indicators measure. The term is taken from Jacobson et al. (2019) who describe low-impact areas as "areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes, or faunal assemblages". For this report, we use the union of the following datasets as an indicator of the baseline state of areas where natural processes predominate: Low Impact Areas (Jacobson et al., 2019), Intact Forest landscapes (Potapov et al., 2017), and Key Biodiversity Areas (BirdLife International, 2019). These datasets were selected based on a comparison by Consortium members of the reliability for conditions in their country of several, recent globally consistent spatial datasets that attempt to identify places with high levels of biological activity and/or low levels of human disturbance (Kennedy et al., 2019; Newbold et al., 2016; Venter et al., 2016)(for full comparison details, see Annex 1).

Table 1 *Global targets formulated by the FABLE Consortium by target domain*

TARGET DOMAIN		TARGET FORMULATION	SUPPORTING DOCUMENTS
Land and Biodiversity	Land where natural processes predominate	**A minimum share of earth's terrestrial land supports biodiversity conservation.** *No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate.*	Dinerstein et al.(2017) ; Jacobson et al. (2019) ; Noss et al. (2012) ; Wilson (2016)
	Protected area	**A minimum share of Earth's terrestrial land is within protected areas.** *At least 30% of global terrestrial area by 2030*	Aichi Target 11; Maron et al. (2018)
	Zero net deforestation	**Zero net deforestation.** *Forest gain should at least compensate for the forest loss at the global level by 2030*	Aichi Target 5; SDG 15; Maron et al. (2018); New York Declaration on Forests (NYDF) (2019)
Greenhouse gas emissions from AFOLU	GHG from Agriculture	**Greenhouse gas emissions from crops and livestock** *compatible with keeping the rise in average global temperatures to below 1.5°C, which we interpret as below 4 $GtCO_2e$ yr^{-1} by 2050 (3.9 Gt for non-CO_2 emissions and 0.1 Gt for CO_2 emissions)*	Hadjikakou, Bowles, & Bryan (in preparation)
	GHG from LULUCF	**Greenhouse gas emissions and removals from Land-Use, Land-Use-Change, and Forestry (LULUCF)** *compatible with keeping the rise in average global temperatures to below 1.5°C. Negative global greenhouse gas emissions from LULUCF by 2050*	Griscom et al.,(2017); Popp et al.,(2017); Rogelj et al., (2018)
Food security	Zero hunger	**Zero hunger.** *Average daily energy intake per capita higher than the minimum requirement in all countries by 2030*	SDG 2, Laborde et al. (2016); Springmann et al. (2016)
	Low dietary disease risk	**Low dietary disease risk.** *Diet composition to achieve premature diet related mortality below 5%*	Afshin et al.(2019); Willett et al. (2019)
Freshwater use	Freshwater use	**Water use in agriculture** *within the limits of internally renewable water resources, taking account of other human water uses and environmental water flows. Blue water use for irrigation <2453 km^3yr^{-1} (global estimates in the range of 670-4044 km^3yr-1) given future possible range (61-90%) in other competing water uses*	Hadjikakou et al., (in preparation)
Nitrogen and Phosphorus release	Nitrogen release	**Nitrogen release from agriculture within environmental limits.** *N use <69 Tg N yr^{-1} total Industrial and agricultural biological fixation (global estimates in the range of 52-113 Tg N yr^{-1}) and N loss from agricultural land <90 Tg N yr^{-1} (global estimates in the range of 50-146 Tg N yr^{-1}) by 2050*	Hadjikakou et al., (in preparation)
	Phosphorus release	**Phosphorus release from agriculture within environmental limits.** *P use <16 Tg P yr^{-1} flow from fertilizers to erodible soils (global estimates in the range of 6.2-17 Tg P yr^{-1}) and P loss from ag soils & human excretion <8.69 Tg P yr^{-1} flow from freshwater systems into ocean by 2050*	Hadjikakou et al., (in preparation)

Our protected area target is supported by ecologically robust species-area relationships that suggest that the Aichi Target for conservation are insufficient and will lead to the extinction of thousands of species (Roberts et al., 2020). The authors (Roberts et al., 2020) call for higher coverages of intact and restored ecosystems inside protected areas and estimate that such ecosystems need to cover at least 30% of terrestrial land to halt biodiversity loss. The CBD zero-draft also proposes that 30% of land and sea areas should be protected. Aiming for the protection of 30% of land is substantially more ambitious than Aichi target 11, which was the basis of our 2019 target. We used the ecoregion boundaries (Venter et al., 2016) to implement the protected areas expansion target in the FABLE Calculator in order to reflect regionally unique biological qualities and allow countries to consider differences in status and potential actions required to conserve biodiversity at the ecoregion level. In both the FABLE Calculator and the Model of Agricultural Production and its Impact on the Environment (MAgPIE) land-use model (Dietrich et al., 2019), the area of land where natural processes predominate decreases with the loss of forest or other natural land and increases when agricultural land is abandoned.

Most countries have national forest management standards and objectives. However, only a subset of countries has implemented ambitious standards successfully. Forest target formulations on the global level is a more recent phenomenon. We use a zero-net forest-cover-loss target by 2030 which has its beginning with the quantitative assessments around the WWF's Living Forest Report (WWF, 2015). This report provided additional forest conditions for the definition of forests to ensure the ecological integrity of the target, for example, ruling out fast growing plantations. Subsequently, the zero net deforestation target by 2030 has been included in the SDGs (Target 15.3) and the New York Declaration on Forests (NYDF Assessment Partners, 2019).

In addition, we recognize the importance of agroecological farming and agricultural landscape complexity for conserving biodiversity and maintaining crucial ecosystem services both to and from agriculture (Bommarco et al., 2013; Kremen et al., 2012; Kremen & Miles, 2012; Rosa-Schleich et al., 2019; Rusch et al., 2016; Tscharntke et al., 2005, 2012). While there is currently no globally consistent spatial data available on agricultural management practices (organic, conventional, tillage practices, local crop diversity, agrochemical applications), higher levels of natural habitat in agricultural landscapes can be used as an indicator of more biodiversity-friendly farming contexts (Garibaldi et al., 2020). We use the proportion of natural or semi-natural vegetation in cropped areas as a measure of cropland landscape complexity and set the percentage of natural or semi-natural vegetation required to support biodiversity and ecosystem functioning to at least 10% within a ~1x1km window as proposed by Willett et al. (2019). This is a first step towards the consideration of a FABLE target on biodiversity-friendly agriculture in the future.

2.1.2 GHG emissions from AFOLU

The FABLE target for greenhouse gas emissions must be compatible with the ambition of the Paris Agreement to keep global warming to "well below 2°C and to pursue efforts to limit the temperature increase even further to 1.5°C" (UNFCCC, 2015). We interpret this target to require staying within 1.5°C of global warming, since the additional risks of 2°C warming are now understood to be high, particularly for land-use and food systems (Arneth et al., 2019; Masson-Delmotte et al., 2018).

There is general agreement that global human-induced CO_2 emissions will need to reach net zero levels by mid-century if global warming is to be limited to 1.5°C (Masson-Delmotte et al., 2018). Informed by new scenario ensembles (Huppmann et al., 2018; Roe et al., 2019), the FABLE Consortium therefore aims for a maximum of 4 Gt CO_2 in non-CO_2 and CO_2emissions from crops and livestock by 2050. We identify a separate target for emissions from land-use, land-use change and forestry (LULUCF). The viability of negative emission technologies and the extent to which these will be required to offset residual emissions across sectors in order to meet the 1.5°C target is the subject of scientific debate

(Griscom et al., 2017; Popp et al., 2017; Rogelj et al., 2018). The FABLE Consortium accounts for this uncertainty by setting a global target of net-negative emissions from LULUCF by 2050.

To summarize, the FABLE Consortium aims to achieve two GHG emission targets for the AFOLU sector:

1. GHG emissions from crops and livestock below 4 Gt CO_2e/year by 2050 (3.9 Gt for non-CO_2 emissions and 0.1 Gt for CO_2 emissions)
2. Net-negative GHG emissions and removals from Land-Use, Land-Use-Change, and Forestry (LULUCF) by 2050.

2.1.3 Food security

SDG 2 calls for ensuring food security by 2030. This target is, therefore, a core objective for the FABLE analysis. As this stage, our tools are unable to capture the distribution of food security within a population. Therefore, for the time being, our food security targets focus on average values. Specifically, the FABLE target for food security requires that the excess in the average daily energy intake per capita exceed the minimum daily energy requirement (MDER) (Cafiero, 2014) in all countries by 2030. National MDERs reflect the structure of the population by age class, sex, and activity level.

A second dimension of food security is the nutritional quality of diets, which in turn affects their environmental impacts. In this report, we compare our projections on future diets with the EAT-Lancet report (Willett et al., 2019) and the recommended intake of fats and proteins. In the future, we also will aim to add a target on low dietary disease risk by 2050, based on the recommendations of the Global Burden of Disease Collaboration (Afshin et al., 2019).

2.1.4 Freshwater use

Human activities have largely appropriated freshwater globally both by disrupting the flow of freshwater systems with dams used for hydropower and storing water for human consumption and irrigation (Grill et al., 2019). Irrigation water accounts for nearly 80% of freshwater use (Foley et al., 2011). This appropriation has severe impacts on natural ecosystems including the loss of wetland, delta, and freshwater ecosystems (Foley et al., 2011; Vörösmarty et al., 2010).

Therefore, for the first time, the 2020 FABLE pathways include a global target for water use. Drawing from the literature (Campbell et al., 2017; Hejazi et al., 2014; McIntyre, 2009; Rockström, Steffen, Noone, Persson, Chapin, et al., 2009; Steffen et al., 2015; Tallis et al., 2018; UNCCD, 2017; Wada & Bierkens, 2014), we set a planetary boundary target of consumptive blue water use in agriculture of 2,453km^3 per year in 2050. This target derives from accounting for the possible trajectories in the share of agriculture versus industry and domestic water use. Other global estimates are in the range of 670-4,044 km^3 per year. Blue water is water that has been sourced from surface or groundwater resources (Hoekstra et al., 2012). Consumptive blue water use accounts for any returns to the environment and provides a metric of net use of water resources (as opposed to withdrawals).

This global target has several limitations. Water management is mainly relevant at the local level, therefore meeting the global target can hide unsustainable water use in some basins. Moreover, using an annual average ignores seasonal water scarcity. It is estimated that nearly half the global population already lives in areas that are potentially water scarce for at least one month per year and that this number could increase to some 4.8–5.7 billion in 2050 (Burek et al., 2016).

2.1.5 Nitrogen and phosphorus release

Nutrient flows into freshwater and marine ecosystems have severe environmental consequences (Rockström, Steffen, Noone, Persson, Chapin III, et al., 2009; Steffen et al., 2015; Stevens, 2019). Curbing them has therefore been recognized as a key priority in the SDGs (Target 14.1). We recognize that so-called planetary boundaries (Rockström, Steffen, Noone, Persson, Chapin III, et al., 2009; Steffen et al., 2015) for nitrogen and phosphorous have been challenged by some (Carpenter & Bennett, 2011; De Vries et al., 2013). Still, in the absence of alternative boundaries we use the 2015 proposal by Hadjikakou et al. (in preparation).

2.2 Step 2: Develop national pathways

2.2.1 Developing alternative pathways

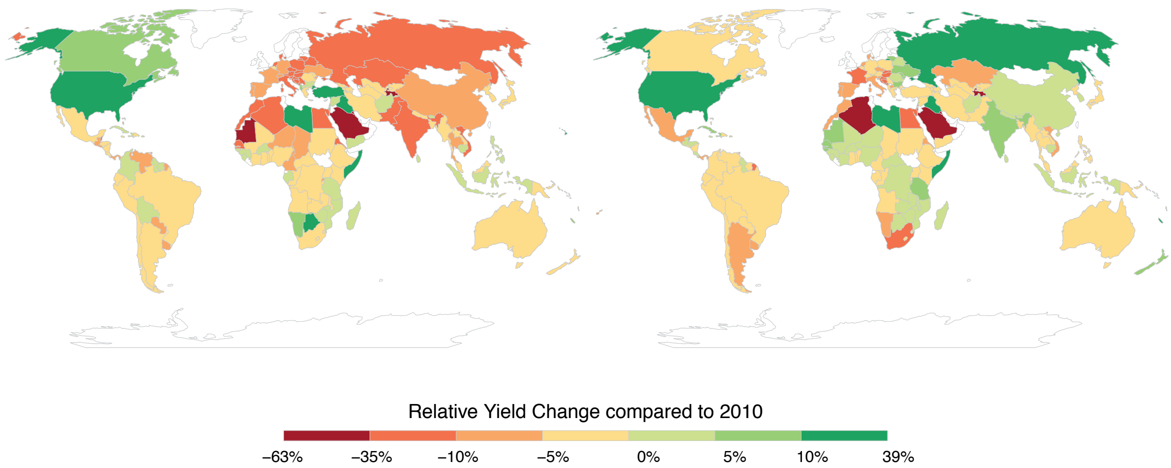
In this report, each FABLE country team presents and compares at least two pathways. Their Current Trends and Sustainable Pathways correspond, respectively, to the lower and higher boundary of realistic action to reach sustainable development objectives in relation to land-use and food systems. This allows country teams to illustrate the impact of ambitious strategies compared to a business-as-usual approach. The national pathways for all FABLE countries are described in the country chapters in section 5 and the aggregated global results are presented in section 3.

In addition to these two pathways, six FABLE country teams (Brazil, Canada, Germany, Sweden, the UK, and the US) present a third pathway with an intermediate level of ambition. We therefore refer to the three pathways in these chapters as: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition. Nearly all FABLE countries developed their national pathways using the FABLE Calculator (Mosnier et al., 2020). The FABLE country team in India used the MAgPIE land-use model (Dietrich et al., 2019).

2.2.2 Inclusion of climate change impacts

Another addition of our 2020 analysis is the inclusion of climate change impacts on national pathways by 2050. We drew on publicly available data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Frieler et al., 2017; Warszawski et al., 2014), which gathers climate-impact modelers from around the world. Using a common set of climate impact data and other data necessary to ensure consistent impacts simulations

Figure 5 *Average corn yield change by country in 2050 compared to 2010 in the Current Trends (left) and in the Sustainable Pathways (right)*



Note. Projections forced with crop model GEPIC, GCM HadGEM2-es without CO2 fertilization effect. Countries in white have no simulated values for corn yield with GEPIC. The Current Trends Pathway corresponds to RCP 6.0; the Sustainable Pathway corresponds to RCP 2.6.
Source. Authors' computation based on data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Frieler et al., 2017; Warszawski et al., 2014), and IFPRI's Spatial Production Allocation Model (SPAM) (International Food Policy Research Institute, 2019)

across sectors, ISIMIP provides data on climate change impacts on annual crop productivity, and in some cases water use and fertilizer use, at 50x50 km resolution, for the period 2000 to 2100.

This year's national pathways are embedded in global GHG concentration trajectories. Current Trends Pathways use a global GHG concentration trajectory that would lead to a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures by 2100 (RCP 6.0). The Sustainable Pathways use a global GHG concentration trajectory that aims to keep global warming likely below 2°C above pre-industrial temperatures by 2100 (RCP 2.6) (van Vuuren et al., 2011).

All the countries using the FABLE Calculator used national averages of the climate change impacts estimated by the crop model GEPIC for 4 crops (corn, rice, soy and wheat) using climate estimates from the model HadGEM2-es, without CO_2 fertilization effects. Impacts of climate change are included in the FABLE Calculator as national averages of the relative changes in crop yields (Figure 5), fertilizer use, and water use (Mosnier et al., 2020). In the MAgPIE model, climate impacts on crop yields (rainfed and irrigated), carbon densities of natural vegetation (vegetation, litter and soil carbon pools), and surface freshwater availability are included at the level of the spatial clusters (Dietrich et al., 2019). This should be seen as a first attempt to take climate change impacts into account. Future work should emphasize the uncertainties around these estimates by using a larger ensemble of crop and climate models.

2.2.3 Other improvements to the FABLE Calculator

Since our 2019 FABLE report, we made several important improvements to the FABLE Calculator. These include:

- ***Biofuels:*** Many countries have established biofuel mandates with the aim of reducing their GHG emissions. However, studies have shown that, in some cases, higher biofuel demand might increase global GHG emissions (Mosnier et al., 2013; Plevin et al., 2015; Searchinger et al., 2008). Biofuels are now represented in the FABLE Calculator as an additional demand for crops and vegetable oils.

- ***Protein and fat intake:*** Proteins and unsaturated fats (plant-based oils) are key nutrients for human health (e.g. legumes, pulses, unsaturated fats such as olive oil or palm oil). The types and quantities of fats and proteins consumed have particularly significant impacts on human health and several environmental variables. Over-consumption of animal protein and fat is an important driver of disease risk, notably cardio-vascular disease risk, whereas transitions to plant-based proteins and oils would significantly lower this risk. Therefore, the FABLE Calculator now monitors the evolution of protein and fat intake, both in terms of quantity and source.

- ***Food waste:*** The FAO database does not include statistics on food loss at the consumption level (i.e. during distribution and at the household level). In our 2019 report, we assumed that losses currently represent 10% of total consumption. For this report, we included different shares of consumption-based losses by food group and by large regions (based on FAO, 2011) in the FABLE Calculator.

- ***Alternative levels of post-harvest losses in the future:*** Post-harvest losses (i.e. during storage and transportation) are especially large in low-income regions due to improper harvesting methods, poor storage, and the lack of infrastructure and refrigerated transport (Kiaya, 2014). We included alternative scenarios for reducing the share of post-harvest losses to reflect potential improvements in these domains.

- ***Separated food group for nuts:*** The EAT-Lancet report (Willett et al., 2019) recommends consuming 50 g of nuts and seeds (0-75 g range) per day. The Global Burden of Disease

Collaborative suggests a minimum value of 20 g per day and estimates global consumption at 2.5 g per day on average. In order to better account for the potential implications this could have on land-use and food systems at the national and global levels, we created a new food group in the FABLE Calculator to separate nuts from other food categories.

- ***Indicators on the resilience of the food system:*** The COVID-19 crisis exposes the fragility of food and land use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. In this report, we examine two indicators to gauge countries' resilience to agricultural trade and supply disruptions: the rate of self-sufficiency and diversity of agricultural production and trade.

2.2.4 Automatic verification of key model parameters and results

To facilitate the identification of potential weaknesses or mistakes, we verify country pathways based on key model parameters and variables. These verifications use a "traffic light" system (Figure 6) to indicate a technical problem that needs to be solved before the next iteration of the Scenathon.

Assumptions regarding the evolution of crop and livestock productivity are especially difficult to assess but are critical to our pathways. Therefore, we began to systematically compare crop yield projections with the FAO's "Food and agriculture projections to 2050" report and the Global Yield Gap Atlas (GYGA) database (Grassini & van Ittersum, 2020). In some cases, we found that our yield assumptions were too optimistic. Country teams were encouraged to revise their assumptions except when they were supported by further evidence. In the future, we would like to expand this database on benchmarks for productivity projections to cover both crops and livestock, integrating, for instance, expert knowledge from national crop and livestock research centers and CGIAR.

2.3 Step 3: Scenathon to ensure globally consistent national pathways

If developed in isolation, national FABLE pathways tend to suffer from two inconsistencies. First, the level of ambition of the sum of national pathways does not reach global FABLE targets, such as greenhouse gas emissions consistent with 1.5°C, because country teams conclude that other countries can more easily reduce emissions. A central purpose of the FABLE Consortium is to ensure consistency between the ambition of national pathways and global targets.

Projected trade flows can introduce a second source of inconsistency across national FABLE

Figure 6 *Traffic light system for verification of the model parameters and results*

RED: There is an imbalance, impossible value, or large difference between computed variables and historical values or other benchmark values for which a solution must be found.

YELLOW: There is a moderate difference between computed variables and historical values or other benchmark values which need to be reviewed.

GREEN: No problems have been identified.

pathways. If looked at in isolation, country pathways may lower the environmental footprint of their domestic agricultural production through increased imports, but other countries may not be in a position to generate the corresponding volume of exports. Conversely, major increases in agricultural productivity and reductions in food loss and food waste may allow countries to increase agricultural exports, but there may not be a commensurate increase in demand for imports from other countries. For these reasons, FABLE country teams compare trade projections to identify and address inconsistencies for each commodity.

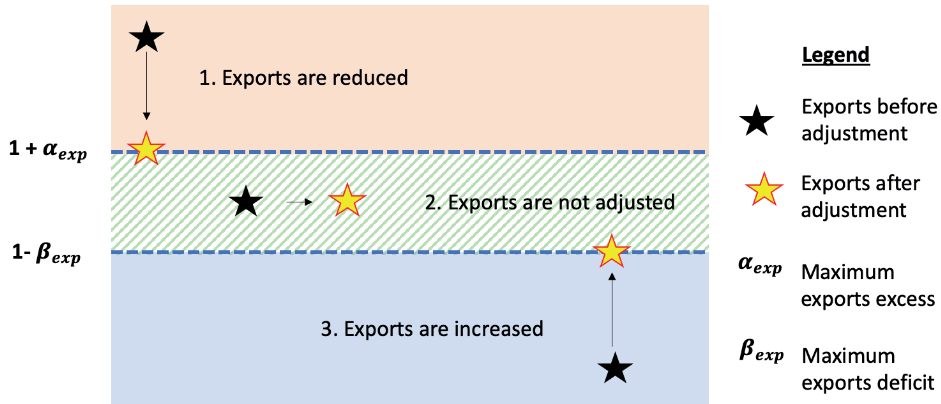
The FABLE Consortium has developed the "Scenathon" process to ensure national-global consistency of pathways. A Scenathon consists of iterative coordinated submissions of FABLE pathways from all country teams plus the rest of the world regions using a standardized reporting worksheet. Country teams can participate in the Scenathon using different models as long as the tools provide the information required for each country's reporting worksheet. For the 2020 Scenathon, we used two models - the FABLE Calculator and MAgPIE.

Each Scenathon consists of several iterations and each iteration has two rounds. In the first round, trade is defined by each country's own assumption about the evolution of its exports and imports. In the second round, national pathways are constrained by trade quantities that are consistent at the global level. The FABLE country teams monitor the collective progress toward achieving the global FABLE targets in each round and, if necessary, try to increase their level of ambition during the next iteration.

For our 2020 pathways we refined two key aspects of the methodology for adjusting trade flows in national pathways. While in 2019 we adjusted either imports or exports that were in excess depending on imbalances at the global level, we now only adjust exports. In other words, we assume that exports will adjust to the level of imports estimated by each pathway. Second, we changed our calculation method to correct trade imbalances based on the historically reported trade imbalances for each commodity (Figure 7).

The Scenathon results can be monitored on the online Scenathon dashboard, which covers all FABLE targets and visualizes the contribution of each country pathway to each global target and in global trade flows. The Scenathon dashboard is publicly available at the following address: [https://www.scenathon.org/pgepublicscen20].

Figure 7 *Methodology to adjust exports during the Scenathon 2020*



2.4 Step 4: Stakeholder engagement to test assumptions and build buy-in

Many stakeholders, who may legitimately have divergent interests and limited experience in working together, are involved in and affected by changes to land-use and food systems and efforts to make them sustainable. These include numerous government departments, indigenous communities, business sectors ranging from smallholder farmers to large multinational corporations, local and international civil society organizations, the general public, and many scientific disciplines. Participatory engagement science (Leach et al., 2018) demonstrates that they need to be engaged in the design and implementation of the transformation, in order to build buy-in (Sachs et al., 2016), anticipate and resolve challenges in the design and implementation of the transformation, particularly with regards to equity (Leach et al., 2018) and other trade-offs (Sachs et al., 2019). This requires modeling approaches to be transparent and well communicated to ensure they are not seen as opaque, technocratic, or based on unrealistic assumptions.

To ensure the acceptability and use of our pathways, each FABLE country team therefore engages with national experts and stakeholders on developing and refining national pathways and the underlying tools. For example, the UK country team convened a stakeholder forum with various government departments, devolved administrations, and other stakeholders to review initial findings, identify knowledge gaps, and explore how policy reforms could chart a course toward sustainable land-use and food systems (Box 4). Country teams in Australia, India, Mexico, and the Nordic regions have organized consultations on emerging findings with business, civil society, and government representatives, which has led to significant improvements in the assumptions and modeling underlying their pathways.

Box 4 *The UK FABLE team's stakeholder engagement*

The UK FABLE team from the UK Centre for Ecology & Hydrology and the University of Oxford held a successful stakeholder consultation exercise between the 2019 and 2020 Scenathons. This is an important time for UK land-use and environmental policy, as the UK has recently committed to net zero emissions by 2050; while agricultural subsidies and environmental policies are being fundamentally reviewed following our exit from the European Union.

We created a 2-page flyer summarizing the FABLE approach and preliminary findings for the UK, and sent this to key policy-makers from UK government, the devolved regions (Scotland and Wales), UK Research and Innovation (the main public research funding organization) and expert researchers from the Royal Society and the Royal Academy of Engineering. These stakeholders were invited to a round-table forum in London on 8th October 2019. We presented results from the 2019 Scenathon and held structured discussions to establish how FABLE could address UK policy needs, and to explore how we could collaborate to enhance and extend our analysis.

Following the workshop, we circulated a draft document of our initial assumptions for the Current Trends and Sustainable Pathways in the 2020 Scenathon and gathered feedback from stakeholders via email and an online workshop on 10th February 2020. Suggestions for key policy documents or data sources that could help to inform the selection of suitable parameters were also requested. Further iteration with stakeholders via email between February and April 2020 enabled us to co-design our pathways, so that they are aligned with policy needs. Stakeholders also identified priorities for enhancing the UK FABLE model, including moving to spatially-explicit predictions. Options for technical implementation of this next phase of work were explored through a 1-month secondment to the FABLE team from the UK government's Department of Environment, Food and Rural Affairs (DEFRA) in March 2020.

Stakeholders felt that the integrated modeling of land-use taking account of trade and global environmental targets was a major strength of FABLE, as it emphasizes links between the UK and other countries' emission reduction ambitions. It enables exploration of the trade-offs and challenges associated with the major land-use change needed to deliver the UK's net zero target, whilst simultaneously meeting our biodiversity and other environmental commitments.

3. Global FABLE results

In this section, we present the global results of the national and regional Current Trends and Sustainable Pathways. For the aggregate FABLE Sustainable Pathway, we take into account all Sustainable Pathways or the Sustainable High-Ambition Pathways for Brazil, Canada, Germany, Sweden, the UK, and the US. Below we provide a brief description of the choices on national drivers that countries have made in defining their respective scenarios. We then present the global results for each FABLE target (section 2.1). Country pathways are presented in section 5 (National pathways).

3.1 Overview of assumptions and achievement of FABLE targets across pathways

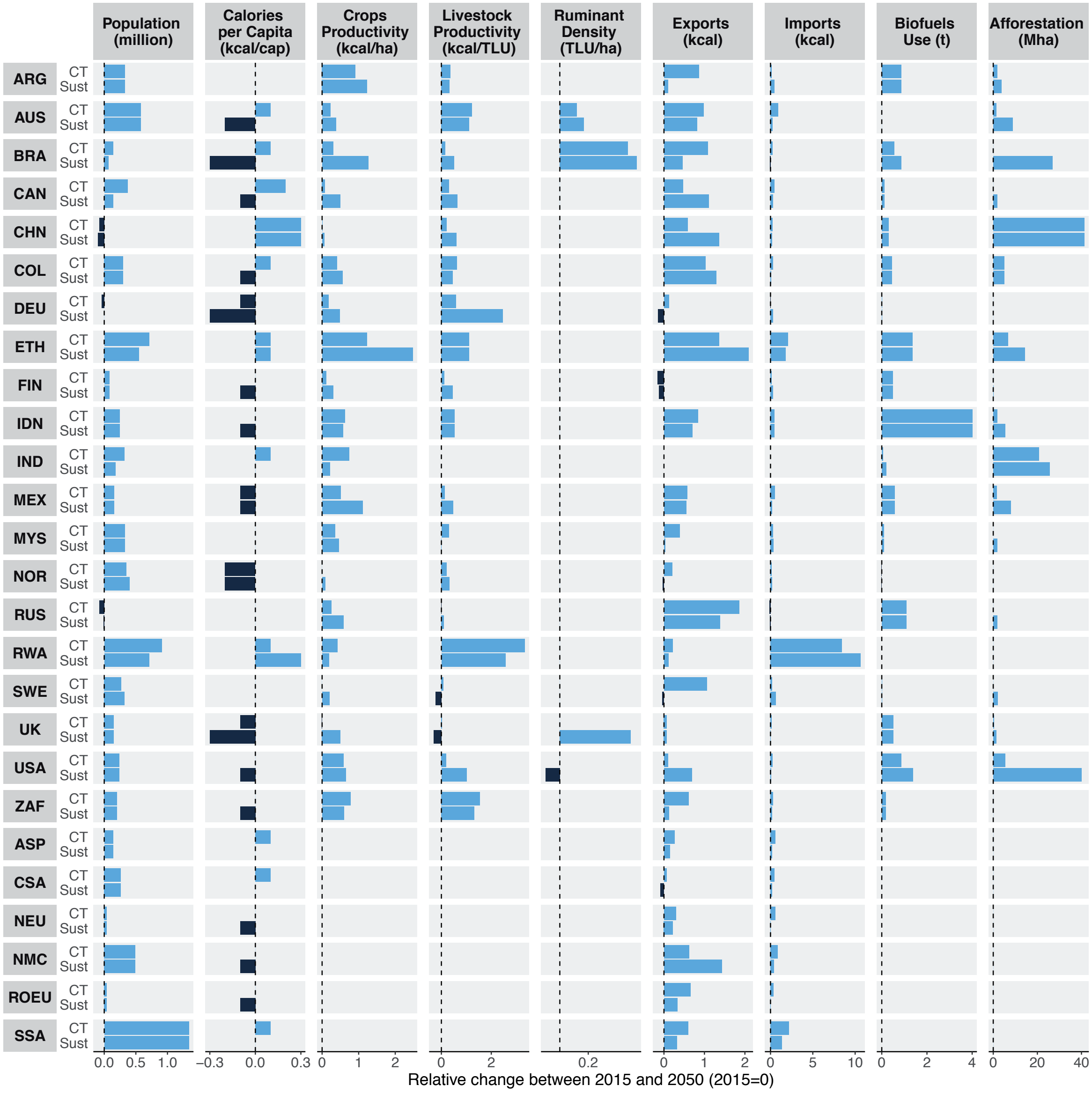
Table 2 provides an overview of the key scenarios[1] that the FABLE country teams selected to develop their Current Trends and Sustainable Pathways. Scenarios provide alternative values for some parameters of the model before computation and reflect the key assumptions that form the basis of their respective pathways. Assumptions are shown as relative changes between 2015 and 2050 for each key driver, which makes them easily comparable. Box 5 presents the list of parameters that can be changed through scenarios in the FABLE Calculator and MAgPIE.

Another important assumption that is not summarized in Table 2 relates to the constraints on agricultural land expansion. For example, in their Current Trends Pathways, Argentina, Colombia, and Malaysia stopped forest conversion to any other land use after 2030. Australia, Germany, Mexico, Norway, and South Africa prevented any agricultural land expansion beyond currently farmed areas, while China prevented the reduction of cropland area below the currently farmed area. In the Sustainable Pathways, forest conversion to any other land use is also reduced to zero in Brazil, Canada, Indonesia, and Rwanda after 2030, and agricultural land expansion is prevented in Argentina, Ethiopia, Malaysia, and Russia.

Table 3 summarizes the achievement of each FABLE target under the Current Trends and Sustainable Pathways. While some targets are met in both pathways, the zero net deforestation and GHG emissions from the LULUCF targets are only achieved in the Sustainable Pathway and one of the two biodiversity targets is not met in either. Similarly, the target on GHG emissions from agriculture is almost achieved in the Sustainable Pathway, but is far from being achieved in the Current Trends Pathway.

1 We define a pathway as a combination of scenarios that represents the coherent development of a system along a certain trajectory. Scenarios are the suite of possible actions that set a pathway on a certain trajectory; assumptions are the conditions that a modeler establishes before the model is run to make predictions on, for example, causality chains and changes in specific parameters of the model according to the selected scenarios; a parameter is a constant in model simulations except when it is changed for a specific scenario (i.e. the modeler decides on its value before running the model) - this is an input of the model; a variable represents a model state and results from the model's computations (i.e. the modeler does not decide on its value before the model is run) - this is an outcome of the model.

Table 2 *Overview of scenarios by FABLE countries and for the Rest of World regions for the Current Trends and Sustainable Pathways*



Note. Population is measured in million people. Calories per capita is measured in average daily kilocalorie intake. Crop productivity is measured in average kilocalorie output per hectare of cropland. It results from the combination of the assumption on the evolution of crop yield growth and climate change impacts. Livestock productivity is measured in average kilocalorie per Tropical Livestock Unit (TLU – one unit is equivalent to 250 kg animal weight). Ruminant density is measured in TLU per hectare of pasture. Biofuel consumption is measured in metric tons of biofuels used. Exports and imports are measured in kilocalories. Afforestation is measured in absolute million hectare change between 2015 and 2050.

FABLE country teams ARG: Argentina; AUS: Australia; BRA: Brazil; CAN: Canada; CHN: China; COL: Colombia; DEU: Germany; ETH: Ethiopia; FIN: Finland; IDN: Indonesia; IND: India; MEX: Mexico; MYS: Malaysia; NOR: Norway; RUS: Russia; RWA: Rwanda; SWE: Sweden; UK: United Kingdom; USA: United States of America; ZAF: South Africa. Rest of the world regions - ASP: Rest of Asia and Pacific; CSA: Rest of Central and South America; NEU: Rest of Europe (non EU27); NMC: Rest of North Africa, Middle East and Central Asia; ROEU: Rest of European Union; SSA: Rest of Sub-Saharan Africa.

Table 3 *Overview of achievement of global FABLE targets under the Current Trends and Sustainable Pathways*

GLOBAL FABLE TARGET	CURRENT TRENDS	SUSTAINABLE
Land and Biodiversity		
Land where natural processes predominate. No net loss by 2030 (globally)...	*Achieved*	*Achieved*
Land where natural processes predominate...and an increase of at least 20% by 2050 in the area of land where natural processes predominate (globally)	*Not achieved*	*Not achieved*
Zero net deforestation. Forest gain should at least compensate for the forest loss at the global level by 2030	*Not achieved*	*Achieved*
GHG emissions from AFOLU		
Global greenhouse gas emissions from crops and livestock compatible with keeping the rise in average global temperatures to below 1.5°C, which we interpret as below 4 $GtCO_2e\ yr^{-1}$ by 2050 (3.9 Gt for non-CO2 emissions and 0.1 Gt for CO_2 emissions)	*Not achieved*	*Almost achieved (4.1 $GtCO_2e\ yr^{-1}$)*
Global greenhouse gas emissions and removals from Land-Use, Land-Use-Change, and Forestry (LULUCF) compatible with keeping the rise in average global temperatures to below 1.5°C. Negative global greenhouse gas emissions from LULUCF by 2050	*Not achieved*	*Achieved*
Food Security		
Zero hunger. Average daily energy intake per capita higher than the minimum requirement in all countries by 2030	*Achieved*	*Achieved*
Freshwater Use		
Water use in agriculture within the limits of internally renewable water resources, taking account of other human water uses and environmental water flows. Global consumptive blue water use <2,453 km^3yr^{-1} (global estimates in the range of 670-4,044 km^3yr^{-1}) given future possible range (61-90%) in other competing water uses	*Achieved* *(but not achieved for the lower boundary of the literature estimates)*	*Achieved* *(but not achieved for the lower boundary of the literature estimates)*

Box 5 *Defining scenarios in the FABLE Calculator and MAgPIE*

Each pathway is defined by a combination of scenarios that allow for variation across key parameters of the models. Each of our country teams could select different values for the following parameters:

- DEMAND: GDP (*), population (*), diets (*), and biofuel use (*);
- TRADE: the share of domestic consumption that is imported for key imported commodities (ˆ), the evolution of exported quantity for key exported commodities(ˆ);
- FOOD LOSS: the share of the production that is lost during storage and transportation (i.e. post-harvest losses) (ˆ) and the share of food consumption that is wasted at household level (*);
- PRODUCTIVITY: livestock productivity per livestock unit (*), ruminant density per hectare of pasture (ˆ), crop yields (*), and nitrogen use efficiency (“).
- LAND USE: restrictions on agricultural land expansion or reduction (*), expansion of protected areas (*), and afforestation target (*);
- WATER USE: irrigation of bioenergy crops (“), protection of environmental flows (“);
- GHG: animal waste management systems (“), GHG price (“);
- CLIMATE CHANGE: which combination of crop model, RCP, and global climate model is used to compute impacts of climate change on crop yields, water use, and fertilizer use (*).

The parameter is part of the scenario selection:
* in both the FABLE Calculator and in MAgPIE
ˆ in the FABLE Calculator only
“ in MAgPIE only

Some of FABLE country teams have adapted or created additional scenarios that affect other parameters of the model. These are described in the respective country chapters.

3.2 Land and biodiversity

3.2.1 Current state

In 2010, land cover maps indicated total global land was 18% cropland, 9% grassland (managed and natural), 30% forest, less than 1% urban (built-up), 17% other natural land, 13% bare, 10% snow and ice, and 2% water (land cover data aggregated from ESA (2010) as shown on Map 1). Most agricultural areas were located in temperate regions while forest and other natural land were mostly found in tropical and northern boreal regions. Human activities, including agricultural production, are accelerating global biodiversity loss with some claiming we are entering a sixth mass global extinction (Ceballos et al., 2015). Preserving and increasing the area of land where biodiversity can flourish is critical to halt further biodiversity loss and erosion of ecosystem function and services (Ceballos et al., 2020).

We estimate that land where natural processes predominate[2] accounted for 56% of ice-free global terrestrial land area in 2010. This value is unevenly distributed however and ranges from 89% in boreal/taiga and 88% in tundra biomes to 20% in tropical & subtropical dry broadleaf forests and 27% in temperate grasslands. Russia, Canada, and Australia account for the largest area of land where natural processes predominate globally (Map 2 and Map 3), while boreal forests, tundra, and temperate conifer forests are the world's biomes with the largest share of land where natural processes predominate (Table 4). Ecoregion analysis, covering distinct ecosystems within biomes, further points to over half (51%) of the world's ecoregions having less than 50% of areas where natural processes predominate. In these ecoregions, extinctions are likely to persist, if not accelerate, without strong conservation actions.

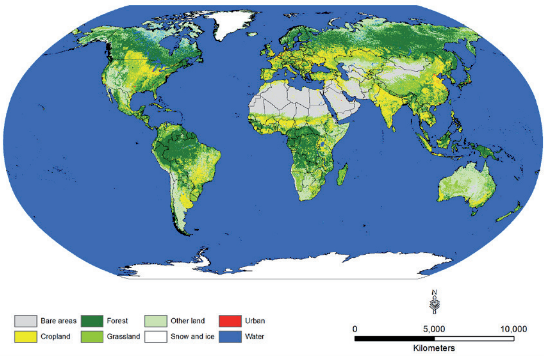
Across the globe, while 17,886,490 km^2 of land is under formal protection, covering 13% of ice-free land, no single biome enjoys 30% protection (Table 4). Mangroves come closest with 29% protected. Several biomes have only 10% protection and are subject to increasing conversion pressure such as dry tropical forests. Only 20% of land where natural processes predominate is formally protected. This indicates that targets to increase the share of the Earth's terrestrial land under protection can be met in areas where natural processes already predominate at a global scale.

34% of global cropland had at least 10% natural or semi-natural vegetation within a 1x1km window, in 2010 (Map 4). The share of this relatively biodiversity-friendly cropland is highest in the tundra biome, followed by the montane grasslands and shrublands and tropical and subtropical coniferous forests. Each of these biomes are regions that are under relatively low natural habitat conversion pressure. Six biomes have less than 30% of biodiversity-friendly croplands. Grassland biomes, often the most arable regions, have been subjected to the greatest amount of natural habitat conversion and simplification characterized as losses in species richness (e.g. extensive monocultures). As fewer arable lands remain, combined with growing agrarian economies in tropical regions, there is increased pressure on the conversion of forests in the tropical forest biomes to agriculture.

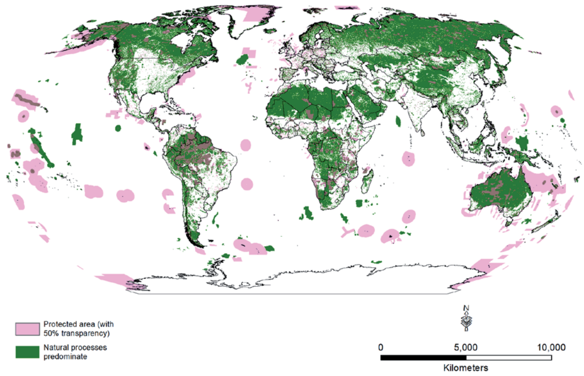
2 We follow Jacobson et al. (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Maps 1, 2, 3, and 4 *Global land cover, distribution of protected areas where natural processes predominate, and natural or semi-natural vegetation in cropped landscapes at country-ecoregion level in 2010*

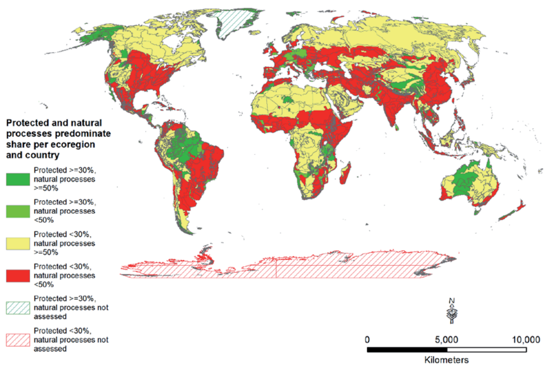
Map 1 | Global land cover



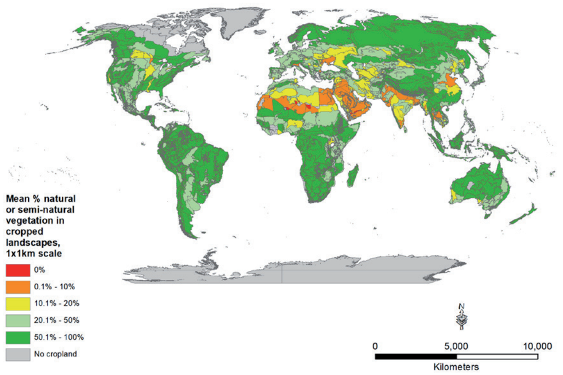
Map 2 | Global distribution of protected areas and land where natural processes predominate



Map 3 | Global share of protected land and land where natural processes predominate at the country-ecoregion level

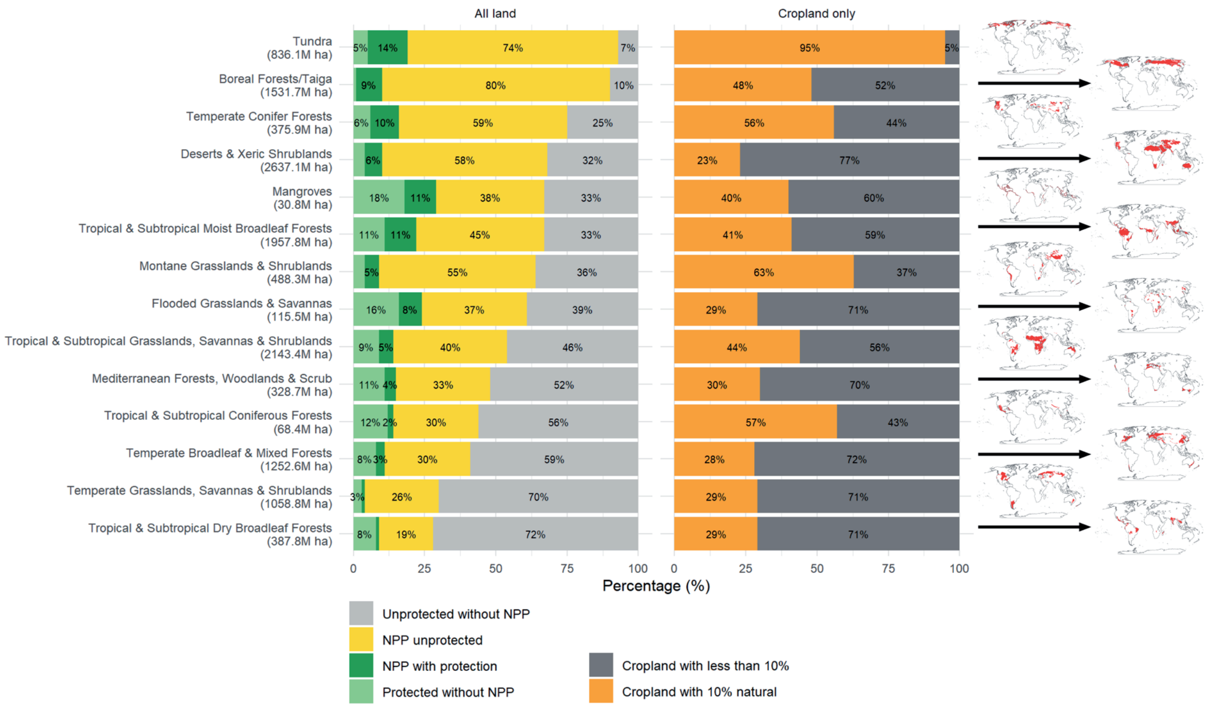


Map 4 | Global distribution of natural or semi-natural vegetation in cropped landscapes at country-ecoregion level



Note. Maps in Robinson projection.
Sources. Map 1: European Space Agency (ESA) Climate Change Initiative (CCI) land cover map for 2010, available at ~300m resolution. Correspondence between original ESACCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 2. Maps 2 and 3: Land where natural processes predominate results from the combination of three datasets: low impact areas from Jacobson et al. (2019), intact forest landscapes from Potapov et al. (2017) and Key Biodiversity areas (BirdLife International, 2019). Protected areas are from the UNEP-WCMC and IUCN (2020). Map 4: Percentage of natural or semi-natural vegetation in cropland: modified from ESA CCI 2010 land cover data. See Annex 2 for details of how this dataset was created.

Table 4 *Biodiversity status at the biome level*



Sources. countries - GADM v3.6; ecoregions Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2017), and low impact areas – Jacobson et al. (2019).

3.2.2 Pathways and results

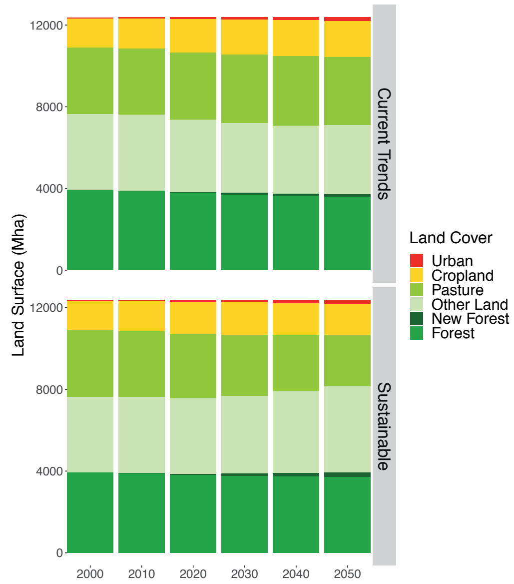
In the Current Trends Pathway, we estimate that the main changes in land cover will result in a 17% and 4% increase in cropland and pasture areas, respectively, and a 5% and 8% decrease of forest and other land areas, respectively, by 2030. This trend slows but remains relatively constant over the period 2030-2050 (Figure 8). The loss of forest and other natural land result in a decline in land where natural processes predominate of 2% by 2030 (-131 Mha) and 1% by 2050 (-58 Mha) compared to 2010, respectively.

The expansion of the planted area for wheat, corn, and sorghum explains one third of cropland expansion between 2010 and 2030 at the global level. Higher livestock feed demand causes 31% of wheat expansion, 60% of corn expansion, and 80% of sorghum expansion. Therefore, when we include pasture expansion, at least 45% of the total agricultural area expansion between 2010 and 2030 is driven by higher consumption of livestock products. This also explains cropland expansion between 2030-2050, despite productivity increases for wheat, corn, and sorghum. Falls in pastureland are explained by lower demand for milk and ruminant meat while the pace of pasture intensification remains similar to the period 2010-2030.

In comparison to the Current Trends Pathway, the Sustainable Pathway achieves the following outcomes (i) avoids the destruction of 84 Mha of forest between 2020 and 2050, (ii) the land where natural processes predominate reaches 58% of the Earth's surface in 2050 instead of 54% (Figure 9), (iii) cropland area begins to decline after 2030 instead of 2045 and is 12% lower in 2050, (iv) pasture area begins decreasing after 2020 instead of 2040 and is 25% lower in 2050; and (v) total afforested land in 2050 is 102 Mha higher.

Our results for the Sustainable Pathway show that shifts towards more sustainable diets will require significant changes in the composition of cropland globally. The reduction in meat consumption and higher consumption of nuts and pulses leads to a

Figure 8 *Evolution of area by land cover type under each pathway*



Note. In our models "grassland" is split across the category "pasture" which corresponds to the grassland used by domestic livestock, while the category "other land" includes grassland not used by domestic livestock.
Sources. Authors' calculations based on ESA (2010), Food Security Information Network (2020) and FAOSTAT (2020) for the area by land cover type for 2000

reduction of the planted area for corn by 70 Mha and an increase in the planted area for nuts by 40 Mha and peas by 14 Mha in 2050 compared to the Current Trends Pathway.

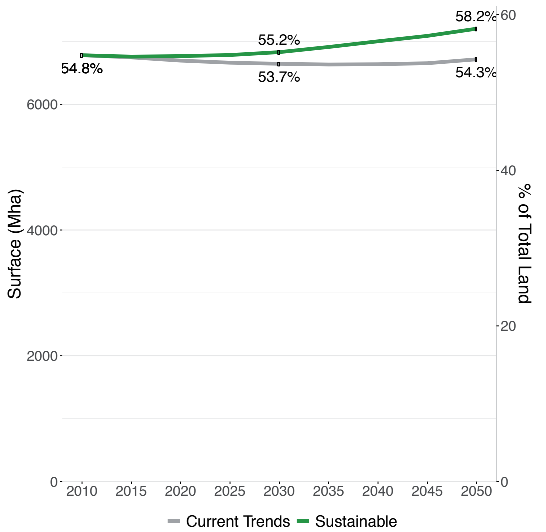
3.2.3 Comparison with the global targets

FABLE country teams work towards two targets for land and biodiversity: (1) no net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate; and (2) forest gain should at least compensate for forest loss at the global level by 2030 (deforestation target).

Under the Current Trends Pathway, countries fall short of the deforestation target, with a net forest loss of about 20 Mha between 2030 and 2035. This gap narrows, but is not closed, by 2050 when net loss reaches 15 Mha of forest per five-year period. However, our results under the Sustainable Pathway show that it might be possible to achieve the target as soon as 2020-2025, when gains in global new forests exceed forest losses by a difference of 16 Mha (Figure 10).

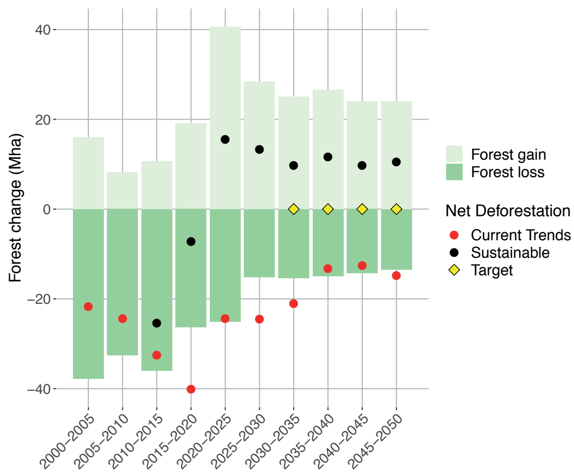
More ambitious outcomes under the Sustainable Pathways are mainly due to reductions in deforestation and increases in afforestation in Brazil, reductions in deforestation in Canada and Indonesia, and increases in afforestation in the US, India, Australia, and Ethiopia (Figure 11). The non-linear evolution of the net forest cover change is explained by the fact that several countries

Figure 9 *Evolution of the area where natural processes predominate*



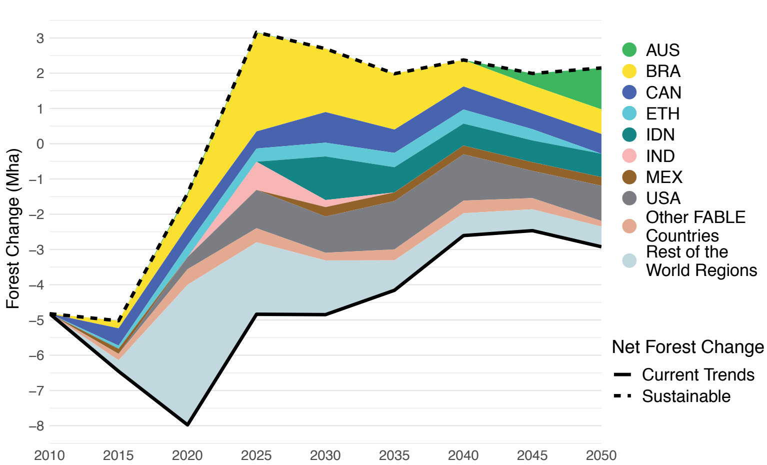
Source. Authors' calculations.

Figure 10 *Forest change in the Sustainable Pathway*



Source. Authors' calculations.

Figure 11 *Aggregate global net forest change in the Sustainable and Current Trends Pathways and main contributors to forest cover increase*



Note. FABLE country teams - AUS: Australia; BRA: Brazil; CAN: Canada; ETH: Ethiopia IDN: Indonesia; IND: India; MEX: Mexico; USA: United States of America. **Other FABLE countries -** Argentina, China, Colombia, Finland, Germany, Malaysia, Norway, Russia, Rwanda, South Africa, Sweden, United Kingdom. **Rest of the world regions -** Rest of Asia and Pacific; Rest of Central and South America; Rest of Europe (non EU27); Rest of North Africa, Middle East and Central Asia; Rest of European Union; Rest of Sub-Saharan Africa.
Sources. Authors' calculations.

apply zero deforestation after 2030, and continue afforestation after 2030 at a stable pace, except for India where the afforestation peaks over 2020-2025.

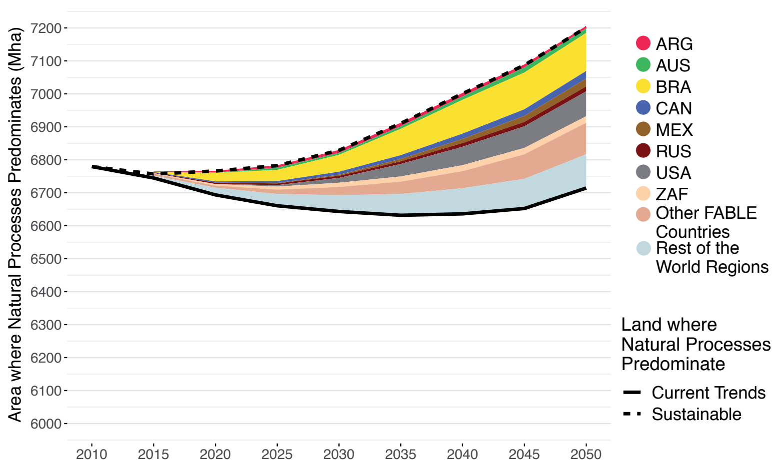
Our results show that, under both the Sustainable and Current Trends Pathways, it might be possible to achieve "no net loss by 2030 in the area of land where natural processes predominate". However, they fall short of the target to achieve an "increase of at least 20% by 2050 in the area of land where natural processes predominate". Instead countries achieve a 1% increase by 2050 in the Current Trends Pathway and an 8% increase by 2050 in the Sustainable Pathway compared to 2010. This increase in the expansion of areas where natural processes predominate in the Sustainable Pathway compared to the Current Trends Pathway is driven mostly by changes in Brazil, the US, and China. Their contributions represent 65% of the total difference between the pathways over the period 2015-2050 (Figure 12).

3.3 GHG emissions from AFOLU

3.3.1 Current state

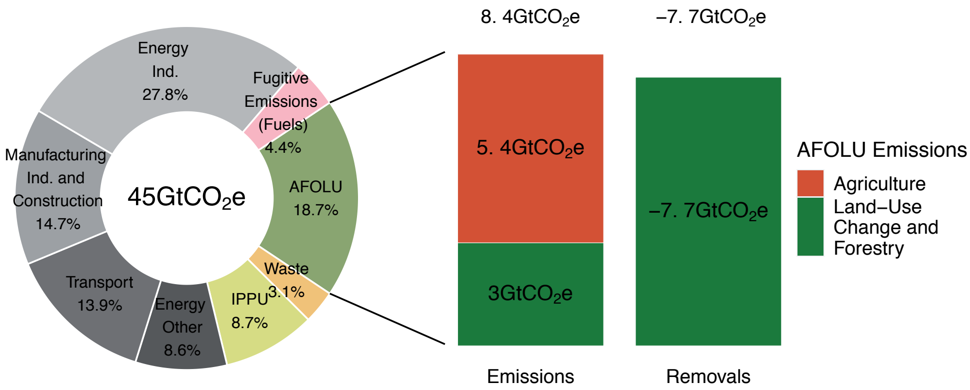
The Agriculture, Forestry, and Other Land Uses (AFOLU) sector accounts for an estimated 12 Gt CO_2e per year of net anthropogenic GHG emissions and 23% of total GHG emissions between 2007-2016 (IPCC, 2019). It is estimated that 80% of nitrous oxide (N_2O) emissions from human activities come from AFOLU globally (IPCC, 2019). LULUCF emissions represent the net balance between emissions from land-use change and carbon sequestration from the regeneration of vegetation and soils. While the AFOLU sector generates significant emissions, the residual terrestrial sink (i.e. the accumulation of carbon in the terrestrial biosphere excluding land sinks from land use, land use change, and forestry (LULUCF), which we cannot explain with bottom-up LULUCF accounting), also currently sequesters around 30% of annual anthropogenic emissions. Land is, therefore, vitally important to draw carbon out of the atmosphere (IPCC, 2019).

Figure 12 *Change in the aggregate global area where natural processes predominate in the Sustainable and Current Trends Pathways and main contributors to area where natural processes predominate increase*



Note. FABLE country teams - ARG: Argentina; AUS: Australia; BRA: Brazil; CAN: Canada; MEX: Mexico; RUS: Russia; USA: United States of America; ZAF: South Africa. **Other FABLE countries-** China, Colombia, Ethiopia, Finland, Germany, India, Indonesia, Malaysia, Norway, Rwanda, Sweden, United Kingdom. **Rest of the world regions-** Rest of Asia and Pacific; Rest of Central and South America; Rest of Europe (non EU27); Rest of North Africa, Middle East and Central Asia; Rest of European Union; Rest of Sub-Saharan Africa.
Sources. Authors' calculations.

Figure 13 *Historical global GHG emissions and contribution of each sector to total emissions, and historical decomposition of country level net GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) by source in 2018*



Note. Figured based on data available for the most recent year for all countries, in most cases this is 2018 but in others it is earlier. AFOLU emissions and removals are at the country net emissions level. The total removals are made up of the sum of removals from countries that have a negative net balance of GHG emissions from land-use change and forestry. The same methodology is applied to emissions with countries with a positive net balance.
Sources. UNFCCC Greenhouse Gas Inventory Data (UNFCCC, 2020a, 2020b).

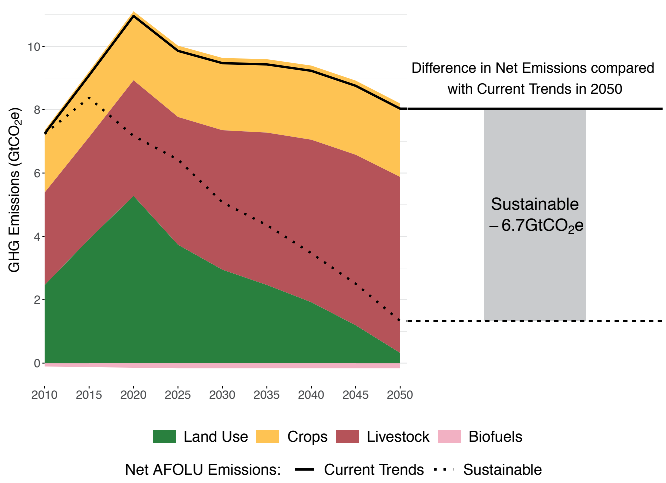
The principal sources of AFOLU emissions from agriculture are soils and enteric fermentation, which together represent 78% of the net AFOLU emissions from agriculture. LULUCF emissions represent the net balance between emissions from land-use change and carbon sequestration from the regeneration of vegetation and soils. Changes in forest and other woody biomass stocks, forest land and forest and grassland conversion represent 72% of the sinks for countries that have a negative net balance of GHG emissions from LULUCF ("removals" in Figure 13). Forest and grassland conversion also acts as a source of GHG emissions for countries that have a positive net balance of GHG emissions from LULUCF (emissions from LULUCF in Figure 13) by accounting for 69% of the net emissions from LULUCF.

For the year 2015, our models are able to reproduce global GHG emissions from agriculture reported by countries to the UNFCCC quite well, with 5.2 Gt CO_2e per year compared to 5.4 Gt CO_2e (Figure 13). The comparisons are more challenging for emissions from LULUCF (Annex 3) but it seems that the main source of deviation between our calculations and the UNFCCC GHG Inventory database may be due to removals from LULUCF - we only estimate 0.5 Gt CO_2e GHG removals per year compared to 7.7 Gt CO_2e per year reported. These discrepancies are explained by the FABLE Calculator's and MAgPIE's partial coverage of emission and removal processes reported in the UNFCCC Inventory database. This is described in Annex 3.

3.3.2 Pathways and results

The Current Trends Pathway for agriculture and LULUCF differ significantly. While emissions from agriculture are projected to steadily increase from 5 Gt CO_2e per year in 2010 to 8 Gt CO_2e per year between 2010 and 2050 under the Current Trends Pathways, the emissions from the land use sector covered by the FABLE calculations are already expected to decline sharply after 2020 from 3 Gt CO_2e in 2010 to almost zero in 2050 (Figure 14). Methane emissions from livestock account for 52% of the emissions in 2050.

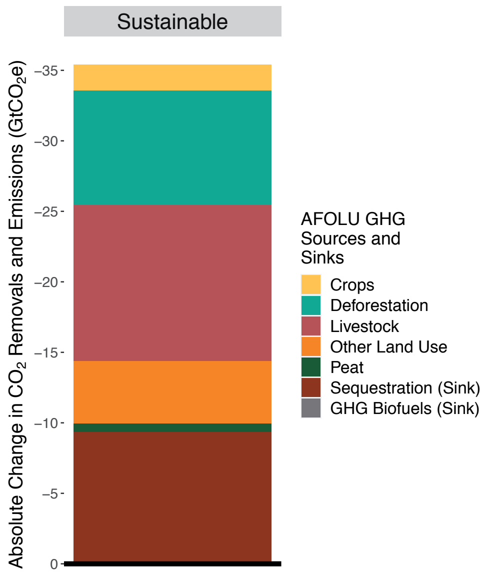
Figure 14 *AFOLU emissions reduction trajectory under the Sustainable and Current Trends Pathways*



Note. Emissions by subsectors (land use, crops, livestock and biofuels) are shown for the Current Trends Pathways. The Crops category also includes CO2 emissions from on farm energy use. The right-hand bar indicates the emission saving attributable to measures under the Sustainable Pathways.
Sources. Authors' calculations.

The Sustainable Pathway projects an 83% reduction in net GHG emissions from AFOLU compared to the Current Trends Pathway in 2050 (Figure 14). This potential decrease in emissions is dominated by decreasing GHG emissions from deforestation and livestock emissions (Figure 15). Moreover, total emissions from crops and livestock begin to decrease in 2030. If we remove emissions from energy use in agriculture and from fossil fuel substitution by biofuels, which are not included in AFOLU, computed emissions from agriculture reach 4 Gt CO_2e per year in 2050. Total net emissions from LULUCF become negative in 2030 and reach -3 Gt CO_2e per year in 2050.

Figure 15 *Comparison of cumulated projected GHG emissions reduction over 2020-2050 by AFOLU type compared to the Current Trends Pathways*



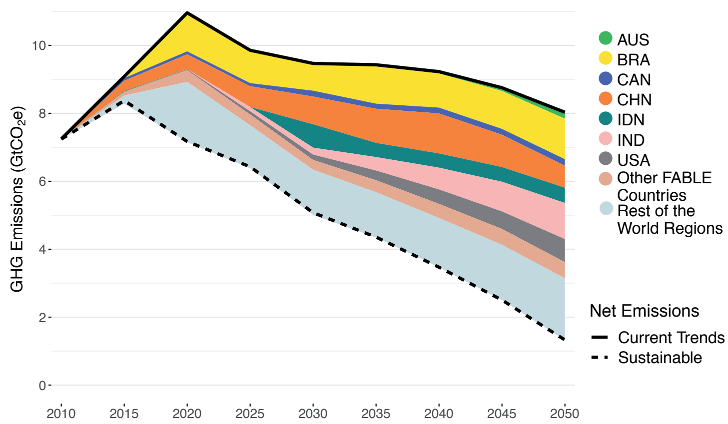
Source. Authors' calculations.

3.3.3 Comparison with the global targets and closing the GHG emission gap from AFOLU

We aim to achieve two targets for reducing greenhouse gas emissions from AFOLU: (1) greenhouse gas emissions from crops and livestock below 4 Gt CO_2e per year by 2050; and (2) greenhouse gas emissions and removals from Land-Use, Land-Use Change, and Forestry (LULUCF) become negative by 2050.

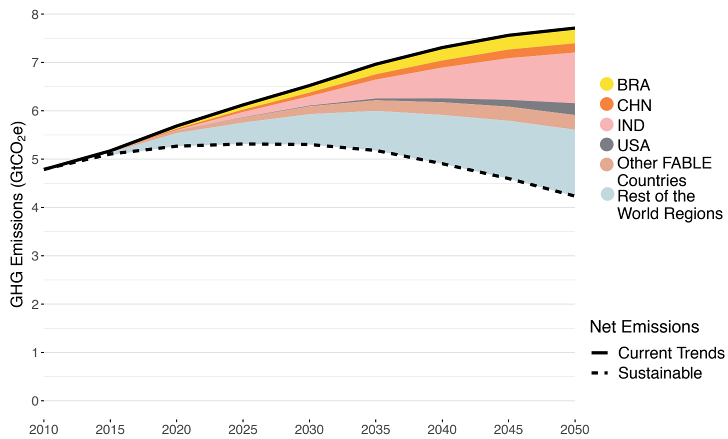
Our results show that it might be possible to reach GHG emissions from the agricultural and the land use sectors (AFOLU) that are compatible with the ambition of the Paris Agreement under the Sustainable Pathway. However, under the Current Trends Pathway, our GHG estimates in 2050 miss the target by a wide margin: GHG emissions from AFOLU exceed the maximum level by 80%. This confirms that there is sufficient potential to meet

Figure 16 *Aggregate global AFOLU net emissions in the Sustainable and Current Trends Pathways and main contributors to emissions reduction*



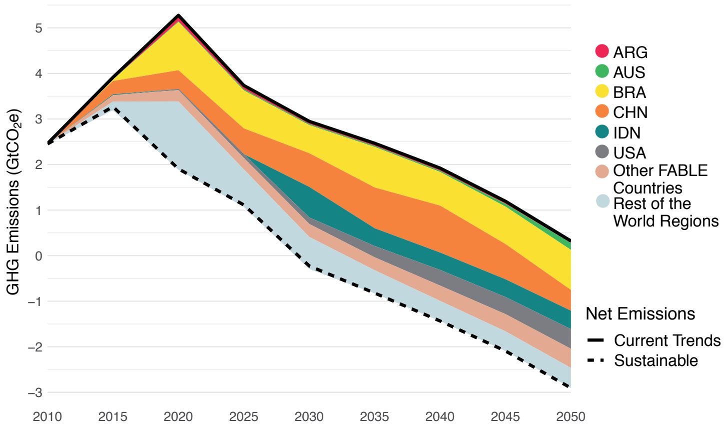
Note. FABLE country teams - AUS: Australia; BRA: Brazil; CAN: Canada; CHN: China; IDN: Indonesia; IND: India; USA: United States of America. **Other FABLE countries -** Argentina, Colombia, Ethiopia, Finland, Germany, Mexico, Malaysia, Norway, Russia, Rwanda, South Africa, Sweden, United Kingdom. **Rest of the world regions -** Rest of Asia and Pacific; Rest of Central and South America; Rest of Europe (non EU27); Rest of North Africa, Middle East and Central Asia; Rest of European Union; Rest of Sub-Saharan Africa.
Sources. Authors' calculations.

Figure 17 *Aggregate global emissions from agriculture in the Sustainable and Current Trends Pathways and main contributors to emissions reductions*



Note. FABLE country teams - BRA: Brazil; CHN: China; IND: India; USA: United States of America. **Other FABLE countries -** Australia, Argentina, Canada, Colombia, Ethiopia, Finland, Germany, Indonesia, Mexico, Malaysia, Norway, Russia, Rwanda, South Africa, Sweden, United Kingdom. R**est of the world regions -** Rest of Asia and Pacific; Rest of Central and South America; Rest of Europe (non EU27); Rest of North Africa, Middle East and Central Asia; Rest of European Union; Rest of Sub-Saharan Africa.
Sources. Authors' calculations.

Figure 18 *Aggregate global net emissions from land use and land use change in the Sustainable and Current Trends Pathways and main contributors to emissions reduction*



Note. FABLE country teams - ARG: Argentina; AUS: Australia; BRA: Brazil; CHN: China; IDN: Indonesia; USA: United States of America. **Other FABLE countries -** Canada, Colombia, Ethiopia, Finland, Germany, India, Mexico, Malaysia, Norway, Russia, Rwanda, South Africa, Sweden, United Kingdom. **Rest of the world regions -** Rest of Asia and Pacific; Rest of Central and South America; Rest of Europe (non EU27); Rest of North Africa, Middle East and Central Asia; Rest of European Union; Rest of Sub-Saharan Africa. **Sources.** Authors' calculations.

an ambitious climate mitigation target by 2050 but countries need to substantially increase their current efforts. In Figure 16, Figure 17, and Figure 18 we present country-level contributions to closing this GHG emissions gap from AFOLU. These gaps are assessed as the difference between projected GHG emissions from AFOLU in the Current Trends and Sustainable Pathways.

Under the Sustainable Pathways it might be possible to achieve a 2 Gt CO_2e per year emissions reduction in the agricultural sector (Figure 17) and additional carbon sequestration of another 3 Gt CO_2e per year by 2050 in the LULUCF sector (Figure 18).

In 2050, 50% of the emission reductions from agriculture can be attributed to actions in India, followed by contributions from Brazil (15%), the US (12%), and China (9%) (Figure 17). One explanation is that these countries are the main contributors to global emissions from agriculture. Another is that India, Brazil, and the US implemented measures in the Sustainable Pathways that lead to the strongest relative reduction of emissions from agriculture among FABLE countries.
The reduction of the consumption of animal-based products combined with the increase in livestock productivity are the key drivers of GHG emissions reductions from agriculture in these countries (Table 2). Mitigation potential from agriculture could be even higher if the FABLE Calculator accounted for mitigation options such as conservation tillage, improved feed, methane capture from pork and dairy operations (Frank et al., 2018; Murray et al., 2005).

In 2050, a little under half of the entire mitigation efforts from LULUCF can be attributed to Brazil, followed by China, the US, and Indonesia (Figure 18). A large share of LULUCF mitigation comes from additional carbon sequestration from the regrowth of natural vegetation on abandoned agricultural land and from afforestation. Avoided deforestation due to the implementation of zero-deforestation policies after 2030 and productivity gains also contribute to one-third of the emission reduction in Brazil and two-thirds in Indonesia.
In Indonesia, additional mitigation is obtained through the implementation of the moratorium on new permits in peatland, thus avoiding emissions from peatland decomposition. Our results could underestimate the total mitigation potential from LULUCF as our models do not take into account mitigation opportunities within the forestry sector (Baker et al., 2017; Van Winkle et al., 2017; Wade et al., 2019).

3.4 Food security

3.4.1 Current state

The "Triple Burden" of Malnutrition

Undernutrition

11% of the global population is undernourished in 2017. This share has decreased steadily until 2015, before increasing since then (World Bank, 2019d).

21% of children under 5 are stunted and 7% are wasted in 2019 (World Bank, 2019c, 2019e).

Micronutrient Deficiency

33% of women and 42% of children suffer from anemia in 2016, which can lead to maternal death (World Bank, 2016, 2019b).

About 30% of children under 5 are deficient in vitamin A (Wirth et al., 2017) which can notably lead to blindness and child mortality (WHO, 2020a), and 2 billion people are deficient in iodine, which can lead to developmental abnormalities (Biban & Lichiardopol, 2017).

Overweight/ Obesity

13% of the global population was obese in 2016. These shares have nearly tripled since 1975 (WHO, 2020b).

39% of the global population was overweight in 2016. These shares have increased since 1975 (WHO, 2020b).

Disease Burden due to Dietary Risks

Nearly 20% of deaths worldwide are attributable to dietary risks, or 11 million deaths in 2017 (IHME, 2018). 9% of the global population (ages 20 to 79) suffers from diabetes and 32% from cardiovascular diseases, which can be attributable to dietary risks (IHME, 2018; World Bank, 2019a).

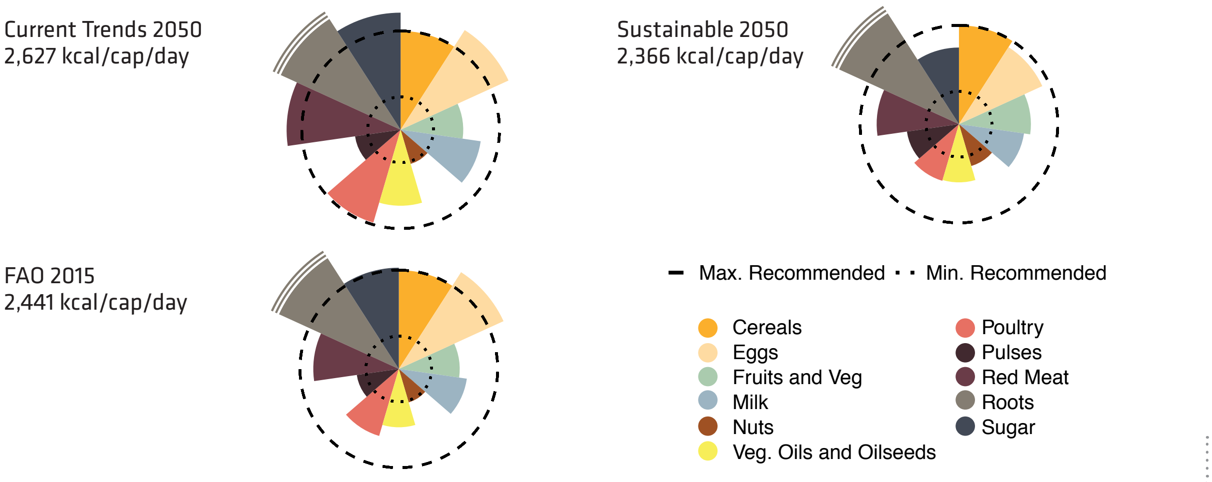
3.4.2 Pathways and results

The average global calorie intake was 2,441 kcal per capita per day in 2015 (FAOSTAT, 2020). Compared to the EAT-Lancet recommendations (Willett et al., 2019), the average global per capita consumption of roots and tubers, sugar, cereals, and eggs is too high, and far too low for nuts and pulses (Figure 19).

Most of the FABLE country teams assumed lower calorie consumption per capita in the Sustainable Pathway compared to the Current Trends Pathway. However, Rwanda and Ethiopia assumed higher calorie consumption per capita in the Sustainable Pathway (Table 2). In these two countries, as in many low-income countries, the challenge is to increase overall calorie intake, especially from animal protein, in order to ensure nutritious diets. Ten FABLE countries project a reduction in the per capita intake of calories per day both in the Current Trends and in the Sustainable Pathways – the European countries, Argentina, Colombia, Mexico, Indonesia, Russia, and the US.

Compared to 2015, the Current Trends Pathway projects an increase in average calorie consumption per capita per day at the global level by 8% while the Sustainable Pathway projects a decrease by 3% (Figure 19). In the Current Trends Pathway, the global average of sugar and red meat consumption exceeds the maximum recommended levels and poultry meat reaches the maximum. The average consumption of vegetable oil and oilseeds and dairy products also exceed the recommended average levels (Figure 19). Increases in the production and consumption of protective or healthy foods were not as large. Notably, the production and consumption of beans and pulses, and nuts, important sources of plant-based proteins and fiber, remained close to the minimum recommended.

Figure 19 *Comparison of the computed daily average kilocalorie intake per capita per food category across the Current Trends and Sustainable Pathways in 2050 with the EAT-Lancet recommendations*



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is lower than the average recommendation it is displayed on the minimum ring and if it is higher, it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.
Source. FAOSTAT(2020) for 2015; Willett et al. (2019) for EAT Lancet minimum, average and maximum recommendations and FABLE pathways for the 2050 projections.

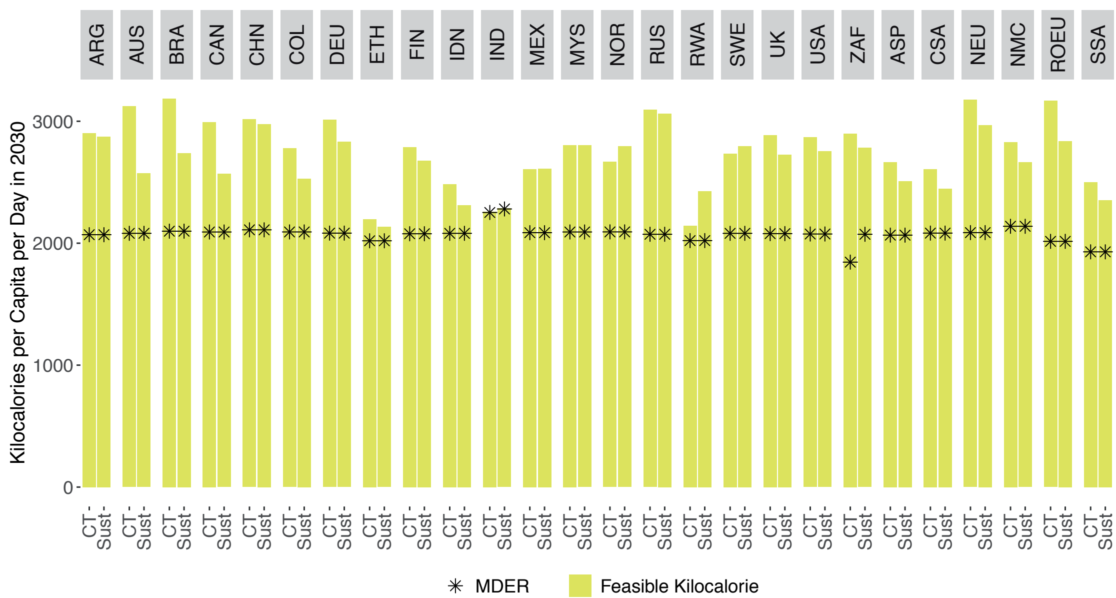
There are significant differences in food composition between the Current Trends and Sustainable Pathways. Except for roots and tubers, the average consumption of all food groups falls within the recommended boundaries in the Sustainable Pathway. There is a particularly strong reduction in the consumption of red meat and sugar in the Sustainable Pathway (Figure 19). However, while below the maximum recommended level, average consumption remains significantly higher than the recommended average. Under the Sustainable Pathway the production of foods that are harmful when overconsumed decreases, reaching the upper range of recommended levels. Conversely, the production of protective or healthy food increases, reaching the lower range of recommended consumption levels. Notably, roots (especially potatoes) remain overproduced and overconsumed in all pathways.

3.4.3 Comparison with the global target

All FABLE pathways project the food security target to be met. They all achieve a per capita average intake per day that exceeds applicable average Minimum Daily Energy Requirement (MDER) in both pathways (Figure 20). The computed MDER varies between 1,844 and 2,280 kcal per capita per day in 2030 among all FABLE countries, depending on their demographics (age distribution and gender).

Between 2000 and 2050, in the Current Trends Pathways, the largest relative increases in energy intake occur in China, Ethiopia, and Rwanda, while the largest reductions in energy intake occur in Norway, Mexico, and Germany. Results are similar in the Sustainable Pathways. Ethiopia and India still indicate feasible kilocalorie levels that are only slightly greater than the MDER, which may lead to risks to

Figure 20 *Kilocalories per capita per day for all countries and regions in 2030*



Note. FABLE country teams - ARG: Argentina; AUS: Australia; BRA: Brazil; CAN: Canada; CHN: China; COL: Colombia; DEU: Germany; ETH: Ethiopia; FIN: Finland; IDN: Indonesia; IND: India; MEX: Mexico; MYS: Malaysia; NOR: Norway; RUS: Russia; RWA: Rwanda; SWE: Sweden; UK: United Kingdom; USA: United States of America; ZAF: South Africa. **Rest of the world regions-** ASP: Rest of Asia and Pacific; CSA: Rest of Central and South America; NEU: Rest of Europe (non EU27); NMC: Rest of North Africa, Middle East and Central Asia; ROEU: Rest of European Union; SSA: Rest of Sub-Saharan Africa.
Sources. Authors' calculations.

food security. In the Sustainable Pathway, several densely populated countries retained kilocalorie levels that approach 3,000 kcal per capita per day. These values present some options for continued reductions in further analyses so long as they do not compromise the resilience of food systems.

A higher average intake of calories per capita compared to the average MDER is positive but unlikely to eradicate hunger. The higher the incidence of poverty in a country, the higher the difference between the average intake of calories per capita and the average MDER must be. Although all FABLE countries meet the food security target, some (Ethiopia, India, Rwanda, and, to a lesser degree, Indonesia) are at a higher risk when it comes to eliminating hunger by 2030. This is due to higher levels of poverty and food insecurity in these countries.

3.5 Freshwater

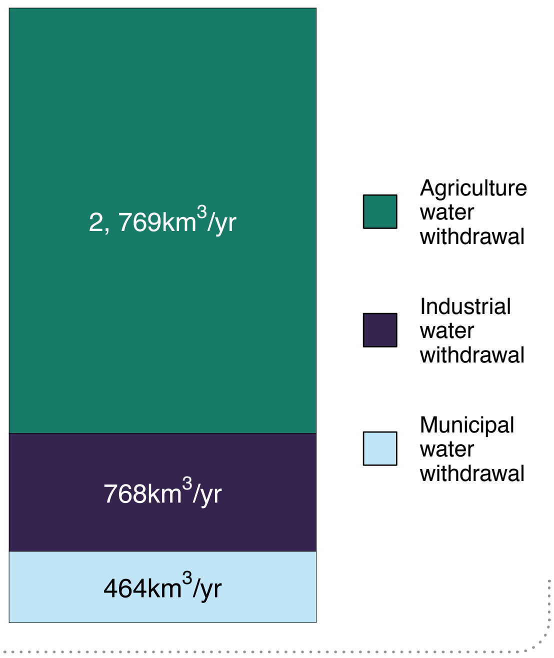
3.5.1 Current state

Freshwater available for human use is only a small share of the Earth's total water. 1% is in liquid form, of which only 0.4% is renewable and only a portion can be exploited under current economic and environmental conditions. Nine countries (Brazil, Canada, China, Colombia, India, Indonesia, Peru, Russia, and the US) are home to nearly 60% of the world's renewable water resources.

Over the past century, population growth and changing consumption patterns have led to a sixfold increase in global water use (FAO, 2020). Each year, two thirds of water withdrawals are used for agriculture (Figure 21) (FAO, 2020). India is far and away the main freshwater consumer (freshwater withdrawals), followed by China and the US (FAO, 2020). Though enough freshwater is available to meet global demand on an annual basis, spatial and temporal variations mean that around 70% of the global population face moderate to severe water scarcity at least one month each year (Mekonnen & Hoekstra, 2016). In 2019, 17 countries faced extreme water stress (Luo et al., 2015), with climate change projected to exacerbate this trend.

For the FABLE pathways, we use the consumptive blue (irrigation) water use as our water-use indicator. This indicator excludes water from precipitation and the share water withdrawals for irrigation that returns to the environment, including due to irrigation inefficiencies. At the global level, consumptive water use for crop production was estimated in the range of 600-1500 km^3 per year around 2000 (Mekonnen & Hoekstra, 2011). In addition, consumptive water use for grazing is estimated to be less than 50 km^3 per year (Mekonnen & Hoekstra, 2010). At the national level, between 1996-2005, more than 50% of the global blue water consumptive use came from three countries (India, China and the US) and three crops (wheat, rice, and corn).

Figure 21 *World freshwater withdrawals in 2016*



Source. FAO (2016)

3.5.2 Pathways and results

The Current Trends Pathway projects an increase in consumptive blue water use by 230 km^3 per year from 2010 to 2050. Consumptive blue water use is expected to decrease in India (by 185 km^3 per year) and increase in all other countries. The highest water footprint is achieved in 2045, with a total of 1,403 km^3 per year globally (Figure 22). In 2050, our results show that India will remain a major consumer of water for crop irrigation, followed by China and the US. We project that the Northern Africa, Middle East, and Central Asia and Sub-Saharan Africa regions will represent more than half the consumptive blue water use for crops by 2050 at the global level. However, as the FABLE Calculator does not take into account water availability for irrigation, further analysis is needed to verify the feasibility of these results.

The largest relative increases in water use between 2000 and 2050 for the Current Trends Pathway are computed for Ethiopia, Brazil, and Indonesia. According to the climate scenario, climate model, and crop model that we used (section 2), the strongest impacts of climate change on the average irrigation water use per unit produced by 2050 are on wheat in South Africa (+70%), rice and corn in Indonesia (+40%), and rice in Argentina, Mexico (+30%), and Brazil (+20%). In India, the US, and China, the three main consumers of irrigated water globally, climate change is projected to reduce the demand for irrigated water for rice, wheat, and soybean by between 10% and 20% on average at the national level. In contrast, in China, corn and rice is projected to lead to a 10% increase in demand for irrigated water.

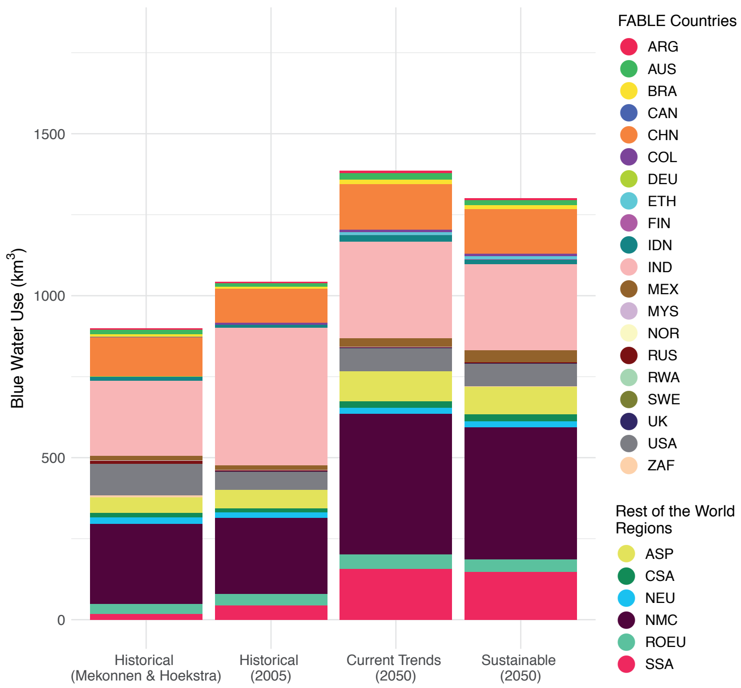
The Sustainable Pathway follows a similar trend, with a reduced water footprint of 1,302 km^3 per year by 2050 (Figure 22). China and India, as well as the Rest of North Africa, the Middle East, and Central Asia region, remain the dominant consumers of blue water. Water consumption is projected to fall compared to the Current Trends Pathway due to lower climate change impacts and the reduction in the production of the three leading irrigated crops (corn, rice, and wheat) due to dietary changes. In addition, in India, water withdrawals are restricted in the MAgPIE model by incorporating environmental flow requirements to reserve a certain fraction of water for environmental purposes.

3.5.3 Comparison with the global target

We aim to achieve one target on freshwater use, consumptive blue water use that is less than 2,453 km^3 per year by 2050. FABLE pathways project that this target will be met under both the Current Trends and Sustainable Pathways. By 2050, the blue water footprint is projected at 1,386 km^3 per year in the Current Trends Pathway and 1,302 km^3 per year in the Sustainable Pathway (Figure 22). However, one should note that having a global target on freshwater use does not correctly represent the challenges of future water management at, for instance, the river basin level. Our global target also corresponds to the middle point of estimates from the literature i.e. the lower boundary of these estimates would not be met under both the Current Trends and the Sustainable Pathways.

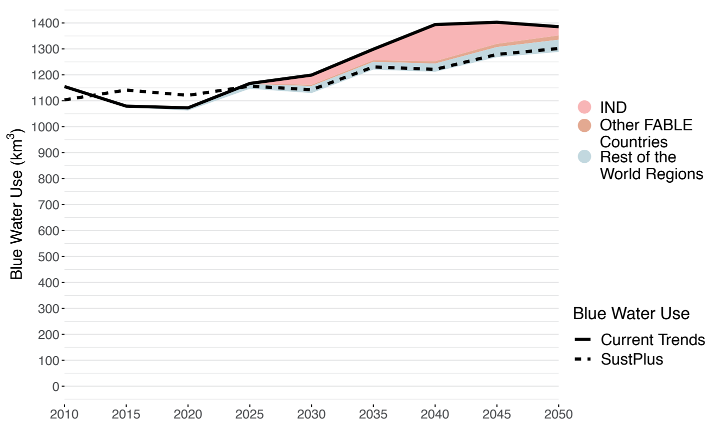
India accounts for 57% and the Rest of North Africa and Middle East and Central Asia region for 17% of the reduction in cumulative blue water use between the two pathways between 2025 and 2050 (Figure 23). These changes are driven by a reduction in the production of rice and crops combined with lower climate change impacts in the Rest of North Africa, Middle East, and Central Asia region, and a significant reduction in rice production and restrictions on water withdrawals in India.

Figure 22 *Consumptive water use for irrigation*



Notes. Water withdrawals computed by MAgPIE-India have been converted to consumptive water use by removing the losses due to evaporation on the field. **FABLE country teams** - ARG: Argentina; AUS: Australia; BRA: Brazil; CAN: Canada; CHN: China; COL: Colombia; DEU: Germany; ETH: Ethiopia; FIN: Finland; IDN: Indonesia; IND: India; MEX: Mexico; MYS: Malaysia; NOR: Norway; RUS: Russia; RWA: Rwanda; SWE: Sweden; UK: United Kingdom; USA: United States of America; ZAF: South Africa. **Rest of the world regions -** ASP: Rest of Asia and Pacific; CSA: Rest of Central and South America; NEU: Rest of Europe (non EU27); NMC: Rest of North Africa, Middle East and Central Asia; ROEU: Rest of European Union; SSA: Rest of Sub-Saharan Africa. **Source.** Historical data on consumptive use from Mekonnen and Hoekstra (2011) includes crops and is an average over the period 1996-2005. Historical (2005), Current Trends, and Sustainable Pathways are calculated by the authors.

Figure 23 *Aggregate global blue water use change in the Sustainable and Current Trends Pathways and main contributors to blue water use reduction*



Notes. FABLE country teams - IND: India. **Other FABLE countries -** Argentina, Australia, Brazil, Canada, China, Colombia, Ethiopia, Finland, Germany, Indonesia, Malaysia, Mexico, Norway, Russia, Rwanda, South Africa Sweden, United Kingdom, United States of America. **Rest of the world regions -** Rest of Asia and Pacific; Rest of Central and South America; Rest of Europe (non EU27); Rest of North Africa, Middle East and Central Asia; Rest of European Union; Rest of Sub-Saharan Africa.
Source. Authors' calculations.

4. Policy implications and recommendations

The 2020 FABLE pathways have been technically improved and cover more FABLE targets compared with last year's versions. To our knowledge these are among the only national mid-century pathways towards sustainable land-use and food systems that are broadly consistent with the objectives of the Paris Agreement, the proposed post-2020 Biodiversity Framework, and other SDGs. The pathways underscore the complexity of land-use and food systems, which differ massively across countries. Yet, they also show how these systems can become more sustainable in every country and point towards lessons and priority issues that governments and other stakeholders should address.

4.1 Large potential to sustainably transform land-use and food systems

A first lesson is that the differences between Current Trends and Sustainable Pathways are large. The lack of political ambition towards greater sustainability puts the achievement of the objectives of the Paris Agreement and SDG 15 on the protection, restoration, and sustainable use of terrestrial ecosystems at major risk. These bottom-up findings from national FABLE country teams are consistent with findings from global models, as reported by the climate change (Arneth et al., 2019; Masson-Delmotte et al., 2018) and the biodiversity communities (Leclère et al., 2020). They show that decisive public sector action over the coming years can put countries on a different long-term trajectory. Since systems take time to change, action must be taken urgently to ensure that the 2021 "super year" for nature and climate is the beginning of concrete and tangible action to sustainably transform land-use and food systems over the long term.

4.2 Need for a systems approach

Countries need integrated long-term strategies that cover the three pillars of sustainable land-use and food systems – efficient and resilient agriculture systems that ensure farmers' livelihoods, conservation and restoration of biodiversity, and food security and healthy diets – that are embedded in integrated land-use design and international trade and supply chains (Figure 3). Our results show, for example, that shifts towards healthier diets or efforts to limit food loss and waste are among the most consequential measures to protect biodiversity and contribute significantly towards curbing greenhouse gas emissions. Yet, today's climate and biodiversity strategies under the UNFCCC and the CBD generally do not refer to diets or food loss and waste. The FABLE pathways provide a framing for designing and implementing integrated strategies.

Our countries increasingly recognize the need for integrated approaches and the pressure for reform is rising, but current strategies do not integrate policies across land-use and food systems. One fledgling exception is the European Union's proposed Farm to Fork Strategy, which if implemented would tackle all the major dimensions considered in our FABLE pathways. As part of the Food and Land Use Coalition, we will work with interested governments to support integrated strategies that address short-term pressures on land-use and food systems and are consistent with meeting long-term goals.

One area where integrated strategies are particularly important is the need to manage competition for land and other scarce resources. Such competition is strong and will become stronger, especially in countries with high population and economic growth. Countries need participatory planning mechanisms that ensure coherence across all food and land-use-system sectors. Research groups, such as those participating in the FABLE consortium, can contribute to these processes through participatory modeling with stakeholders and decision-makers.

These systems approaches might help successfully mitigate tradeoffs. For example, tree planting can help countries reverse biodiversity decline and increase carbon sequestration, but this will require the planting of native species, avoidance of tree planting on natural grasslands, wetlands, savannas, and peatlands and adding grassland and wetland restoration to the repertoire of greenhouse gas emission removal options.

4.3 Major levers for domestic action

Our report identifies major levers for domestic action to make land-use and food systems sustainable that align well with the Ten Critical Transitions in the Growing Better Report (FOLU, 2019) and global climate and biodiversity objectives. While every land-use and food system is different, these levers could play a major role across the FABLE countries depending on their specific contexts.

- **Dietary shifts:** Most middle- and high-income FABLE countries assumed significantly reduced per capita consumption, lower production of foods that are harmful when overconsumed, and an increase in the consumption of protective or healthy food in their Sustainable Pathways (Table 2). These dietary shifts play a large role in reducing cropland and grazing lands and lowering greenhouse gas emissions in the Sustainable Pathway. Our results also show that such shifts will lead to significant changes in the composition of agricultural land globally – fewer cereals and more nuts and pulses. They can also provide opportunities for diversifying production and trade. These shifts will require food and land-use system actors to prepare now to ensure availability and affordability of these healthier diets. In contrast, the low-income FABLE countries assumed higher calorie intake and higher consumption of animal-based foods to reach nutritious diets in their Sustainable Pathways. In this context, the challenge is to accompany this transition by minimizing the impacts of the higher food demand on ecosystems.

  Dietary shifts might be difficult to adopt, in particular at the pace required to reach mid-century targets. Countries could rapidly implement measures to better inform consumers through nutrition-focused education campaigns, include nutrition advice into primary healthcare, and integrate sustainability principles into National Dietary Guidelines. Countries could also incentivize shifts towards healthier diets. This could include policies and programs for sustainable food labeling, aligning value added tax levels with the impacts of food products on health, providing guidelines for the sale or distribution of food and beverages in schools and workplaces, and aligning public food assistance programs with recommended diets. The associated costs and benefits of these different policy instruments would, however, need to be assessed. Moreover, as one of the principal drivers of sustainable land-use and food systems, dietary shifts should be reflected in climate, biodiversity, and related strategies.

- **Sustainable and productive agriculture:** Complementary to lowering demand for agricultural commodities through diet shifts are sustainable increases in agricultural productivity, including through regenerative agriculture. All FABLE country teams assume higher crop and livestock productivity as a key component of greater sustainability of their food and land use systems. Several countries assume productivity increases in their Sustainable Pathways that are at the higher bound of what has been technically achievable in the past.

We acknowledge that the high environmental and human health dangers from some high-productivity practices of industrialized farming, such as the excessive use of agrochemicals, fertilizers (including manure), and animal pharmaceuticals warrant caution about how such high productivity scenarios are achieved. Many FABLE country teams identify opportunities for sustainable increases in agricultural yields through investments in precision farming, rotational grasslands, advanced manure management, natural pest control, and research and development for the improvement of the genetic base. Broader consultation with national crop and livestock and CGIAR research centers should help with identifying the realistic range of productivity increases related to the adoption of these technologies. The deployment and adoption of new technologies should take into account the large uncertainty related to future climate change impacts.

Besides aiming to achieve highly productive agricultural systems capable of sparing land for nature conservation, we also recognize the importance of "land sharing" or integrated nature conservation approaches on agricultural land. While opportunities for land sharing have not yet been quantified in our pathways, agroecology and agroforestry should be considered when evaluating options to reach greater sustainability of food and land-use systems.

- **Improved land-use planning, particularly for protecting and restoring nature:** In most FABLE pathways, constraints on land-use change, including the expansion of agricultural lands, are critical for meeting the FABLE targets. Countries use different policy tools, such as forest codes, moratoria on the expansion of specific crops (e.g. the soy moratorium in parts of Brazil or the palm oil moratorium in Indonesia), zero-deforestation labels, or protected areas. As demonstrated by the drastic reduction of deforestation in Brazil between 2004-2012 and recent policy innovations in China (Box 3), improved policies for land-use design can have a large impact. Success will require effective, whole-of-government land-use plans and policies involving national and – where applicable – regional and local governments. Of particular importance are financial transfer payments to compensate local populations for maintaining public environmental goods, such as upstream watersheds. As the example of China further illustrates, such land-use planning mechanisms need to include agriculture and ecosystem services, but also processes for managing the use of land for human habitats, industry, mining, and infrastructure. We recognize fully that such land-use planning might well represent one of the toughest policy challenges, but it is one that countries need to grapple with in order to promote sustainable land-use and food systems.

- **Rapid reductions of food loss and waste:** Many FABLE country teams see substantial potential for reducing food loss and waste, which will greatly improve the efficiency of the food system. Food loss and waste has traditionally not been a focus of government policies and corporate action, so the potential for rapid progress is substantial.

4.4 Greater integration of climate and biodiversity under International Conventions

Greater international cooperation and shared learning are needed to make land-use and food systems sustainable. Our countries need to learn from one another what works in shifting diets, reducing food loss and waste, increasing agricultural productivity without destroying biodiversity in production landscapes, strengthening participatory land-use design, greening supply chains, and so forth. Dedicated communities of scientists and practitioners work on each of these questions, but they need greater policy support.

International conventions, including the UNFCCC and the CBD, are critical mechanisms for promoting integrated, ambitious national strategies as well as learning across counties. Yet, today's climate strategies (including NDCs and LT-LEDS) and National Biodiversity Strategy Action Plans are not fit for purpose. About one-quarter of the 2030 mitigation pledged by countries in their initial NDCs is expected to come from land-based mitigation options (IPCC, 2019) but they lack the information necessary to understand what land-based mitigation is anticipated (Fyson & Jeffery, 2019), and they lack the spatial data needed for integrated strategies (Khan & Schmidt-Traub, 2020; Schmidt-Traub et al., 2020). These shortcomings are particularly grave for biodiversity, since only integrated strategies can tackle the many powerful drivers of biodiversity loss and bend the curve (Díaz et al., 2019; Leclère et al., 2020).

In the run-up to the climate and biodiversity COPs countries should integrate biodiversity conservation and restoration as well as food systems into their climate strategies. This integration can be supported by maps of desired land-use, including for food production, biodiversity conservation and restoration, ecosystem services management, and disaster risk reduction. If it is not possible to update an NDC or a long-term climate strategy ahead of the COPs, countries can announce their commitment towards this integration and complete the technical and policy work until the 2023 stock-take under the UNFCCC. The same strategies and maps could then also serve as national strategies under the Convention on Biological Diversity.

4.5 Greening international supply chains

Trade in agricultural and forest commodities ("soft commodities") must align with the SDGs and the objectives of the Paris Agreement. Countries cannot simply "export" the environmental and social costs of food production to other countries. At the same time, sustainable policies in exporting countries will affect trade flows. Contrary to what might be expected, we find that sustainable policies can improve supply and long-term food security for food importers through lower demand and greater productivity in exporting countries. Anticipated reductions in the long-term climate forcing owing to sustainable policies will further strengthen food security in countries that are dependent on trade for meeting their needs in food and animal feed.

All of this implies that measures to green international supply chains will make critical contributions towards sustainable land-use and food systems, but they need to be embedded in a broader transformation strategy. Perhaps the largest levers to reduce the international environmental footprint of countries that import food and animal feed is domestic demand reduction through dietary shifts, reductions in food loss and waste, and sustainable intensification of domestic agriculture. Clearly, supply-side action is needed, too, by promoting sustainable land-use and food system policies in producer countries. Together, these supply- and demand-side levers will reduce the need for imports.

Moreover, large agricultural importers, such as the EU and China, have an incentive to promote sustainable policies in exporting countries since the pursuit of FABLE pathways in producer countries enhances long-term food security and secures the supply of agricultural commodities for everyone. This provides an added motivation for the hosts of next year's UNFCCC and CBD COPs to pursue ambitious outcomes, including greater financial support for the transformation of land-use and food systems in exporting countries.

4.6 Next steps for the FABLE Consortium

In a short period of time, our global consortium of FABLE country teams has developed major analytical capacities on land-use and food systems, pioneered new tools, and built the capacity for bottom-up national analyses of land-use and food systems, including agricultural production, greenhouse gas emissions, biodiversity and ecosystem services, diets, and international trade. Building on these initial successes, we plan to focus upcoming work on the following priorities:

1. As part of the Food and Land Use Coalition, we will work with interested governments to support integrated strategies, including climate and biodiversity strategies under the Conventions, that address short-term pressures on land-use and food systems and are consistent with meeting long-term goals.

2. Through the new Food, Environment, Land, and Development (FELD) Action Tracker (Box 6), we will advance a deeper understanding of how countries can design, implement, and monitor better policies to transform their land-use and food systems.

3. Partnering with the Food Systems Economics Commission and the Nature Map Initiative, we want to improve modeling tools to develop pathways and model policy options for land-use and food systems. This will include better integration of economic, biophysical and geospatial analyses.

4. The FABLE Consortium members want to train the next generation of analysts and policymakers in developing long-term pathways towards sustainable land-use and food systems, so that FABLE tools can be applied by any research group or government that would like to do so.

5. And finally, we will strengthen and expand the FABLE Consortium, including by welcoming new country teams.

Box 6 *Food, Environment, Land, and Development (FELD) Action Tracker*

A lot of knowledge exists on how to make land-use and food systems sustainable, but this knowledge is not widely available, and there are major gaps. We are inspired by the Climate Action Tracker (CAT), which over the past 10 years has been tracking and evaluating country policies, budgets, and other actions to meet the energy-related objectives of the Paris Agreement. CAT issues biannual reports that transparently assess the level of ambition of national strategies in relation to the 1.5°C objective. The reports also inventory "policy actions" in a publicly available database (www.climatepolicydatabase.org) and ascertain their scope and level of ambition in relation to the policy objectives (UNEP, 2019).

CAT has had a significant impact on global discussions around energy decarbonization through three key drivers:

1. **Clarity on countries' level of ambition:** The transparent inventory and assessment of countries' targets in relation to the energy transformation helps to show whether these countries and the world are on track towards meeting the Paris objectives. Similar assessments of policy action do not yet exist for land-use and food systems.

2. **Learning how to transform energy systems:** CAT's climate policy database and reports provide comparative information on policy actions related to energy transformation in some 36+ countries. This has become a critical resource for inspiring other countries to aim higher, providing a practical foundation for them to better understand what works and what does not work. CAT uses a simplified tool along the lines of the FABLE Calculator that quantitatively assesses the impact of policy changes on decarbonization outcomes. Together, the systematic policy analysis and the modeling work by CAT have become an important mechanism to promote learning about how to decarbonize energy systems by systematically chipping away at policy implementation challenges.

3. **Greater visibility and rewards for pioneering countries:** Over the past few years, the CAT has developed the capacity to pick up, review and showcase major policy reforms undertaken by individual countries within a short period of time. The CAT-enabled shift from tracking 'backward-looking' outcomes (e.g. GHG emissions) to tracking 'forward-looking' policies (e.g. moratoria on deforestation) is critical for building momentum, advancing policy learning, and rewarding pioneers. By flagging regress elsewhere, it strengthens accountability.

Working closely with the FABLE Consortium, the CAT team and partners at FOLU (Box 2), the FELD Action Tracker will adapt the CAT model to land-use and food systems, thereby filling an important knowledge gap on existing policies. Initial results will be available in mid-2021 in the context of the Just Rural Transition (JRT) initiative.

5. National pathways

Argentina

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Argentina. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders from Instituto Nacional de Tecnología Agropecuaria (INTA), Fundación Bariloche, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Ministerio de Ambiente y Desarrollo Sustentable (MAyDS), FUNDAPAZ, Fundación "Nuestros Bosques", AAPRESID, Fundación Vida Silvestre Argentina, and others, and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Argentina's Nationally Determined Contribution (NDC), long-term low greenhouse gas emissions development strategy (LT-LEDS), and Forest Reference Emission Level (FREL) treat the FABLE domains. According to its NDC, Argentina has committed to reducing its GHG emissions by 18% (unconditional) or 37% (conditional upon receiving international funding) by 2030 compared to a business-as-usual (BAU) scenario (MAyDS, 2017). Moreover, according to the latest advances in the ongoing LT-LEDS preparations (INTA, 2020), Argentina is working to develop four targets on GHG emissions reductions for the agriculture, forestry, and other land use (AFOLU) sector, including "carbon neutral agriculture". This process, which should be merged with the ongoing Energy 2050 Long Term Strategy (Climate Transparency, 2019), includes emission reduction efforts from the AFOLU sector, including afforestation, rehabilitation of deteriorated forests and other ecosystems, intensification of production, and land sparing. Under its current commitments to the UNFCCC, Argentina does not mention biodiversity conservation, at least not explicitly (MAyDS, 2017).

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC, LT-LEDS, and FREL

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2030	570	2030	483 (18% unconditional reduction from BAU) 369 (37% conditional reduction from BAU)	energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Forests Water Biodiversity
LT-LEDS (2020)	2016 (submission in preparation)	136	2050	Four levels for AFOLU sector: 73, 59, 15 and 0	agriculture, land-use change and forestry	Y	N	Y	Forests Water Food
FREL (2019)	Average 2002-2013 (submission in 2019)	101	2030	Reduction of 27 Mt from this sector (included in NDCs)	land-use change and forestry	Y	N	N	Forests

Note. The NDC "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019).
Source: Argentina (2016)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. In comparison with the FABLE Targets, the NBSAP targets are less ambitious, but cover a broader range of issues (e.g. education, indigenous knowledge, marine ecosystems, etc.).

Argentina's new Biodiversity Strategy and Action Plan (2016-2020) represents a cross-cutting component of the public agenda and an essential tool for achieving inclusive sustainable development, calling for the involvement of all ministries, levels of government, institutions, academics and scientists, indigenous peoples, the private sector and civil society organizations in implementation. It is made up of 9 strategic objectives and 21 priority national targets. The National Biodiversity Commission (CONADIBIO) will be responsible for coordinating activities and monitoring implementation, and the actions will be implemented by competent State entities. Environmental protection efforts are increasingly being assumed by national and provincial entities. In 2012, national spending on biodiversity conservation represented 0.48% of the GDP, while a growth rate of 350% in such spending was determined for the 2006-2012 period (MAyDS, 2015).

Table 2 | Overview of the latest NBSAP Targets in relation to FABLE Targets

NBSAP Target	FABLE Target
(1) **The adequate proportions (of protected areas) will be maintained to fulfil the viability of long-term conservation, buffering, and connectivity among protected areas, according to each region's characteristics and conservation objectives.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate. At least 30% of global terrestrial area protected by 2030.
(2) **Reaching a minimum protected area of 13% of the national land, setting priorities in relation to the existing percentage of protected areas and their connectivity, endemism, and threatened species and ecosystems, and a minimum of 4% in each ecoregion. While the minimum goal is 13% coverage, the NBSAP refers to 17% coverage (as per CBD Aichi Biodiversity Target 11) as desirable.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate. At least 30% of global terrestrial area protected by 2030.
(4) **Augmenting by 20% the current protected wetland areas and integrating them into the public planning system at the local, regional, and national levels.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate. At least 30% of global terrestrial area protected by 2030.
(7) **Fostering sustainable production in regional economies, together with family farming and indigenous populations (...). Incorporation of agroecological production, integrated livestock production and others, compatible with sustainable use and conservation of biodiversity and its ecosystem services.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Argentina.

Our Current Trends Pathway corresponds to the lower boundary of feasible action, even though it is not a continuation of ongoing trends (e.g. 2000-2020). It represents a strong decision to improve Argentina's sustainability without losing competitiveness or total production or income. It is characterized by high population growth (from 45 million inhabitants in 2020 to 65 million in 2050), limited constraints on agricultural expansion, a low afforestation target, high productivity increases in the agricultural sector, no change in diets, and a significant increase in the balance of trade (both an increase in exports and a decline in imports) (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to stopping deforestation (MJyDH, 2007) and reducing post-harvest losses. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on yields by 2050 for corn, rice, soybean, wheat, sugarcane, sunflower, and other minor crops (see Annex 2).

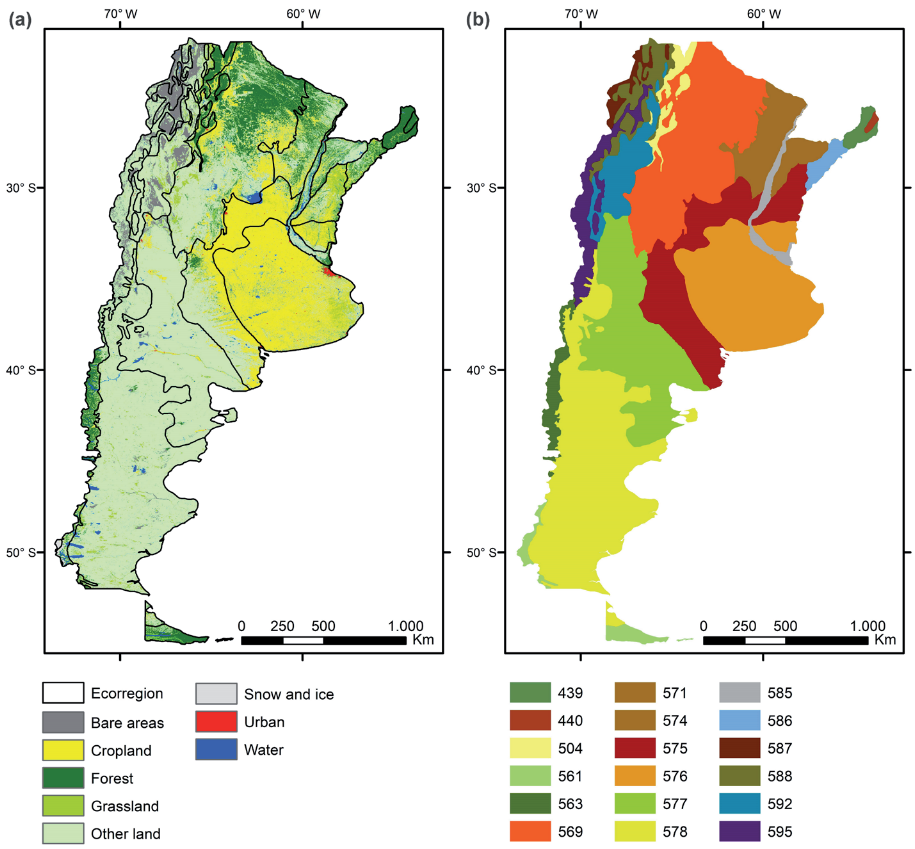
Our Sustainable Pathway represents a future in which further significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to comparatively lower exports and higher imports of commodities, together with a significant reduction in food waste, releasing pressure on the environment (see Annex 2). This corresponds to a future based on no expansion of agricultural areas, increased afforestation (INTA, 2020), and increased irrigation water efficiency (banning gravitational irrigation, as many provinces have begun to do). With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

In 2016, Argentina was covered by around 15% cropland, 40% grassland and pastures, 12% forest, less than 1% urban area, and 32% other natural land. Most agricultural area is located in the center-east, while forest can be mostly found in the north (504-Southern Andean Yunga, 569-Dry Chaco, 586-Southern Cone Mesopotamian Savanna, 439-Alto Parana Atlantic Forest, and 574-Uruguayan Savanna) and in the southwest (440-Araucaria Moist Forests, 561-Magellanic Subpolar Forests, and 563-Valdivian Temperate Forests). Other natural lands, such as grasslands and shrublands (including semi-arid ones) occupy Argentina's entire western latitude (Map 1). Following the IUCN's threats classification scheme, the most important threats to biodiversity are due to changes in land use for agriculture and livestock (threats 2.11, 2.32, 5.1.2, 7.1.1., 8.1) and fires (9.3.3), where an important displacement fauna of has occurred. However, the main threat to biodiversity-rich areas, such as protected areas, is the high-level of tourist activity (threat 1.3).

Map 1 | Land cover in 2010 by aggregated land cover types (a) and ecoregions (b)



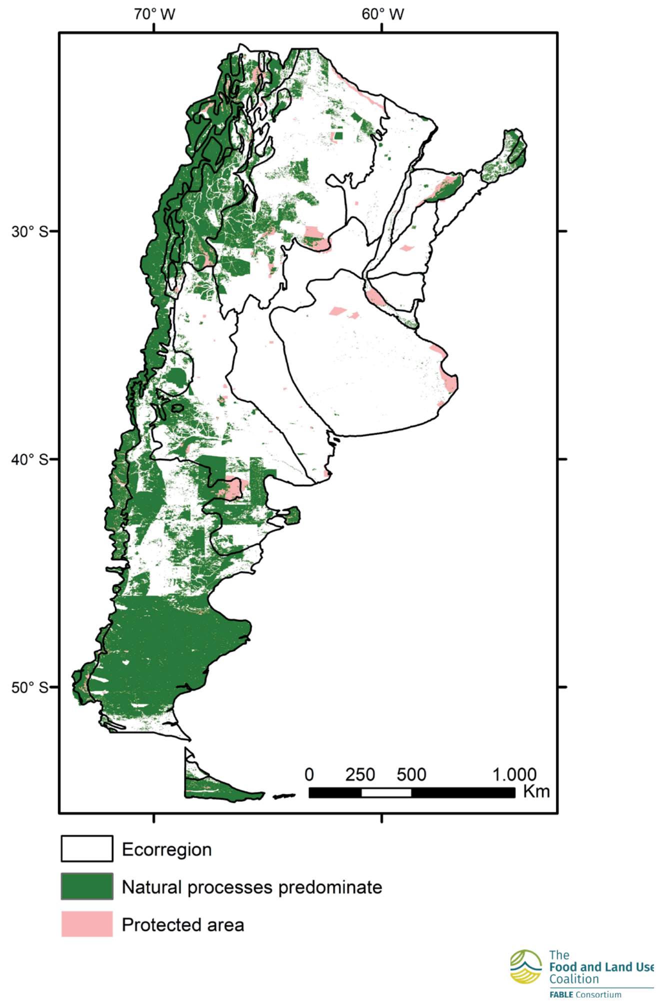
The Food and Land Use Coalition
FABLE Consortium

Notes. See ecoregion names in Annex 4. Correspondence between original ESACCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

We estimate that land where natural processes predominate[2] accounted for 37.3% of Argentina's terrestrial land area in 2010 (Map 2). The 578-Patagonian steppe (semi-arid grassland) holds the greatest share of land where natural processes predominate, followed by 569-Dry Chaco (temperate forest) and 577-Low Monte, a semi-arid shrubland (Annex 4). Across the country, while nearly 23 Mha of land are under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 17.5% of land where natural processes predominate is formally protected. This indicates that the area under legal protection must be expanded to achieve these goals. The ecoregion areas 439-Alto Paraná Atlantic Forest, 504-Southern Andean Yungas, 569/571-Chaco forest, 578-Patagonian Steppe, 563-Valdivian, and 561-Magellan Subpolar forests contain the highest biodiversity and ecosystem service values. Given that at least 50% of currently protected areas lack effective protection (MAyDS, 2015), it is critical to strengthen conservation management, which should be treated with the same level of importance as protected area expansion.

Approximately 35% of Argentina's cropland was in landscapes with at least 10% natural vegetation in 2010 (Annex 4). These relatively biodiversity-friendly croplands are most widespread in 576-Humid Pampas, followed by 575-Espinal, 569-Dry Chaco, and 571-Humid Chaco. However, most of the area in 576-Humid Pampas is either cropland or pastures, while in 575-Espinal, 569-Dry Chaco, and 571-Humid Chaco it is a matrix of natural vegetation that has been colonized by cultivation. In the Monte, Patagonian Steppe, and the Andean regions, the percentage of cultivation is low due to unfavorable climate and soil conditions.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Source. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

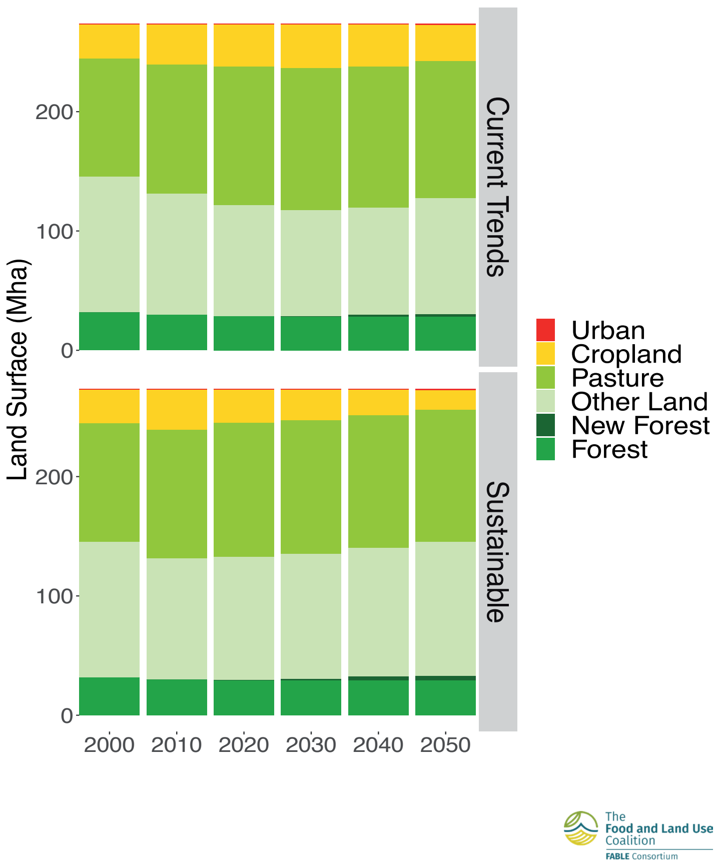
2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including the prevention of deforestation by 2030, 2 Mha of afforestation by 2050, and maintaining protected areas at 23 Mha, representing 8.4% of total land cover (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in pasture and cropland area and a decrease in the area of other land, a trend that stabilizes by 2050 (Figure 1). The expansion of the planted area for soybean, corn, and groundnut explain almost 80% of total cropland expansion between 2010 and 2030. Soybean expansion is explained by an increase in exports (international demand for feed) and high revenues, while corn and groundnut expansion are due mainly to an increase of internal feed consumption and exports and an increase of internal demand for nonfood consumption, respectively. Pasture expansion is mainly driven by the increase in internal demand for beef and milk consumption, while livestock productivity per head also increases and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, the stabilization of land use classes is explained by limiting deforestation and meeting Argentina's export targets (without further intensification). This is a promising result for this less ambitious pathway, even if these changes initially result in a decline in the area where natural processes predominate, falling to approximately 34% of total land by 2030, and only increase in later years, reaching a little over 37% by 2050 (Figure 2).

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

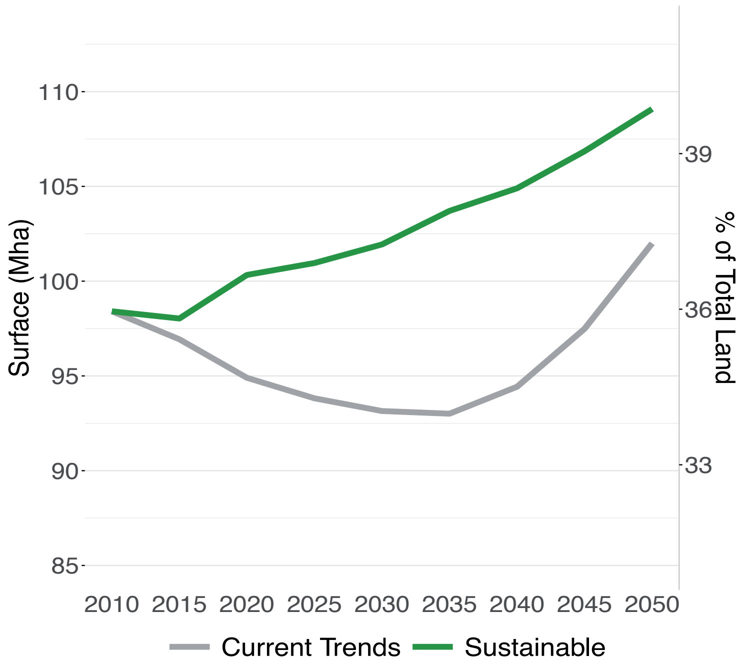


Source: Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000.

In the Sustainable Pathway, assumptions on agricultural land expansion and reforestation have been changed to reflect ongoing discussions and projections made by stakeholders during the Strategic Partnerships for the Implementation of the Paris Agreement (SPIPA) Project (INTA, 2020). The main assumptions include constraints on the expansion of agricultural land beyond its current extent, and 4 Mha of reforestation or afforestation by 2030 (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Argentina in the Sustainable Pathway: (i) a decline in cultivated area and the stabilization of pasture area, (ii) a moderate increase in forests and new forests areas, (iii) an increase in other lands (due to the decrease in cropland area). In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by an increase in productivity, a decrease in food loss, and more balanced international trade for foodstuffs (all of which relieve pressure on land). This leads to a 10% increase in the area where natural processes predominate between 2020 and 2050.

Figure 2 | Evolution of the area where natural processes predominate

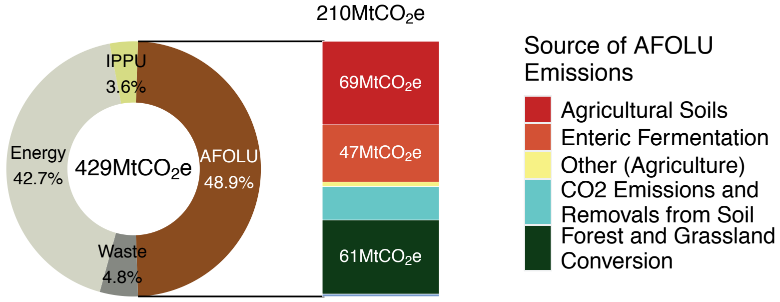


GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 48.9% of total emissions in 2012 (Figure 3). The principle source of AFOLU emissions is agricultural soils, followed by land conversion, and enteric fermentation. This can be explained both by the historical importance of agriculture and animal husbandry in Argentina's economy and deforestation, with over 600 kha deforested in 2012 (Gómez Lende, 2018). Currently, deforestation for agricultural purposes is prohibited, although illegal deforestation remains an issue.

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2012

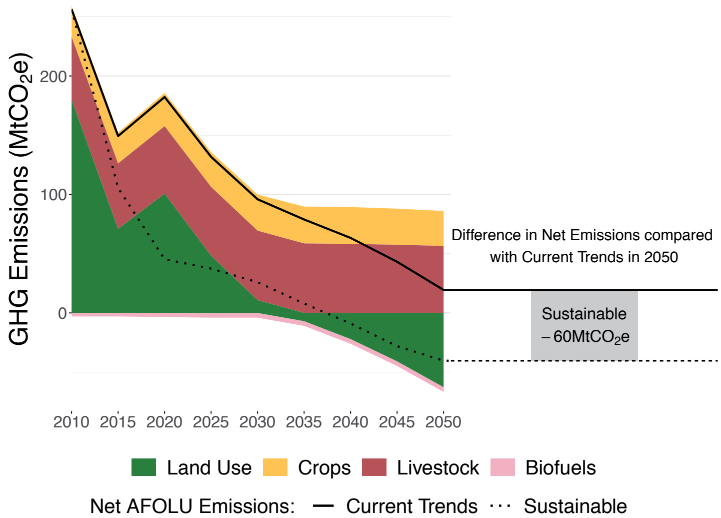


Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 96 Mt CO_2e/yr in 2030, before reaching 19 Mt CO2e/yr in 2050 (Figure 4). In 2050, livestock is the largest source of emissions (57 Mt CO_2e/yr) while land-use change (afforestation) acts as a sink (-64 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increases in GHG emissions are for crops (70%), while emissions from livestock increased around 7%. There is a strong relative increase in GHG sequestration, which reduces Argentina's total emissions by around 33%.

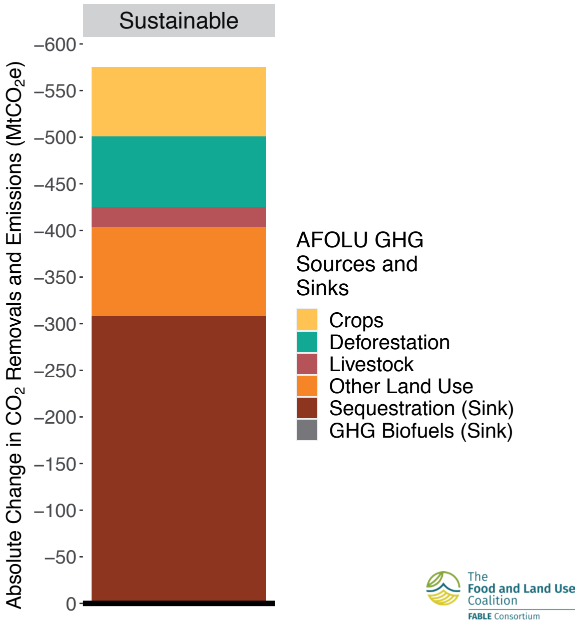
Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by 70% by 2050 compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Pathway are achieved by a reduction in GHG emissions from crops (due to the comparative reduction in total crop area) and a noticeable increase in carbon sequestration due to land use changes (no deforestation and increased afforestation), while there are less significant changes regarding emissions from livestock (Figure 5).

Compared to Argentina's commitments under the UNFCCC (Table 1), our results show that AFOLU could contribute to as much as 33% of its total conditional objective for GHG emissions reduction by 2030. Such reductions could be achieved through the following policy measures: halting all deforestation, promoting afforestation, and enhancing productivity in order to spare natural lands. These measures could be particularly important when considering options for long-term strategies for reducing GHG emissions. Regarding the ongoing LT-LEDS preparation process, the Sustainable Pathway results point to how Argentina could fulfill its less ambitious goal of "less than 2°C", although they would still fall short a "carbon neutral agriculture" goal.

Figure 5 | Cumulated GHG emissions reduction computed over 2020–2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition	Micronutrient Deficiency	Overweight/ Obesity
4.6% of the population was undernourished in 2016-2018. This share has increased since 2015, when the share stood at around 3.3%.	18.6% of women of reproductive age suffered from anemia in 2016, which can lead to maternal death (FAO, 2017).	22.5% of adults and 9.9% of children were obese in 2005. The share of adult obesity has since increased linearly and reached 28.5% in 2016 (FAO, 2017).
In 2005, 8.2% of children under 5 were stunted and 1.2% were wasted (FAO, 2017).	14.3% of children are deficient in vitamin A, which can notably lead to blindness and child mortality, and most children and pregnant women from northern provinces are deficient in iodine, which can lead to developmental abnormalities (Disalvo et al., 2019).	

Disease Burden due to Dietary Risks

Each year, 203 deaths per 100,000 population are attributable to dietary risks (Afshin et al., 2019).

10% of the adult population suffers from diabetes and 24% of all deaths in 2012 were caused by cardiovascular diseases, both closely related to dietary risks (INDEC & MINSAL, 2013).

Table 3 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,921 (2,051)	2,903 (2,070)	2,875 (2,070)	2,905 (2,070)	2,898 (2,070)
Fats (g) (recommended range	108 (65-97)	108 (65-97)	106 (64-96)	108 (65-97)	107 (64-97)
Proteins (g) (recommended range	93 (73-256)	93 (73-254)	91 (72-252)	93 (73-254)	92 (72-252)

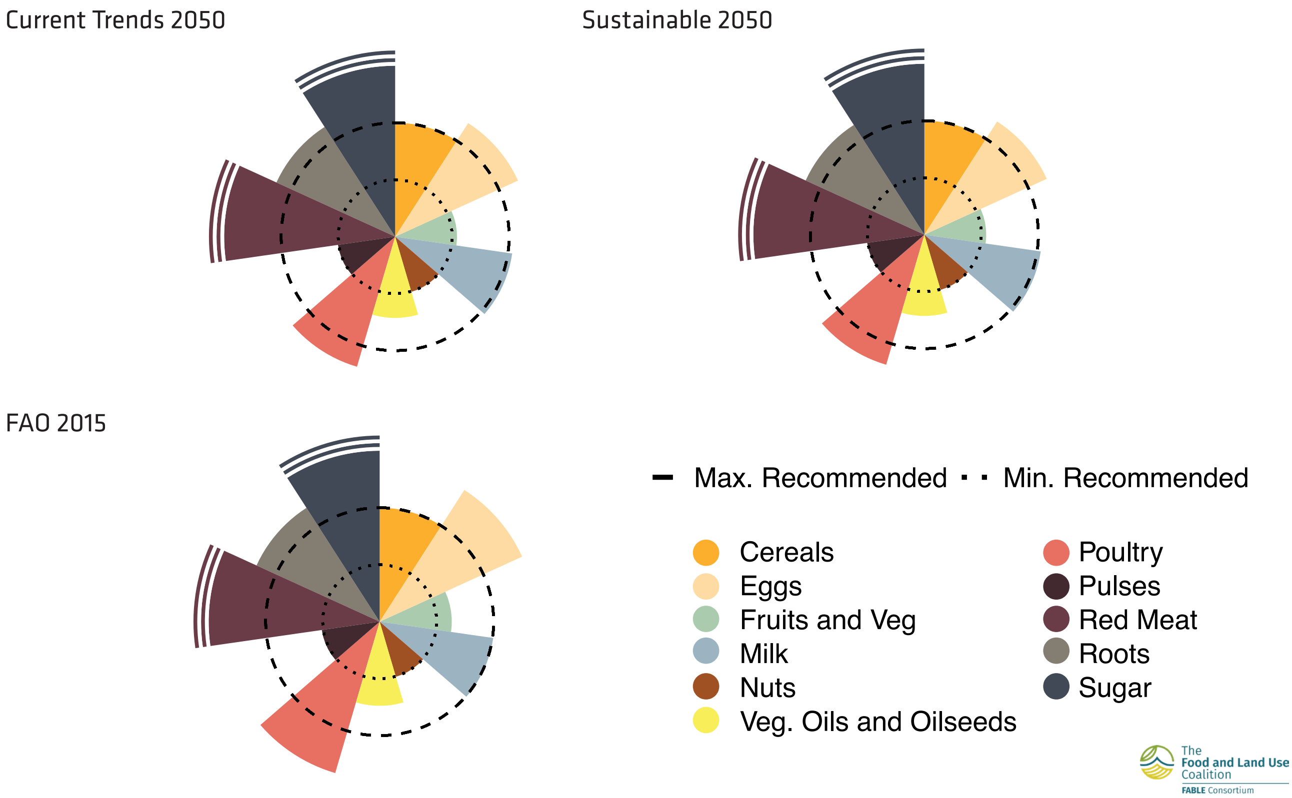
Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement by sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalorie consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 40% higher in 2030 and 2050 (Table 3). The current average intake is mostly satisfied by cereals, sugar, red meat, and milk, while animal products represent 31% of the total calorie intake. We assume that the consumption of animal products and in particular red meat will remain constant between 2020 and 2050. The same assumption stands for eggs, poultry, cereals, sugar, and oils consumption. Compared to the average EAT-Lancet recommendations (Willett et al., 2019), red meat, sugar, eggs, poultry and cereals are over-consumed (Figure 6).

Under the Sustainable Pathway, we assume that diets will remain similar to those under the Current Trends Pathway, as we have primarily prioritized discussing environmental concerns with stakeholders. Although this assumption may not be internally consistent with the rest of the Sustainable Pathway storyline, we will be reaching out to national stakeholders and experts regarding these issues in the future stages of our analyses.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



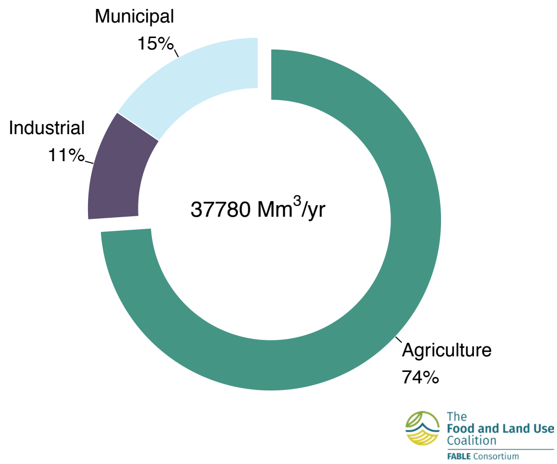
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is lower than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

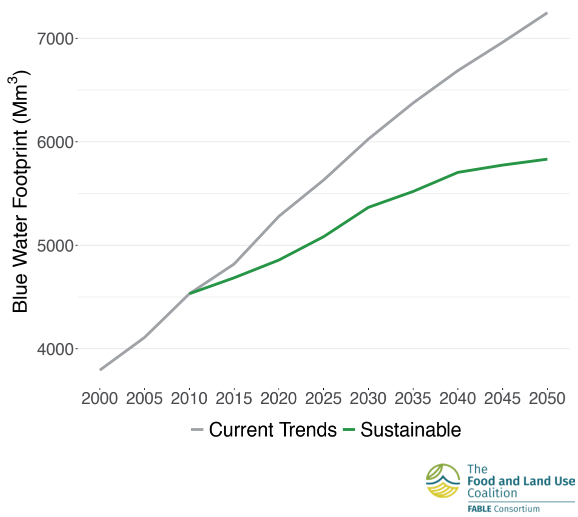
Due to its size, its predominantly latitudinal extension (3,780 km, from 21° 46' 52" S to 55° 03' 21" S) and an altitude variation of almost 8,000 meters, Argentina contains a wide range of climate types. Summers are the warmest and wettest season in most of the country except in most of Patagonia, where it is the driest. Winters are normally mild in the north, cool in the center and cold in the south, which experiences frequent frost and snow. In general, the north is characterized by hot, humid, rainy summers and mild winters with periodic droughts. Mesopotamia, in the northeast, is characterized by high temperatures and abundant precipitation throughout the year, with droughts being uncommon. West of this lies the Chaco region, where precipitation decreases, resulting in the vegetation changing from forests in the east to shrubs in the west. Northwest Argentina is predominantly dry and hot although the rugged topography makes it climatically diverse, ranging from the cold, dry Puna to thick jungles. The center of the country, which includes the Pampas to the east and the drier Cuyo region to the west has hot summers with frequent tornadoes and thunderstorms, and cool, dry winters. Patagonia, in the south, has a dry climate with warm summers and cold winters, strong winds throughout the year and one of the strongest precipitation gradients in the world. In terms of water withdrawals, agriculture is the main source, accounting for 74% in 2011 (FAO, 2020), with most of it occuring in the central part of the country. Moreover, from the 40 Mha suitable for crop and cattle production, only 2.4 Mha are irrigated, most of them through gravitational irrigation (MAGyP, 2020) .

Figure 7 | Water withdrawals by sector in 2011



Source. Adapted from AQUSTAT Database (FAO, 2017).

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000-2015 (3,793 Mm^3/yr and 4,819 Mm^3/yr), before reaching 6,027 Mm3/yr and 7,248 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with sugarcane, rice, and grape representing respectively 14.6%, 13.8% and 12.3% of computed blue water use for agriculture by 2050[3]. In contrast, under the Sustainable Pathway, blue water footprint in agriculture reaches 5,366 Mm^3/yr in 2030 and 5,832 Mm3/yr in 2050, respectively. This improvement is explained by changes in the crop composition of the harvested area (i.e. each crop has a different water consumption coefficient) and climate change impacts.

3 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

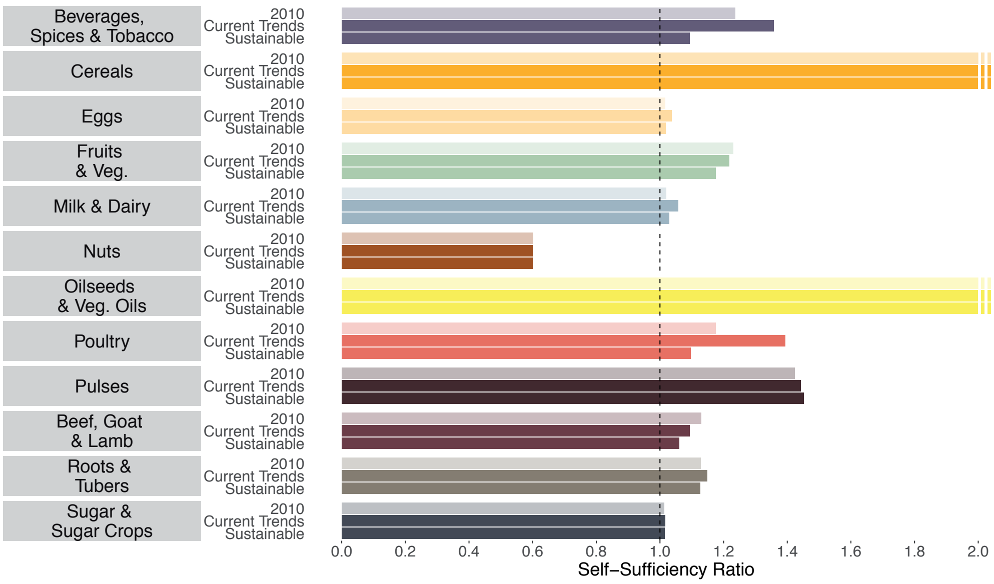
The COVID-19 crisis has exposed the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Argentina resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Argentina has long been self-sufficient in food production, with an estimated 40% of total of food produced exported annually. For example, the exported value of food products of 2010 was around 80 billion USD (MINAGRO, 2016).

Under the Current Trends Pathway, we project that Argentina would be self-sufficient in virtually all product groups in 2050, with self-sufficiency by product group slightly increasing for the majority of products from 2010 – 2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are nuts, for which no noticeable changes are observed between 2010 and 2050. In the Sustainable Pathway we project that Argentina would still remain self-sufficient, but that these levels would decrease between 2010 and 2050 for most products. Nevertheless, no additional groups fall below the level of self-sufficiency due to lower production or increased consumption.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for cereals and oilseeds and vegetable oils, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

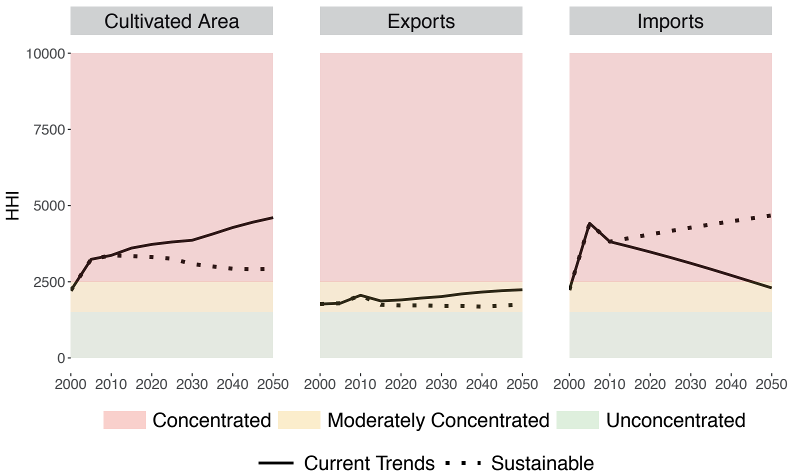
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

In 2010, Argentina's imports and exports of food products were diverse. The values of the HHI Index were 818 for the export and 226 for the import market (calculated from trade values of main products for that year according to Hausmann et al., 2011). These values were obtained from official import and export records, which differ compared to our calculations (HHI values of 2,056 and 3,818, respectively). In addition, we found a HHI Index of 3,366 for the planted crop area in 2010, which is not at all diverse. This is unsurprising given that 60% of the crop area is planted with soybean and more than 95% of cultivated area is covered by only seven crops (MAGyP, 2020).

Under the Current Trends Pathway, we project a mild increase in the concentration of crop exports and a decrease in that of imports over the period 2010 to 2050. The difference in the 2010 values found in the literature and our results is due to the number and categories of food products considered and should be checked more carefully in future reports. Regarding the concentration in the range of crops planted between 2010 and 2050, the trend shows a marked increase in the HHI index. This indicates lower levels of diversity across the national production system. In contrast, under the Sustainable Pathway, we project a comparatively lower concentration of crop exports, fairly stable during the whole period, but a relatively higher concentration of imports towards 2050 (Figure 10). This is explained by a less ambitious export target and a higher dependency on imports in this pathway, and the fact that only two or three of the most relevant products are used to implement import-export scenarios.

Figure 10 | Evolution of the diversification of the cropland area, crop imports, and crop exports using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

The pathways presented in this chapter can be summarized as "compromises between development and environmental objectives", with each slightly leaning in favor of one or the other. In both, land-use changes by 2050 are moderate. In both pathways, greenhouse gas emissions increase at first, disappear from deforestation after 2030 and reach levels similar to those in 2000 by midcentury. Moreover, emissions from crops, livestock, and land-use change would account for only 2.5% of the targeted 4 Gt CO_2e from crops and livestock and negative and zero from land use changes by 2050, which all FABLE country teams aim to achieve collectively. Finally, under these pathways, Argentina would achieve zero net deforestation by 2030, which also contributes to the zero-net -emissions target from land-use change.

To achieve these climate goals, it is necessary to halt the expansion of the current crop area (which should, in fact, decrease slightly), increase productivity, diversify production, minimize emissions from agriculture (including transport logistics), and expand the area of biodiversity protection, biomass carbon stocks and water retention. Our ongoing Nature Map prioritization studies (Annex 5) show that expanding protected areas to 30% could conserve more than 75% carbon in biomass, almost 90% of endemic species, and more than 81% of pure water sources. However, if this expansion were to take place without considering crop distribution, around 12% of crop-producing areas would be lost. This tradeoff would lead to production losses of around 7.6 Mt/year, provided crops are not relocated and yields remain at their 2017 and 2018 levels (Table 4). However, these results were obtained without applying constraints to the expansion of protected areas within the most productive zones. Preliminary results from the Nature Map Argentina indicate that this overlap could be strongly reduced without significantly affecting the fulfillment of conservation targets.

Table 4 | Production loss of main crops due to protecting 30% of key natural areas as compared to 2017 and 2018

	Production Loss (t/year)	Production value in 2017/2018 (t/year)	Percentage of loss (%)
Rice	173,801	1,367,968	12.7%
Oat	12,243	491,713	2.5%
Barley	52,624	3,741,158	1.4%
Rye	2,033	86,098	2.4%
Sunflower	180,647	3,537,545	5.1%
Corn	2,952,293	43,462,323	6.8%
Peanut	57,849	921,231	6.3%
Soybean	2,434,654	37,787,927	6.4%
Sorghum	177,768	1,563,445	11.4%
Wheat	796,096	18,518,045	4.3%
Sugarcane	796,095	17,760,997	4.3%
Total	**7,636,101**	**129,238,450**	**6.1%**

Regarding the principal trade-offs between competing uses of land, we found no significant compromises between conservation goals and food provision. Similarly, there are no visible trade-offs in terms of food security as Argentina can easily cover the dietary requirements of its population (Feeney & MacClay, 2016). In other words, there are no biophysical limits to produce healthy food in a sustainable way. Rather, the main trade-off would be between sustainability and an export policy that primarily sells a single commodity (e.g. soybean and its byproducts) to very few importing countries.

This relates to the important issue of "spillover effects", understood here as the effects of the decisions taken in one country on other countries, which needs further attention. For example, the positive (i.e. income and job creation) and negative effects (i.e. deforestation, pollution, GHG emissions, population displacement, and biodiversity loss) of China´s and the European Union's imports from Argentina (Hoff et al., 2019). When richer countries buy food abroad for their internal consumption to make progress towards achieving the SDGs and spare land within their own territories, this creates spillover effects on producing countries.

In regard to the key limitations of this analysis, the FABLE Calculator currently has its limits as a tool for territorial environmental planning given that it is not spatially explicit, as it is not currently possible to define priority areas. With Nature Map Argentina we are moving to bridge this gap. Similarly, we have not yet explicitly considered the supply of food from small and medium producers of fruits and vegetables in our pathways. Family farming and agroecology, as well as small peri-urban vegetable crops, are important contributors to Argentina's food security. Therefore, these aspects will be particularly important to explore in the future given that the Ministry of the Environment and Sustainable Development of Argentina now lists reducing the prevalence of monocultures and increasing agroecological production among its highest priorities. Finally, food distribution is not properly accounted for in this assessment. Our results show a plentiful supply of food, which means that hunger is the results of its unequal distribution. This raises the need for a specific indicator to address this problem, such as, for example, one that "corrects" the food supply by its unequal distribution.

To overcome these limitations, our next steps include integrating the Nature Map and the FABLE tools to prioritize areas for conservation and food production. We are working on the construction of an Environmental Territorial Planning Map of Argentina using Nature Map and the FABLE Calculator with the Ministry of Environment and Sustainable Development, which will directly inform the implementation of sustainable policies. In parallel, we will continue the participation in the ongoing Strategic Partnerships for the Implementation of the Paris Agreement (SPIPA) Project, which aims at the development of Argentina's LT-LEDS for reducing GHG emissions by 2050. To this end, we also intend to include mitigation measures in our modeling.

Annex 1. List of changes made to the model to adapt it to the national context

No significant changes have been made to the Argentinian FABLE Calculator. However, in order to comply with Argentina's method for measuring national GHG emissions, we added a method that allowed us to estimate emissions in line national calculations (results not showed in this report). The only substantial differences between these calculations relates to forests (the Argentinian NDCs consider forests as net emitters of GHG). In addition, in certain cases we replaced the default FAO data when more accurate or more recent data were available. Finally, we modified the Bonn Challenge scenario to account for stakeholder input; an increase from 1 Mha to 2 Mha in Current Trends Pathway and an additional scenario targeting 4 Mha in the Sustainable Pathway.

Annex 2. Underlying assumptions and justification for each pathway in the FABLE Calculator

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
Population is expected to increase by 33% between 2015 and 2050 from 43 million inhabitants to 57 million. Based on combined extrapolations from INDEC (2019) and Baumann Fonay & Cohan (2018). (SSP3 scenario selected)	

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
We assume that deforestation will be halted beyond 2030. We made our choice based on the existence of a new law that establishes forest protection (MJyDH, 2007). (NoDefor 2030 scenario selected)	We assume no productive land expansion beyond 2010. We made our choice based on the preferences declared by most stakeholders during the meetings for the SPIPA Project (INTA, 2020). (NoExpansion scenario selected)

LAND Afforestation or reforestation target (Mha)

Current Trends Pathway	Sustainable Pathway
We assume new afforested area to reach 2 Mha by 2050, based on a more ambitious target than the Bonn Challenge commitment. Argentina's national commitment is to restore 1 Mha by 2030 (Bonn Challenge, 2019).	We assume new afforested area will reach 4 Mha by 2050, based on the preferences declared by some of the stakeholders during the meetings for the SPIPA Project (INTA, 2020).

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.	

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Pathway

We assume that between 2015 and 2050 crop productivity increases:
- from 8 t/ha to 21 t/ha for corn
- from 3 t/ha to 5.6 t/ha for soybean
- from 3.7 t/ha to 10.4 t/ha for wheat

These assumptions are based on estimated yield gaps in Argentina, which stand at 100% for corn, 140% for wheat, and 130% for soybean (Global Yield Gap Atlas, 2019). Although we assumed productivity to be the same across pathways, some minor differences could appear due to the two different climate change scenarios.

PRODUCTION Livestock productivity for the key livestock products in the country (in kg/TLU)

We assume that between 2015 and 2050, productivity increases:
- from 76 kg/TLU to 90 kg/TLU for beef
- from 5.9 t/TLU to 6.9 t/TLU for cow milk

The estimated yield gap in Argentina is 54% for cow-calf and 60% for finishing (Rearte, 2010).

PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

The average livestock stocking density remains constant at 0.32 TLU/ha of pastureland between 2015 and 2050. This is a conservative assumption. (Rearte, 2010) estimates that it could increase by 15-20% with better management of forage resources only, but increasing stocking rate elevates the number of heads, thus elevating GHG emissions, and that is an issue among stakeholders (INTA, 2020).

PRODUCTION Post-harvest losses

Argentina wastes 16 Mt/year of food (Roulet, N, 2018, unpublished data). In order to release pressure on land and resources, loses were reduced by half. Based on discussions with stakeholders during the SPIPA Project (INTA, 2020).

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway
The share of total consumption which is imported decreases: • from 72% in 2010 to 36% in 2050 for bananas. The share of total consumption which is imported remains constant at 2010 level for the other products.	The share of total consumption which is imported increases: • from 72% in 2010 to 100% in 2050 for bananas. The share of total consumption which is imported remains constant at 2010 level for the other products.

TRADE Evolution of exports for key exported products (Mt)

Current Trends Pathway	Sustainable Pathway
The exported quantity increases: • from 17 Mt in 2010 to 71 Mt in 2050 for corn • from 13 Mt in 2010 to 54 Mt in 2050 for soybean • from 5 Mt in 2010 to 20 Mt in 2050 for soy oil • from 0.16 Mt in 2010 to 0.48 Mt in 2050 for milk The exported quantity remains constant at 2010 level for the other commodities.	The exported quantity increases: • from 17 Mt in 2010 to 36 Mt in 2050 for corn • from 13 Mt in 2010 to 27 Mt in 2050 for soybean • from 5 Mt in 2010 to 10 Mt in 2050 for soy oil • from 0.16 Mt in 2010 to 0.32 Mt in 2050 for milk The exported quantity remains constant at 2010 level for the other commodities.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 2,900 kcal and comes mainly from cereals, sugar and red meat, with animal products representing 32% of the total calorie intake. We assume no significant dietary changes in either pathway between 2020 and 2050, except that we assume the consumption of eggs and poultry will increase while cereals, sugar, and oils consumption will decrease. For this analysis, we prioritized the discussion of environmental concerns rather than food security issues (in part due to Argentina's "overproduction" of food – this points to the importance of food distribution, which is not yet considered in the modelling efforts). In the following stages, we will be contacting expert and stakeholder groups regarding these issues.	

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
Between 2015 and 2050, the share of final household consumption which is wasted remains stable at 10%.	Argentina wastes 16 Mt/year of food (Roulet, N, 2018, unpublished data). In order to account for feasible improvements, we selected the scenario *Reduced*, in which household food consumption is reduced by half by 2050.

BIOFUELS Targets on biofuel and/or other bioenergy use (Mt)

Current Trends Pathway	Sustainable Pathway
Both in the Current Trends and Sustainable pathways, the OECD_AGLINK Scenario was assumed, which corresponds to maintaining projections until 2028, and then stable values. This represents an initial demand for the following products: sugarcane (3.4 Mt), soyoil (1.8 Mt), and other minimal contributions from corn and rice.	

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km^2 (%)
439	Alto Paraná Atlantic Forests	2,263.5	9.9	51.9	17.4	82.6	39.3	97.6
440	Araucaria Moist Forests	463.1	10.4	73.4	13.3	86.7	5.0	92.9
587	Central Andean Dry Puna	3,011.9	36.0	88.4	37.9	62.1	0.5	100.0
588	Central Andean Puna	8,749.8	26.0	72.8	28.3	71.7	62.0	88.2
569	Dry Chaco	49,102.3	5.1	25.8	16.5	83.5	8,034.4	46.1
575	Espinal	29,922.7	1.7	6.7	9.1	90.9	14,645.3	27.0
592	High Monte	11,698.6	12.9	68.0	13.7	86.3	108.2	76.1
571	Humid Chaco	16,228.4	10.1	23.2	24.4	75.6	3,051.6	64.5
576	Humid Pampas	39,904.8	3.0	6.8	10.6	89.4	30,050.7	29.4
577	Low Monte	35,411.7	5.4	29.6	11.7	88.3	940.6	55.5

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that are protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
561	Magellanic Subpolar Forests	2,842.3	36.2	88.0	39.4	60.6	77.4	91.1
585	Paraná Flooded Savanna	3,714.6	34.5	31.4	41.3	58.7	254.7	66.3
578	Patagonian Steppe	53,542.8	6.3	64.2	9.4	90.6	247.7	87.2
0	Rock and Ice	124.0	99.0	100.0	99.0	1.0	0.5	51.8
595	Southern Andean Steppe	9,485.4	26.2	92.2	27.7	72.3	23.1	78.4
504	Southern Andean Yungas	4,765.0	9.2	48.5	17.6	82.4	479.0	67.2
586	Southern Cone Mesopotamian savanna	2,683.9	1.6	17.2	7.3	92.7	327.6	80.7
574	Uruguayan Savanna	24.0	0.6	32.9	1.0	99.0	0.8	94.8
563	Valdivian Temperate Torests	4,467.7	37.4	92.4	40.1	59.9	194.1	89.0

Source. countries - GADM v3.6; ecoregions Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Annex 5. Application of Nature Map in Argentina

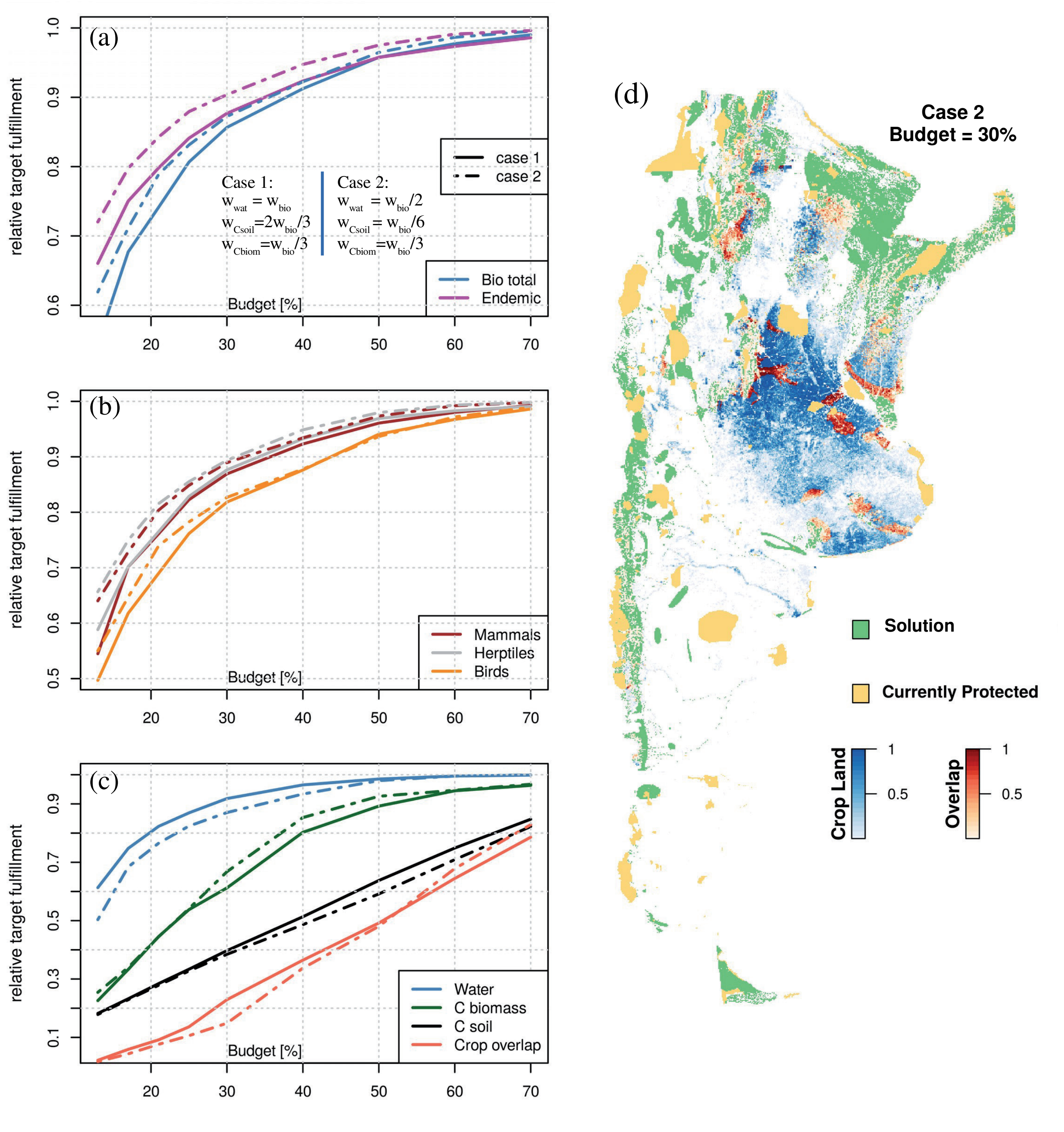
The Nature Map project (IIASA, IIS, UNEP-WCMC and SDSN, 2020) is an international effort to produce integrated maps of terrestrial areas of significance for conservation and restoration of biodiversity, carbon storage, water provision, and other ecosystem services. In Argentina, we are currently mapping habitats of endemic and non-endemic species, vulnerable soil and plant carbon, and potential sources of clean water provision. The aim is to build a map that combines each of these features and prioritizes them for conservation through a spatial optimization algorithm. To do so, we map the entire country by planning units of either protected or unprotected areas. Within the bounds of an overall "budget" that limits the maximum extent of protected areas, we then prioritize these units by identifying those which maximize the relative target fulfillment of each feature.

For this preliminary study, we considered 359 endangered species that are present in 17 biomes in Argentina. We set a target to preserve 80% to 100% of their original distribution ranges, depending on their IUCN endangerment category, including endemism into the prioritization. Furthermore, we set the target to preserve 100% of vulnerable (prone to loss) soil and biomass carbon and freshwater supply to downstream beneficiaries.

The variables were then charted against the protection budgets (from 0 to 100% of the country area) needed to reach the desired targets, considering different relative weights (Figure 11a-c). A preliminary solution is presented in Figure 11d: a map of the optimal way to preserve biodiversity, water, and carbon with a total given budget of 30% of the area (green areas, in addition to the already preserved yellow ones). This would result in the conservation of more than 75% of the carbon in biomass, almost 90% of endemic species, and more than 81% of potential clean water provision. Since soil carbon is distributed more evenly than the other variables, only around 30% of it can be protected. The areas in red correspond to the overlap of the proposed protected areas with the current cropland distribution, which account for around a 10% loss of some of the most productive areas. Considering current crop distribution and productivity, this could mean a loss of near 7.6 Mt of grain, around 6% of 2017-2018 value.

The preliminary Nature Map Argentina results show that potentially contrasting objectives can be achieved jointly through the use of prioritization models designed to answer how much area is needed for successful conservation of natural resources (and where protected areas should be located). The 30% budget solution is not entirely satisfactory due to the overlap of conservation and crop production. Future optimizations should be carried out applying additional constraints to protecting croplands and other productive areas, or even attempting to achieve both food production targets and environmental targets by allocating cropland, grazing and conservation areas at the same time, to better address this trade-off.

Figure 11 | Prioritization analysis



Notes. Calculation of the relative target fulfillment for different sets of features, as a function of the allowed budget: (a) mean biodiversity (total and endemic), (b) mammals, reptiles and birds, and (c) water and carbon, both in soil and in biomass. In addition, the overlap with current cropland areas is shown in panel (c) (relative to total cropland). Two cases using different weights for water and carbon are shown (see panel (a)). The resulting map for case 2 for budget 30% is shown in (d).

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Australia

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines options for sustainable food and land-use systems to contribute to achieving sustainable development priorities in Australia. It presents two potential pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable Pathways. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including from The Commonwealth Scientific and Industrial Research Organisation (CSIRO), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context. Ongoing work as part of the Australian Land Use Futures initiative[1] will undertake geospatially explicit analysis and more extensive consultation with Australian stakeholders to develop more detailed sustainability pathways for the sector.

1 https://www.climateworksaustralia.org/project/land-use-futures/

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, are essential tools for achieving emission reductions. Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Australia's Nationally Determined Contribution (NDC) relate to the FABLE domains. According to the NDC, Australia has committed to reducing its GHG emissions by 26% to 28% by 2030 compared to 2005. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Under its current commitments to the UNFCCC, Australia does not mention biodiversity conservation.

Mitigation measures from agriculture and land-use change currently included in the Australian Climate Solutions Fund (Australian Government, 2020) are:

- Animal effluent management
- Beef cattle herd management
- Estimating sequestration of carbon in soil using default values
- Fertilizer use efficiency in irrigated cotton
- Measurement of soil carbon sequestration in agricultural systems
- Reducing GHG emissions in beef cattle through feeding nitrate-containing supplements
- Reducing GHG emissions in milking cows through dietary feeding additives
- Avoid clearing of native regrowth
- Avoid deforestation
- Designated Verified Carbon Standard (VCS) projects
- Human-induced regeneration of a permanent even-aged native forest
- Measurement-based methods for new farm forestry plantations
- Native forest from managed regrowth
- Plantation forestry
- Reforestation and afforestation
- Reforestation by environmental or mallee plantings
- Savanna fire management (GHG emissions avoidance)
- Savanna fire management (GHG sequestration and emissions avoidance)

Table 2 provides an overview of the biodiversity targets included in the 2010 National Biodiversity Strategies and Action Plan (NBSAP), as listed on the CBD website (CBD, 2020), which are related to the FABLE biodiversity targets (Natural Resource Management Ministerial Council, 2010). In comparison with the FABLE Targets, Australia's NBSAPs targets are less ambitious and have shorter timeframes for implementation.

Table 1 | Summary of the mitigation target, sectoral coverage, and direct references to AFOLU, biodiversity, spatially-explicit planning, and other FABLE targets in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)*	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[2] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2005	N/A	2030	26% to 28% reduction	Energy; Industrial processes and product use; Agriculture; Land-use, land-use change and forestry; Waste	N	N	N	N/A

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source. Australia (2015)

Table 2 | Overview of the latest NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(4) **By 2015, achieve a national increase of 600,000 km² of native habitat managed primarily for biodiversity conservation across terrestrial [...] environments.**	**BIODIVERSITY:** 1. No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate. 2. Protected areas cover at least 30% of global terrestrial land by 2030.
(5) **By 2015, 1,000 km² of fragmented landscapes [...] will be restored to improve ecological connectivity.**	
(7) **By 2015, reduce by at least 10% the impacts of invasive species on threatened species and ecological communities in terrestrial, aquatic and marine environments.**	

2 We follow the United Nations Development Programme (UNEP) definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Brief Description of National Pathways

Among possible futures, we present two possible alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Australia.

Our Current Trends Pathway corresponds to the continuation of trends observed over the last 20 years and assuming little change in the policy environment. It is characterized by high population growth (from 26 million in 2020 to 38 million in 2050), significant constraints on agricultural expansion, a low afforestation target, on-trend productivity increases in the agricultural sector, and no change in diets. These and other important assumptions are justified using historical data, experts' advice, and results from integrated science assessment models (see Annex 2). This Current Trends Pathway is embedded in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, millet, nuts, rapeseed/canola, rice, soybean, sugarcane, sunflower and wheat (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices that are consistent with higher-than-trend productivity growth and corresponds to a high boundary of feasible action. Similar to the Current Trends Pathway, we assume that this future would result in high population growth and no agricultural expansion. However, the Sustainable Pathway assumes higher agricultural productivity growth, higher carbon sequestration via afforestation and regrowth, adoption of more sustainable diets, and lower blue water footprint than under the Current Trends Pathway (see Annex 2). This corresponds to a future based on the adoption and implementation of new ambitious policies that support farmers in achieving greater yields at lower environmental costs and which enable the development of negative-carbon technologies to bridge the gap between what industry can achieve in terms of emission reductions and the net-zero emissions target. This Sustainable Pathway is embedded in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

In 2010-11, around 54% of the Australian landmass was used for grazing in lands with native and modified vegetation, 23% for nature conservation, 4% for cropland and horticultural activities, 2% for forestry plantings, 0.2% for urban use, and the rest were lands with minimal human use (Figure 1). Australia's intensive agricultural zone (spanning livestock, broadacre (large scale crop operations), and horticultural production) covers the south-eastern and south-western parts of the country, but high-value horticultural production is also present in the high-rainfall zones of north-east Australia. Livestock production is present throughout (except desert areas). Forest and other natural lands can also be found throughout the country. The 2016 Australia State of the Environment report (Cresswell & Murphy, 2016) found that in most jurisdictions, the status of threatened species is poor and declining due to the pressure of invasive species (particularly feral animals), habitat fragmentation and degradation, and climate change. There are concerns that current investments in biodiversity management and monitoring are inadequate considering the magnitude of such a decline in the status of many species. Past investments in biodiversity management have reported inadequate resources to monitor and measure their outcomes for long enough to demonstrate effectiveness (Cresswell & Murphy, 2016).

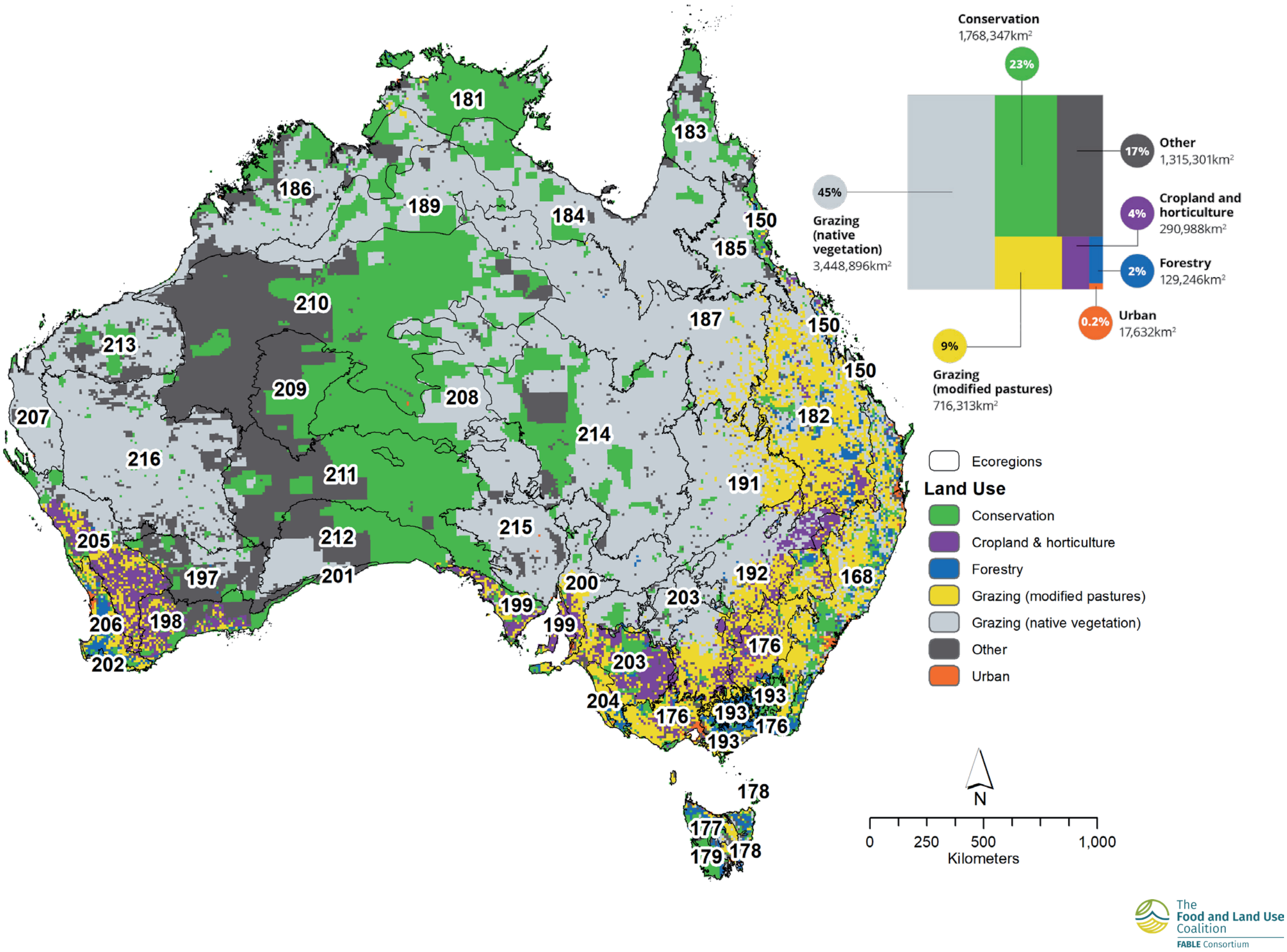
The FABLE Secretariat estimates that land where natural processes predominate[3] (e.g. native vegetation areas, conservation lands, and regions with minimal human use) accounted for around 89% of Australia's terrestrial land area in 2015. Ecoregion *210-Great Sandy-Tanami Desert* holds the greatest share of land where natural processes predominate (12% of total), followed by *210-Simpson Desert* (8.7% of total) and *187-Mitchell Grass Downs* (7% of total) (Table 3)[4]. However, there is a great disparity in the proportion of land where natural processes predominate within Australia's Intensive Agriculture Zone (IAZ) – corresponding approximately to the ecoregions with cropland areas great than 100kha, located in the south-east and south-west – and the rest of Australia (Bryan et al., 2015). Ecoregions within Australia's IAZ account for only 17% of the total land where natural processes predominate, and their share of land supporting biodiversity ranging from 14% to 86% with an average share of 59%. The rest of Australia accounts for 83% of the total land where natural processes predominate, with an average share of land supporting biodiversity of 99% (range 90%-100%). For context, the IAZ occupies 85.3 Mha of land (20.8% of total agricultural land in 2010). The low levels of biodiversity habitat in intensively farmed areas suggest these production areas are under-benefiting from the ecosystem services that support agricultural production (pollination, biological pest control, flood mitigation). It highlights the need for integrated farming approaches to achieve food production and biodiversity conservation targets simultaneously.

Across the country, 148 Mha of land (19% of total land) is under formal protection, falling short of the 30% zero-draft CBD post-2020 target. In ecoregions within the IAZ, 13% of the land is under formal protection (range 4-58%) compared to 22% in the rest of Australia (range 2-100%). Of all the land where natural processes predominate, 22% of it is formally protected in both the IAZ and the rest of Australia. This indicates that there has been an effort to protect areas in regions where competition for land is the strongest, and this has resulted in the equal shares reported here. Despite these efforts, it is likely that agriculture and other human activities will continue to put pressure on biodiversity and ecosystem services. Scientific, technical, behavioral, and policy innovation will be essential pillars of sustainable agricultural production.

3 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".
4 Ecoregions information were obtained from Olson et al. (2001).

In 2015, approximately 34% of Australia's cropland was in landscapes with at least 10% natural vegetation within a 1km² range. Outside of Australia's IAZ, this percentage increases to 83%. These relatively biodiversity-friendly croplands are most widespread in ecoregion *176-Southeast Australian Temperate Forests* (7% of total and 42% of ecoregion), followed by *192-Southeast Australia Temperate Savanna* (6.6% of total and 38% of ecoregion) and *182-Brigalow Tropical Savanna*, *168-Eastern Australian Temperate Forests*, *205-Southwest Australia Savanna* and *203-Murray-Darling Woodlands and Mallee* (about 3% of total each and percentages per ecoregion varying between 20-70%) (Figure 1). The regional differences in the extent of biodiversity-friendly cropland can be explained by differences in agroclimatic suitability which leads to landscape specialization into croplands and to the necessary reduction of nutrients and water available for vegetation. In ecoregions with smaller total cropland area, it is more common to have significant proportions of natural vegetation (defined here as at least 10%) within the neighborhood of crop paddocks (neighborhood defined as 1km around a paddock).

Map 1 | Land use types and ecoregions in 2010

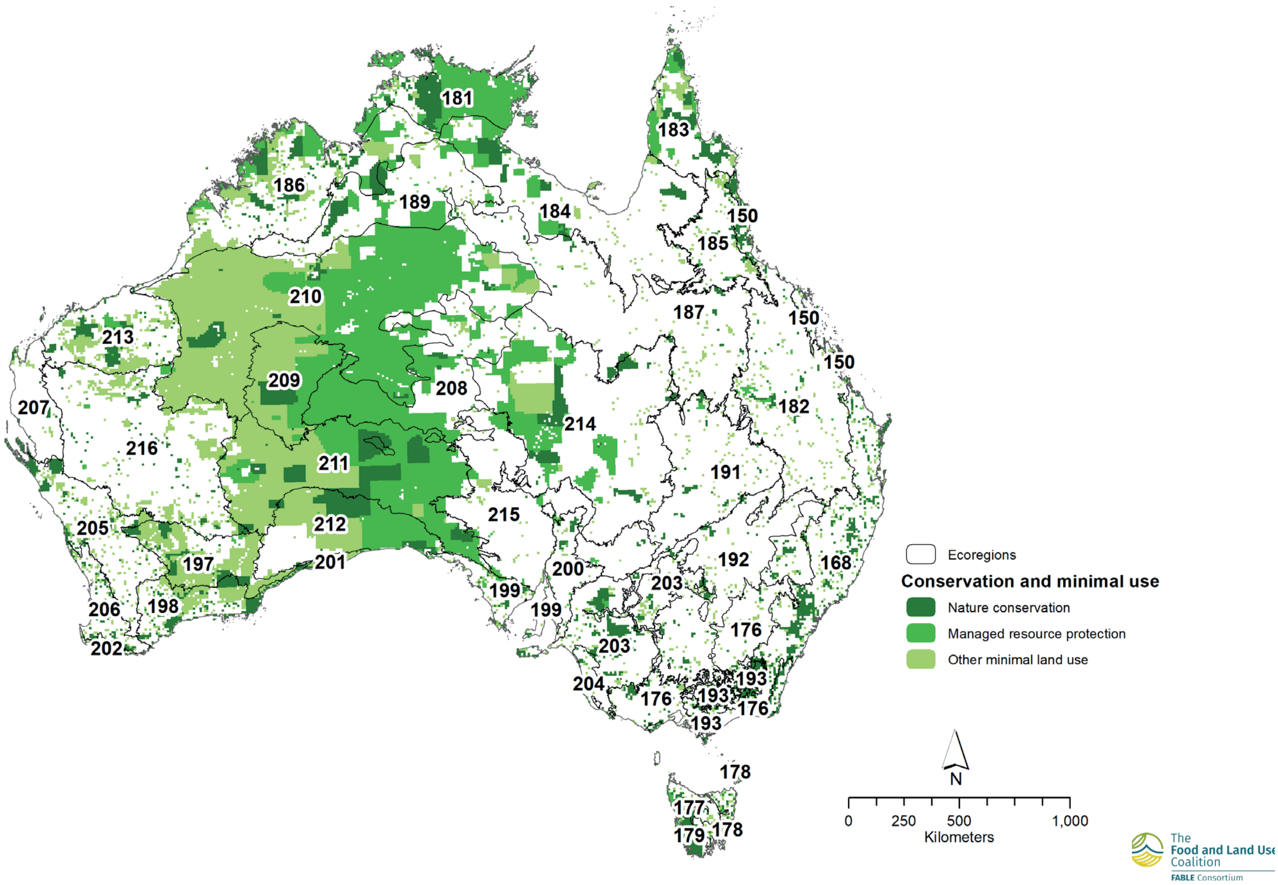


Note. Based on the Australian land use map 2010-11 (ABARES, 2016). Numbers in the map indicate ecoregions' identifiers. In this figure, conservation land corresponds to protected areas, grazing corresponds to grasslands, and the category Other corresponds to other lands with minimal human

Australia's land use

Australia's landmass extends to around 7.7 million km^2, making it the world's 6th largest country. This vast continent and its natural resources underpin Australia's economic, social, and environmental health, and support a large range of uses. Agriculture covers over half of our land and directly employs around 304,000 people across approximately 86,000 farms. In total, agriculture supports around 1.6 million direct and indirect jobs. Agriculture accounts for around 3% of Australia's gross domestic product (GDP). Over half (65%) of the food and other agricultural products produced in Australia is sent overseas. Livestock grazing on native vegetation in more arid regions makes up the largest use of agricultural land, occupying almost half of Australia's total landmass (Figure 1). After agriculture, the second largest category of land use in Australia is conservation land and minimal land use land, which together cover almost 40% of Australia's surface (Figure 2). Land with trees or shrubs planted for wood production covers around 2% of Australia. Land used most intensively for agriculture (the IAZ), is concentrated along south-western and south-eastern coasts. This area makes up just over 13% of Australia's landmass. Yet, due to its suitable climate, soil and access to markets, the area accounts for almost all agricultural production (ClimateWorks Australia, 2019).

Map 2 | Conservation and minimal use land, and ecoregions in 2010



Note. Based on the Australian land use map 2010-11 (ABARES, 2016). Numbers in the map indicate ecoregions' identifiers. Conservation land is equivalent to protected areas.

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[5]

Zone		Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
Rest of Australia	**210**	Great Sandy-Tanami desert	82785	38.3	99.3	38.2	61.8	0.5	100
Rest of Australia	**214**	Simpson desert	58633	21.6	99.3	21.2	78.8	5.8	81.3
Rest of Australia	**187**	Mitchell Grass Downs	47420	2.4	99.7	2.4	97.6	10.9	92.1
Rest of Australia	**216**	Western Australian Mulga shrublands	46382	4.5	99.1	4.6	95.4	5.4	99.3
Rest of Australia	**211**	Great Victoria desert	42402	30.6	99.7	30.7	69.3	28.6	53.2
Intensive Agriculture	**182**	Brigalow tropical savanna	41062	4.6	67.8	6.4	93.6	3621	48.8
Intensive Agriculture	**168**	Eastern Australian temperate forests	29553	18.9	46.9	37.6	62.4	2384	68
Intensive Agriculture	**192**	Southeast Australia temperate savanna	27869	3.8	52	6.7	93.3	10243	38.3
Intensive Agriculture	**203**	Murray-Darling woodlands and mallee	20819	17.7	53.2	31.4	68.6	7073	20.1
Intensive Agriculture	**176**	Southeast Australia temperate forests	18905	9.8	35.7	25.4	74.6	9015	41.6
Intensive Agriculture	**205**	Southeast Australia temperate forests	17799	10.6	41.2	23.7	76.3	9557	16.8

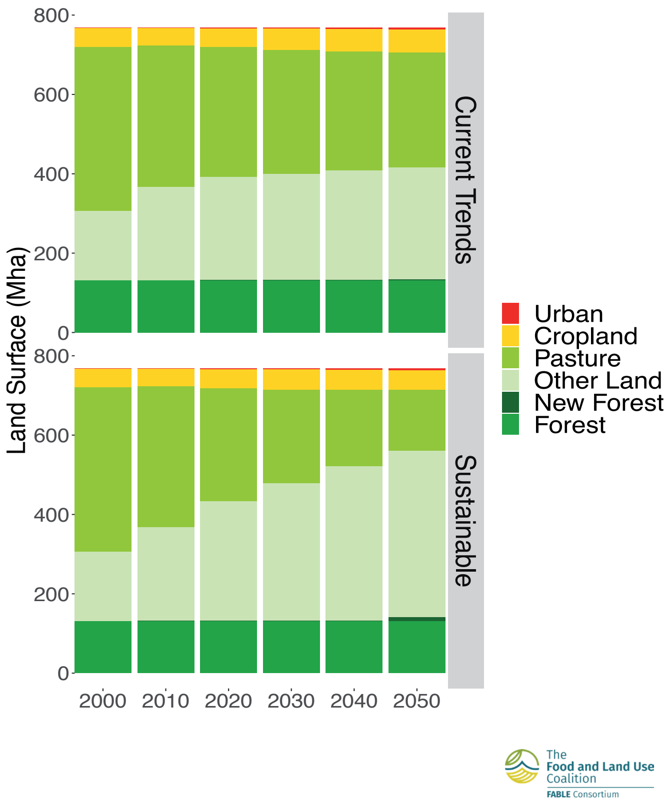
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

5 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no productive land expansion beyond its 2010 value, and 2 Mha of carbon and environmental tree plantings by 2050. By 2030, the model projects that the main changes in land cover in the Current Trends Pathway could result from an increase in other types of land cover area and a decrease of pasture area. This trend remains stable over the period 2030-2050: pasture area further decreases at an average rate of 1 Mha/yr and other types of land cover displays an expansive mirroring trend (Figure 3). By 2050, this pathway projects an expansion of croplands of 10 Mha (21%) relative to 2015: The expansion of the planted areas for pulses, cereals, sugar and fruit and vegetables explain 50%, 32%, 8%, and 2%, respectively, of total cropland expansion between 2015 and 2030. For all crops, area growth is due to the combination of a growing population with little change in domestic diets and moderate growth in crop yields on-trend with historical increases. To meet demand, area sown for crops must grow. Pasture decrease is mainly driven by increases in livestock productivity per head and ruminant density per hectare of pasture over the period 2020-2030. Abandoned pastureland is subject to vegetation regrowth, which contributes to an expansion of land where natural processes predominate by 1% by 2030 and by 3% by 2050, compared to 2010. Since this expansion is due to pasture abandonment and afforestation in more marginal lands, it is likely that the projected increase of land where natural processes predominate would occur mostly outside of Australia's Intensive Agriculture Zone (IAZ).

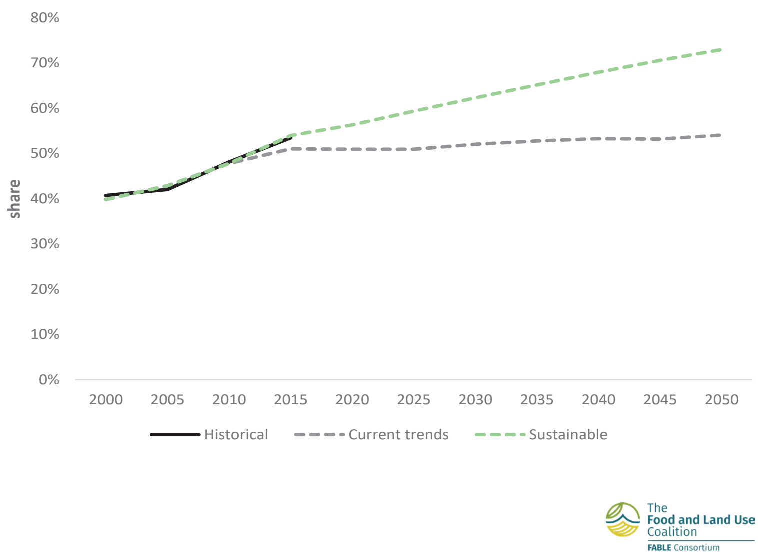
Figure 1 | Evolution of area by land cover type under each pathway



Source: Authors' computation based on FAOSTAT (FAO, 2020), ESA CCI (2017) and Land Use of Australia 2010-11 (ABARES, 2016) for the area by land cover type for 2000

In the Sustainable Pathway, the assumption on forest expansion has been changed to represent an ambitious scenario with stronger productivity growth, increasing resource-use efficiency, and overall reductions in environmental impacts. These conditions could support the Australian agriculture sector to maintain and anticipate changes in social license and enhance the resilience and competitiveness of the sector in international markets. The main difference in assumptions compared to the Current Trends Pathway includes 9.4 Mha of carbon and environmental plantations by 2050 (see Annex 2). The afforestation scenario corresponds to the lower bound of a multi-model ensemble that assessed potential Australian land-use futures under ambitious economic and environmental sustainability settings (Brinsmead et al., 2019).

Figure 2 | Evolution of the share of the terrestrial land which can support biodiversity conservation



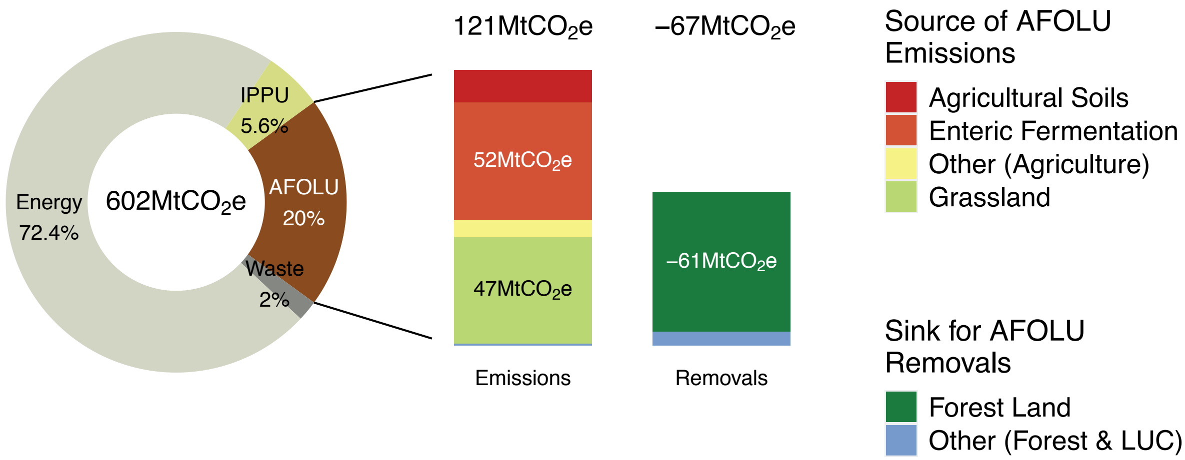
Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Australia in the Sustainable Pathway: (i) a decline of crop and pasture areas, and (ii) an increase in forest, urban and other land areas. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by increased productivity growth in crops, increased livestock density growth and global changes in diets impacting the configuration of Australian landscapes. This leads to an increase in the share of the Australian landmass that can support biodiversity conservation (FABLE 2019 target) from 54% in 2015 to 73% by 2050 for the Sustainable Pathway (Figure 4). The share remains almost unchanged for the Current Trends Pathway.

GHG emissions from AFOLU

Current State

Direct GHG emissions from AFOLU accounted for 20% of total emissions in 2017 (Figure 5). Enteric fermentation is the principal source of AFOLU emissions, followed by grassland, agricultural soils, and manure management. This is due to the sheer size of the livestock industry in Australia, including approximately 25 million heads of beef cattle, 4 million heads of dairy cattle and 70 million heads of sheep in 2015 (ABS, 2017). Burning of fossil fuels to power on-farm operations, the production of farm fertilizer and pesticide inputs and their transport are estimated at 7%, 26%, and 2% of direct GHG emissions (Navarro et al., 2016) which indicates that resource use efficiency gains in Australia's agriculture sector could influence significantly more than 20% of total emissions, potentially closer to 30%.

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2015



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease from 95 Mt CO_2e/yr to 52 Mt CO_2e/yr between 2000-2020, then further decrease to 45 Mt CO_2e/yr in 2030, before declining to 25 Mt CO_2e/yr in 2050 (Figure 6). In 2050, livestock is the largest source of emissions (73 Mt CO_2e/yr) while afforestation and regeneration act as a sinks (-31 Mt CO_2e/yr and -36 Mt CO_2e/yr, respectively). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for croplands (43%) while a reduction is computed for livestock (2%).

In comparison, the AFOLU GHG emissions in 2050 in the Sustainable Pathway are 160 Mt CO2e/yr lower than in the Current Trends Pathway (25 Mt CO_2e/yr in the Current Trends Pathway, -135 Mt CO_2e/yr in Sustainable Pathway)(Figure 7). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from livestock and crops (25% reduction on both) resulting from increasing crop and livestock productivity, increasing livestock density, and international shifts in diets. Compared to national commitments under UNFCCC (Table 1), our results show that AFOLU could contribute 26-43% of Australia's total GHG emissions reduction objective by 2030.

Figure 4 | Potential AFOLU emissions reductions by 2050 by trajectory compared to Current Trends

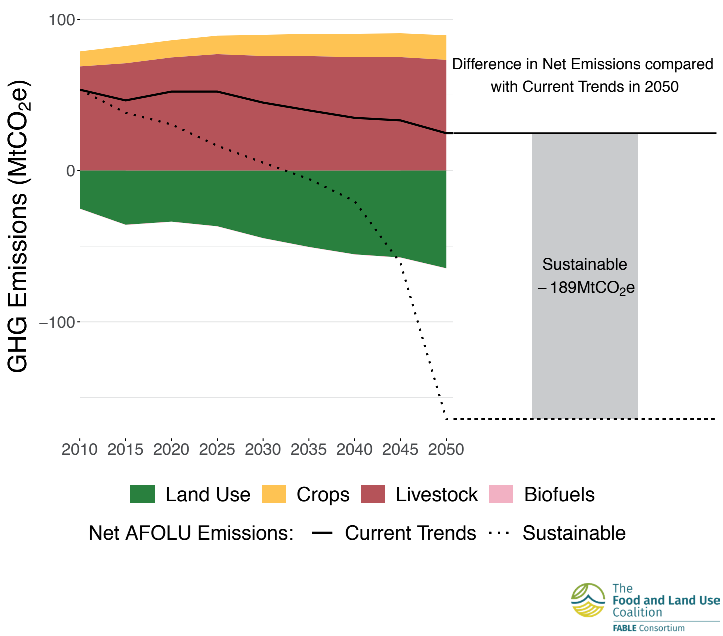
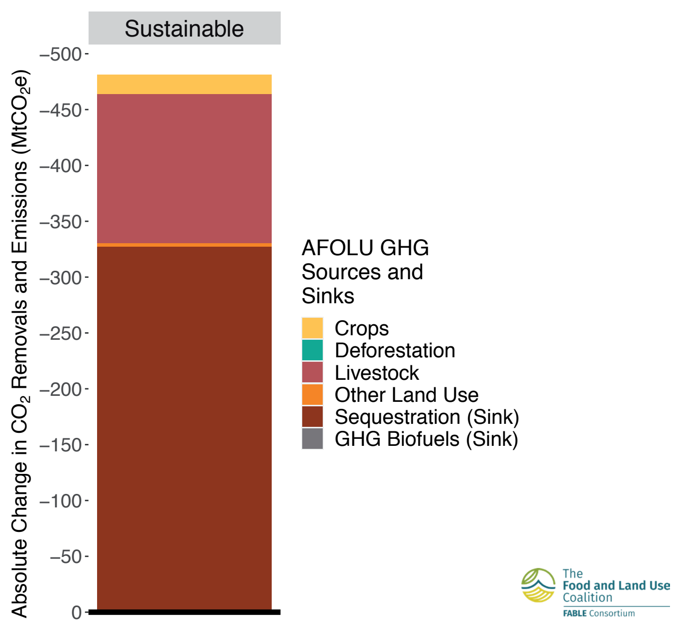


Figure 5 | Comparison of cumulated projected GHG emissions reduction over 2020-2050 by AFOLU type compared to the Current Trends Pathway



Food Security

Current State at the National Level

The Burden of Malnutrition and Overweight/Obesity

Malnutrition

Malnutrition is common in Australia. This is primarily due to micronutrient deficiencies, although certain groups are more at risk (including First Nations people who are addressed below). Specifically, up to 50% of older Australians are at risk of malnutrition or malnourished (Healdirect.gov.au, 2019), and up to 40% of all hospital admissions result in hospital-acquired malnutrition (Australian Commission on Safety and Quality in Health Care, 2019)

9.1% of women of reproductive age, 20.1% of pregnant women, and 14% of children suffered from anemia in 2016, which can lead to maternal death (WHO, 2020).

3% of children under five years suffered nutritional deficiencies in 2017 (range 2.2%-4%) (The Lancet, 2017). Most children are not eating enough fruit and vegetables, and most older girls (9-16) are not drinking enough milk (Australian Institute of Health and Welfare, 2012)

There are still major concerns around the very low intake of fresh fruit and vegetables - Most Australian (91%) do not meet their recommended minimum number of servings of vegetables, while only 50% consume enough fruit (NHMRC, 2013).

Overweight/ Obesity

36% of adults were overweight, and 31% of adults were obese in 2017-18. Obesity shares have increased from 19% since 1995. 25% of children were overweight or obese in 2017-18 (Australian Institute of Health and Welfare, 2019).

Disease Burden due to Dietary Risks

An estimated 15% of premature deaths are attributable to dietary risks (13.4-16.7%), or 106 deaths/yr (per 100,000 people) (92-123) (The Lancet, 2017).

Dietary risks are also estimated to lead to/cause 420 (364-490) thousand disability-adjusted life years (DALYs), or 342 (296-397) thousand years of healthy life lost (YLL) due to an inadequate diet (*The Lancet,* 2017). This equates to 0.02 DALYs or 0.013 YLLs per capita.

An estimated 0.06% (0.05%-0.07%) of the population (14,760 people) suffers from type 2 diabetes, and 0.29% (0.27-0.31) (71,300 people) from cardiovascular diseases; both are associated with lifestyle risk factors such as diet, but also have strong genetic risk factors (*The Lancet,* 2017).

Current State of First Nations People

The above statistics do not reflect the disparity between the population average and disadvantaged groups like Indigenous Australians and low socio-economic groups. McKay et al. (2019) found a prevalence of food insecurity is significantly affected by the type of question being asked when surveying insecurity, and also varied greatly between the general population and other disadvantaged groups such as First Nations People. For example, while the prevalence of food insecurity in the general population can vary between 1.6-8% using the single-item measure, other methodologies such as the USDA Household Food Security Survey Module measure (USDA, 2019) or the Kleve et al. (2018) Household Food and Nutrition Security Survey (HFNSS) measure observe the prevalence of 29% and 57% respectively. Disadvantaged groups (including First Nations People) in urban locations have an estimated food-insecurity of 16-25% using the single-item measure (that's on average 4.3 times greater than the general population), whereas food insecurity amongst remote First Nations People has been estimated at 76% using the single-item measure (on average 18 times greater than the general population (McKay et al., 2019). The 2016 Australian Burden of Disease Study (Australian Institute of Health and Welfare, 2019) shows First Nations People experience a burden of disease 2.3 times greater than that of non-First Nations People, and that about 37% of this burden was preventable by modifying risk factors including tobacco/alcohol use (20% of burden), and high BMI/physical inactivity/diet (24%).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,852 (2,091)	3,122 (2,081)	2,573 (2,078)	3304 (2,081)	2,259 (2,078)
Fats (g) (recommended range	138 (63-95)	150 (69-104)	118 (57-86)	158 (73-110)	95 (50-75)
Proteins (g) (recommended range	90 (71-250)	101 (78-273)	83 (64-225)	110 (83-289)	77 (56-198)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

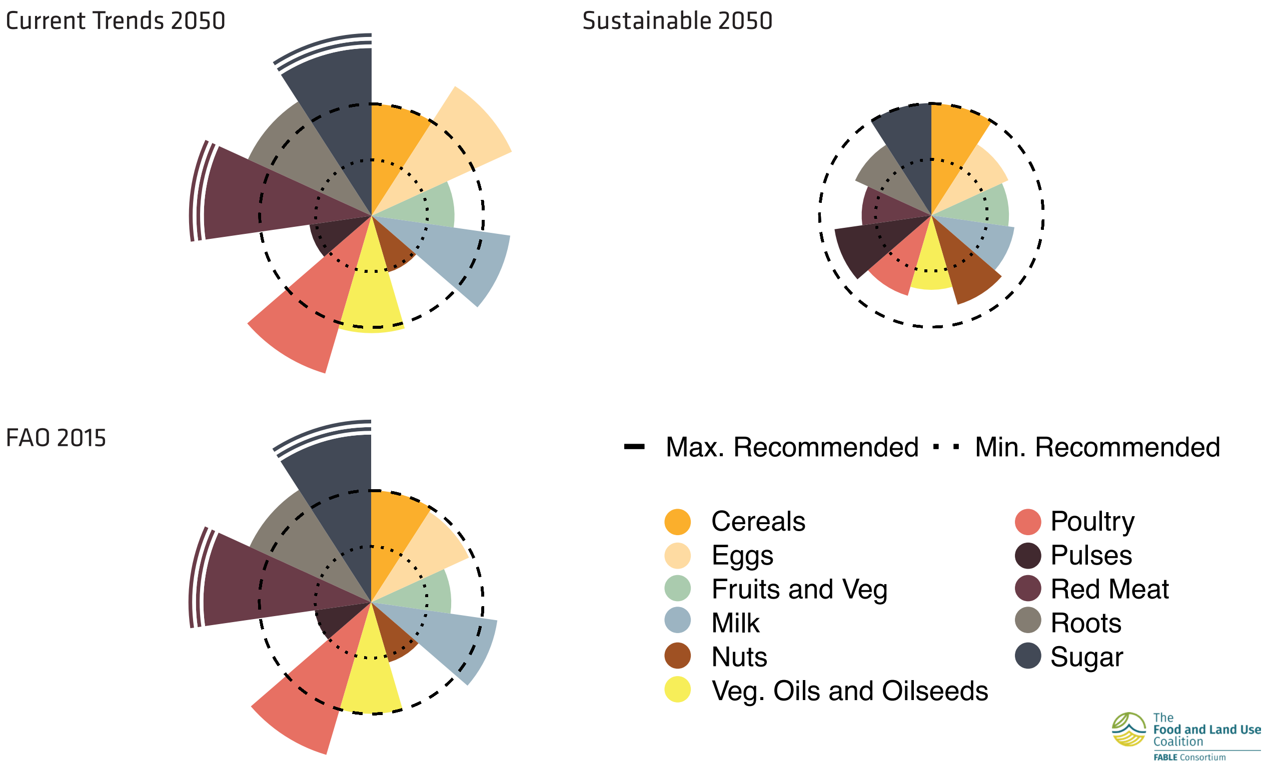
Under the Current Trends Pathway, the average calorie intake is 50% and 59% higher in 2030 and 2050, respectively, than the average Minimum Dietary Energy Requirement (MDER) (Table 4). The average calorie intake in 2010 was mainly composed of oil and animal fat (24%), cereals (19%), sugars (14%), and red meats (6%) for an aggregated 63% of the total calorie intake. Projected diet changes indicate that the consumption of animal products could increase by about 20% between 2010 and 2050. Average diet estimates indicate per capita overconsumption of red meat, poultry, roots, sugars, fish, and eggs by 2050; other food categories are within the EAT-*Lancet* healthy diet recommended ranges (Figure 8).

Under the Sustainable Pathway, we assume that domestic diets would transition towards an overall healthy diet (based on the EAT-Lancet report (Willett et al., 2019) but adapted to Australian conditions. The average calorie intake is 24% and 9% higher than the MDER in 2030 and 2050, respectively. Compared to the EAT-*Lancet* healthy diet recommendations, by 2050, under the Sustainable Pathway, only fish consumption is above the recommended range (Figure

8). However, estimates for such commodities are still under calibration in the FABLE Calculator. All other crops and animal commodities are within the recommended range of a healthy diet.

Current climate change mitigation policies in Australia still largely concentrate on reducing emissions from the energy and industry sectors (Brinsmead et al., 2019). While there are some important schemes and attempts to also reduce emissions and improve the resource use efficiency in the agricultural and land-use sectors, e.g. the Australian Emission Reduction Fund (Australian Government, 2020), these have yet to be combined with incentives to promote healthier and more sustainable diets and to achieve significant reductions in household waste. This could reduce resource use and emissions associated with domestic consumption. Some recent trends towards more plant-based eating are encouraging, as seen in a 1.5% (from 9.7% to 11.2%) rise from 2012 to 2016 in the number of vegetarians (Roy Morgan, 2019), as well as the increasing number of people reducing their red meat consumption in favor of more non-animal sources of protein (Waldhuter, 2017). However, the main challenge is that Australians at present consume high-calorie diets with very high amounts of meat, with the current average consumption for red meat estimated to be 24% higher than the maximum recommended intake in the Australian Dietary Guidelines (ADGs) (NHMRC, 2013). Introducing stronger sustainability principles in the upcoming iteration of the ADGs, along with strong monetary incentives to push consumption patterns towards more sustainable diets, could accelerate ongoing positive trends.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



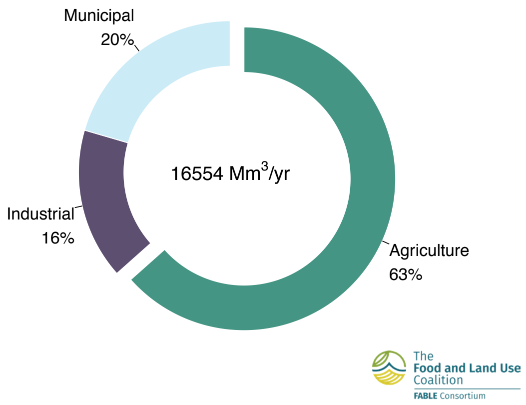
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring, and if it is higher it is displayed on the maximum ring. The discontinuous lines for some food groups indicate that the average kcal consumption for such a group is significantly higher than the maximum recommended. The discontinuous lines that appear at the outer edge of sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

The agricultural sector accounted for 63% of domestic water withdrawals in 2017 (Figure 9). In 2011, around 0.46% of the domestic agricultural land was irrigated, representing around 0.26% of the Australian landmass (ABARES, 2016). Irrigated land produces around a third of the agricultural sector's economic value. During the harvest period 2017-2018, around 9.7 million megaliters (ML) of water were used to irrigate crops and pastures in around 2.3Mha of agricultural land. Crops accounted for 69% of the total water use, and the remaining proportion was applied in pastures. The three crops with the largest water use were cotton, sugar cane, and rice, which accounted for 29%, 10%, and 8% of the total irrigation water and for 16%, 9%, and 3% of the total irrigated area, respectively (ABS, 2019c). Australia exported around 95% of its cotton production, 80-85% of its raw sugar, and around 85% of rice in 2019 (Department of Agriculture, 2019).

Figure 7 | Water withdrawals by sector in 2016

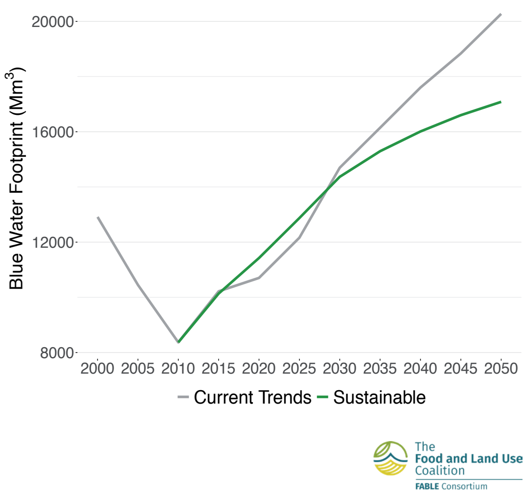


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Annual blue water use decreased from 12,900 Mm^3/yr to 8,400 Mm^3/yr between 2000 and 2010 (Figure 10). Such reductions in blue water use were in the context of extreme drought conditions in Australia. Indeed, the so-called "*Millennium drought*" observed during the 2000s is considered as the worst drought since European settlements in the country in 1788. Under the Current Trends Pathway, blue water use increases to 14,700 Mm^3/yr in 2030 and 20,300 Mm^3/yr in 2050[6]. In the Sustainable Pathway, blue water footprint in agriculture is estimated at 14,400 Mm^3/yr in 2030 and 17,100 Mm^3/yr in 2050.

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable pathways



6 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

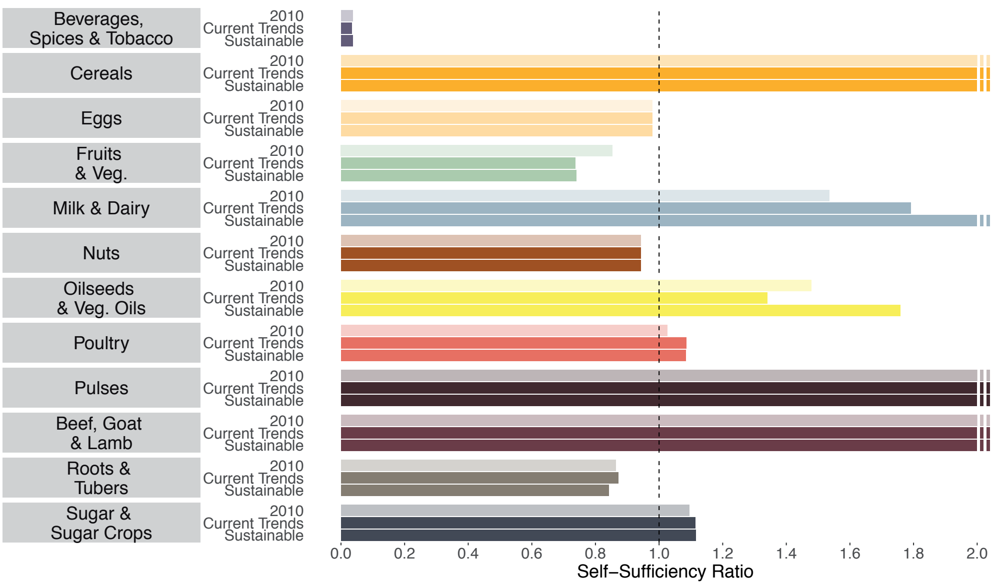
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Australia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

We estimate self-sufficiency as the ratio of total internal production (tons) over total internal demand (tons). A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. This metric is presented to facilitate the identification of Australian agricultural commodities focused on international markets. We note that importing items is not a weakness of a productive system if it allows a country to specialize in other items for which it has competitive advantages.

Under the Current Trends and Sustainable Pathways, Australia is projected to remain self-sufficient in cereals, milk and dairy, oilseeds and vegetable oils, poultry meat, pulses, beef and goat and lamb meat, and sugar and sugar crops from 2000 to 2050. Self-sufficiency increases for most product groups from 2010 – 2050 (Figure 11). The product groups that the country depends the most on and has to import to satisfy internal consumption are beverages, spices, and tobacco. This dependency remains stable during the projection period. The high increase in the self-sufficiency index for beef, goat and lamb meat is due to increases in the productivity of the livestock sector in both pathways. The increase for such a commodity group is larger in the Sustainable Pathway due to national changes in diets that result in significant reductions in the consumption of red meat.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines for some food groups indicate Self-Sufficiency higher than 2. The discontinuous lines on the right side of this figure, as appear for cereals, milk and dairy, pulses, beef, goat and lamb, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

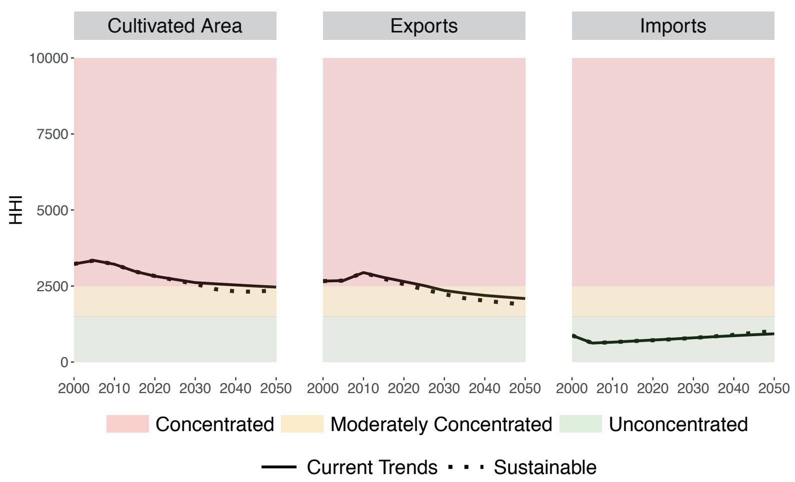
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, a moderate concentration between 1,500 and 2,500, and high concentration above 2,500 (Basher et al., 2013).

According to the HHI estimated from 2000 to 2015, a few commodities concentrate a large share of Australian exports (e.g. wheat, beef, wool, dairy; DFAT, 2017) which could pose some trade risks to the domestic agricultural sector if supply chains are disrupted (Figure 12). Import quantities are not concentrated, although there are concerns that in the future a much more significant percentage of fruit and vegetables will need to be imported to maintain nutritious diets (Candy et al., 2015; Ridoutt et al., 2017). The large area required for livestock production generates a concentrated HHI estimate during the historical period.

Under both the Current Trends and Sustainable Pathways, we project a gradual reduction in the concentration of exports and cultivated area across modelled commodities, reaching moderate HHI levels by 2050. The HHI of projected imports under both scenarios increased from 2005 to 2050, reaching the levels observed in 2000. This indicates a continuation of small import shares across import commodities. Reductions in the concentration of export and cultivated area across a few commodities are generated by domestic increases in agricultural productivity, livestock density, and global shifts in diets.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

Australian food and fiber exports are a key driver of regional economic growth within the country and contribute to the food security of millions in the Asia-Pacific region. However, this sector faces growing global and domestic issues (e.g. climate change, trade barriers and other supply chain disruptions, changes in diets). The results suggest that there are pathways to more a sustainable and resilient Australian future with better socio-economic and environmental outcomes than under current trends. However, its achievement requires significant structural changes and coordinated interventions in several components of the domestic system to increase its resilience and environmental and socio-economic performance. Significant buy-in from key stakeholders about the need for systemic change could help drive coordinated actions to maintain the local and global relevance of the Australian agricultural and food sector.

An optimistic Sustainable Pathway, as modeled here with a high degree of technical feasibility, enables the identification of conditions needed to achieve multiple sustainability targets simultaneously. However, the robust identification of pathways towards a sustainable and resilient Australian FABLE system requires a significant level of interaction with multiple stakeholders, decision-makers, and scientists. This work is being undertaken as part of the ClimateWorks Australia Land Use Futures program. Using a participatory-based approach to scenario development, the Land Use Futures program[7] will assess sustainable future pathways for the Australian food and land use system with more robust modeling approaches and extensive stakeholder engagement to inform implementation efforts.

Results from the Australian FABLE modeled pathways indicate that a Sustainable Pathway could result in multiple environmental and economic successes. However, such a scenario appears to be at the higher bound of what is technically or socially achievable in terms of productivity increases and environmental performance. In particular, on the issue of changing diets towards those similar to the recommended EAT-Lancet diet, the current starting point for Australia is a high animal-protein intake diet, with an average of 95 kilograms per capita per year of meat intake, which is significantly more than the OECD average of 69 kilograms per capita per year (OECD, 2020). While there have been some encouraging signs of shifts towards plant-based diets, the magnitude of the shift required to achieve the EAT-Lancet diet is very high compared to the current Australian reality, already significantly higher than the generous recommended meat intake in the latest edition of the Australian Dietary Guidelines (NHMRC, 2013). Such a drastic change in diet would require significant incentives through price-based mechanisms, nutrition education campaigns and the ubiquitous availability, affordability, and palatability of alternatives.

It is also important to consider that in the case of a key food exporter such as Australia, domestic food consumption will always account for a small percentage of overall food and land-use emissions. The quest to boost exports and continue growing the agricultural sector (National Farmers Federation, 2020), will therefore always present the biggest challenge in improving the environmental performance of the food and land-use sector, in the absence of disruptive technological breakthroughs (Herrero et al., 2020). However, given Australia's role as a major food exporter, providing the option of consumption-based accounting in the FABLE Calculator to encompass resources and emissions embodied in trade (Wiedmann & Lenzen, 2018), would be a fairer way to apportion responsibility at the global scale, particularly if Australia is a more efficient producer for a given commodity compared to other major producers. Optimizing the location of agricultural production can have a significant positive impact on reducing global environmental impacts (Davis et al., 2017; West et al., 2014).

7 More information about the ClimateWorks Australia's Land Use Futures program can be found here: https://www.climateworksaustralia.org/project/land-use-futures/

The FABLE Calculator is a useful tool for quick assessments of potential global-local trade-offs associated with multi-target sustainability pathways. However, there are significant uncertainty and feasibility concerns regarding future values of key input data and parameter assumptions (e.g. changes in productivity, exports, diets). While endogenous modeling of stochastic components is always a challenging task, accounting for the compounded effect of uncertainty on sustainability targets could improve the use of the calculator for robust decision making.

As part of the Land Use Futures project, ClimateWorks Australia, CSIRO, and Deakin University are working on the next generation of high-resolution spatiotemporal modeling of Australian land use that aims to build on and expand the findings from the FABLE Calculator. Such capability is expected to inform future assessments of alternative sustainability pathways as defined through discussions with diverse stakeholder groups.

Annex 1. List of changes made to the model to adapt it to the national context

Multiple components of the FABLE Calculator were modified to adapt the analysis to Australian conditions. In addition, we generated scenarios grounded on expert consultation and peer-reviewed projections of plausible Australian futures, e.g. the Australian National Outlook (Brinsmead et al., 2019).

Some changes include:

- Projections of crop and livestock productivity (including livestock density) based on historical spatiotemporal data, statistical models, and literature review.
- Inclusion of Australian-specific Gross Domestic Product (GDP), trade, and population projection to improve the representation of domestic food demand. This was based on econometric analysis of historical data and results from integrated assessment models published in peer-reviewed studies.
- Changes in implementation rates for multiple variables, e.g. defining expected time when carbon plantings become profitable due to global climate abatement efforts impacting carbon offset prices.
- Modification of default AFOLU carbon coefficients to make them representative of Australian conditions.
- The FABLE Calculator estimates interactions and responses across environmental and economic components of the FABLE system to assess potential outcomes of possible scenarios. However, errors in input data or in the representation of how the system responds to changes in some of its drivers could impact the results. Our team developed a modeling improvement that allows estimation of the robustness of the Australian FABLE Calculator results from to errors in input data or in the representation of linkages or system responses in the model. This capability is ready to be implemented in future implementations of the Australian FABLE Calculator.

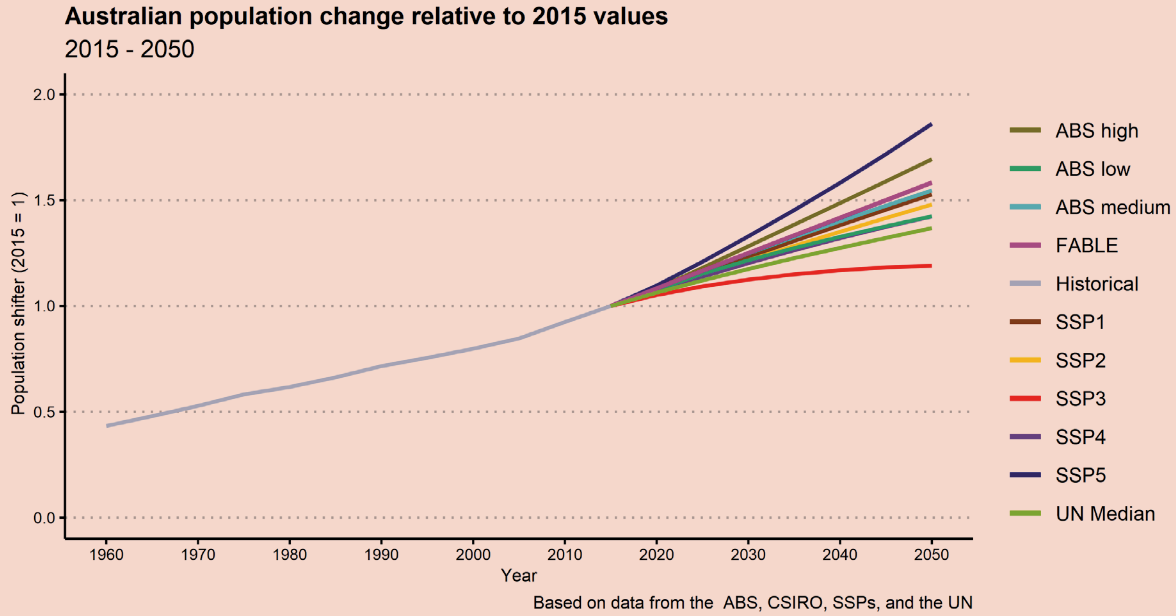
Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	**Sustainable Pathway**

Population : 38 million by 2050

The Australian population is expected to increase by 58% between 2015 and 2050 from 24 million to 38 million.
Net overseas migration is the main driver of Australian population growth. This parameter accounted for around two-thirds of the population increase in 2016-17 (ABS, 2019a). Population projections are based on Australian-specific assumptions of fertility, mortality, international, and domestic migration informed by historical trends (ABS, 2013).



Notes. ABS (Australian Bureau of Statistics) scenarios correspond to low, medium and high increases in the Australian population. The FABLE projection corresponds to population projections slightly larger than the ABS medium scenario generated for the Australian National Outlook 2019 (Brinsmead et al., 2019). This scenario was selected for the Current Trends and Sustainable Pathways. Population projections for all the SSPs (Shared Socioeconomic Pathways) and median projections from the UN (United Nations) are also included for comparison of the scenario selected in FABLE.

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
We assume that there is no productive land expansion beyond 2010 agricultural area levels for both the Current Trends and Sustainable Pathways. Land clearing regulations combined with agricultural productivity improvements result in no expansion of the farming frontier. Farmed land in Australia has reduced from around 65% of the Australian landmass in 1973 to about 53% in 2015 (National Farmers Federation, 2020). Spatially explicit analysis of historical land cover change in Australia and projected expansion of forest cover in the country indicate a continuation of the decreasing trend of the domestic agricultural footprint (Marcos-Martinez et al., 2018, 2019). In addition, the National Farmers Federation specifies a target of maintaining Australia's total farmed land area at 2018 levels by 2030 (National Farmers Federation, 2020).	

LAND Afforestation or reforestation target (1000 ha)

Current Trends Pathway	Sustainable Pathway
Continuation of current forest cover expansion trends results in 3.1 Mha of new forest or forest regrowth. High-resolution forest cover data indicate increases in forest cover within Australia's intensive agricultural region of around 342 thousand hectares per year from 2008 to 2014 (Marcos-Martinez et al., 2018). Total forest cover in Australia increased by about 0.8 Mha per year from 2011 to 2016 (Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, 2018). Historical forest cover change trends suggest the continuation of forest expansion or regrowth during the next decades (Marcos-Martinez et al., 2019). Statistical projections of forest cover change indicate a potential increase of around 2 Mha of forest in Australia's intensive agricultural region by 2050 due to improvements in agricultural productivity, climate change impacts, and changes in input and output prices (Marcos-Martinez et al., 2019). The Australian Government, through its Emission Reduction Fund, has spent around US$1.8 billion on multiple mechanisms to offset GHG emissions and plans to spend a similar amount during the next year to achieve Paris emission reduction commitments (Clean Energy Regulator, 2019; Nong & Siriwardana, 2018). Most of the funds have been spent on human-induced regeneration of disturbed landscapes which could also contribute to increasing forest cover area in the country.	Carbon and environmental plantings increase forest area by around 10.5 Mha. Global climate change abatement action generates market incentives for carbon and environmental plantings. Such incentives combined with higher than trend increases in agricultural productivity, social license to expand forestry plantings in agricultural land, and available infrastructure to allow such expansion, generate high levels of forests plantings after 2040. 10.5 Mha of new forests by 2050 represents a 7.8% increase in Australian forest land observed in 2018. New tree plantings would cover around 1.4% of the Australian landmass. This target corresponds to a conservative estimate of the Green and Gold scenario of the Australian National Outlook 2019 (Brinsmead et al., 2019).

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
The share of the Australian land that can support biodiversity conservation is estimated based on the default calibration of the FABLE Calculator (FABLE, 2019).	

Australia

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Pathway
Historical yields trends are maintained: - from 2.13 t/ ha in 2015 to 2.62 t/ha in 2050 for wheat, - from 9.85 t/ ha in 2015 to 9.2 t/ha in 2050 for grapes.	Strong historical yield declines (<-0.5%/yr) are halved (i.e. still declining but at a slower pace). Weak historical yield declines (>-0.5%/yr) are inversed (i.e. switch to growth). Historical yield increases are doubled for broadacre crops and increased by 25% (i.e. x1.25) for horticulture. - from 2.13 t/ ha in 2016 to 3.24 t/ha in 2050 for wheat, - from 9.85 t/ ha in 2016 to 10.54 t/ha in 2050 for grapes.

Our assumptions are based on a spatially explicit statistical analysis of productivity growth from 1985-2016 combined with CSIRO's productivity change projections (Brinsmead et al., 2019) that account for ambitious policy environment and significant technological improvements.

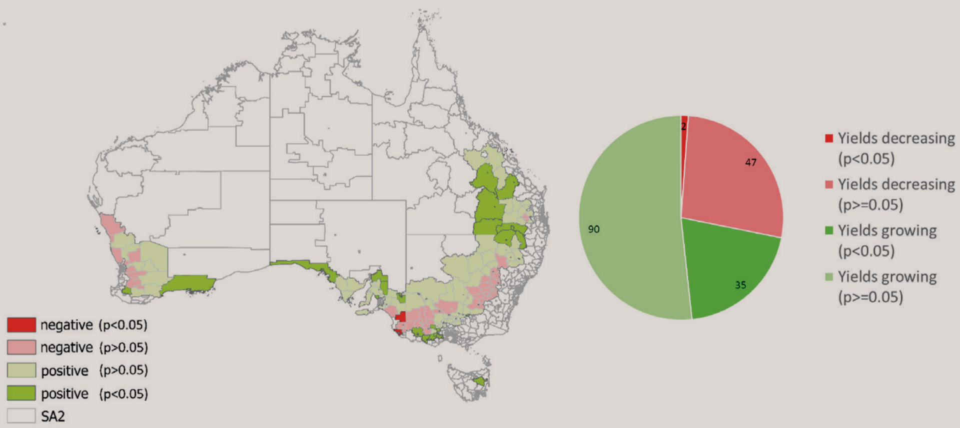
Annual agricultural production data from 1985 to 2016 (ABS, 2017) was used to investigate historical changes in average yields for each commodity. Yield comparisons were made at the local area level (SA2, the smallest spatial statistical unit during census years) for SA2s within main production areas (area sowed> 500 ha on any given year). The yield trend for each commodity-SA2 pair was modeled via linear regression of yearly yields. The regression parameters of each commodity at the national scale were derived via the area-weighted sum (total sown area per commodity over the whole period) of individual SA2-level parameters where p-score <0.05 (i.e. where regressions were statistically significant). Regressions that were not statistically significant were included in the national mix as zero growth. National estimates of yield growth were computed for the broadacre and horticulture sectors and then aggregated to national growth using 2010 revenue as weights. Revenue weights offer a more balanced picture of the relative importance of broadacre and horticultural sectors (83% and 17% of crop revenues respectively), whereas area weights would be very heavily skewed towards the broadacre sector (97% and 3% of total area 1985-2016 respectively).

Overall, annual revenue-weighted yield growth between 1985 and 2016 is estimated to be at 0.75%/yr. Average growth for broadacre crops is estimated at 0.78%/yr, whereas horticultural crops growth was weaker at 0.62%/yr. Yearly yields are highly variable as they depend on very specific climate conditions, the timing or amount of which can significantly affect yield (e.g. rainfall amount can be adequate but not occur at critical points for plant growth and development) and which only process-based models can accurately represent. This means linear models to represent growth can only explain a relatively small proportion of yield variability. Similarly, the aggregate historical growth does not mean all commodities had growing yields over time. In fact, some commodities experienced yield declines.

A visual representation of the yield trend method for wheat (see below) shows it is more likely to observe historical yield growth in wheat than yield decline at the local area (SA2) level, both when yields have varied in a statistically significant manner (35 vs 2 regions) and when yields have varied in a non-statistically significant manner (90 vs 47 regions). However, to ensure statistical robustness, we count non-statistically significant trends as zero growth. The datasets used in this analysis are consistent with Yield Gap Australia (CSIRO, 2016).

Wheat yield growth (1985-2016) linear regression slope and statistical significance (p-value)

Notes. Negative and positive refers to the direction of the linear regression slope, which indicates decreasing or increasing yields, respectively. P-value <0.5 indicates the statistical significance of the results. Yield trends with p-value > 0.05 are not statistically significant and are counted as zero-growth.



Aggregate (revenue-weighted) productivity changes:

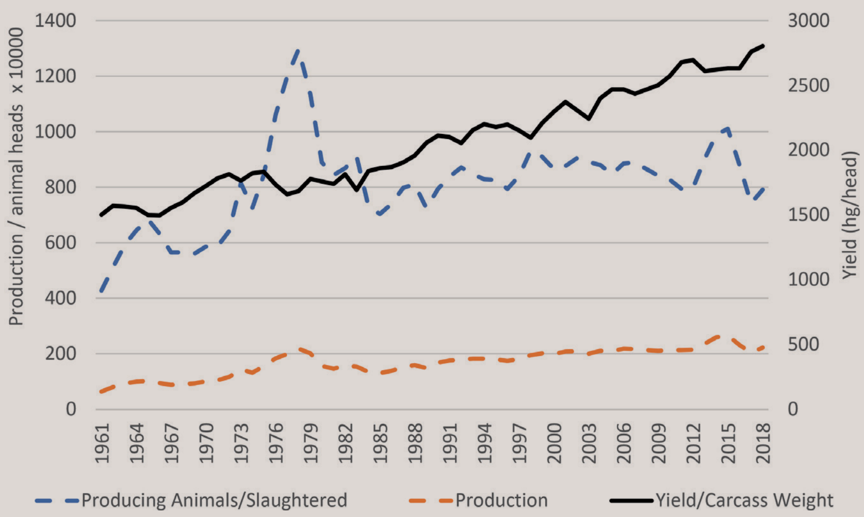
Industry	Revenue weight	Weighted growth BAU	Weighted growth sustainability
Broadacre (large scale crop operations)	83%	0.78%	1.59%
Horticulture	17%	0.62%	1.12%
All		0.75%	1.51%

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

1.5%/yr livestock productivity growth.

Livestock productivity growth over the last few decades has likely been >1%. Future livestock productivity (kg per animal) growth of 1.5%/yr is feasible (Dr. Toni Reverter - Senior CSIRO scientist in computational and systems biology in livestock systems, personal communication, 2020). Low hanging fruits in terms of productivity growth involve increasing the number of cattle that are finished in feedlots and/or the time cattle spend in feedlots. Historical livestock production data from FAO indicate a national average growth of beef productivity (between 1985-2018) of 1.25% per annum, which further supports this parameter value).

Beef production statistics, Australia 1961-2018 (FAOSTAT, 2019)



PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

21% increase in livestock density between 2015 and 2050, 90% of which occurring by 2030 and slowing down from there onwards. This is equivalent to a 0.5% linear growth per year.

Baseline data obtained from historical livestock heads and FAO pasture areas contained in the FABLE Calculator. ABARES farm survey data for specialist beef, specialist sheep and dairy industries (ABARES, 2020) were used to validate the order of magnitude of our assumption. We calculated livestock density using reported values of heads per farm and average hectares per farm, for every year from 1985 to 2015 and by ABARES region (ABARES, 2020). The estimated historical average growth in livestock density using this method is 0.3%/yr, which is in the same order of magnitude as the adopted parameter.

33% increase in livestock density between 2015 and 2050, 90% of which occurring by 2030 and slowing down from there onwards. This is equivalent to a 0.82% linear growth per year and is a midpoint between current trends growth and doubling the current trend. This could be achieved by increasing the number of cattle being finished in feedlots, by increasing the time cattle spend in feedlots, or via an intermediate solution.

Further increases to livestock productivity could be achieved by extending the current typical period livestock spend in feedlots (30 days) to 60 or even 90 days (Dr Toni Reverter, pers. comm.). The Australian Lot Feeders' Association (Australian Lot Feeders' Association, 2019) states the typical time spent in feedlots is 50-120 days or 10-15% of cattle's lifetime. Above-average livestock productivity growth in this scenario is associated with an increase in livestock density resulting from more cattle spending longer in feedlots.
Livestock density growth would have two positive environmental effects: 1) reduce the amount of land required for pasture and, 2) increase the amount of GHG emissions that could be mitigated through FutureFeed[8] supplementation. Current (conservative) estimates for FutureFeed towards 2030 are to produce around 7000 tons of dry weight seaweed supply to around 200,000 animals, resulting in 300,000 tons of CO2 abated by 2030, or up to 3 million tons of CO2 (Michael Battaglia, CEO of Future Feed, pers. comm.).

8 FutureFeed is a livestock feed supplement which can increase production and reduce methane emissions (https://research.csiro.au/futurefeed/).

PRODUCTION Post-harvest losses

Continuation of post-harvest loss rates observed from 1961 to 2014.

FAO's data indicates that Australia's post-harvest losses have been historically marginal oscillating at around 0.69% for crops and 0.05% for livestock production. The Current Trends Pathway assumes that such rates are constant to 2050.

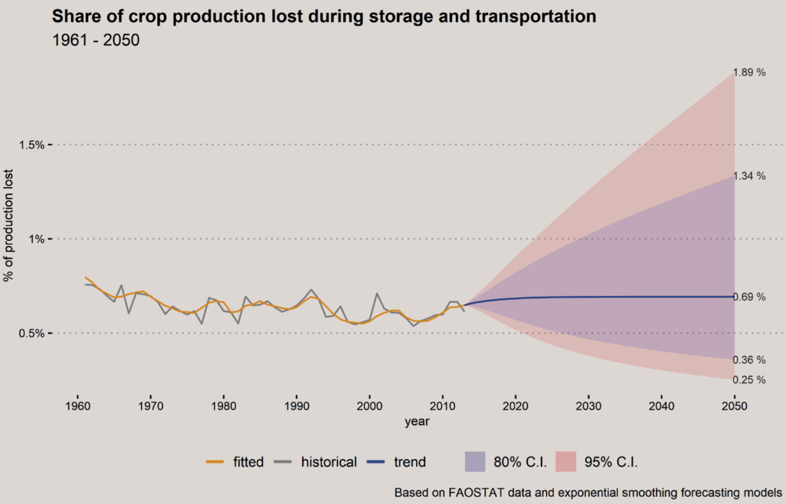
We assume a 30% reduction in post-harvest losses by 2050 relative to average historical levels.

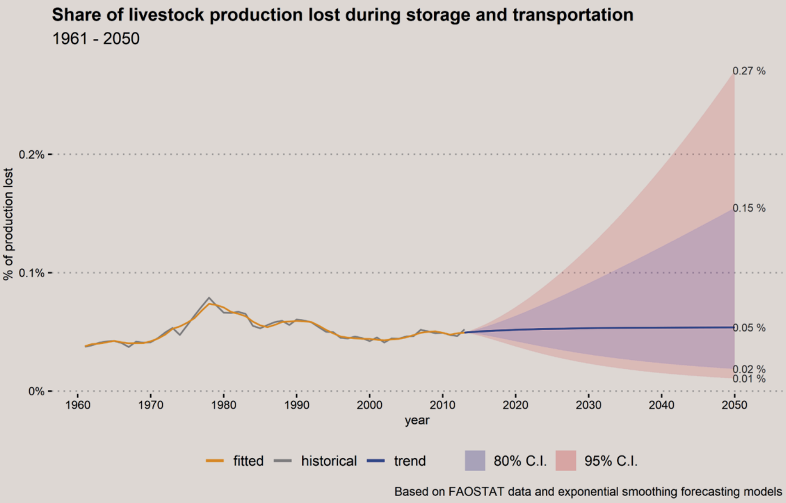
This target is consistent with historical post-harvest losses trends observed through statistical analysis of FAO data (FAOSTAT, 2019).

The National Farmers Federation has set a target of 50% reduction in food waste throughout the value chain by 2030 (National Farmers Federation, 2020). Reductions in Australia's freight costs are of significant relevance to achieve such a target and to improve the international competitiveness of the domestic agricultural sector. The CSIRO's Transport Network Strategic Investment Tool (TraNSIT) estimates potential freight savings (on-road costs and labor) from road upgrades to be between 1% and 5% (Higgins et al., 2015). TranNSIT does not quantify potential gains that reduced travel time could have on produce quality, increased shelf-life of perishable items, and potential price premiums for fresher produce.
If industries realize this opportunity and increase capital investment in the quality of their logistics chain (RIRDC, 2020) (as opposed to relying on cheaper transport for improved gross margin), product quality and shelf life could improve, pushing post-harvest losses down, and reducing household food waste.

The FAO defines post-harvest losses as the amount of a commodity wasted during its storage and transportation from farm gate to the household. This metric excludes losses before and during harvest and household waste.

FAO data (FAOSTAT, 2019), and exponential smoothing forecasting models for time series data (Hyndman et al., 2002) were used to investigate historical trends in the share of crop and livestock production lost during storage and transportation.



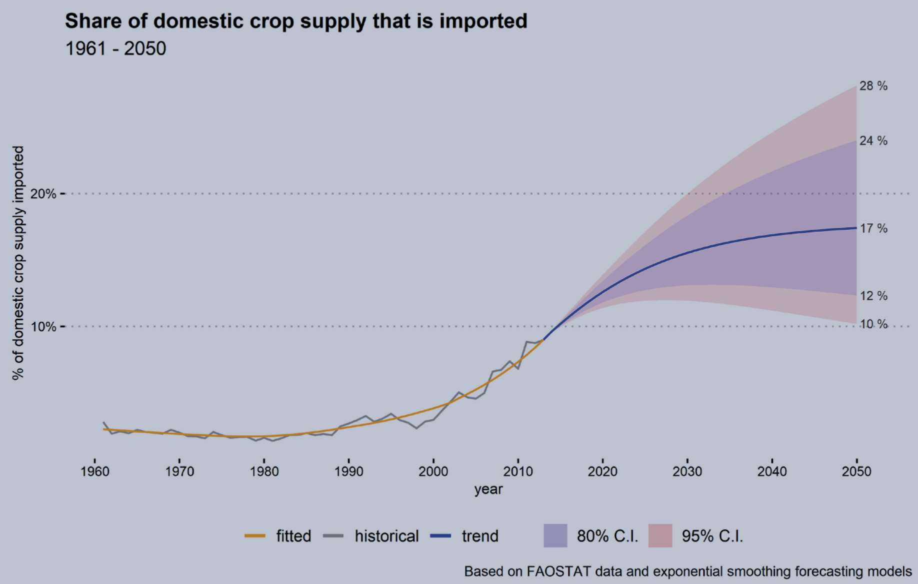


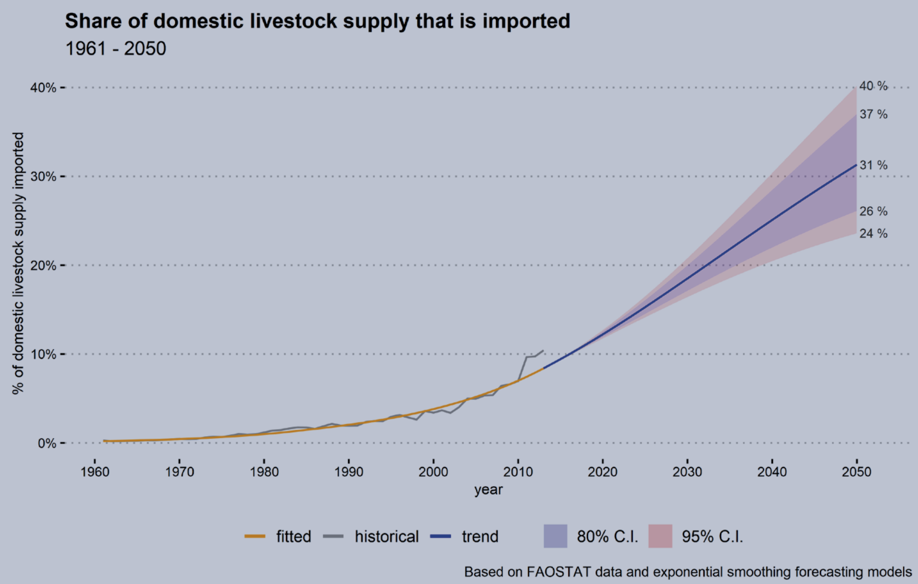
TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway

Increasing imports. The proportion of the domestic consumption that is imported doubles between 2000 and 2050.

The annual share of the domestic crop and livestock consumption that is imported was 2% and 1% from 1961 to 2000, on average. By 2013, such share increased to around 9% for crops and 3% for livestock. Trend analysis indicates that by 2050 the share of imports to fulfil internal consumption could reach around six times the share observed in 2000 for crops and nine times the share of livestock imports. Historical trends suggest a larger dependence on imports to satisfy domestic consumption than assumed in the Australian FABLE Calculator. A conservative scenario was selected under the assumption that changes in agricultural productivity and domestic diets could diminish Australian food import volumes.

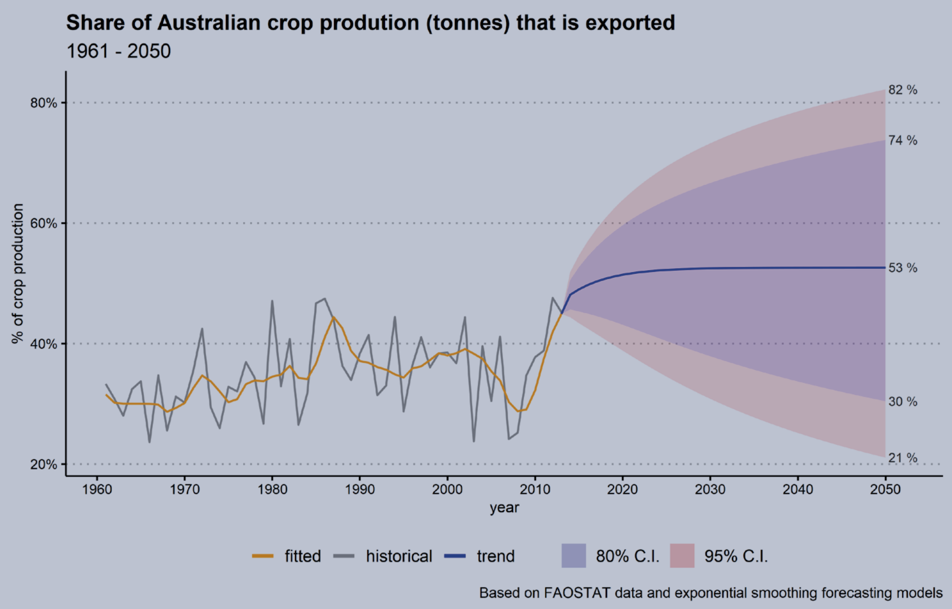


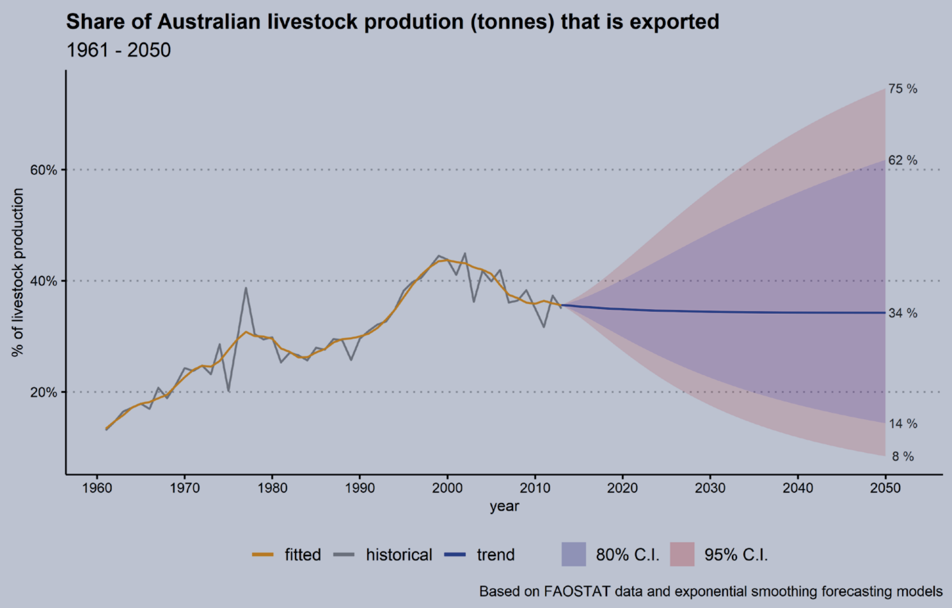


TRADE Evolution of exports for key exported products (1000 tons)

Increasing exports. By 2050 export quantity for crops is two times the levels observed in 2000, and 2.4 times for livestock products.

The selected export targets are based on projections from a multi-sector assessment of plausible Australian economic and environmental futures (Brinsmead et al., 2019). On average, around one-third of the Australian crop production was exported between 1961 and 2000. After 2010, crop exports have been above the historical average, reaching 45% of the crop production by 2013. However, in terms of weight, Australian crop exports in 2013 were only 7% higher than the exported crops (tons) in 2000. The share of Australian livestock production that is exported increased from 13% to 44% between 1961 and 2000. By 2013 only around one-third of the livestock production was exported. Similarly, the tonnage of livestock exports decreased around 29% from 2000 to 2013. Historical export trends suggest that achievement of the Current Trends and Sustainable Pathways export targets would require significant improvements in agricultural productivity.





FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)	
Current Trends Pathway	**Sustainable Pathway**
No change in Australian diets relative to 2000-2010.	Gradual adoption of healthy domestic diets. Relative consumption/cap: decreases 6% for red and monogastric meat and increases 8% for cereals and 11% for pulses by 2050. A gradual transition towards healthy diets is modeled based on recommendations from the Eat-*Lancet* Commission on healthy diets from sustainable food systems (Willett et al., 2019).
The diet scenarios consider the structure of the domestic population (age and sex composition) to set an average calorie/cap intake target to 2050. We used as a baseline 2500 kcal/cap, which is the average minimum daily energy activity for 20 to 24-year-old people with intermediate activity. Such baseline is consistent with the EAT-Lancet recommendation. The Australian diets scenario in the FABLE calculator is based on adjusted EAT-Lancet scenarios. The initial diet target by product group was multiplied by the ratio between the average national minimum dietary energy requirement and the total kilocalories in the EAT-Lancet diet to approximate a healthy diet specific to the Australian population.	

FOOD Share of food consumption which is wasted at household level (%)	
No change to household food waste levels relative to 2010 values. This scenario was selected to estimate potential implications of the continuation of food waste levels at current levels.	Reduction of household food waste of 20% by 2050 relative to 2010 levels. Existing investment and government/research focus on improved logistics to lift the value of Australian exports could have a knock-on effect on household waste resulting from produce arriving in better condition to market and having a longer shelf life. This is compounded with increased household awareness around food waste and healthy national diets (e.g. EAT-Lancet and Australian Dietary Guidelines recommending a larger share of wholegrain and wholemeal foods than under current diets). The Australian Government has set a target to halve food waste by 2030. Some of the actions to achieve such target include: negotiating voluntary waste reduction commitments for the food industry; redistributing food to the food rescue sector; educational campaigns; and research and technological improvements (DAWE, 2020). Here we set 20% reduction in household waste, which in addition to the 30% reduction in post-harvest losses by 2050 modeled under the Sustainable Pathway, is close to a delayed implementation of the National Farmers Federation 2030 target (National Farmers Federation, 2020).

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway

Biofuel demand continues at 2010 levels.

Biofuels in the model introduce additional demand for crops and vegetable oils based on projections from the OECD-FAO Agricultural Outlook 2019. This outlook only makes projections until 2028. Biofuel production also leads to some CO2 savings compared to fossil fuel use which are added to the total GHG accounting. Substitution of animal feed by biofuel by-products is not included in the analysis.

According to the USDA Foreign Agricultural Service data (USDA Foreign Agricultural Service, 2018), the biofuel industry in Australia is small with around 290 million liters of production from 2017 to 2019 which represents a 27.5% decline of its production peak in 2014. Around 86% of the domestic biofuel production is comprised of fuel ethanol and the rest by biodiesel. Fuel ethanol in Australia is manufactured from wheat waste, sorghum grain and sugar, and accounts for around 2% of the total petrol sales in Australia. Its production has been relatively stable due to regulatory incentives in New South Wales, and Queensland. Biodiesel production has reduced due to high production costs and low oil prices. Lack of country-level biofuel support programs, low international oil prices and high feedstock prices limit the expansion of biofuels production for the foreseeable future. If second-generation biofuels (e.g. algae-based fuels) become commercially viable, the assumption of no changes in the domestic production capacity and demand for biofuels may need to be revised.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
RCP 6.0; GCM:HadGEM2-ES; crop model: GEPIC	RCP 2.6; GCM: HadGEM2-ES; crop model: GEPIC

Climate change impacts on crop yields, water withdrawal and fertilizer use, were estimated through the GIS-based Environmental Policy Integrated Climate (GEPIC) model (Liu et al., 2007). Climate change scenarios from the corresponding to RCP 6.0 and RCP 2.6 were agreed by the FABLE consortium as representative of global Current Trends and Sustainable Pathways. The Hadley Centre Global Environmental Model, version 2 (HadGEM2-ES), was used to estimate the effects of historical and projected greenhouse gas emissions associated with the Representative Concentration Pathways (RCPs) 6.0 and 2.6 (Caesar et al., 2013). No fertilization effects were considered in the analysis.

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

ML - megalitres

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Brazil

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Brazil. It presents three pathways for food and land-use systems for the period 2020–2050: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition (referred to as "Current Trends", "Sustainable", and "Sustainable +" in all figures throughout this chapter). These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. These pathways were modeled with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Brazil's NDC treat the FABLE domains. According to the NDC, Brazil has committed to reducing its GHG emissions by 37% by 2025 compared to 2005. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include "strengthening and enforcing the implementation of the Forest Code at federal, state, and municipal levels; strengthening policies and measures with a view to achieve, in the Brazilian Amazon, zero illegal deforestation by 2030 and compensating for greenhouse gas emissions from legal suppression of vegetation by 2030; restoring and reforesting 12 million hectares of forests by 2030, for multiple purposes; enhancing sustainable native forest management systems, through georeferencing and tracking systems applicable to native forest management, with a view to curbing illegal and unsustainable practices; and strengthening the Low Carbon Emission Agriculture Program (ABC)[1] as the main strategy for sustainable agriculture development, including by restoring an additional 15 million hectares of degraded pasturelands by 2030 and enhancing 5 million hectares of integrated cropland-livestock-forestry systems (ICLFS) by 2030" (Government of Brazil, 2018). Biodiversity conservation is included in the current Brazilian commitments to the UNFCCC.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[2] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2017)	2005	2,735	2025	37% reduction	economy-wide	Y	Y	N	Sustainable water use, deforestation reduction

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns adapted from IGES NDC Database (Hattori, 2019), except for the GHG emissions baseline, which is extracted from Third National Communication of Brazil to UNFCCC (Ministério da Ciência, Tecnologia e Inovações, 2019).
Source: Brazil (2015)

1 The purpose of the ABC Plan is to encourage and monitor the adoption of practices of sustainable production technologies in order to reduce GHG emissions (Ministério da Agricultura, Pecuária e Abastecimento, 2012).
2 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2017, as listed on the CBD website (CBD, 2020) which are related to at least one of the FABLE Targets. NBSAP and FABLE Targets are defined for different years (2020 for the NBSAP, and 2030 or 2050 for FABLE). NSBAP Target 5 refers to a reduction of loss of native habitats by at least 50% while the FABLE Target describes a fixed amount of land which supports biodiversity conservation. The NBSAP Target 11 has the goal to conserve at least 30% of the Amazon biome, which matches the FABLE Target. NBSAP Target 15 has no mention of reaching zero GHG emissions from LULUCF and only pledges to restore 15% of degraded ecosystems.

Table 2 | Overview of the latest NBSAP Targets in relation to FABLE Targets

NBSAP Target	FABLE Target
(5) **By 2020, the rate of loss of native habitats is reduced by at least 50% (in comparison with the 2009 rate) and, as much as possible, brought close to zero, and degradation and fragmentation is significantly reduced in all biomes.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(11) **By 2020, at least 30% of the Amazon, 17% of each of the other terrestrial biomes, and 10% of the marine and coastal areas, [...], are conserved through protected areas foreseen under the SNUC Law and other categories of officially protected areas such as Permanent Protection Areas, legal reserves, and indigenous lands with native vegetation [...].**	**BIODIVERSITY:** At least 30% of global terrestrial area protected by 2030
(15) **By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced through conservation and restoration actions, including restoration of at least 15% of degraded ecosystems, prioritizing the most degraded biomes, hydrographic regions and ecoregions, thereby contributing to climate change mitigation and adaptation and to combatting desertification.**	**GHG EMISSIONS:** Zero or negative global GHG emissions from LULUCF by 2050

Brief Description of National Pathways

Among possible futures, we present three alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Brazil.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 214 million inhabitants in 2020 to 236 million in 2050), no constraints on agricultural expansion, no afforestation target, no deforestation control, an evolution towards a SSP2 diet, and a BAU scenario regarding biofuel feedstock use for ethanol (see Annex 2). This corresponds to a future based on current policies and historical trends that would also see a considerable increase with regards to the volume of exports of the main commodities and moderate agricultural productivity growth. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, rice, soybeans, and wheat (see Annex 2).

Our Sustainable Medium Ambition Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to higher productivity in the agricultural sector, lower population growth, moderate constraints on agricultural expansion, an evolution towards a SSP1 diet, a renewable-fuel-oriented scenario, and no deforestation beyond 2030. This pathway also considers the restoration of 12 Mha of forest by 2030 (Government of Brazil, 2018; Bonn Challenge, 2014), and food waste and post-harvest loss reductions when compared to the historical period. With the other FABLE country teams, we embed this Sustainable Medium Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C (see Annex 2).

Our Sustainable High Ambition Pathway represents a future in which significant efforts are made to adopt ambitious sustainable policies and corresponds to the highest boundary of feasible action. Assumptions on diets and reforestation targets are different from the Sustainable Medium Ambition Pathway. First, in order to go beyond Brazil's NDC commitment of restoring 12 Mha of forests by 2030, we considered an overall restoration target of approximately 27 Mha by 2050. This restoration goal takes into account the amount of environmental debt from the Rural Environmental Cadastre (CAR) (Guidotti et al., 2017) for all biomes but the Atlantic Forest, where we consider the Atlantic Forest Pact target of restoring 15 Mha. Second, we assume this future would lead to an evolution towards an EAT-Lancet recommended diet (Willett et al., 2019), which defines a universal reference diet healthy for both humans and the planet, minimizing chronic disease risks and maximizing human wellbeing. This diet is rich in fruits and vegetables, with carbohydrates from whole grains, and protein and fats mainly from plant-based foods (see Annex 2).

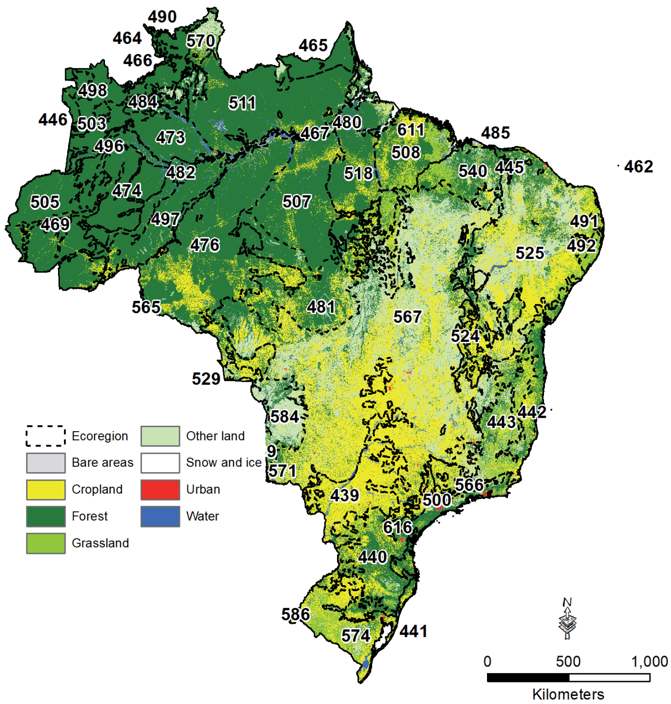
Land and Biodiversity

Current State

In 2010, Brazil was covered by 8% cropland, 21% grassland, 69% forest, 0.3% urban and 2% other natural land (Souza et al., 2020; PAM/IBGE, 2020). Map 1 shows the land cover by aggregated land cover types in 2010 and ecoregions from ESA CCI (ESA, 2017). As can be seen in Map 1, most of the agricultural area is located in the south and center-west while forest and other natural lands can be mostly found in the Amazon biome.

Land where natural processes predominate[3] accounted for 47% of Brazil's terrestrial land area in 2010 (Map 2). The 490-Pantepui forests and shrublands holds the greatest share of land where natural processes predominate, followed by 464-Guianan Highlands moist forests and 498-Rio Negro campinarana (Table 3). Across the country and according to this data, while 250 Mha of land is under formal protection, meeting the 30% zero-draft CBD post-2020 target, only 56% of land where natural processes predominate is formally protected. In order to monitor key biodiversity areas, the Brazilian Ministry of the Environment defined a set of priority areas for biodiversity, last updated in 2018 (Ministério do Meio Ambiente, 2018). The priority areas are spread across all the biomes and the Atlantic coast. Different conservation targets were considered in the identification of these areas, such as the number of endemic and endangered species, remnants of native ecosystems, climatic refuges, important areas for migratory and pollinating species, among others (Ministério do Meio Ambiente, 2005). One of the practices that endangers biodiversity in some of these areas is the illegal occupation of public lands, which leads to deforestation, fires, crime, and corruption, causing damage to ecosystems and biodiversity.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

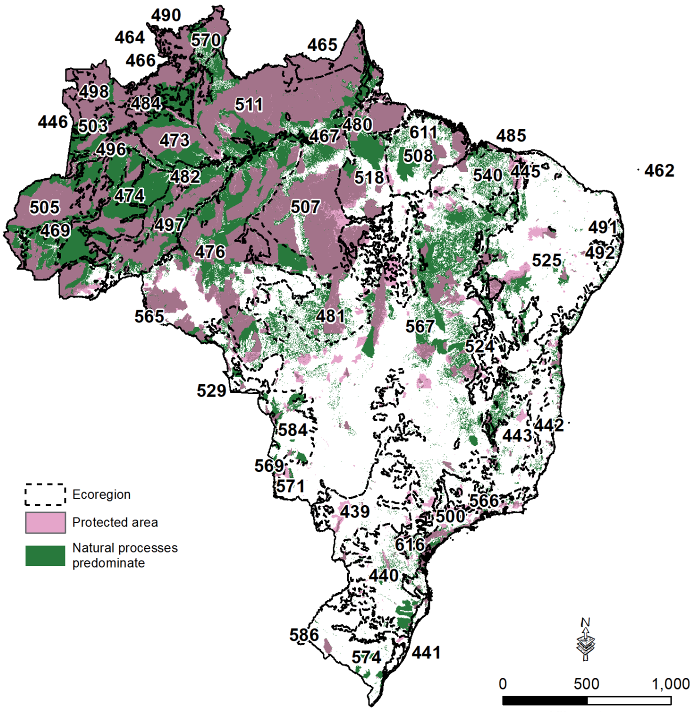


Notes. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

3 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 54% of Brazil's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in 490-Pantepui forests and shrublands, followed by 464-Guianan Highlands moist forests and 498-Rio Negro campinarana (Table 3).

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Notes. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Brazilian ecoregions with the greatest share of land where natural processes predominate and the greatest share of cropland with at least 10% of natural vegetation[4]

Ecoregion		Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
490	Pantepui forests & shrublands	558	96.9	99.7	96.9	3.1	0.3	100
464	Guianan Highlands moist forests	2770	91.8	99.6	91.9	8.1	2.1	97.9
498	Rio Negro campinarana	8097	63.9	99.4	63.9	36.1	4.7	96.8

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

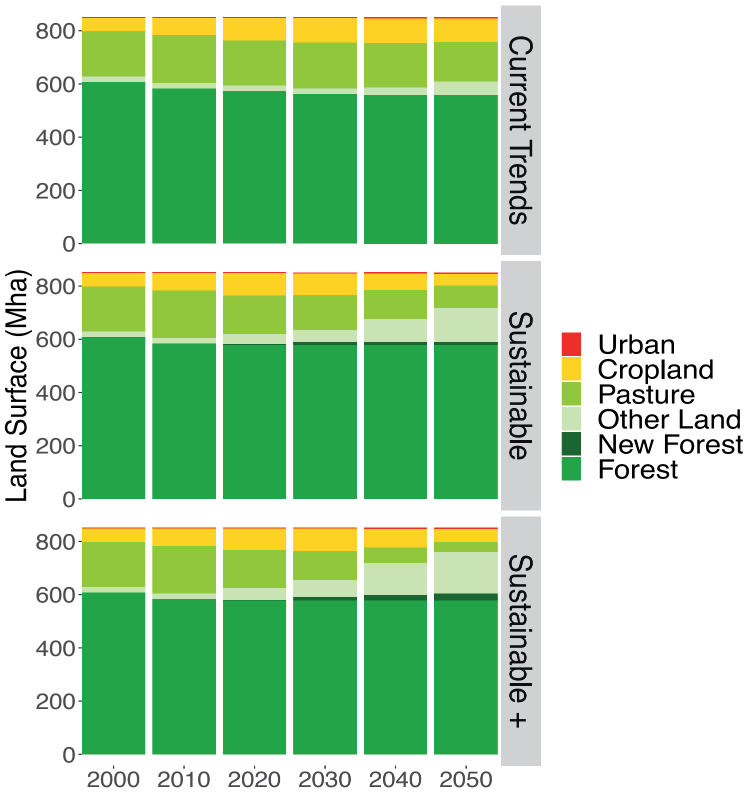
4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, no planned afforestation or reforestation (see Annex 2).

From 2010–2030, we estimate that the main changes in land cover in the Current Trends Pathway result from an increase of cropland (from 66 to 93 Mha), a decrease of forest (from 584 to 563 Mha) and grassland (from 180 to 172 Mha), and an increase in the cattle herd (147 to 183 MTLU). The results suggest that cattle ranching intensification is sparing land for cropland expansion. However, since the cropland increase surpasses the reduction of pasture areas, the results also suggest deforestation is mainly driven by cropland expansion through this period (Figure 1). The expansion of the planted area for soybeans, corn, and sugarcane corresponds to 97% of the total cropland increase between 2010 and 2030. For soybeans, the expansion occurs due to an increase in exports, which follows the export trend assumed for the three pathways (see Annex 2). For corn, 69% of expansion is due to an increase in exports and 28% an increase of internal demand for feed. Finally, for sugarcane, 59% results from an increase of internal demand of biofuels and 32% an increase of processed products. On the other hand, our projections for the period 2030–2050 show a slight reduction in the cropland areas (from 93 to 90 Mha), and a decrease in pasture areas (from 172 to 149 Mha) and an increase in the cattle herd (from 183 to 192 MTLU), which is explained by increases in agricultural productivity and ruminant density. There is no deforestation after 2035 and the forest stocks stabilize at 559 Mha. The land abandonment increases over the period 2040–2050 from 27 to 49 Mha while, at the same time, pasture and cropland areas decrease to 19 Mha and 5 Mha, respectively.

Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Source. FABLE Calculator results obtained when using MapBiomas/IBGE as the initial land cover data for the base year 2000.

In the Sustainable Medium Ambition and Sustainable High Ambition Pathways, assumptions on agricultural land expansion, reforestation targets, and the creation of protected areas are different from the Current Trends Pathway. In these sustainable scenarios, there is no deforestation in Brazil after 2030; and the restoration targets reflect Brazil's international commitments. The major differences between the Sustainable Medium Ambition and the Sustainable High Ambition Pathways are that the latter considers an EAT-Lancet diet, instead of a SSP1 diet, and a higher restoration target (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Brazil in the Sustainable Medium Ambition Pathway: zero deforestation reached by 2020; restoration of 12 Mha by 2030; reduction in cropland areas (from 66 to 46 Mha); a large reduction of pasturelands (from 179 to 83 Mha); and a significant decrease in cattle herd (from 147 to 112 MTLU); an increase in forest areas (from 584 to 591 Mha); and an increase in land abandonment (from 20 to 96 Mha) over the period 2010–2050. In addition, the Sustainable Medium Ambition Pathway also assumes higher crop productivity increases, the inclusion of afforestation/reforestation targets, and a healthier diet compared to the Current Trends Pathway.

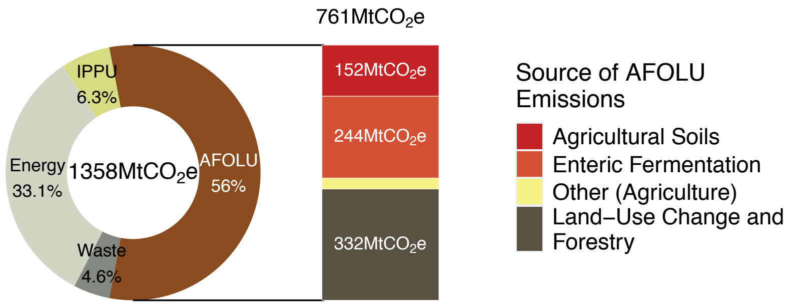
Compared to the Sustainable Medium Ambition Pathway, the Sustainable High Ambition Pathway shows an increase in forest areas (from 584 to 606 Mha) between 2010 and 2050. We also observe a decrease in cropland areas (from 66 to 48 Mha), and a significant reduction of pastures (from 179 to 37 Mha) and cattle herd (from 147 to 50 MTLU), which leads to an increase in land abandonment (from 20 to 154 Mha) over the same period. The increase in the forest areas is explained by the more ambitious afforestation/restoration targets, with approximately 15 Mha more restored forests by 2050. The higher afforestation/restoration targets combined with the EAT-Lancet reference diet explain the huge pasture and cropland reduction between the sustainable pathways. The EAT-Lancet reference diet reduces the consumption of red meat (from 84 to 25 kcal/cap/day) in 2050.

GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 56% of total emissions in 2015 (Figure 2). Land use change emissions are the principle source of AFOLU emissions, followed by enteric fermentation, agricultural soils, and manure management. Historically, the deforestation in the Amazon and the Cerrado biomes were the main sources of the land use change emissions in Brazil (SEEG, 2018b; Angelo & Rittl, 2019). Between 1990 and 2014, the increase of emissions in the agricultural sector accompanied the growth in production of Brazil's main commodities: soybeans and beef (SEEG, 2018a). In 2015, Brazil had approximately 215 million cattle heads (PPM/IBGE, 2020) which explains the high emissions from the livestock sector.

Figure 2 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2015

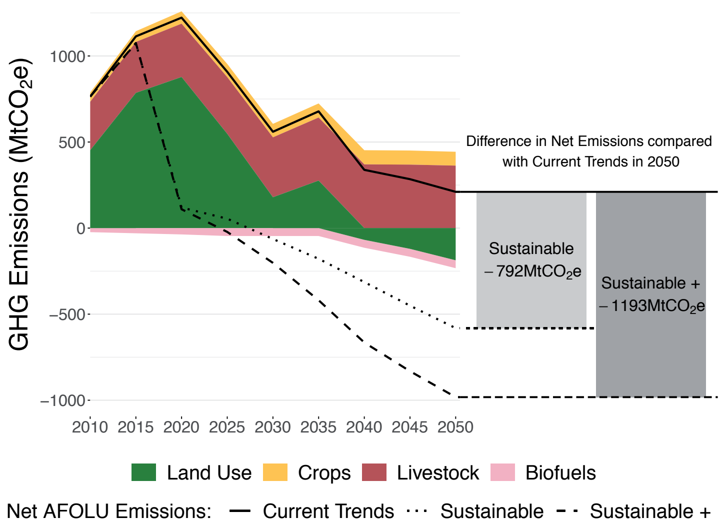


Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 560 $MtCO_2e$/yr in 2030, before declining to 211 $MtCO_2e$/yr in 2050 (Figure 3). Over the period 2020–2050, the strongest relative increase in GHG emissions is computed for enteric fermentation (from 211 to 249 $MtCO_2e$/yr) while a reduction is computed for CO_2 sequestration due to regeneration on abandoned agricultural land (from -60 to -220 $MtCO_2e$/yr). The GHG emissions projections from

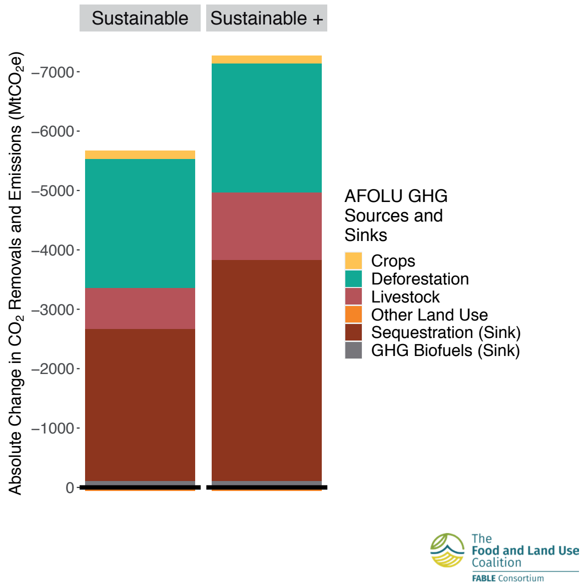
Figure 3 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



land abandonment are calculated by multiplying the abandoned lands by a factor of 5.23, based on Brazil's CO_2 stock in forest areas. This reduction almost compensates for the GHG emissions for enteric fermentation in this pathway, which will be investigated in the future.

In comparison, the Sustainable Medium Ambition Pathway leads to a reduction of AFOLU GHG emissions from 221 $MtCO_2e$/yr in 2010 to -581 $MtCO_2e$/yr in 2050, and the Sustainable High Ambition Pathway to a reduction from 221 to -981 $MtCO_2e$/yr by 2050 through the same period (Figure 4). The potential emissions reductions under the Sustainable Medium Ambition Pathway is dominated by the CO_2 sequestration from the forestry and land use change sector and a reduction in GHG emissions from enteric fermentation and manure management. The evolution towards healthier diets, which reduces animal protein and fat consumption, the ban on deforestation, and the carbon uptake from natural vegetation regrowth and afforestation are the most important drivers of this reduction. Under the Sustainable High Ambition Pathway, GHG emissions from CO_2 sequestration from the forestry and land use change sector, enteric fermentation, and manure management are further reduced when compared to the Sustainable Medium Ambition Pathway thanks to the ambitious afforestation/reforestation targets and a healthier diet assumption, which decreases the cattle herd.

Figure 4 | Cumulated GHG emissions reduction computed over 2020–2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



According to Brazil's commitments under the UNFCCC (Table 1), the country pledged to reduce its GHG emissions by 37% by 2025 compared to 2005 (i.e., a reduction of 1.01 $GtCO_2e$ in 20 years). In the Current Trends Pathway, AFOLU GHG emissions will not fulfill the commitment, reducing only 0.63 $MtCO_2e$ from 2005 to 2025. The commitment is achieved in both sustainable pathways. The AFOLU GHG emissions are reduced by 1.49 and 1.56 $GtCO_2e$ in the Sustainable Medium Ambition and Sustainable High Ambition Pathways, respectively, over the same period. Such reductions could be achieved through the following policy measures: fulfillment of commitments regarding afforestation/reforestation targets, an evolution towards healthy diets, and the increase of use of renewable fuels. These measures could be particularly important when considering options for NDC enhancement.

Food Security

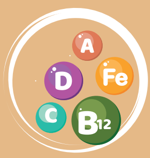
Current State

The "Triple Burden" of Malnutrition

Undernutrition

2.5% of the population were undernourished in 2017. This share has decreased since 2000 (World Bank, 2020a).

7.1% of children under 5 were stunted (World Bank, 2020b) and 1.6% were wasted in 2007 (World Bank, 2020c).



Micronutrient Deficiency

18.9% of women and 8.04% of children under the age of 5 suffered from anemia in 2017, which can lead to maternal death (IHME, 2020).

13.2% of women/the population are deficient in vitamin A, which can notably lead to blindness and child mortality (IHME, 2020), and 0.24% of women/the population are deficient in iodine, which can lead to developmental abnormalities (IHME, 2020).

Overweight/ Obesity

19% of adults and 6% of children were obese in 2015 (EAT, 2017).

49% of adults and 17% of children were overweight in 2015 (EAT, 2017).

Disease Burden due to Dietary Risks

0.53% of deaths are attributable to dietary risk, or 3.4 deaths per year (per 100,000 people) (IHME, 2020).

7.4% of the population suffers from diabetes and 24.5% from arterial hypertension, which can be attributable to dietary risks (Ministério da Saúde, 2019).

Table 4 | Daily average fats, proteins and kilocalorie intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways in 2030 and 2050

	2010	2030			2050		
	Historical Diet (FAO)	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition
Kilocalories (MDER)	2,994 (2,084)	3,185 (2,099)	2,836 (2,099)	2,740 (2,099)	3,384 (2,090)	2,726 (2,090)	2,287 (2,090)
Fats (g) (recommended range)	105 (67-100)	103 (71-106)	104 (63-95)	102 (61-91)	101 (75-113)	102 (61-91)	95 (51-76)
Proteins (g) (recommended range)	86 (75-262)	93 (80-279)	84 (71-247)	82 (69-240)	100 (85-296)	83 (68-239)	75 (57-200)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

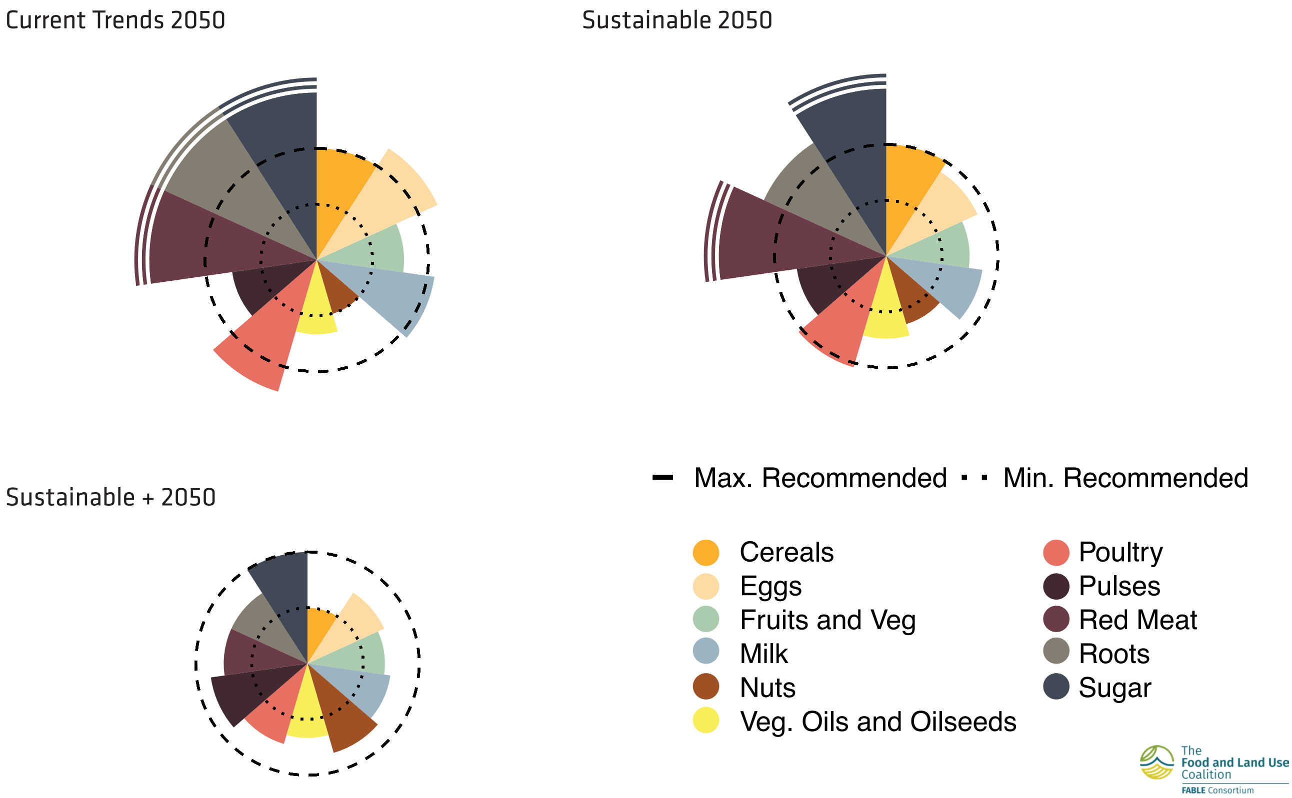
Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 52% higher in 2030 and 62% higher in 2050 (Table 4). The current average intake is mostly satisfied by the following food groups: cereals, oilseed and vegetables oils, sugar, and milk. Animal products represent 26% of the total calorie intake. We project the consumption of animal products and, in particular, red meat, will increase by 16% between 2020 and 2050. The consumption of cereals, pork, milk, eggs, roots, and sugar will also increase while oilseeds and vegetable oils consumption will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), red meat, roots, sugar, eggs, milk, and poultry are over-consumed while nuts are under-consumed (Figure 5). Moreover, fat intake per capita exceed and protein intake per capita is within the range of the dietary reference intake (DRI) in 2030 (Table 4).

Under the Sustainable Medium Ambition Pathway, we assume that diets will transition towards a SSP1 scenario, while we assume an EAT-Lancet recommended scenario in the Sustainable High Ambition Pathway. The ratio of the computed average intake over the MDER decreases to 35% in 2030 and 30% in 2050 under the Sustainable Medium Ambition Pathway, and 31% in 2030 and 9% in 2050 under the Sustainable High Ambition Pathway.

Compared to the EAT-Lancet recommendations, the consumption of eggs and milk are within the recommended range in the Sustainable Medium Ambition Pathway when compared to the Current Trends Pathway (Figure 5). Since we assume an EAT-Lancet diet in the Sustainable High Ambition Pathway, all food products are within the recommended range. Moreover, the fat intake per capita exceeds the dietary reference intake (DRI) in both sustainable pathways by 2030, but the protein intake per capita is reduced when compared to the Current Trends Pathway (Table 4).

Substantial reductions in food loss and waste, major improvements in food practices, and the implementation of policies that provide the public with important health information and encourage healthy behaviors will be particularly important to promote this shift in diets (EAT-Lancet, 2019; Gorski and Roberto, 2015).

Figure 5 | Comparison of the computed daily average kilocalorie intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



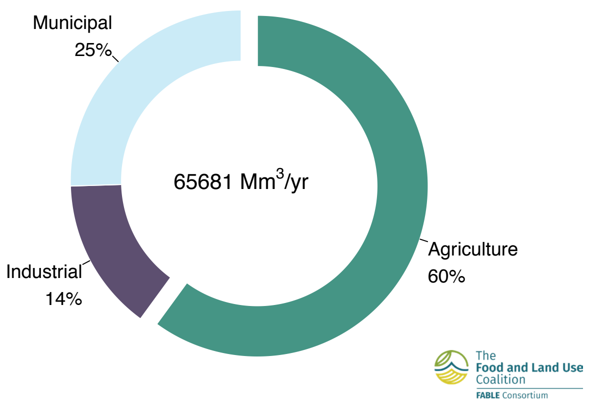
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines in the outer part of the sugar, roots and red meat area indicates that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

Brazil is characterized by a tropical climate with a dry season in most of the northeast and central areas, and a humid equatorial climate in the Amazon region with 1,761 mm average annual precipitation that mostly occurs over the summer season (FAO, 2020). The agricultural sector represented 60% of total water withdrawals in 2017 (FAO, 2020) (Figure 6). In 2016, 6% of agricultural land was equipped for irrigation, representing 17% of estimated-irrigation potential (FAO, 2020). According to our results, the three most important irrigated crops were sugarcane, rice, and coffee, accounting for 20%, 39%, and 2% of the total harvested irrigated area in 2010. Brazil exported 72% of sugar, 9% of rice (OECD-FAO, 2020), and 61% of coffee (FAO, 2020) in 2017, which indicates that a share of the blue water is indirectly destined to meet export demand.

Figure 6 | Water withdrawals by sector in 2017

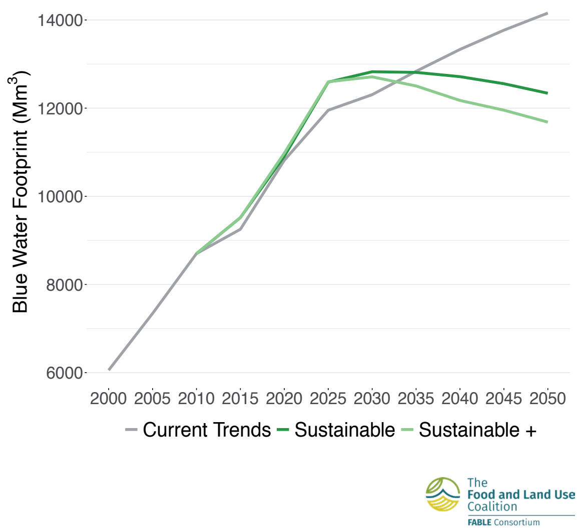


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000–2015 (6,054 and 9,252 Mm^3/yr), before reaching 12,306 Mm^3/yr and 14,157 Mm^3/yr in 2030 and 2050, respectively (Figure 7), with sugarcane and rice accounting for 47% and 35% of computed blue water use for agriculture by 2050[5]. In contrast, under the Sustainable Medium Ambition Pathway, the blue water footprint in agriculture reaches 12,826 Mm^3/yr in 2030 and 12,338 Mm^3/yr in 2050, respectively, which projects a reduction in blue water use when compared to the Current Trends Pathway. Under the Sustainable High Ambition Pathway, the blue water footprint further decreases when compared to the Sustainable Medium Ambition Pathway and reaches 11,683 Mm^3/yr in 2050. This is explained by the changes in the assumptions with diets with less animal fat and protein consumption (Annex 2) and changes in the production of sugarcane and rice due to a decline in internal food demand.

Figure 7 | Evolution of blue water footprint in the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways



5 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

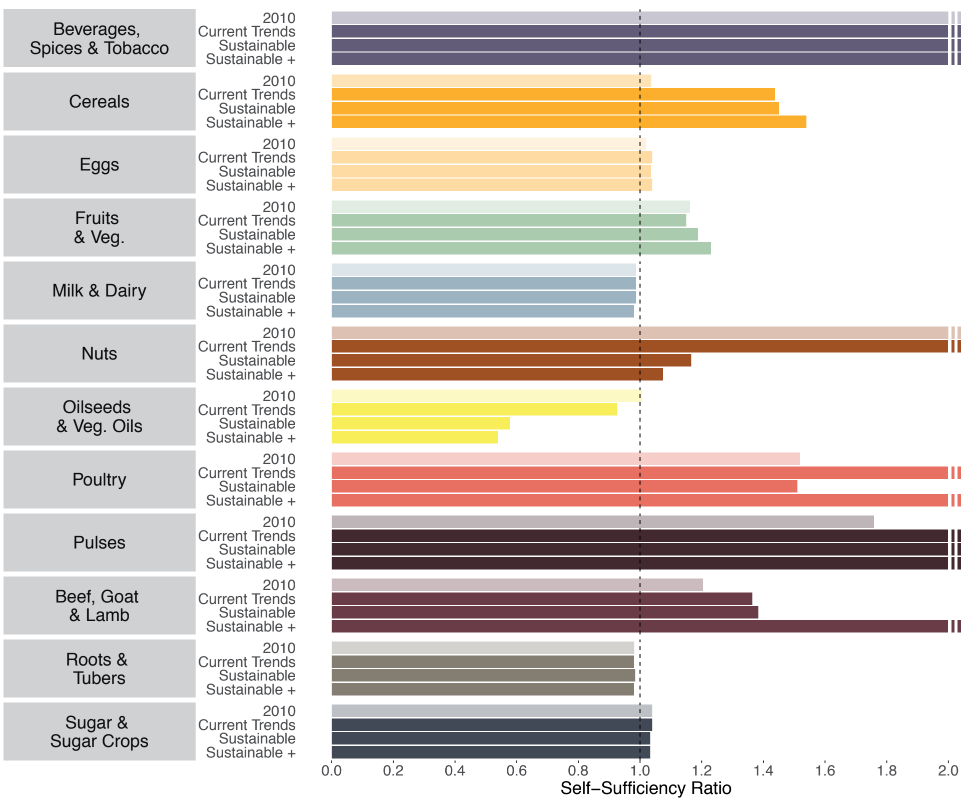
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Brazil's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Defined by FAO (2012), the self-sufficiency ratio (SSR) represents the percentage of food consumed that is produced domestically. Brazil had an SSR between 80%-100% from 2005–2009 (Puma et al., 2015) and was included in the group of countries that met dietary needs while still exporting food over the period 2005–2009 (Clapp, 2015).

Under the Current Trends Pathway, we project that Brazil would be self-sufficient in beverages, spices and tobacco, cereals, eggs, fruits and vegetables, nuts, poultry meat, pulses, beef, goat and lamb, and sugar and sugar crops in

Figure 8 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the righthand side of this figure, which appear for beverages, spices and tobacco, nuts, poultry, pulses, beef, goat and lamb, indicate a high level of self-sufficiency in these categories.

2050, with self-sufficiency by product group increasing for the majority of products from 2010–2050 (Figure 8). Figure 8 shows Brazil does not need to import most product groups by 2050. The projections indicate that Brazil is close to self-sufficiency for roots and tubers, milk and dairy, and oilseeds and vegetable oil groups. Under the Sustainable Medium Ambition and the Sustainable High Ambition Pathways, Brazil remains self-sufficient in the same list of product groups by 2050, representing stable self-sufficiency, increasing the exports of products from pulses and beef, goat and lamb groups. This is mainly explained by changes to healthier diets, which include more fruits and vegetables, and protein from planted-based foods, and reduces the intake of animal products. There is an increase in the use of renewable fuels in the sustainable pathways and, consequently, the whole production of soy oil is assigned to meet biofuel demand by 2050. While our results show that Brazil is not self-sufficient in oilseeds and vegetable oils, it is important to note that the country is a major producer and exporter of soybeans.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- ❑ **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- ❑ **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

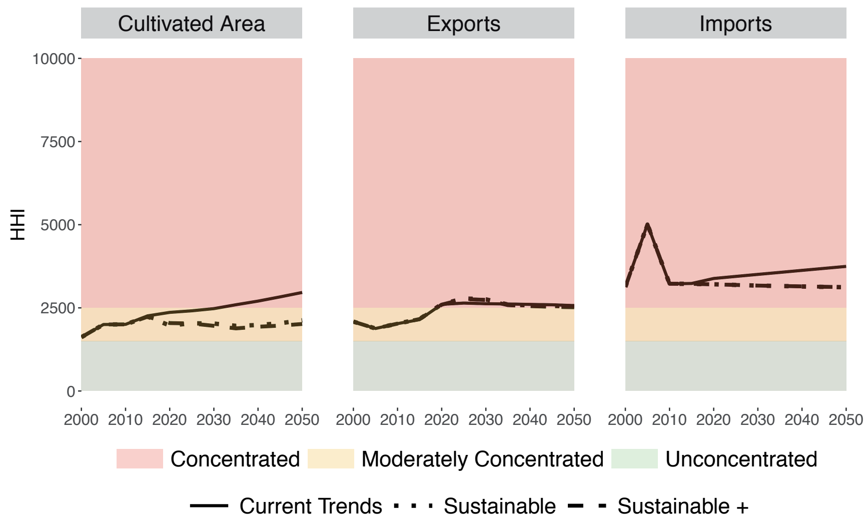
We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Figure 9 shows HHI indicates a large share of the imports is represented by a few commodities over the period 2000–2015, while the index indicates a medium concentration of exports in the same period. The cropland area is dominated by a few crops with medium shares of the total cultivated area during the historical period.

Under the Current Trends Pathway, we project high concentration of crop exports and imports (Figure 9). In addition, a high concentration of crops planted is observed in 2050, mostly represented by soybeans and corn fields, a trend which increases over the period 2015–2050. Soybeans and wheat respectively represent the greatest share of total exported and imported quantities of the 92 products considered in the FABLE Calculator. According to our projections, wheat represents 53%, 70%, and 54% of the total share of imports in 2000, 2005, and 2010, respectively. The increase in the share of wheat imports in 2005 compared to 2000 and 2010 leads to a peak in the HHI value in 2005 (Figure 9). However, according to official data provided by FAO (FAOSTAT, 2020), wheat represents 62%, 69%, and 70% of the total share of imports in 2000, 2005, and 2010, respectively. These differences will be investigated in the future following improvements to the FABLE Calculator.

In contrast, under the Sustainable Medium Ambition and Sustainable High Ambition Pathways, we project high concentration of crop exports and imports and moderate concentration in the range of crops planted in 2050, indicating low levels of diversity across the national production system and imports and exports. This is explained by the changes towards healthier diets. The reduction of animal fat and protein intake lowers the soybean and corn production used for animal feed, which changes the crop production proportions when compared to the Current Trends Pathway.

Figure 9 | Evolution of the diversification of the cropland area, crop imports, and crop exports using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

In this study, we presented three pathways for the period 2010-2050 developed using the FABLE Calculator: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition. The Current Trends Pathway is a business-as-usual scenario that considers the historical trends over the period 2000–2010. It also captures what happens in a food and land-use system in which deforestation is left to continue uncontrolled and where restoration and afforestation policies are not implemented. The Sustainable Medium Ambition and Sustainable High Ambition Pathways assume a series of targets to promote a sustainable food and land-use system, attempting to reach goals such as food waste and post-harvest loss reductions when compared to the historical period. In both sustainable pathways, there is an increase in the use of renewable fuels, improvements in the water use efficiency, and assumptions leading to healthier diets. When compared with the Sustainable Medium Ambition Pathway, the Sustainable High Ambition Pathway has ambitious targets concerning diets and afforestation/reforestation goals, including the restoration of almost 27 Mha instead of 12 Mha, and the implementation of an EAT-Lancet reference diet instead of a SSP1 diet.

First, we would like to highlight that the Current Trends Pathway, as simulated by the FABLE Calculator, generates results that are too optimistic in terms of emissions (for example, carbon uptakes due to land abandonment appear to be overestimated), deforestation reductions, and agricultural productivity gains. A more realistic scenario should be included in future analyses in order to better capture the historical trends of Brazil's AFOLU sector. In the Current Trends Pathway, from 2010 to 2030, deforestation in Brazil amounts to 21 Mha. During the same period, croplands expands by 27 Mha due to the increase in export demand, and the pasture areas decrease by 7 Mha due to cattle ranching intensification. From 2030 to 2050, our results project a slight reduction in cropland areas and a more significant decrease in pastures, which causes land abandonment. The Sustainable Medium Ambition and Sustainable High Ambition Pathways, on the other hand, project an agricultural productivity increase leading to a significant reduction in cropland and pasture areas between 2010–2050. The FABLE Calculator projects forest regrowth and the control of deforestation after 2015 in both sustainable pathways. An increase of crop diversity and a reduction in red meat intake were also observed. The Bonn Challenge and NDC commitments of restoring 12 Mha are reached only in the two sustainable pathways with a slight expansion of protected areas when compared to the Current Trends Pathway (from 30% to 32% in both pathways). The major differences between the sustainable pathways are the higher cropland and pasture reduction due to the different diet assumptions, and the additional 15 Mha of forest restoration in the Sustainable High Ambition Pathway when compared to Sustainable Medium Ambition Pathway.

The average GHG emissions from the AFOLU sector are projected to reach -581 MtCO_2e/yr by 2050 in the Sustainable Medium Ambition Pathway, and -981 MtCO_2e/yr in the Sustainable High Ambition Pathway. The Current Trends pathway projected 211 MtCO_2e/yr by 2050. The negative emissions observed in the sustainable pathways are mainly caused by CO_2 sequestration from restoration/afforestation and an end to deforestation. Brazil's commitment of reducing its GHG emissions by 37% by 2025 compared to 2005 is only fulfilled in the Sustainable Medium Ambition and Sustainable High Ambition Pathways. However, the FABLE Calculator has lower values for the AFOLU GHG emissions in the historical period (39%, 47%, and 19% lower for 2005, 2010, and 2015, respectively) when compared to official data provided by the System for Estimating Greenhouse Gas Emissions (SEEG, 2020b). Improvements to the GHG emissions data used in the FABLE Calculator must be made to address this issue.

In terms of trade, the export assumptions are adjusted for soybeans, corn, and beef to follow the historical trends provided by FAO (FAOSTAT, 2020) and the projections from the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA, 2019), irrespective of the differences in each pathway. Nonetheless, the results of this report have the imports and exports adjusted depending on which products were in excess at the global level. After this international trade adjustment, the soybean exports in 2025 as projected by the Current Trends Pathway are 17% lower (74 Mt) than the expected exports estimated by MAPA (90 Mt). In addition, the Sustainable Medium Ambition and Sustainable High Ambition Pathways lead to a reduction of approximately 35% and 30% in total exports and imports, respectively, by 2050 compared to the Current Trends Pathway. These problems might occur due to the global trade adjustment methodology, which should be improved in the future.

Other refinements are necessary in Brazil's FABLE Calculator beyond GHG emissions and the trade adjustment methodology. A comprehensive validation and calibration against historical data and MAPA projections is necessary before using the FABLE Calculator for estimating future trends of Brazil's AFOLU sector. For the Current Trends Pathway, the tool overestimates the area of dry beans by 65% and underestimates the area of rice by 55%, when compared to MAPA projections in 2025 (MAPA, 2019). Regarding livestock production, livestock productivity (t/head) and stocking rate (head/ha) growth appears to be based on linear extrapolations of historical trends for all three scenarios. Although a higher livestock productivity growth rate was assumed for the sustainable pathways, the FABLE Calculator projects similar growth rates in the three pathways. These assumptions need to be further investigated in the future. Additionally, agroforestry should be included in the next version of the FABLE Calculator, since it represents systems which can mitigate GHG emissions and increase livestock growth and welfare due to thermal comfort (Pereira, 2019). Finally, the FABLE Calculator should generate results per biome or state level, improving deforestation estimates and making it possible to investigate leakages and regional production displacements due to climate change, as captured by other modelling approaches (Soterroni et al, 2018; Zilli et al, 2020).

Annex 1. List of changes made to the FABLE Calculator to adapt it to the Brazilian context

- The historical land cover maps from years 2000, 2005, 2010, and 2015 were replaced based on data provided by MapBiomas (MapBiomas, 2020) and IBGE (PAM/IBGE, 2020).
- The biofuel feedstock use for sugarcane was replaced by the data computed in de Andrade Junior et al. (2019). Three potential scenarios of ethanol demand in Brazil for 2030 were developed in this paper. For the Current Trends Pathway, we used the data related to the BAU (Business as Usual) scenario. For both sustainable pathways (medium and high), the data were replaced by the ones computed for the RFO (Renewable Fuels Oriented).
- Area and production for soybeans, corn, sugarcane, beans, rice, wheat, and cassava were replaced by values provided by IBGE.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
The population is expected to reach 236 million by 2050. Brazil's population will peak around 233 million by 2050, according to data from IBGE, of which the closest scenario is SSP2 (IBGE, 2020).	The population is expected to reach 221 million by 2050. According to Lampe et al. (2016), a sustainable scenario is found to be close to SSP1, and the population data from SSP1 can be used for the scenario.	Same as Sustainable Medium Ambition Pathway

LAND Constraints on agricultural expansion		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
We assume that there will be no constraint on the expansion of the agricultural land outside beyond existing protected areas and under the total land boundary. The low enforcement of environmental protection laws in the last years provides multiple opportunities for infractions to go undetected or unpunished (Carvalho et al., 2019).	We assume that deforestation will be halted beyond 2030. This is in line with Brazil's NDC (Government of Brazil, 2018) which commits to strengthen its policies and measures with a view to achieve zero illegal deforestation in the Brazilian Amazonia by 2030.	Same as Sustainable Medium Ambition Pathway
LAND Afforestation or reforestation target (1000 ha)		
We do not expect afforestation/reforestation. There is an upward trend in deforestation occurring since 2012 in Brazil. For example, the rate of deforestation in the Amazon in 2019 represents an increase of 29.54% in relation to the deforestation rate in 2018, according to PRODES/INPE (PRODES/INPE, 2020). (No afforestation scenario selected)	We assume total afforested/reforested area reaches 12 Mha by 2030. The Brazilian government pledged to reforest 12 Mha by 2030 under the Bonn Challenge commitment (Bonn Challenge, 2014) and Brazil's NDC pledges (Government of Brazil, 2018). (Bonn Challenge scenario selected)	We assume total afforested/reforested area reaches 26.84 Mha by 2050. In addition to the Bonn Challenge commitment by 2030, we take into account the Atlantic Forest Pact, which aims to restore 15 Mha of degraded/deforest lands in Atlantic Forest by 2050 (Crouzeilles et al., 2019). The assumption also includes to restore by 2050 the environment debts per municipality based on the Rural Environmental Cadastre (CAR) (Guidotti et al., 2017). (Bonn Challenge+ scenario selected)

BIODIVERSITY Protected areas (1000 ha or % of total land)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Protected areas remain stable: by 2050 they represent 30% of total land. We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.	Protected areas increase: by 2050 they represent 32% of total land. We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.	Same as Sustainable Medium Ambition Pathway

PRODUCTION Crop productivity for the key crops in the country (in t/ha)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
By 2050, crop productivity reaches: • 3.2 tonnes per ha for soybeans. • 8.5 tonnes per ha for corn. • 96.6 tonnes per ha for sugarcane. The selected assumption of the same productivity growth as over 2000–2010 is based on projections provided by MAPA (2019) for the main crops for the period 2019–2029.	By 2050, crop productivity reaches: • 5.2 tonnes per ha for soybeans. • 15.9 tonnes per ha for corn. • 127 tonnes per ha for sugarcane. A better analysis of the sustainable pathway could be achieved by implementing national policies, such as the National Plan for Low-Carbon Agriculture (ABC Plan) (Ministério da Agricultura, Pecuária e Abastecimento , 2012). The ABC Plan focuses on the nationwide adoption of technologies such Crop-Livestock-Forestry, No-Till, and Double Cropping. These technologies could be important to develop a sustainable pathway for Brazilian agriculture. Based on these policies, we assume a higher productivity growth than 2000¬–2010.	Same as Sustainable Medium Ambition Pathway
PRODUCTION Livestock productivity for the key livestock products in the country (in kg/head of animal unit)		
By 2050, livestock productivity reaches: • 80 kg per head for cattle beef. • 3044 kg per head for cattle milk. Despite many recent technological advances, it is necessary to create strategies to increase the weight and fertility of the herd, which enable greater animal performance with improved feed efficiency and, consequently, an increase in productivity. Most of the Brazilian pasturelands still maintain an extensive system that depends basically on the nutrient supply of the pastures (Barbosa et al., 2015).	By 2050, livestock productivity reaches: • 84 kg per head for cattle beef. • 3324 kg per head for cattle milk. The use of sustainable technologies, such as the agroforestry systems can contribute to the preservation of soil quality, water conservation, the increase in animal yield and welfare due to thermal comfort, mitigation of the effects of greenhouse gases and the recovery of degraded areas (Pereira, 2019). We assume a higher productivity growth than 2000–2010.	Same as Sustainable Medium Ambition Pathway

PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

By 2050, the average ruminant livestock stocking density is 0.66 TLU/ha. We keep the low historical density growth as over 2000¬–2010 because, despite recent advances, the productivity of Brazilian pasturelands is still below its potential (Strassburg et al., 2014). According to LAPIG (Image Processing and Geoprocessing Lab) LAPIG (2017), almost 64 Mha of pastures contain signs of degradation in 2017.	By 2050, the average ruminant livestock stocking density is 0.69 TLU/ha. To achieve production and preservation goals in the future, the cattle ranching sector needs higher intensification compared to historical growth. Therefore, cattle ranching intensification will spare land for cropland expansion and decrease the pressure of native vegetation conversion (Soterroni et al., 2018).	Same as Sustainable Medium Ambition Pathway

PRODUCTION Post-harvest losses

By 2050, the share of production and imports lost during storage and transportation remains stable. Post-harvest losses continue to be a persistent problem in Brazil, despite of the modernization of logistics and production systems. One of the greatest challenges in facing the food loss issue is the convergence of interests among public, private, and scientific stakeholders (Henz and Porpino, 2017).	By 2050, the share of production and imports lost during storage and transportation is reduced by 50%. The Brazilian government committed to the United Nations (SDG 12.3.1br) to reduce food loss along production and supply chains by 2030 (IPEA, 2016).	Same as Sustainable Medium Ambition Pathway

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2050, the share of total consumption which is imported is: • 51% by 2050 for wheat. Brazilian imports will be almost the same for 2029 over 2019 for wheat (main imported product), according to projections from MAPA (2019). Hence, we choose a stable scenario that reflects that trend.	Same as Current Trends Pathway	By 2050, the share of total consumption which is imported is: • 59% by 2050 for wheat. Brazilian imports will be almost the same for 2029 over 2019 for wheat (main imported product), according to projections from MAPA (2019). Hence, we choose a stable scenario that reflects that trend.

TRADE Evolution of exports for key exported products (Mt)

By 2050, the volume of exports is: • 95.5 Mt by 2050 for soybeans • 4.2 Mt by 2050 for beef • 69.7 Mt by 2050 for corn Exports are multiplied by different values for soybeans, corn and beef, based on projections from the MAPA (2019) report. The exported quantity remains constant at the 2010 level for the other commodities.	By 2050, the volume of exports is: • 58.5 Mt by 2050 for soybeans. • 2.7 Mt by 2050 for beef • 39.2 Mt by 2050 for corn Exports are multiplied by different values for soybeans, corn and beef, based on projections from the MAPA (2019) report. The exported quantity remains constant at the 2010 level for the other commodities.	By 2050, the volume of exports is: • 57.6 Mt by 2050 for soybeans • 2.6 Mt by 2050 for beef • 39 Mt by 2050 for corn Exports are multiplied by different values for soybeans, corn and beef, based on projections from the MAPA (2019) report. The exported quantity remains constant at the 2010 level for the other commodities.

Brazil

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2030, the average daily calorie consumption per capita is 3,384 kcal and is: • 977 kcal for cereals • 446 kcal for sugar • 151 kcal for red meat The scenario for diets follows FAO projections at the horizon of 2050 for a BAU scenario (FAO, 2018). The SSP2 food demand scenario represents a moderate consumption growth and increasing share of livestock products in the diet (Fricko et al., 2017).	By 2030, the average daily calorie consumption per capita is 2,726 kcal and is: • 803 kcal for cereals • 323 kcal for sugar • 120 kcal for red meat Sustainable pathways explicitly assume a shifter in preferences in favor of balanced and environmentally sustainable diets (FAO, 2018; Lampe et al., 2016). The SSP1 scenario represents a slow consumption growth and more sustainable and healthy diets (Fricko et al., 2017).	By 2030, the average daily calorie consumption per capita is 2,287 kcal and is: • 786 kcal for cereals • 293 kcal for sugar • 95 kcal for red meat Sustainable pathways explicitly assume a shifter in preferences in favor of balanced, healthy, and environmentally sustainable diets (FAO, 2018; Lampe et al., 2016). The selected scenario uses the EAT-Lancet recommendations for a healthy diet for an intake of 2,500/kcal/day (EAT-Lancet, 2019).

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2030, the share of final household consumption which is wasted at the household level is 10%. Brazil faces the challenge to reduce food waste and ensure sustainability and food security in the face of cyclical social and economic crises in a country with high income inequality (Henz and Porpino, 2017). Also, there is a culture of food waste in all social classes in Brazil (Henz, 2017; Porpino, 2015).	By 2030, the share of final household consumption which is wasted at the household level is 5%. The Brazilian government committed to the United Nations (SDG 12.3.1br) to reduce per capita global food waste at the retail and consumer levels by 2030 (IPEA, 2016).	Same as Sustainable Medium Ambition Pathway

BIOFUELS Targets on biofuel and/or other bioenergy use (kt)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2050, biofuel production accounts for: • 531,099 kt of sugarcane production. In addition to using the OECD-FAO Agricultural outlook for 2019–2028, the biofuel feedstock use for sugarcane was replaced by the data computed in de Andrade Junior et al. (2019). We used the data related to the BAU scenario, mapped with the macroeconomic elements of the SSP2.	By 2050, biofuel production accounts for: • 742,759 kt of sugarcane production. The data from OECD was also used in this sustainable pathway. However, the data used for the biofuel feedstock use for sugarcane were replaced by the ones computed for the RFO (Renewable Fuels Oriented) scenario in de Andrade Junior et al. (2019).	By 2050, biofuel production accounts for: • 743,443 kt of sugarcane production. The data from OECD was also used in this sustainable pathway. However, the data used for the biofuel feedstock use for sugarcane were replaced by the ones computed for the RFO (Renewable Fuels Oriented) scenario in de Andrade Junior et al. (2019).

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields (corn, rice, soybeans, and wheat) are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields (corn, rice, soybeans, and wheat) are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields (corn, rice, soybeans, and wheat) are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Canada

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Canada. It presents three pathways for food and land-use systems for the period 2020-2050: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition (referred to as "Current Trends", "Sustainable", and "Sustainable+" in all figures throughout this chapter). These pathways examine the trade-offs between achieving the FABLE targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways based on an extensive review of peer-reviewed literature and government policy documents and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the global emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Canada's Nationally Determined Contribution (NDC) and Long Term Low Emissions and Development Strategy (LT-LEDS) relate to the FABLE domains. According to the LT-LEDS, Canada has committed to reducing its GHG emissions by 80% by 2050 compared to 2005. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include protecting and enhancing carbon sinks including forests, wetlands and agricultural lands; large-scale afforestation; increased use of long-lived harvested wood products; and increased utilization of waste wood biomass. Under its current commitments to the UNFCCC, Canada does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and LT-LEDS

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2017)	2005	747	2030	30% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	N	N	N	Deforestation
LT-LEDS (2016)	2005	748	2030	80% reduction	Energy, Industrial processes and product use, agriculture, and wastes	Y	N	N	Food security, water, and deforestation

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from Institute for Global Environmental Strategies (IGES) NDC Database (Hattori, 2019)
Source: Canada (2017)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the biodiversity targets included in the National Biodiversity Strategies and Action Plan (NBSAP), as listed on the CBD website (CBD, 2020). Canada's NBSAP combines its 2020 Biodiversity Goals and Targets and the 2006 Biodiversity Outcomes Framework, which are related to at least one of the FABLE Targets. In comparison with the FABLE Targets, the NBSAP Targets are somewhat vague and unambitious.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(6) **By 2020, continued progress is made on the sustainable management of Canada's forests.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(A) **By 2020, Canada's lands [...] are planned and managed using an ecosystem approach to support biodiversity conservation outcomes at local, regional, and national scales.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(1) **By 2020, at least 17 percent of terrestrial areas and inland water [...] are conserved through networks of protected areas and other effective area-based conservation measures.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(3) **By 2020, Canada's wetlands are conserved or enhanced to sustain their ecosystem services through retention, restoration, and management activities.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(7) **By 2020, agricultural working landscapes provide a stable or improved level of biodiversity and habitat capacity.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(15) **By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced through conservation and restoration actions, including restoration of at least 15% of degraded ecosystems, prioritizing the most degraded biomes, hydrographic regions and ecoregions, thereby contributing to climate change mitigation and adaptation and to combatting desertification.**	**GHG EMISSIONS:** Zero or negative global GHG emissions from LULUCF by 2050

Brief Description of National Pathways

Among possible futures, we present three alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Canada.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by high population growth (from 38 million in 2020 to 49 million in 2050), no constraints in agricultural expansion, no afforestation target, no change in the extent of protected areas, low productivity increases in the agricultural sector, an evolution towards high-fat diets, and high economic growth (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable growth in GDP and exports in the coming decades, according to OECD (2020a) and FAO (2019) database projections. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for rapeseed, barley, wheat, and soybeans, which are the main agricultural products exported by Canada (see Annex 2).

Our Sustainable Medium Ambition Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to higher afforestation rates, expansion of protected areas, improved crop and livestock productivities, expanded imports and exports, and greater biofuel consumption. It is also characterized by lower population and GDP growth rates, a lower deforestation rate, reduced calorie consumption, and a declining share of wasted food (see Annex 2). This corresponds to a future based on the adoption and implementation of new ambitious policies on trade, immigration, and climate change that would also see considerable progress concerning biodiversity protection (more and larger protected areas), first generation biofuel consumption, sustainable forest management, and agricultural performance (Bohnert et al., 2015; Mukhopadhyay et al., 2020; Prestele et al., 2016; Wulder et al., 2018). With the other FABLE country teams, we embed this Sustainable Medium Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C. At this level of warming this pathway assumes a positive impact of climate change on crop and pastures productivities given resulting increases in the growing season and suitable agricultural area (Assefa et al., 2018; Jing et al., 2017; Li et al., 2013; Lychuk et al., 2017; Qian et al., 2016; Ray et al., 2013; Thomas & Graf, 2014).

Our Sustainable High Ambition Pathway represents a future in which even more significant efforts are made to adopt sustainable policies and practices and corresponds to the highest boundary of feasible action. Compared to the Sustainable Medium Ambition Pathway, we assume that this future would lead to even higher afforestation rates, expansion of protected areas, improvements to the productivity of key crops, and increased exports. This is coupled with lower GDP growth, reduced imports, and declining use of first-generation biofuel consumption (see Annex 2). This corresponds to a future based on the adoption and implementation of very ambitious policies on biodiversity protection (Andrew et al., 2012; Schulte, 2017) and climate change mitigation programs, like the zero-emission vehicles (ZEVs) target that includes subsidies and other support programs to increase the use of electric vehicles (Natural Resources Canada, 2020). As in the Sustainable Medium Ambition Pathway, we embed this Sustainable High Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

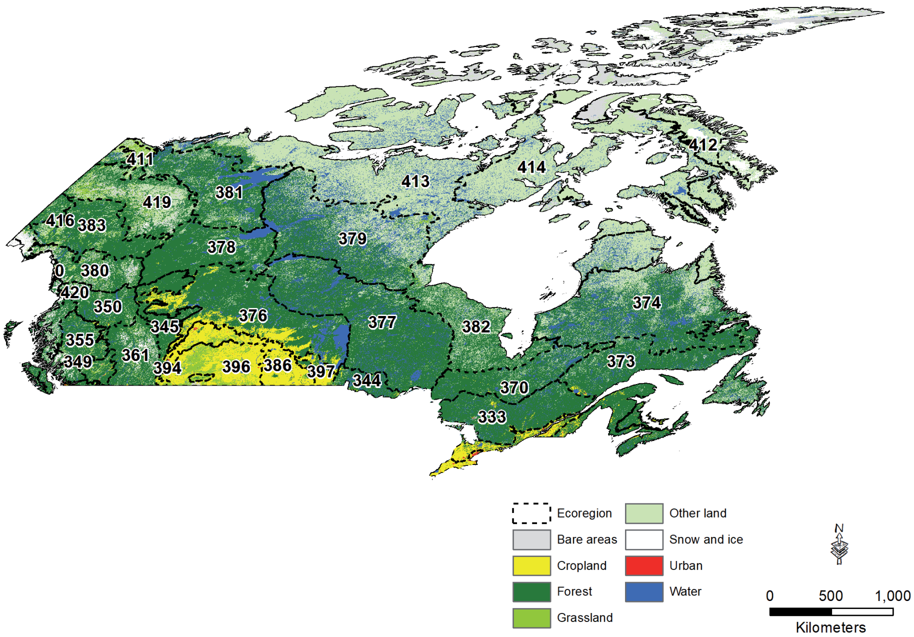
Land and Biodiversity

Current State

In 2010, Canada was covered by 5.8% cropland, 1.6% grassland, 38.1% forest, 0.1% urban and 54.3% other natural land. Most of the agricultural area is located in the provinces of Alberta and Saskatchewan, while forest and other natural land can be mostly found in British Columbia, Ontario, Manitoba, Quebec, and the northern territories (Map 1). The main issues for biodiversity conservation are related to energy production and mining (tar sands production in Alberta), increase in fire frequency and intensity (wildfires in the western region), and diseases that increase natural mortality and produce ecological imbalances.

We estimate that land where natural processes predominate[2] accounted for 80% of Canada's terrestrial land area in 2010 (Map 2). The 411-Brooks-British Range tundra ecoregion holds the greatest share of land where natural processes predominate, followed by the 419-Ogilvie-MacKenzie alpine tundra ecoregion and the 380-Northern Cordillera forests ecoregion (Annex 4). Across the country, while 107Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 17% of land where natural processes predominate is formally protected. This indicates that the 405-Alaska-St. Elias Range tundra, the 396-Northern Shortgrass prairie, and the 365-Queen Charlotte Islands conifer forests ecoregions will remain important for biodiversity into the future as a significant share of their surface is protected. By contrast, the 383-Watson Highlands taiga, the 345-Alberta-British Columbia foothills forests, and the 416-Interior Yukon-Alaska alpine tundra ecoregions may be at risk without action to better protect them.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



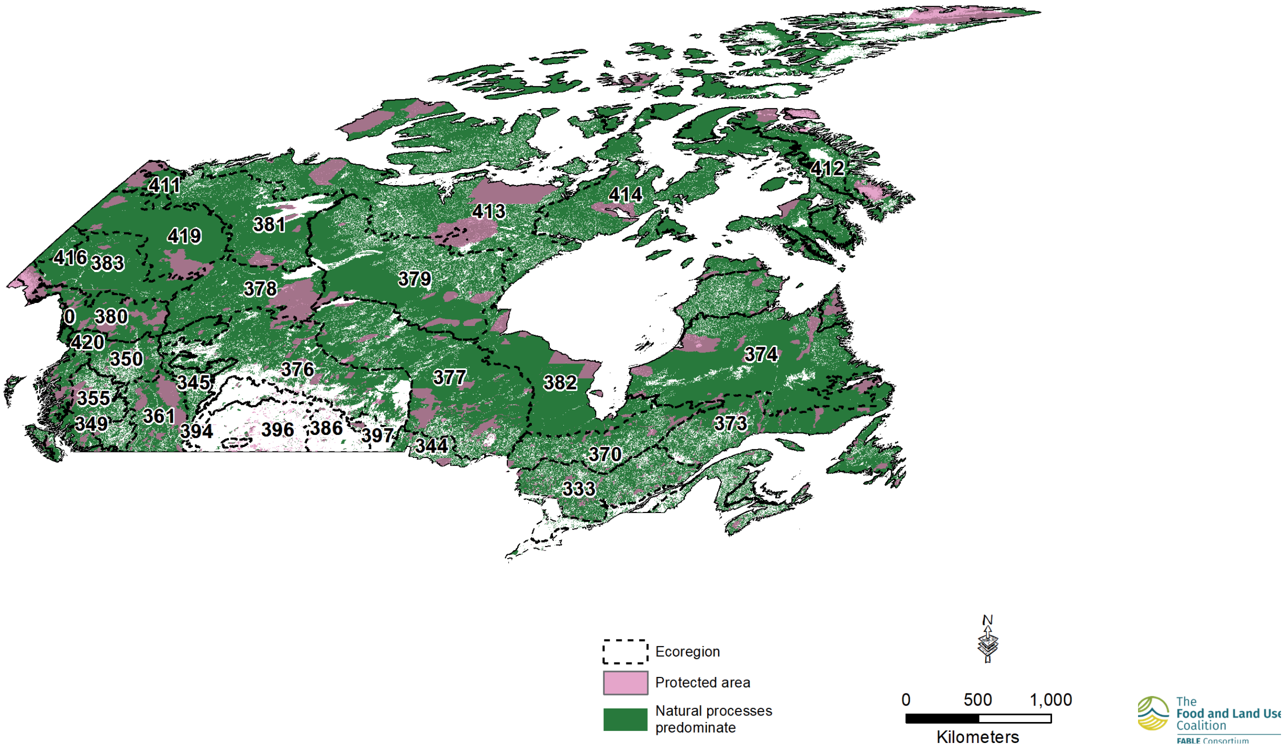
Notes. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Canada

Approximately 20.8% of Canada's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in 386-Canadian Aspen forests and parklands, followed by 396-Northern Shortgrass prairie and 376-Mid-Canada Boreal Plains forests. The regional differences in extent of biodiversity-friendly cropland can be explained by regional production intensity.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.

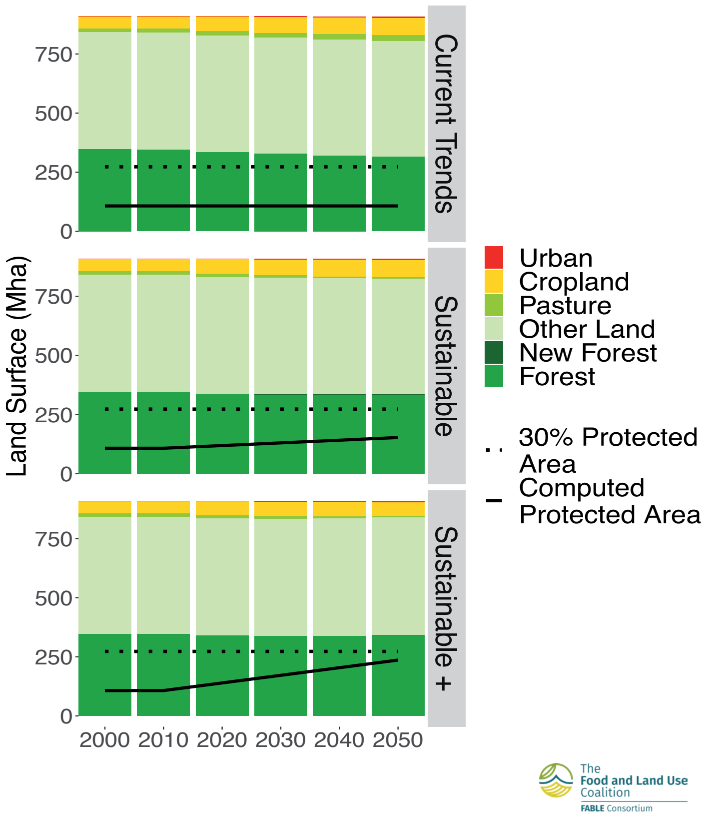
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, no planned afforestation or reforestation, and protected areas remain at 107 Mha, representing 11% of total land cover (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in cropland and a decrease in forest area. This trend remains stable over the period 2030-2050: cropland area further increases, and forest area decreases (Figure 1). The expansion of the planted area for rapeseed, wheat and barley explains 72% of total cropland expansion between 2010 and 2030. For rapeseed, 57% of expansion is explained by an increase in exports, mainly to China, and 43% an increase in domestic consumption (processed food). For wheat, 36% of expansion is due to an increase in exports and 64% an increase in domestic consumption (feeding animals, food, and biofuels). Finally, for barley, 98% results from an increase in domestic consumption for feeding animals. Pasture expansion is mainly driven by the increase in internal food consumption of beef, milk, and derivatives, while livestock productivity per head increases and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, deforestation is explained by cropland and pastures expansion. This results in a reduction in land where natural processes predominate by 5% by 2030 and by 9% by 2050 compared to 2010, respectively.
In the Sustainable Medium Ambition and

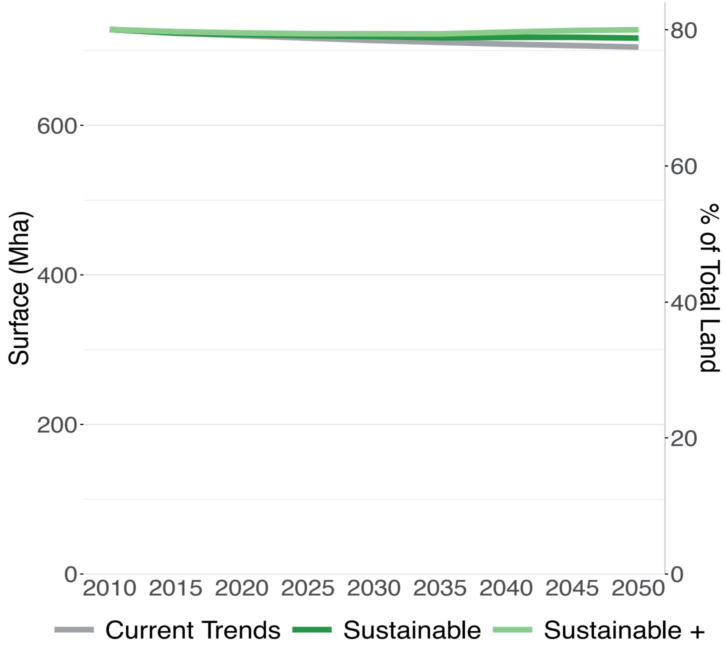
Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Source. Authors' computation based on ESA (2010), for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

Sustainable High Ambition Pathways, assumptions on agricultural land expansion, reforestation, and protected areas have been changed to reflect a higher interest in biodiversity conservation and climate change mitigation (Prestele et al., 2016; Wulder et al., 2018). For the Sustainable Medium Ambition Pathway, the main assumptions include the prevention of deforestation by 2030, 1 Mha afforested by 2050, and protected areas increase from 11% of total land in 2010 to 17% in 2030 (see Annex 2), while for the Sustainable High Ambition Pathway afforested area increases by 2Mha and protected areas to 28%.

Figure 2 | Evolution of the area where natural processes predominate



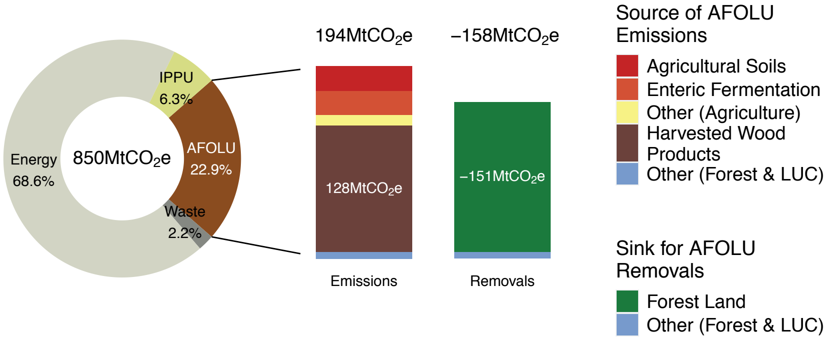
Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Canada in the Sustainable Medium Ambition and Sustainable High Ambition Pathways: (i) a lower deforestation rate, (ii) a small increase in natural land, (iii) the stabilization or even a smaller area of agricultural land, and (iv) a higher afforested land. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by the internal demand for food due to changing diets, a lower population growth rate, between the Current Trends and the Sustainable Pathways, and higher crop productivities (increased productivity leads to reductions in the land required to produce the same volume). This leads to an increase in the area where natural processes predominate: the area stops declining by 2025 and increases by 1% between 2025 and 2050 (Figure 2).

GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 23% of total emissions in 2010 (Figure 3). Harvested wood products is the principle source of AFOLU emissions, followed by enteric fermentation, and agricultural soils. The relatively large emissions from harvested wood products reflects the state of the forestry industry in Canada. The Canadian forest industry contributes over $20 billion to Canada's GDP, employs over 200,000 workers and harvests roughly 150 million cubic meters of roundwood per year (Natural Resources Canada, 2018). Over 95% of the enteric fermentation in Canada comes from raising cattle, primarily for beef but also for dairy. There are slightly over 10 million head of cattle in Canada (Environment and Climate Change Canada, 2020).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2010

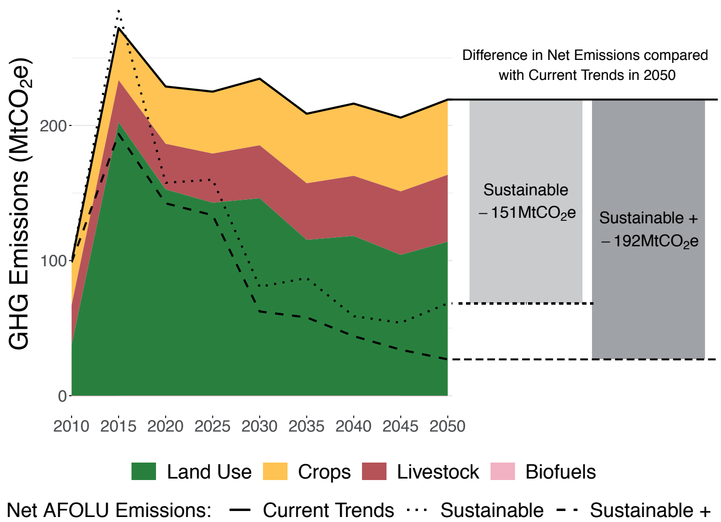


Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU increase to 235 Mt CO_2e/yr in 2030, before reaching 219 Mt CO_2e/yr in 2050 (Figure 4). The abrupt increase in GHG emissions between 2010 and 2015 is the result of an overestimated projection of the increase in key crop production levels, particularly

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

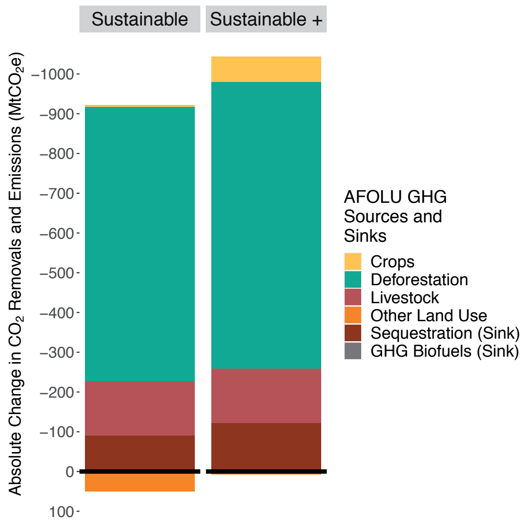


rapeseed and soybeans. This overestimation results from an exponential increase in the production levels of these crops due to a higher Chinese demand between 2005 and 2015. Values decrease after 2015 to reach more realistic values toward 2020 and beyond. In 2050, methane produced by livestock is the single largest source of emissions (35Mt CO_2e per year) while forest regeneration acts as a sink (-1 Mt CO_2e per year). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for livestock (47%) while a reduction is computed for deforestation (25%).

In comparison, the Sustainable Medium Ambition Pathway leads to a reduction of AFOLU GHG emissions by 69% and the Sustainable High Ambition Pathway to a reduction by 88% by 2050 compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Medium Ambition Pathway is dominated by a reduction in GHG emissions from deforestation and livestock production (Figure 5). The most important drivers of this reduction are a lower population growth rate by 2050, a healthier diet and limiting agricultural expansion such that it does not affect forests beyond 2030. Under the Sustainable High Ambition Pathway, GHG emissions from agriculture (crops), and land-use change are further reduced thanks to a higher afforestation rate and a lower consumption of first-generation biofuels.

Compared to Canada's commitments under the UNFCCC (Table 1), our results show that AFOLU could contribute to as much as 69% of its total GHG emissions reduction objective by 2030. Such reductions could be achieved through the following policy measures: banning deforestation beyond 2030; promoting afforestation for carbon sequestration and biodiversity conservation in the context of initiatives like the Bonn Challenge; increasing protected areas (Aichi Biodiversity Targets and beyond); sowing higher productivity crops and improving livestock genetics and pasture productivity; shifting Canadian diets toward the recommendations of the EAT-Lancet Commission; and increasing the use of zero-emission vehicles instead of those based on crop-based biofuels. These measures could be particularly important when considering options for NDC enhancement.

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

2.5% of the population undernourished in 2017. This share has remained relatively constant since 2000 (World Bank, 2017).

Data on the proportion of children under 5 who exhibit stunting and wasting due to malnutrition was not available for Canada. It may not appear chronically within the general population.

Micronutrient Deficiency

4% of women and 2% of children suffer from anemia in 2011, which can lead to maternal death (Cooper et al., 2012).

In 2012 it was estimated that 35% of the population consumed levels of vitamin A below the estimated average requirements- a trend equal amongst men and women (Health Canada, 2012), which can notably lead to blindness (Martini et al., 2018) and child mortality, and 22% of the population is deficient in iodine, which can lead to developmental abnormalities (Statistics Canada, 2012).

Overweight/ Obesity

26.9% of the population, 24.4% of adults and 10.6% of children were obese in 2017 (Statistics Canada, 2017). While the share of childhood obesity has dropped since 2009, levels in the adult and overall population have risen.

33.5% of the population, 31.1% of adults, and 18.3% of children, were overweight in 2017 (Statistics Canada, 2017). Records indicate that the percentage of overweight children has risen over the past decade, while overall levels have fallen. (Rao et al., 2016; Statistics Canada, 2017)

Disease Burden due to Dietary Risks

10% of deaths are attributable to dietary risks, or nearly 30,000 individuals (Kaczorowski et al., 2016).

In 2015, 9.3% of the population suffered from diabetes (Statistics Canada, 2018) and 8.5% from cardiovascular diseases, which can be attributable to dietary risks (Public Health Canada, 2017).

Table 3 | Daily average fats, proteins and kilocalories intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways in 2030 and 2050

	2010	2030			2050		
	Historical Diet (FAO)	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition
Kilocalories (MDER)	2,710 (2,104)	2,994 (2,092)	2,569 (2,092)	2,569 (2,092)	3,276 (2,086)	2,304 (2,086)	2,304 (2,086)
Fats (g) (recommended range)	125 (60-90)	141 (66-100)	118 (57-86)	118 (57-86)	157 (73-109)	104 (51-77)	104 (51-77)
Proteins (g) (recommended range)	85 (68-237)	99 (75-262)	84 (64-225)	84 (64-225)	112 (82-287)	81 (58-202)	81 (58-202)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

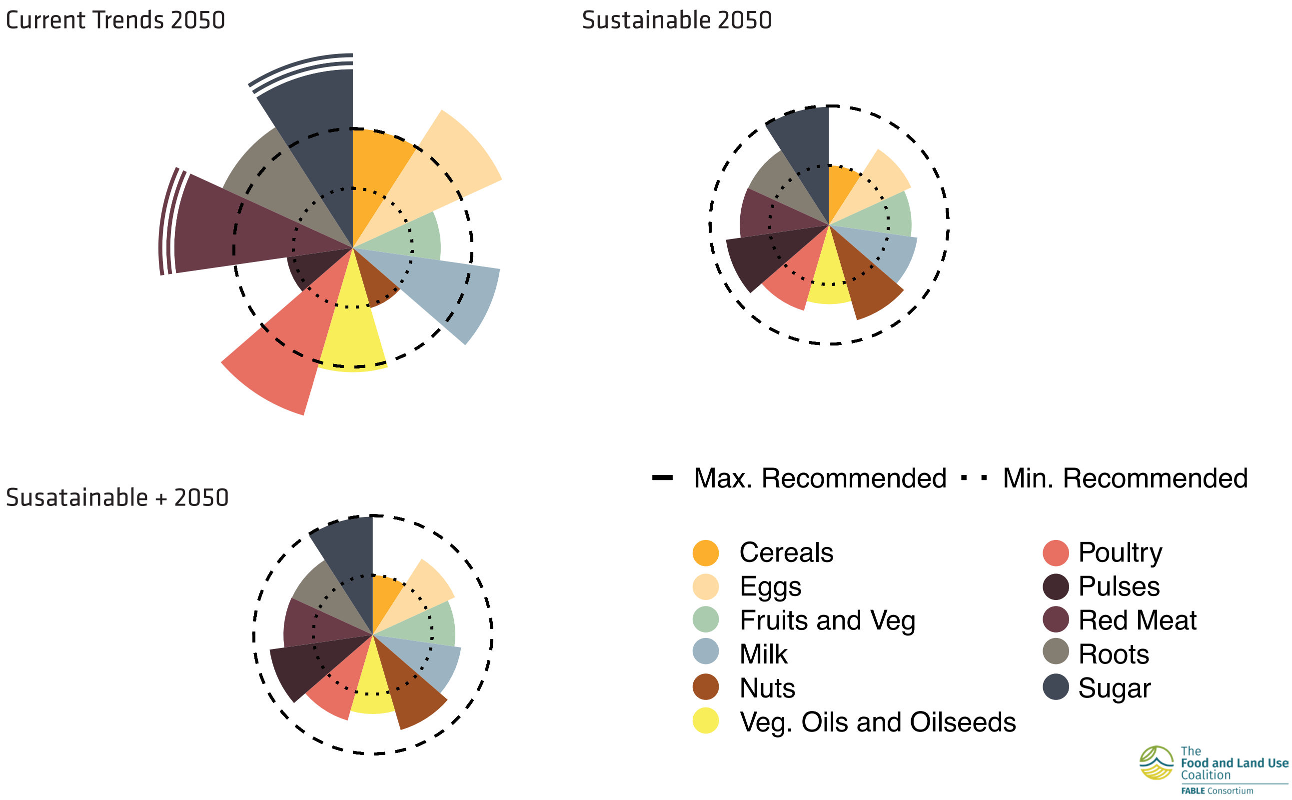
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 43% higher in 2030 and 57% higher in 2050 (Table 3). The current average intake is mostly satisfied by red meat, poultry, milk, eggs, roots and sugar, and animal products represent 21% of the total calorie intake. We assume that the consumption of animal products and in particular milk, will increase by 57% between 2020 and 2050. The consumption of red meat, poultry, and cereals will also increase while pulses, roots, and nuts consumption will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), red meat, poultry, eggs, sugar, roots, and milk are over-consumed while pulses and nuts are under-consumed in 2050 (Figure 6). Moreover, fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050, while protein intake remains in the recommended range. This can be explained by high consumption of red meat, milk, pork, and poultry (Table 3).

Under the Sustainable Medium Ambition Pathway, we assume that diets will transition towards a more balanced diet, with a higher consumption of pulses and vegetables in general, as recommended by the EAT-Lancet Commission. Similar assumptions are made under the Sustainable High Ambition Pathway. The ratio of the computed average intake over the MDER decreases to 86% in 2030 and 70% in 2050 under the two sustainable pathways. Compared to the EAT-Lancet recommendations, only the consumption of animal fat remains outside of the recommended range with the consumption of pulses and nuts being now within the recommended range (Figure 6). Moreover, the fat intake per capita still exceed the dietary reference intake (DRI) in 2030, showing some improvement compared to the Current Trends Pathway.

A significant change in diet is possible and would improve the health of the population and lead to more sustainable land and food systems (Willett et al., 2019). This is not only about energetic content; it is also about food quality and environmental impacts. A diet based on nuts, pulses, a higher consumption of fruits and vegetables, and a lower consumption of ultra-processed food and meat would make it possible to reduce GHG emissions and improve health outcomes. A healthier lifestyle will be particularly important to promote this shift in diets.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



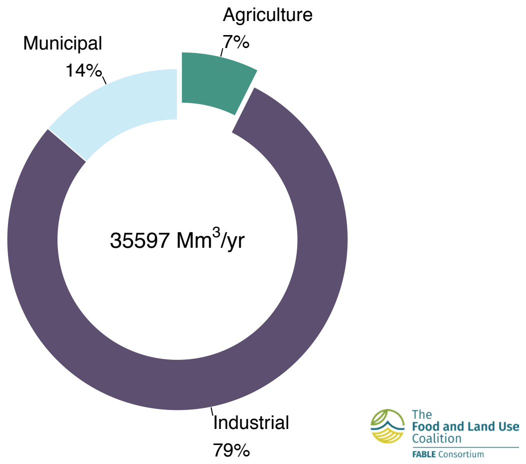
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, the different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

Canada is characterized by an extremely cold climate with 537mm average annual precipitation that mostly occurs over the period November – March. The agricultural sector represented 7.4% of total water withdrawals in the period 2013-2017 (Figure 7; FAO, 2020). Moreover, in 2006, 2.4% of agricultural land was equipped for irrigation, representing 69% of estimated-irrigation potential (FAO, 2016). The three most important irrigated crops, cereals, fodder, and vegetables, account for 60%, 29%, and 5% of total harvested irrigated area. Canada exported 49% of cereals, 0% of fodder, and 19% of fresh vegetables in 2010 (FAO, 2019).

Figure 7 | Water withdrawals by sector in period 2015-2017

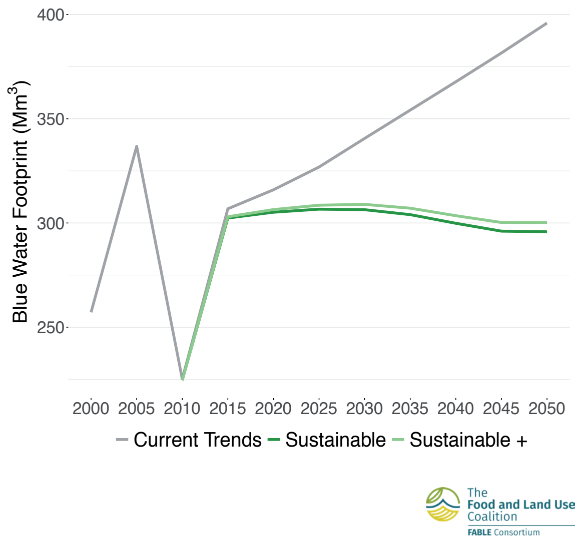


Notes. Agriculture and industrial data from 2015, municipal data from 2017.
Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000-2015 (257 and 307 Mm^3/yr), before reaching 341 Mm^3/yr and 396 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with barley, oilseeds, and oats accounting for 50%, 41%, and 8% of computed blue water use for agriculture by 2050[3]. In contrast, under the Sustainable Medium Ambition Pathway, blue water footprint in agriculture reaches 257 Mm^3/yr in 2030 and 143 Mm^3/yr in 2050, respectively, a trend that remains similar under the Sustainable High Ambition Pathway. This is explained by a change in the production level of cereals, and fodder due to a decline in internal feed demand.

Figure 8 | Evolution of blue water footprint in the Current Trends, Sustainable Medium Ambition and Sustainable High Ambition Pathways



3 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

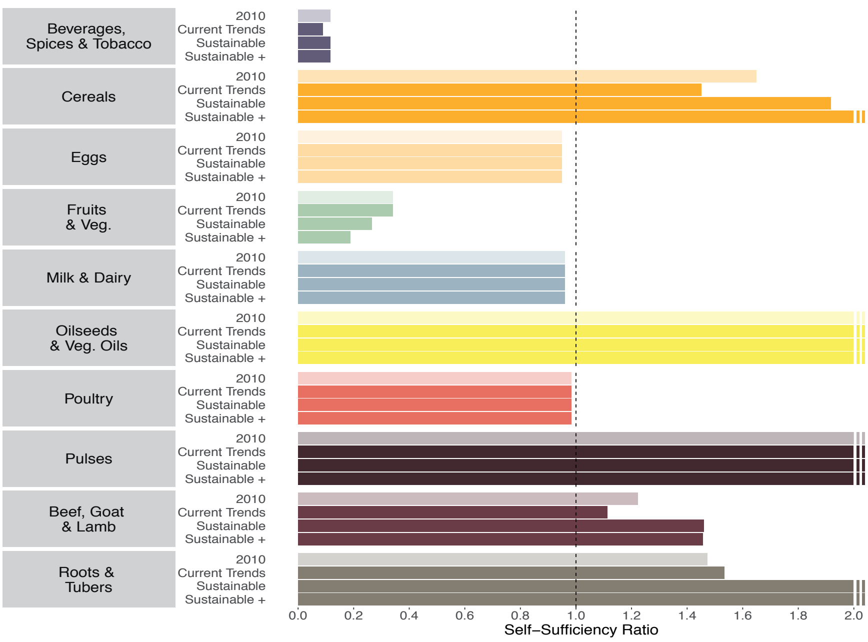
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Canada's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Canada is a large country in terms of territory but has a small population, which implies a positive supply to demand relationship between natural resources (fisheries, agricultural lands, forests, etc.) and people. Canada can be self-sufficient in cereals, fish, red meat, vegetables, and other food groups, as well as timber, energy, water and other goods and services. It should be noted that while production can exceed internal demand, for many products there is a two-way trade such that Canada both exports and imports within the same category of goods.

Under the Current Trends Pathway, we project that Canada would be self-sufficient in cereals, oilseeds and vegetable oils, poultry meat, pulses, read meat (beef, goat and lamb), and roots and tubers in 2050, with self-sufficiency by product group increasing for the majority of products from 2010 – 2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are beverages, spices and tobacco, fruits, and vegetables and this dependency will remain stable until 2050. Under the Sustainable Medium Ambition and the Sustainable High Ambition Pathways, Canada remains self-sufficient in the same eight product groups, but with higher self-sufficiency levels by 2050. This is explained by changes in the volume of imports and exports, productivity, and changes in diets.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for cereals and oilseeds and vegetable oils, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

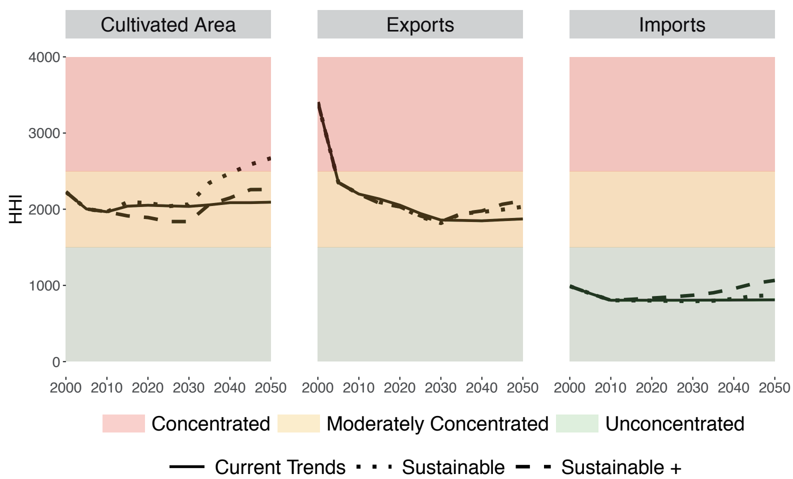
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Wheat and rapeseed were, by far, the main crop sown in 2010, follow by barley, soybeans, lentils, corn (for feed) and oats. Among these, rapeseed, wheat, barley, and soybeans are the main crops exported by Canada. According to the HHI, the planted crop area is moderately concentrated in 2010 as are exports (Figure 10).

Under the Current Trends Pathway, we project medium concentration of crop exports and planted area, and low concentration of imports in 2050, trends which stabilize over the period 2010 - 2050. This indicates moderate levels of diversity across the national production system and exports. Under the Sustainable Medium Ambition Pathway, we project a similar scenario, although a higher concentration of the planted area is possible, which is explained by a higher international demand of some specific crops from China and other important markets. Finally, under the Sustainable High Ambition Pathway, there is a medium and low concentration in exports and imports in 2050, respectively, indicate levels of diversity across the national production system that are similar to the Current Trends Pathway (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports, and crop exports using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

This document provides relevant data about the potential impact that different policies could have for increasing Canada's contribution to climate change mitigation, biodiversity conservation and solving other global challenges as laid out in the Sustainable Development Goals and other international initiatives.

By comparing three different pathways (Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition), we assessed the effect that changes on population, GDP, agricultural production, international trade, and diet and life-styles would have on Canada´s greenhouse gas emissions, biodiversity, water consumption, and resilience of the food and land systems.

The population scenarios vary by about 10 million people by 2050 (50 million under the Current Trends compared to 40 million for the Sustainable Pathways). Population growth along with the levels and types of consumption (e.g. diets) are key factors because they determine the size of the economy, and the resulting pressure on food and land systems, energy consumption, and natural resources depletion.

Diet and lifestyles are key drivers of land-use outcomes, as clearly shown in our modeling results. A high consumption of red meat, pork, and ultra-processed food significantly increases Canada's GHG emissions and is related to a higher share of wasted food (throughout the distribution supply chain), as well as an increased prevalence of health issues. We recommend the inclusion of diets and life-style in climatic policy, as proposed by the EAT-Lancet Commission (Willett et al., 2019), the promotion of physical activity and the consumption of vegetables, fruits, and high-protein content food, such as fish and pulses, which are abundant and locally produced in Canada.

Moreover, international trade is another key driver related to the use of ecosystems. The Canadian internal market for agricultural products is small compared to the country's productive capacity and much of Canada's production is oriented towards the international market, especially the US and China. Canadian agricultural production is moderately concentrated in a group of crops: rapeseed, wheat, barley, soybeans, and lentils. All of this implies a high level of economic dependency and vulnerability, which has been evident in the past cases of political tension between Canada and its trade partners. Diversifying agricultural production and the number of trade partners would allow for potentially greater resilience and independence in Canada's policy development around climate change, land use and environmental and social sustainability.

Our results also show that forests have a key role in reducing greenhouse gas emissions, protecting biodiversity, and preserving fresh water supply. From this perspective, preventing agricultural expansion into forest areas through deforestation bans beyond 2030 could have a significant impact on Canada's contribution to climate change mitigation (Prestele et al., 2016). This would be especially relevant in provinces where agriculture is concentrated and continuously expanding: Alberta, Saskatchewan, Manitoba, and Ontario. In those provinces, agricultural productivity could temporarily improve under moderate climate change through a longer growing season and due to better environmental conditions (higher temperatures and rainfall). Increasing crop productivity is also a key aspect for reducing the impacts of agriculture on forests. Harvesting more tons per hectare has a key role in reducing GHG emissions and agricultural expansion.

At the same time, Canada is a large country, with a population highly concentrated along the US border. This means significant areas of the country have not been extensively disturbed by humans, though some ecoregions are much more deteriorated than others. This is the case of those located in the south, like the Eastern Great Lakes lowland forests ecoregion and others. It is also a country with increasingly strong indigenous land rights over large areas. Compared to other countries, Canada may find it easier to create new protected areas in the near future to reach the 30% goal suggested by the UN Convention on Biological Diversity. The lack of ready access to large territories has already created de facto protected areas, especially in the boreal forest (between 50% and 80% of the total area) (Andrew et al., 2012). Further, the House of Commons created a committee to analyze the future of protected areas that suggested “that the Government of Canada set even more ambitious targets for protected areas than those established in the Aichi Target 11” (Schulte, 2017). This could be included in Canada´s next NDCs, planned for 2025. While the distribution of the population in the territory was not included in both the FABLE Calculator and analysis, we recommend considering it in Canada’s climate strategy as this is not only about biodiversity, it is also about product diversification, vulnerability, and resilience. However, new policies around protected areas and further analysis within the context of FABLE need to account for indigenous land rights over much of the territory that would be considered for protection. Whether formal protected areas administered outside indigenous governance regimes are either feasible or even desirable requires careful consideration.

Additionally, developing a national afforestation program, as called for by the Bonn Challenge, would be a good complement to the increased protection of Canadian ecoregions. Two million hectares of new forests planted in high-value ecoregions, in the context of Canada’s roughly one-billion hectares, is an achievable target and it could have a significant impact on biodiversity. Some initiatives, like the Caribou Habitat Restoration Project, Afforestation Ontario, and the National Greening Program, are already promoting afforestation on degraded lands as a way to recover ecosystem services.

Finally, we note that the analysis conducted was within the context of a dominant economic paradigm that assumes continued economic growth and then views sustainability from the lens of how to reduce future demand and meet that demand with the least impact. Within that context, the Sustainable Pathways are largely based on some changes in demand (e.g. via diet or through lower population growth) and more intensive production (via increased crop yields) with a continued reliance on global markets for both imports and exports. However, there may be other approaches to sustainability worth analyzing. Fundamentally, what does sustainability mean in terms of trade, and economic growth? In our Sustainable High Ambition Pathway, we tried to partially address this issue. For example, we assumed a future more oriented to replacement of first-generation biofuels by locally produced and renewable power for electric vehicles. Additional work could be done examining the role of localizing supply chains within agriculture on both Canada’s SDG attainment as well as spillover effects on other countries. Advancing in this area is one of the main challenges that the FABLE team will have in the near future.

In the coming months, our main challenge will be to engage stakeholders to present and discuss our pathways and projections, while we improve our models, and try to advance in developing alternative paradigms about what sustainability could mean in a context of the ecological and health crisis we are facing today with the emergence of COVID-19.

Annex 1. List of changes made to the model to adapt it to the national context

- Table 3.6 "NationalPdtyScen" was created in the FABLE Calculator to improve estimations about future productivity for rapeseed, barley, wheat and soybeans, according to what specialized paper indicate.
- A new GDP scenario was created (SSP3New) to account for medium levels of economic growth (Sustainable Medium Ambition Pathway).
- A new import scenario was created (Mixed imports) to account for lower imports of some products (corn and sugar), and higher imports of others (mainly vegetables and fruits), according to more local supply chains and healthier diets.
- Two new exports scenarios were created (Sustainable and Sustainable+). The first one is based on medium levels of exports for the main exported crops: rapeseed, barely, wheat, and soybean; according to our export projection. The second scenario is based on the highest level of potential export for those crops.
- A new biofuel consumption scenario was created (National), which projects a progressive reduction in the first-generation biofuel consumption since 2020 to 2030, and its total replacement by electricity (light-duty vehicles).

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Medium speed of population growth that results from low fertility rates of Canadians, which is compensated by a dynamic immigration process. Population grows by 25% by 2050 in comparison to 2015, as cited by Statistics Canada, (2014). Also based on UN DESA (2019)	Low speed of population growth due to higher restrictions for immigrating to Canada. Population grows by 14% by 2050 in comparison to 2015 Based on Bohnert et al. (2015)	Same as the Sustainable Medium Ambition Pathway

LAND Constraints on agricultural expansion		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
We assume that there will be no constraint for agricultural expansion, due to climate change (higher temperatures and better environmental conditions for crops at different zones of the country), higher international demand for commodities, and land availability. Using ESA (2010) and UNEP-WCMC & IUCN (2019), our estimates indicate that, under current land-use trends, agricultural land expands by 26% by 2050,with 84% of new agricultural lands come from deforestation. Also based on Canada's Protected Areas (2019).	Agriculture expansion does not drive deforestation beyond 2030, as new policies ban land use changes that negatively affect forests. Based on ESA (2010), UNEP-WCMC & IUCN (2019) and Canada's Protected Areas (2019)	Same as the Sustainable Medium Ambition Pathway
LAND Afforestation or reforestation target (1000 ha)		
Since deforestation is not a critical issue in Canada, there are no federal goals for afforestation and restoration. We assume that almost no new forests will be planted by 2050, and afforestation will remain as a non-relevant activity in Canada. (NoAfforestation scenario selected)	Programs like the Caribou Habitat Restoration Project, Afforestation Ontario, and the National Greening Program are promoting afforestation on degraded lands as a way to recover ecosystem services. They could reach about 1.000.000 hectares of new forests by 2050 (assuming 2,000 trees per hectare). Based on Government of Ontario (2017), Habitat Conservation Trust Foundation (2020) and Tree Canada (2020) (BonnChallenge scenario selected)	New forests could reach 2,000,000 hectares by 2050 to mitigate climate change, because of successfully implemented programs like the National Greening Program (assuming 1,000 trees per hectare and natural regeneration). (BonnChallenge scenario selected)

BIODIVERSITY Protected areas (1000 ha or % of total land)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
The "other effective area-based conservation measure", which is considered in the Canadian strategy to reach the Aichi Biodiversity Target, could be ineffective to protect ecosystems, as national parks and other formal protected areas do. This would not increment the share of the terrestrial ecosystems under protection (Lemieux et al., 2019)	The "other effective area-based conservation measure," and complementary measures, will be good enough to adequately protect biodiversity in Canada in the next decades, because they achieve the protection of ecosystem functionality and processes beyond what it has been criticized by different authors (MacKinnon et al., 2015)	Protected areas in Canada could cover 28% of the country by 2050, if different initiatives oriented to increase the protection of ecosystems are successfully implemented. (Andrew et al., 2012; ESA, 2010; Schulte, 2017; UNEP-WCMC & IUCN (2019); Canada's Protected Areas, 2019)

PRODUCTION Crop productivity for the key crops in the country (in t/ha)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Negative impacts that result from higher climate variability and extreme weather events will negatively influence crop productivity. In consequence, productivity will increase at a slower pace than in the previous decade.	Advances in crop genetics and better management practices will have positive effects on crop yield, which, would be offset by the negative impacts of climate change. In consequence, crop productivity will increase at the same speed than the previous decade (Assefa et al., 2018; Jing et al., 2017; G. Li et al., 2018; Ray et al., 2013; Thomas & Graf, 2014).	"A better climate" for Canadian crops due to a longer growing season and higher temperatures would increase the productivity of main crops (Lychuk et al., 2017; Qian et al., 2016). This will be strengthened by additional technological advances such as genetic and management improvements (Abberton et al., 2016; Assefa et al., 2018; Bevan et al., 2017; Carpenter, 2010; Jing et al., 2017; G. Li et al., 2018; Ray et al., 2013; Rivers et al., 2015; Smith et al., 2013; Thomas & Graf, 2014).
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)		
Livestock productivity will continue to increase at a similar rate as it was recorded in previous years, in terms of tons of meat, milk and other products per animal. This is because cattle, sheep and goats have already reached an optimum performance.	Livestock productivity will increase greatly by 2050, in terms of tons of product per unit of animal, due to genetic improvements (Mukhopadhyay et al., 2020) and better management practices by farmers.	Same as the Sustainable Medium Ambition Pathway
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)		
Pasture stocking rate will remain stable in the next 30 years, as climate change is not going to produce a positive impact on grass productivity (Li et al., 2013).	"A better climate" in the Canadian prairies and other regions, will increase grass productivity (longer growing season, higher temperatures and enough rain) which will allow to raise more animals per hectares of pastures (Thorpe et al., 2008).	Same as the Sustainable Medium Ambition Pathway
PRODUCTION Post-harvest losses		
This component was not projected in the pathways	This component was not projected in the pathways	This component was not projected in the pathways

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Canadian imports of the main products will proportionally increase at the same rate as Canadian population increases. In terms of imports per person, it will remain stable.	Canadian imports will moderately increase in the coming decades for the main products due to a higher demand of corn for biofuel (Advanced Biofuels Canada, 2019), and a healthier diet adopted by the Canadian population which results in a larger consumption of fruits and vegetables (Willett et al., 2019).	Canadian imports will decrease at least for corn and raw sugar (Taylor, 2017a, 2017b). The former due of a lower consumption of biofuels by 2040 (Advanced Biofuels Canada, 2019). The latter, due to a lower internal demand resulting from healthier diets. By contrast, vegetable imports will double, and orange juice imports will remain constant, following EAT-Lancet Commission's recommendations.

TRADE Evolution of exports for key exported products (1000 tonnes)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Canada exports for the main products will increase by 2050, but at a lower rate than It was expected. International competition, biofuel production, and other issues (i.e. political issues) will increase domestic consumption of crops.	Canadian exports for the main products will increase by 2050, as China, U.S., and other important markets for Canadian products will continue to grow in the coming decades, driven by a higher demand of grains and oilseeds (wheat, rapeseed and soybean) to produce biofuels, and feed livestock and poultry (Advanced Biofuels Canada, 2019; Beckman & Nigatu, 2017; Taylor, 2017b). This increment will be high due to the positive relationship between the large production volume, and the relatively low environmental impacts and costs, which differentiates Canada from other producers (i.e. Brazil) Based on Beckman & Nigatu (2017) and dos Santos et al. (2018).	Canadian exports for the main products will increase by 2050, as China, U.S., and other important markets for Canadian products will continue to grow in the coming decades, driven by a higher demand of grains and oilseeds (wheat, rapeseed, and soybean) to produce biofuels and feed livestock and poultry. The rise will be very high for rapeseed and soybean. All these crops would still likely grow under a sustainable intensification approach with trade as they have non-biofuel uses.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Dietary composition and intake will have a larger share of processed and ultra-processed food and low-quality calories in Canada (Moubarac et al., 2017). While people slowly understand the importance of having a healthier diet, sedentarism, obesity, and other health issues will increase by 2050. Based on Cooper et al. (2012), Health Canada (2012), Kaczorowski et al. (2016); Martini et al. (2018); Public Health Canada (2017); Rao et al. (2016); Statistics Canada (2017)	People change their diets, reduce ultra-processed food consumption and red meat (to reduce GHG emissions), and increase seeds and vegetables. Educational programs and other initiatives to promote healthier lifestyles have a significant impact on Canadians. Based on Willett et al. (2019)	Same as the Sustainable Medium Ambition Pathway
FOOD Share of food consumption which is wasted at household level (%)		
The share of wasted food remains stable by 2050. People's behavior concerning this aspect does not change in the coming decades, due to a perceived abundance of food and natural resources in Canada.	The share of wasted food significantly decreases in the coming decades, as people understand the importance of being more efficient in their consumption habits (save money and being friendlier with the environment). Educational programs have an impact on new generations of Canadians. Based on Government of Canada et al. (2019)	Same as the Sustainable Medium Ambition Pathway

BIOFUELS Targets on biofuel and/or other bioenergy use		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Biofuel demand will remain stable as 2010, due to the lack of international agreements about carbon markets, fossil fuel consumption and climate change mitigation strategies.	Biofuel demand will increase in the coming years based on international agreements about climate change and carbon markets (Advanced Biofuels Canada, 2019). However, new/more efficient technologies will displace biofuels after 2030, thus limiting its demand.	Demand for liquid biofuels will decrease over time as incentives put forth by the federal government to promote zero-emissions vehicles make these fuel sources obsolete in the near future (NRCAN, 2020). We expect demand for these products to fall substantially by 2030.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Average temperature increases by 6.0 Celsius degrees, according to the HadGEM2-ES climate model, the GEPIC crop model, without fertilization effect. Despite of this global change, aspects like growing season, temperature rainfall, and others will remain stable for Canada.	Average temperature increases by 2.6 Celsius degrees, according to the HadGEM2-ES climate model, the GEPIC crop model, without fertilization effect. Region climates are going to be affected in most of the Canadian provinces and territories, with positive impacts on crops (longer growing season and higher average temperatures will increase crop productivity, see crop productivity panel). Similar effects can be expected in northern territories. In general, there will be less snow and ice, and more rain, which could negatively affect forestry operations.	Average temperature increases by 2.6 Celsius degrees, according to the HadGEM2-ES climate model, the GEPIC crop model, without fertilization effect. Under this scenario, climates do not change to such a large extent in Canada. This will allow for a longer growing season as well as better temperatures and rainfall for most crops.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes

Original land cover class from ESA CCI	Aggregated land cover class
Grassland	Grassland
Water	Not Relevant
Shrubland	Other Land
Cropland_rainfed	Cropland
Herbaceous	Grassland
Tree_or_shrub	Forest
Cropland_irrigated	Cropland
Mosaic_crop_natveg	Cropland
Mosaic_natveg_crop	Cropland
Tree_BL_EVG_sup15pc	Forest
Tree_BL_DEC_sup15pc	Forest
Tree_BL_DEC_sup40pc	Forest
Tree_BL_DEC_15_40pc	Forest
Tree_NL_EVG_sup15pc	Forest
Tree_ML	Forest
Mosaic_tree_shrub_herba	Forest
Mosaic_herba_tree_shrub	Grassland
Shrubland_DEC	Other Land
Sparse_vege_low15pc	Other Land
Sparse_herba_low15pc	Other Land
Tree_flooded_fresh	Forest
Tree_flooded_saline	Forest
Shrub_Herba_flooded	Other Land
Urban	Urban
Bare	Not Relevant
Tree_NL_EVG_sup40pc	Forest
Lichens	Other Land
Sparse_shrub_low15pc	Other Land
Conso_bare	Not Relevant
Snow_ice	Not Relevant
Shrubland_EVG	Other Land
Sparse tree	Forest
Unconso_bare	Not Relevant
Tree_NL_EVG_15_40pc	Forest
Tree_NL_DEC_sup15pc	Forest
Tree_NL_DEC_sup40pc	Forest

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km^2 (%)
0	Rock and Ice	1221.0	26.4	99.8	26.4	73.6	0	0
333	Eastern Canadian Forest-Boreal transition	31868.2	9.1	75.8	10.3	89.7	537.0	63.5
334	Eastern Great Lakes lowland forests	8771.0	1.6	16.7	4.5	95.5	5152.0	28.4
335	Gulf of St. Lawrence lowland forests	3539.9	3.6	50.5	6.2	93.8	487.0	48.8
338	New England-Acadian forests	16295.0	7.1	58.9	11	89	1115.9	63.1
342	Southern Great Lakes forests	2495. 8	0.8	8.3	7.3	92.7	1950.2	11.5
344	Western Great Lakes forests	7450.9	12.8	65.9	15.5	84.5	264.6	53.9
345	Alberta-British Columbia foothills forests	12135.0	1.5	77.8	1.8	98.2	554.6	53.9
349	British Columbia coastal conifer forests	10781.9	21.3	93.3	22.5	77.5	14.4	87.2
350	Central British Columbia Mountain forests	13972.9	6.3	82.7	7.4	92.6	135.6	78.4
351	Central Pacific Northwest coastal forests	3495.1	18.6	82.8	19.6	80.4	0.4	100
355	Fraser Plateau and Basin conifer forests	10445.0	14.9	73.8	19.5	80.5	198.5	80.1
358	North Cascades conifer forests	639.0	29.7	85	34.5	65.5	10.9	63.3
361	Northern Rockies conifer forests	18313.7	30	89.4	33.3	66.7	111.7	80.1
362	Okanogan dry forests	5257.1	6.5	67.4	9.1	90.9	141.0	70.3
364	Puget lowland forests	1867.6	11.1	66.2	15.7	84.3	158.2	41.3
365	Queen Charlotte Islands conifer forests	960.8	47.7	87	49.7	50.3	0	0
370	Central Canadian Shield forests	27135.5	9.2	81.8	10.3	89.7	184.3	74.8

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that are protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within $1km^2$ (%)
373	Eastern Canadian forests	46073.3	8.4	87.4	9.2	90.8	222.2	46.9
374	Eastern Canadian Shield taiga	75288.3	9.6	92.8	9.7	90.3	0	0
375	Interior Alaska-Yukon lowland taiga	2066.8	43.9	98.3	44.5	55.5	0	0
376	Mid-Canada Boreal Plains forests	56846.4	8	63.9	10.6	89.4	10228.1	25.4
377	Midwest Canadian Shield forests	75547.0	10.2	87.6	10.8	89.2	10.6	95.7
378	Muskwa-Slave Lake taiga	29791.6	21.5	91.9	22.8	77.2	11.6	79.4
379	Northern Canadian Shield taiga	63056.3	6.4	86.1	7	93	0	0
380	Northern Cordillera forests	16888.0	26.4	99.3	26.6	73.4	2.4	96.9
381	Northwest Territories taiga	33261.5	5.9	84	6.6	93.4	0	0
382	Southern Hudson Bay taiga	37201.0	12.2	98.3	12	88	0	0
383	Watson Highlands taiga	23823.6	4.4	98.4	4.4	95.6	18.8	83.1
386	Canadian Aspen forests and parklands	19255.1	4.8	4.8	42.3	57.7	15672.2	10.9
394	Montana Valley and Foothill grasslands	1488.1	0.3	1.7	10.4	89.6	1078.1	20.3
396	Northern Shortgrass prairie	22371.2	8.2	3.8	53	47	14576.4	16.6
397	Northern Tallgrass prairie	3781.7	1.7	9.3	13.5	86.5	2543.1	14.1
398	Palouse prairie	79.3	16.2	57.9	22.5	77.5	8.8	50.1
405	Alaska-St. Elias Range tundra	2387.7	89.2	57.6	81.4	18.6	1.6	98
408	Arctic foothills tundra	546.9	44.2	95	45.1	54.9	0	0
411	Brooks-British Range tundra	2671.0	27.4	99.8	27.4	72.6	0	0
412	Canadian High Arctic tundra	63315.4	9.5	79.2	9	91	0	0
413	Canadian Low Arctic tundra	82959.1	16.6	83.4	18.7	81.3	0	0
414	Canadian Middle Arctic Tundra	95827.2	6.7	87.5	7.4	92.6	0	0

Canada

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
415	Davis Highlands tundra	9451.4	29.5	62.5	23.3	76.7	0	0
416	Interior Yukon-Alaska alpine tundra	3848.3	0	97.9	0	0	0.4	88
419	Ogilvie-MacKenzie alpine tundra	29104.4	11.8	99.7	11.8	88.2	0.0	100
420	Pacific Coastal Mountain icefields and tundra	2456.9	21.7	84.7	8.2	91.8	0.0	100
421	Torngat Mountain tundra	3196.6	41.6	92.1	42.5	57.5	0	0

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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China

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in China. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how China's NDC treat the FABLE domains. According to the NDC, China has committed to reducing its GHG emissions intensity by 60-65% by 2030 compared to 2005 (National Development and Reform Commission of China, 2015). This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include conserving farmland, improving the potential of soil to store carbon, maintaining a balance between forage and livestock, enhancing afforestation, and protecting and restoring wetlands. Under its current commitments to the UNFCCC, China mentions biodiversity conservation (National Development and Reform Commission of China, 2015). China's President Xi Jinping also pledged that China will achieve carbon neutrality by 2060. Though agricultural was not listed as a key sector to achieve this pledge, proper agricultural land-use management to save more land for nature and afforestation could significantly contribute to China's 2060 carbon neutrality pledge.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2017)	2005	7,466 (without LULUCF) 7,045 (with LULUCF)	2030	60-65% carbon intensity reduction	Energy, Industrial processes, agriculture, waste, LULUCF	Y	Y	N	Food, water, deforestation

Note: "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019), except for the GHG emissions baseline, which comes from UNFCCC (2005).
Source: UNFCCC (2005)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2010, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. In comparison with the FABLE Targets, NBSAP targets are a little outdated, but provided a benchmark against which to assess China's performance on climate change mitigation and biodiversity protection when preparing our scenarios.

Table 2 | Overview of the NBSAP targets in relation to FABLE targets

NBSAP Target	Global FABLE Target
By 2015, forest coverage rate will increase to 21.66% and forest reserves will increase by 600 Mm^3 compared to 2010.	DEFORESTATION: Zero net deforestation from 2030 onwards
By 2020, national forest holdings will exceed 2.33 Mkm^2, an increase of 223,000 km^2 compared to 2010; and national forest reserves will increase to 15 billion m^3, an increase of about 1.2 billion m^3 compared to 2010.	DEFORESTATION: Zero net deforestation from 2030 onwards
By 2020, forest areas and net forest reserves will increase by 52,000 km^2 and by 1.1 Mkm^2 compared to 2010, respectively.	DEFORESTATION: Zero net deforestation from 2030 onwards
By 2020, grassland degradation will be nearly contained and the ecological environment of grasslands will be considerably improved.	BIODIVERSITY: No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
By 2020, the total areas of degraded grasslands will exceed 1.65 Mkm^2, with grassland habitats restored and grassland productivity significantly enhanced.	BIODIVERSITY: No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
By 2020, a system of nature reserves with reasonable layouts and comprehensive functions will be established, with functions of national-level nature reserves stable, and main targets of protection effectively protected.	BIODIVERSITY: At least 30% of global terrestrial area protected by 2030
By 2015, the total area of terrestrial nature reserves will be maintained at around 15% of China's land area, protecting 90% of national key protected species and typical ecosystem types.	BIODIVERSITY: At least 30% of global terrestrial area protected by 2030
By 2020, energy consumption and CO_2 emission per unit of GDP will decrease significantly, with the total amount of main pollutants considerably reduced.	GHG EMISSIONS: Zero or negative global GHG emissions from LULUCF by 2050
By 2020, forest carbon sinks will increase by 416 Mt compared to 2010.	GHG EMISSIONS: Zero or negative global GHG emissions from LULUCF by 2050

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in China.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by a moderate population decrease (from 1.41 billion in 2020 to 1.29 billion in 2050), no constraints on agricultural expansion, a high afforestation target, medium productivity increases in the agricultural sector, an evolution towards higher consumption of animal products, and low livestock productivity increases (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to the ongoing trends of rapid urbanization and increasing incomes. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, rice, wheat, and soybean (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to larger increases in crop and livestock productivity and reduced caloric intake (see Annex 2). This corresponds to a future based on the adoption and implementation of more ambitious policies. It would also see considerable progress with regards to the continuous investment in new technologies in crop and livestock production, which will substantially increase agricultural productivity, increases in production on managed grasslands, which will save more grassland for natural protection, and slight reductions in caloric intake due to healthier diets, although not those suggested by EAT LANCET (Ministry of Agriculture of China, 2016; National Development and Reform Commission of China, 2020; Xi, 2017). With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

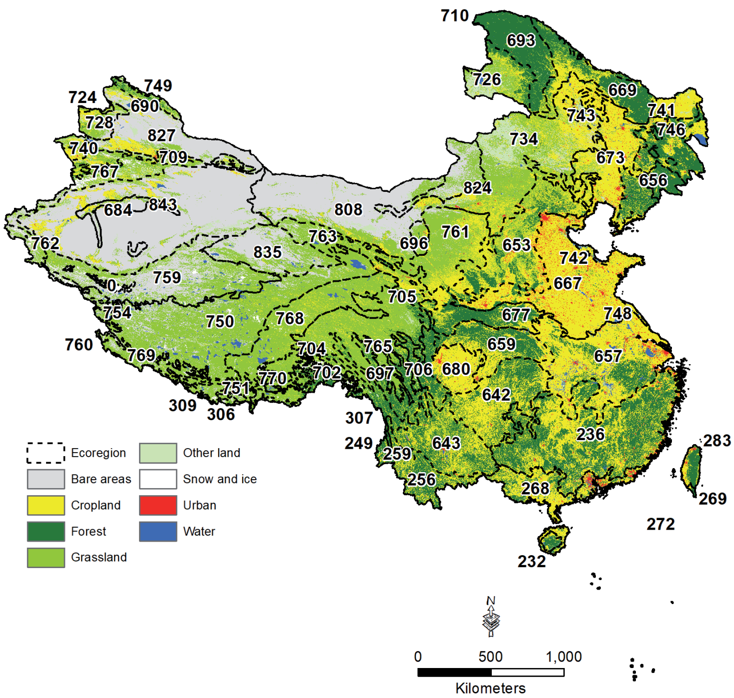
Land and Biodiversity

Current State

In 2010, China's land area consisted of 13% cropland, 41% grassland, 22% forest, less than 1% urban, and 23% other natural land (ESA, 2014; FAO, 2020). Most of agricultural area is located in Northern China and Middle-Lower Yangtze Plain, while forest and other natural land can be mostly found in the northeast and southwest (Map 1). While many threats to biodiversity remain, including habitat destruction and direct exploitation of wild plants and animals, the government has implemented a large system of pro-environment policies under the broad remit of "Ecological Civilization", which has brought about profound changes – many of them positive – to land use and its ecological implications in China (Bryan et al., 2018; Ministry of Ecology and Environment of China, 2010).

We estimate that land where natural processes predominate[2] accounted for 45% of China's terrestrial land area in 2010 (Map 2). The 306-Eastern Himalayan broadleaf forests hold the greatest share of land where natural processes predominate, followed by 307-Northern Triangle temperate forests and 760-Northwestern Himalayan alpine shrub and meadows (Annex 4). Across the country, while 120 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 20% of land where natural processes predominate is formally protected (IUCN, 2016; Jacobson et al., 2019; Potapov et al., 2017). This indicates that future land-based protection efforts should particularly target land where natural processes predominate, and land in regions where formal protection is currently not as strong – notably east of the Heihe-Tengchong Line.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

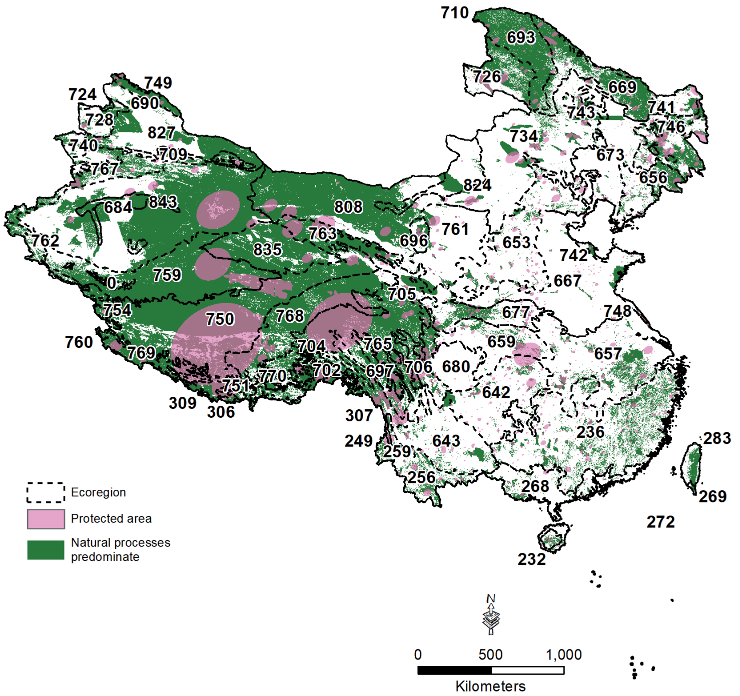


Notes. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 34% of China's cropland was in landscapes with at least 10% natural vegetation in 2010 (Map 2). These relatively biodiversity-friendly croplands are most widespread in 760-Northwestern Himalayan alpine shrub and meadows, 309-Eastern Himalayan subalpine conifer forests, and 249-Mizoram-Manipur-Kachin rain forests (Jacobson et al., 2019; Potapov et al., 2017; IUCN, 2016). The regional differences in extent of biodiversity-friendly cropland can be explained by regional production practices.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020) and Ministry of Ecology and Environment of China; natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Pathways and Results

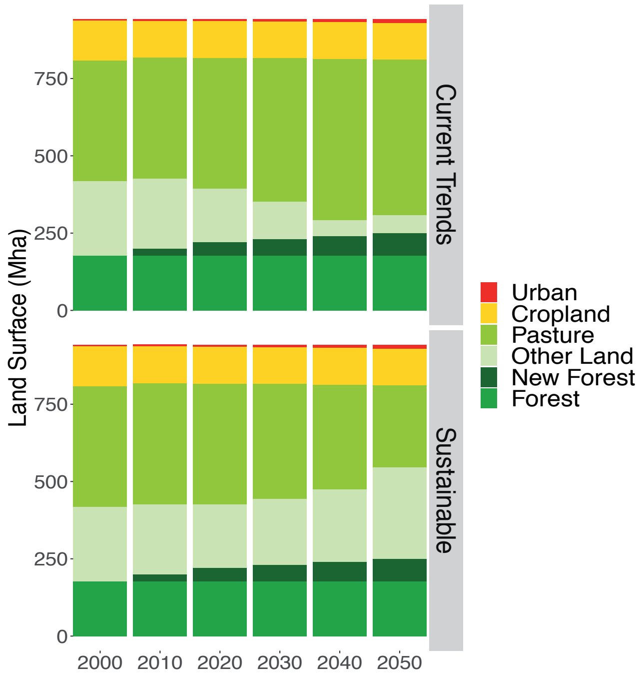
Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas and 72.6 Mha of reforestation or afforestation by 2050 (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in pasture area and a decrease in other land area. This trend remains stable over the period 2030-2050: pasture area further increases and other land area further decreases (Figure 1). Pasture expansion is mainly driven by the rapid increase in domestic consumption of milk, beef and mutton, despite livestock productivity per head increasing slowly and grassland productivity per hectare remaining constant over the period 2020-2030. Between 2030-2050, pasture area first increases before decreasing slightly after 2045. This is explained by initial, rapid increases in milk, beef, and mutton consumption per person followed by declines in the rate of population growth.

This results in a reduction of land where natural processes predominate by 3% by 2030 and an increase by 4% by 2050 compared to 2010, respectively.

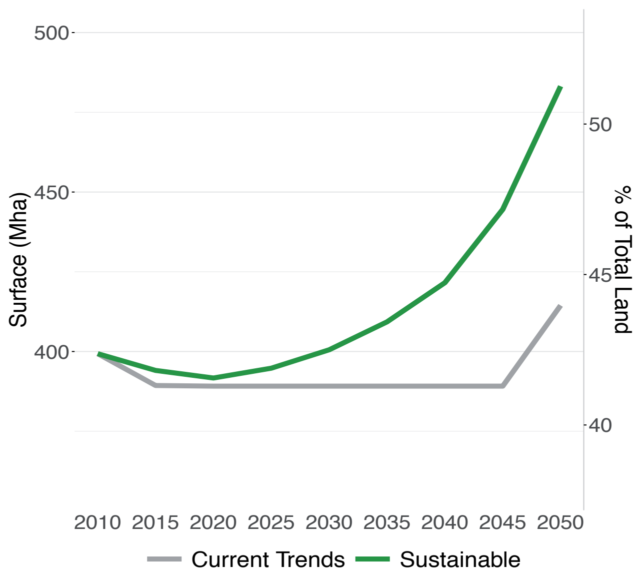
In the Sustainable Pathway, the main assumptions include 72.6 Mha of reforestation or afforestation by 2050 (see Annex 2). Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in China in the Sustainable Pathway: (i) pasture area decreases steadily, (ii) natural land (the combination of forest, new forest and other land) steadily increases from 2020-2050 due to increases of new forest cover and conversion of pasture for other land use, (iii) cropland area remains stable at 120 Mha due to the strict policy on cropland protection; (iv) changes of forest area are similar to ongoing trends. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by lower milk, beef, and mutton consumption, higher livestock productivity growth, and more food imports. This leads to an increase in the area where natural processes predominate: the area stops declining by 2030 and increases by 21% between 2010 and 2050 (Figure 2). However, the demand for grassland could be further reduced if a share of natural grasslands were converted into managed grasslands. China's grasslands are mostly natural with an average biomass production of 0.75 ton per hectare per year, which is low by international standards. Improving the productivity of managed grassland, which has biomass yields that are more than 10 times higher compared compared with natural grassland, could potentially alleviate some of the pressure on natural grasslands. This requires a significant change in current natural grassland management practices and related livestock production systems.

Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000.

Figure 2 | Evolution of the area where natural processes predominate

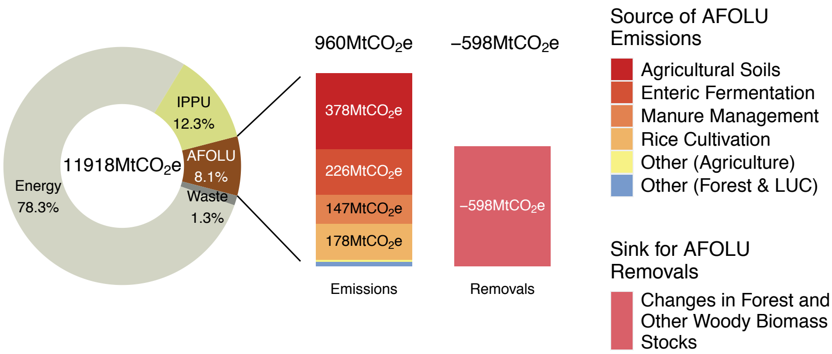


GHG emissions from AFOLU

Current State

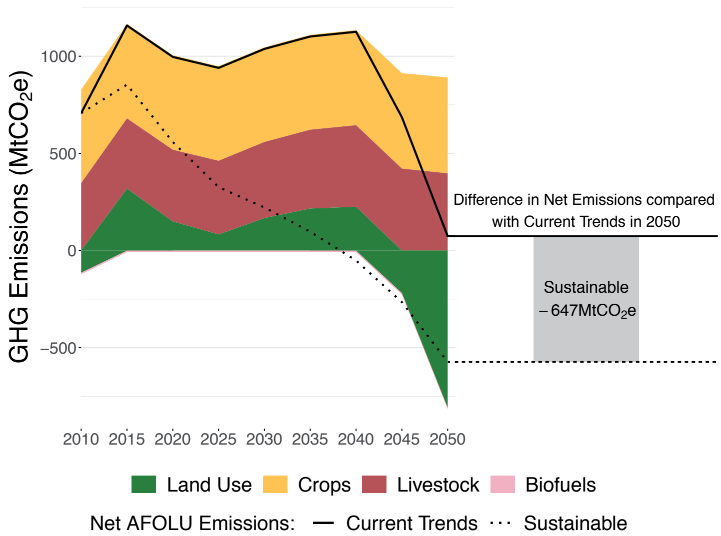
Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 8.1% of total emissions in 2012 (Figure 3). Agricultural soil is the principle source of AFOLU emissions, followed by enteric fermentation, and rice cultivation (UNFCCC, 2020). China has committed to strengthen global climate governance under the framework of multilateral agreements. For example, China signed the Paris Agreement and pledged to reduce the intensity of its GHG emissions by 60-65% by 2030 compared to 2005. Furthermore, President Xi Jinping announced that China would adopt more effective policies and techniques to reduce CO_2 emission, strive to reach peak emissions by 2030, and achieve carbon neutrality by 2060 (Xi, 2020). However, most of the intended reductions in GHG emissions focus on industry. The agricultural sector is only partially considered, mainly due to the strategic importance of agricultural production for securing food supplies. Hence, we have assumed there will be limited changes in GHG emissions from manure management, enteric fermentation, and rice cultivation in the Sustainable Pathway compare to the Current Trends Pathway. On the other hand, the Chinese government does priorities reforestation. It has undertaken large scale reforestation programs (e.g."grain for green") and executed them efficiently to control water loss and soil erosion (Bryan et al., 2018). In recent years, the government has launched other projects, such as Ecological Conservation Redlines; to protect ecosystems, since both the government and general public have realized the importance of the environ-

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total emissions and removals by source in 2012



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



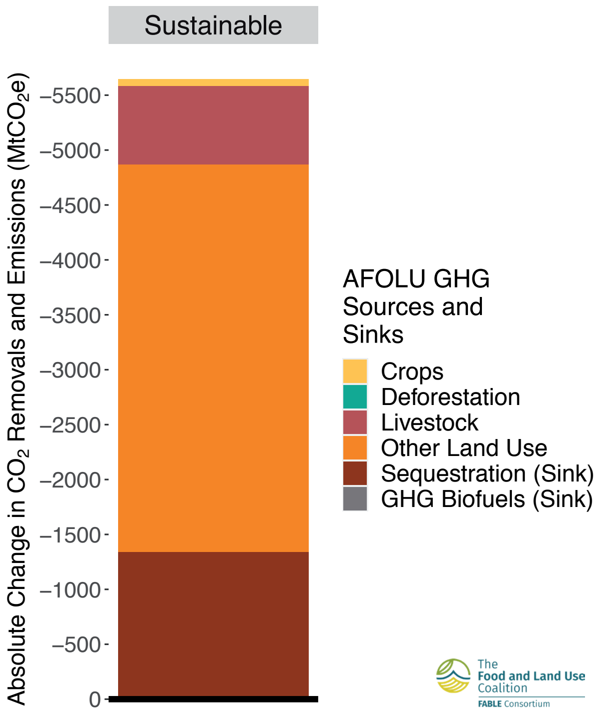
ment for development and human health. This can explain why there is increasing sequestration of carbon in China (Gao, 2019).

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU, increase to 1,038 Mt CO_2e/yr in 2030, before declining to 74 Mt CO_2e/yr in 2050 (Figure 4). In 2050, N_2O from crops is the largest source of emissions (256.1 Mt CO_2e/yr) while sequestration from land use changes acts as a sink (-839.3 Mt CO_2e/yr over the period 2020-2050). The strongest relative increase in GHG emissions is computed for livestock CH_4 (13%) while a reduction is computed for land-use change that does not include deforestation (95%).

In comparison, the Sustainable Pathway leads to a reduction of GHG emissions from AFOLU by 875% by 2050 compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from the land-use change and livestock sectors (Figure 5). Lower beef, milk, and mutton consumption, which reduces the demand for grassland, and reductions in the consumption of corn and wheat, which contributes to lower demand for cropland. and the afforestation of 24.7Mha are the most important drivers of this reduction.

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Compared to China's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute to the total GHG emissions reduction objective by 2030, though it is difficult to quantify its actual contributions due to the lack of a clear mitigation target for agriculture due to China's food-security-first policy. However, the central government has now pledged to achieve carbon neutrality by 2060 (Wang et al., 2020). The land use sector could contribute greatly to this target. It has been reported that carbon sequestration by terrestrial ecosystems was 1.1 billion tonnes CO_2 annually, which can offset 45% of total emissions. Much of this sequestration came from afforestation, which mainly took place in the northwest and northeast, as well as relevant financial measures. Among the 16 main sustainable land use programs, "Grain-for-Green" and the "Three North" have led to 60.15 Mha in increased forest cover from 1998–2014; the Grain-for-Green increased the vegetation cover of the Loess Plateau significantly, from 31.6% to 59.6% between 1999-2013, and the multi-program afforestation of grasslands in Xinjiang increased forest cover by 68% from 2000–2009 (Bryan et al.,2018). These measures could be particularly important when considering options for NDC enhancement and achieving China's goal of reaching carbon neutrality by 2060.

Food Security

Current State

Undernutrition

6% of the population undernourished in 2012. This share has decreased since 2002 (National Health Commission of China, 2015).

11% of children under 5 stunted and 2% wasted in 2015 (Institute for Health Metrics and Evaluation IHME, 2020).

Micronutrient Deficiency

26.4% of women and 21.4% of children (<5 yr) suffered from anemia in 2016, which can lead to maternal death (WHO, 2020).

14% of the population are deficient in vitamin A (IHME, 2020), which can notably lead to blindness (Sommer, 2001) and child mortality, and/or 16.6% are deficient in iodine, which can lead to developmental abnormalities (Fan et al, 2017).

Overweight/ Obesity

10.2% of the population, and 11.9% of adults, and 5% of children were obese in 2010-2012. These shares have increased since 2002 (National Health Commission of China, 2015).

24.7% of the population, and 30.1% of adults and 8.3% of children, were overweight in 2010-2012. These shares have increased since 2002 (National Health Commission of China, 2015).

Disease Burden due to Dietary Risks

29.9% of deaths are attributable to dietary risks, or 221.5 deaths per year (per 100,000 people) (IHME, 2020).

Dietary risks also lead to/cause 80.3 million disability-adjusted life years (DALYs), or years of healthy life lost due to an inadequate diet (IHME, 2020).

10.9% of the population suffers from diabetes and 21% from cardiovascular diseases, which can be due to or caused by dietary risks (National Center for Cardiovascular Diseases, 2019).

Table 3 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,658 (2,130)	3,015 (2,110)	2,978 (2,110)	3,775 (2,090)	3,583 (2,090)
Fats (g) (recommended range)	87 (59-89)	98 (67-101)	96 (66-99)	120 (84-126)	113 (80-119)
Proteins (g) (recommended range)	84 (66-233)	104 (75-264)	95 (74-261)	144 (94-330)	118 (90-314)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

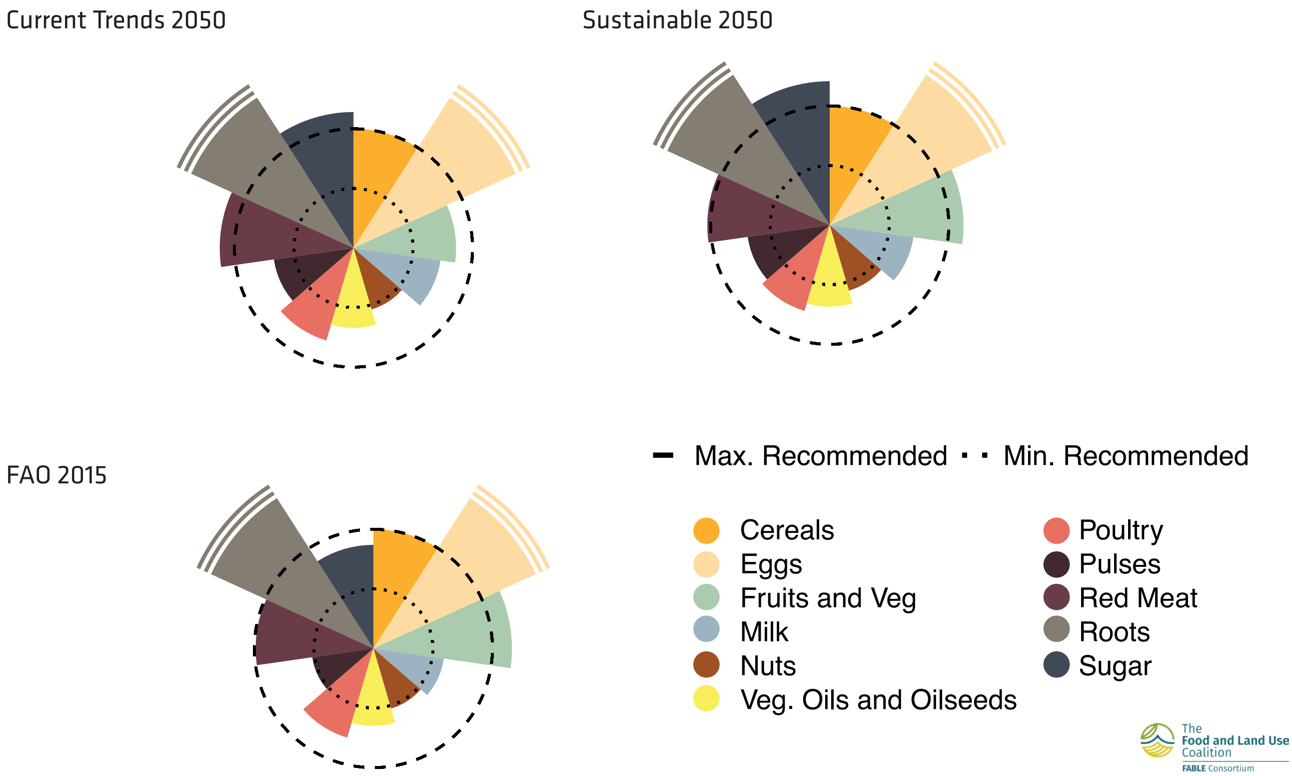
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 43% higher in 2030 and 81% higher in 2050 (Table 3). The current average intake is mostly satisfied by cereals, pork, vegetables and fruits, with animal products representing 23% of the total calorie intake. We assume that the consumption of pulses will increase by 103% between 2020 and 2050. The consumption of milk, sugar, beverages and spices, nuts, and oil seeds and vegetable oils will also increase while the consumption of vegetables and fruits will decrease by 11%. Compared to the EAT-Lancet recommendations (Willett et al., 2019), roots, eggs, and red meat are over-consumed while the consumption of nuts is slightly above the minimum recommended in 2050 (Figure 6). Moreover, fat and protein intake per capita are in line with the dietary reference intake (DRI) in 2030.

Under the Sustainable Pathway, we assume that diets will transition towards lower consumption of animal products and higher consumption of vegetables, fruits, and nuts. The ratio of the computed average intake over the MDER decreases to 41% in 2030 and 71% in 2050. Compared to the EAT-Lancet recommendations, the consumption of red meat is now within the recommended range, though at the upper limit, and the consumption of fruits and vegetables increases to slightly to exceed the upper limit of the recommended range in 2050 (Figure 6). In addition, the fat and protein intake per capita is in line with the dietary reference intake (DRI) in 2030.

Education on healthy diets and curtailing food waste, reducing subsidies for animal products together with higher taxes for high-pollution-livestock-production will be particularly important to promote this shift in diets (Lipinski et al., 2013; Ma et al., 2019).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



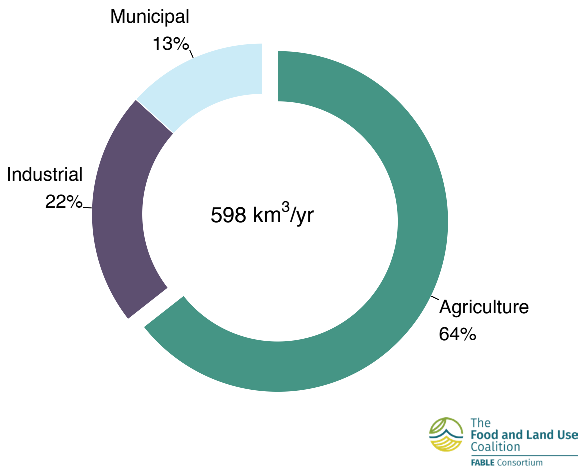
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of roots and eggs indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

China is characterized by a monsoon climate and plateau-mountain climate in Tibet with 630 mm average annual precipitation that mostly occurs between May and October (State Council of China, 2005). The agricultural sector represented 64% of total water withdrawals in 2015 (Figure 7). Moreover in 2013, 51% of agricultural land was equipped for irrigation, representing 52% of estimated-irrigation potential (FAO, 2017). The three most important irrigated crops (rice, wheat, and corn), account for 40%, 20%, and 18% of total harvested irrigated area. These crops were mostly used for domestic consumption in 2010 (FAO, 2020). However, China is continuously suffering from water deficits, especially in the North China Plain and in northwest China. The over depletion of ground water, loss of shallow surface wells and rivers in northern China has created many ecological problems. To offset the water deficit, the central government has launched the South-North Water Transfer project, which required significant investment to launch and maintain. The central government also imitated several policies to phase out the high-water-consuming and low-productivity wheat production in the North China Plain to alleviate severe water deficit issues.

Figure 7 | Water withdrawals by sector in 2015

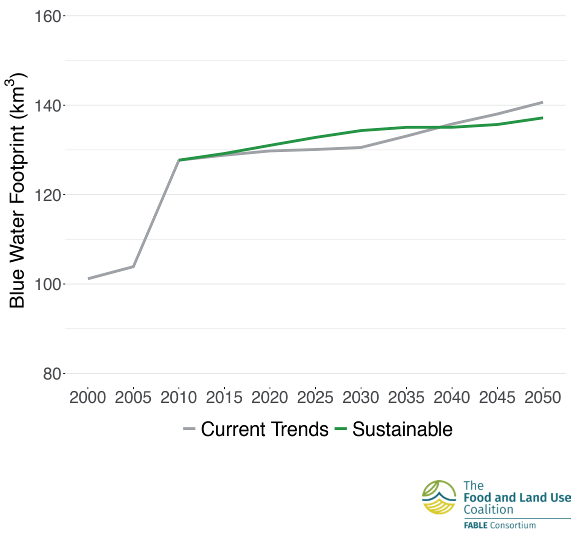


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000-2015 (101 129 km^3/yr and 129 km^3/yr), before reaching 131 km^3/yr and 141 km^3/yr in 2030 and 2050, respectively (Figure 8), with wheat, rice, and corn accounting for 41%, 32%, and 12% of computed blue water use for agriculture by 2050[3]. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture reaches 134 km^3/yr in 2030 and 137 km^3/yr in 2050, respectively. This is explained by the increase of water use efficiency and more sustainable diets (Annex 2) that have led to changes in the production of corn, wheat, and sweet potato due to the decline in domestic food demand and increases in crop productivity.

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



3 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Koekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

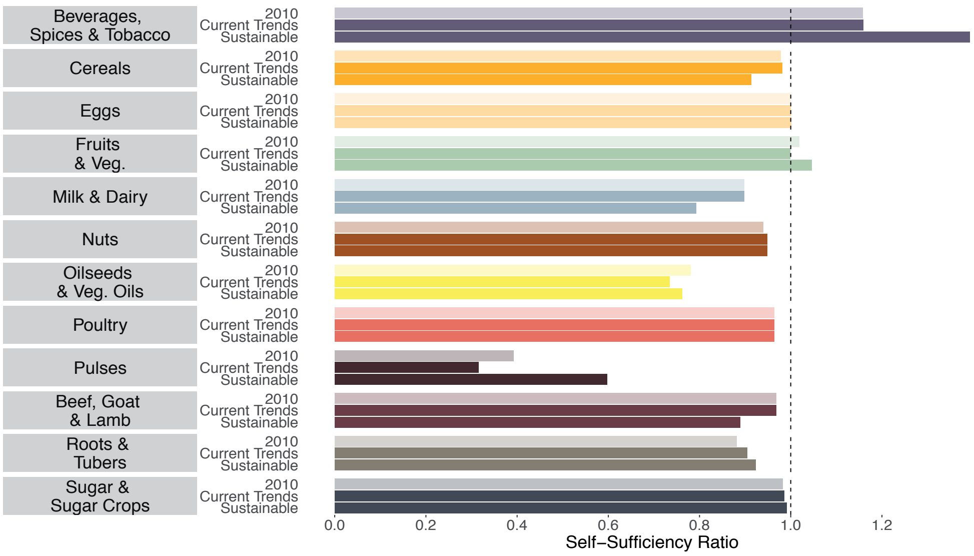
Resilience of the Food and Land-Use System

The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge China's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

In 2010, the self-sufficiency of cereals (excluding beer) and fruits were, respectively, around 99.3% and 103% in China. However, the self-sufficiency of vegetable oils and oil crops was only 67.5% and 50.4%, much lower when compared with that of cereals. Self-sufficiency of animal products was relatively high, except for milk products, for which the self-sufficiency stood at 92% due to the outbreak of the melamine scandal in 2008 (National Bureau of Statistics of China, 2020). Under the Current Trends Pathway, we project that China would be self-sufficient in beverages, spices and tobacco, eggs, and fruits and vegetables in 2050, with self-sufficiency by product group remaining relatively constant for the majority of products from 2010 – 2050 (Figure 9). The product groups for which China is most dependent on imports to satisfy domestic consumption are pulses and oil seeds and vegetable oils. This dependency will slightly increase until 2050. By contrast, under the Sustainable Pathway, China would increase imports of the main cereals and animal products, namely decreasing their self-sufficiency to relieve the huge resources over consumption and environmental pressure of food supply. However, China would be more self-sufficient in pulses to support livestock production.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Diversity

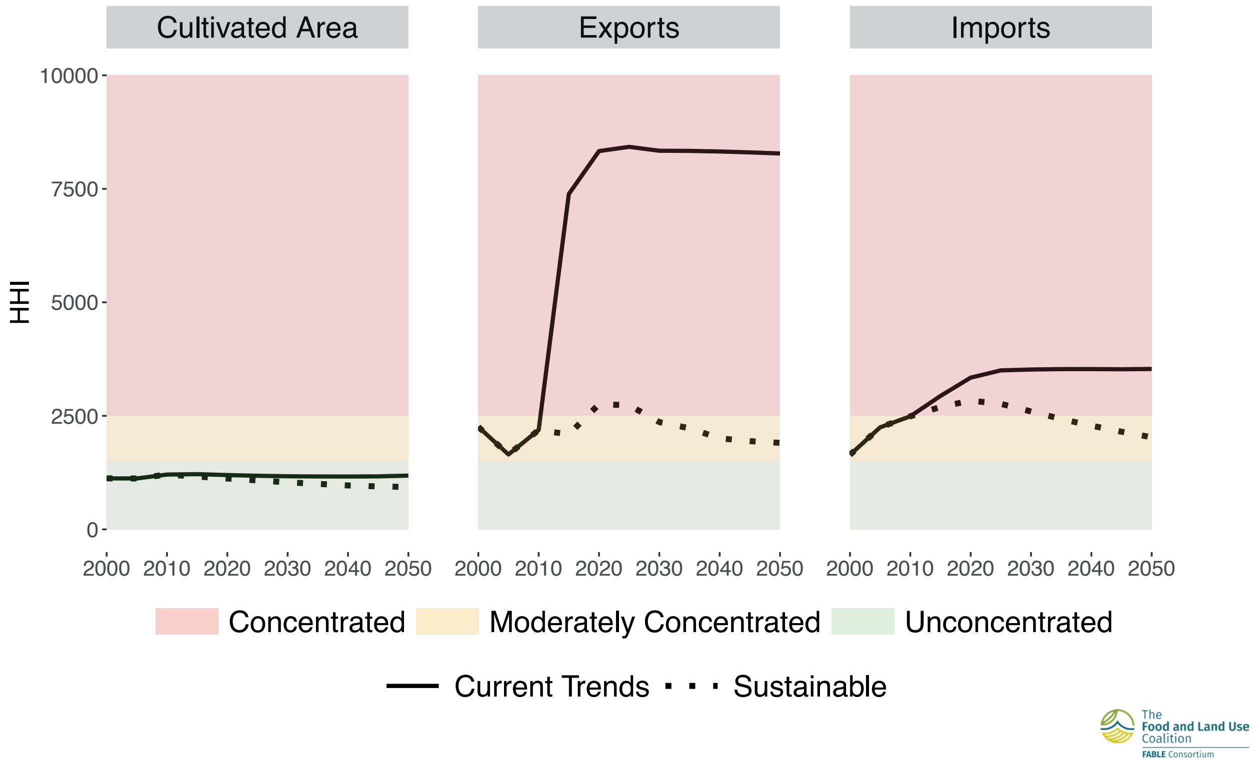
The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

In 2010, four crops represented 66% of the cultivated area with shares of total cropland area varying between 12 and 20%. These are, by order of importance, corn, rice, wheat, and vegetables. Two crops (soybean and cassava), represented 69% of the total volume of imported crops. Finally, fruits and vegetables represented 63% of the total volume of exported crops.

Figure 10 | Evolution of the diversification of the cropland area, crop imports, and crop exports using the Herfindahl-Hirschman Index (HHI)



Under the Current Trends Pathway, we project a high concentration of crop exports and imports and a low concentration in the range of crops planted in 2050. This indicates high levels of diversity across the national agricultural production system and low levels of diversity for food imports and exports. In contrast, under the Sustainable Pathway, we project medium concentration of crop exports and imports, and a low concentration in the range of crops planted in 2050, indicating moderate levels of diversity across the national production system and imports and exports (Figure 10). This is partially due the rapid increase in domestic crop and livestock productivity, which reduces the demand for imported products, mainly soybean. Soybean has accounted for around half of China's agricultural food and feed import in recent years, hence reducing soybean demand will reduce China's concentration of imports. Rapid increases in agricultural productivity will also offset a significant share of cropland for production of products for domestic demand, due to the Cropland Protection Redline. This may increase China's exports for a few agricultural products, which would reduce the concentration of exports (The State Council Information Office of China, 2010, 2019)

Discussion and Recommendations

Increase productivity or adapt to the "Eat Lancet" diet

We found that the reduction of food waste and increases in livestock productivity are two of the most important drivers to move toward a sustainable food and land-use system in China. Dietary patterns also play a role, but, at present, shifting toward diets in line with the Eat-Lancet recommendations seems very difficult. Currently, China's average per capita consumption of beef and milk is only 50% and 20% of the global average (He et al., 2016). These numbers are even lower when compared to developed countries. Moreover, even during the initial wave of Covid-19, the central government imported large quantities of animal products, such as pork and beef, to secure food supplies and decrease the price of meat and the consumer price index(Ministry of Agriculture and Rural Affairs of China, 2020). This helped ensure that quality of life in China did not decline significantly during the pandemic, one of the central government's main objectives. However, there is strong potential to reduce food loss and waste across China's food system and for different foods in particular, as shown in this chapter and in Ma et al. (2019). Recently there is also strong movement by the central government to reduce food wastage, especially in restaurants and schools, after the statement by President Xi to reduce food waste in August 2020 (Central Government of China, 2020).

In addition, China has high potential to improve agricultural productivity, as evidenced by its lower crop and livestock productivity when compared to developed countries (Bai et al., 2018a; Bai et al., 2018b). Over recent decades, China has sought to ensure its food security, which has led to the overuse of groundwater, fertilizers, pesticides and imported feed products. This has significantly contributed to air and water pollution, global land use change, and rising domestic water scarcity (Wu et al.,2016; Xu et al., 2020; Escobar et al.,2020). To address this challenge, multiple technological innovations, such as improved agricultural infrastructure for low-yield fields, high-yielding breeds, and high-water- and nutrient-use efficiency breeds, and precision crop and livestock farming could be implemented to achieve such target. Such improvements will offset many of the negative impacts on the domestic environment, increase agricultural productivity, and prevent land use change in other countries.

Reduce China's reliance on global market

China's demand for meat and dairy products is rising rapidly, outstripping domestic production by large margins. In 2017, China imported 170 Tg of crops and 1.6 Tg of fishmeal, equal to 38 Tg of protein, of which 86% were used as animal feed. Currently, 40% of imported protein feed is dedicated to livestock production in China, including 13 billion chickens and 700 million pigs(FAO, 2020). In 2019, China also imported 20 Tg of livestock products – of which 80% were ruminant-based– to supplement the increasing demand for animal products. Alongside the European Union, North America, India, and other major importers, China's international demand for soft commodities also contributes to deforestation and other environmental damage in major exporters of agricultural and forestry commodities (Escobar et al., 2020). There is growing recognition of the need for sustainable soft commodity supply chains, which may further increase the need for China to reduce its import dependency for animal protein and feed, particularly as China prepares to host the 15th Conference of the Parties under the UN Convention on Biological Diversity in Kunming in 2021(FABLE Consortium, 2020).

China now needs to revolutionize its livestock production system to reduce its reliance on imports to meet50% of its animal meat, dairy, and eggs consumption through domestic production. This will help ensure long-term security, address environmental spillovers, and provide an opportunity to strengthen meat production processes to improve food safety. There are three technically and economically feasible food system revolutions that can greatly reduce China's reliance on imports: (1) a revolution in feed protein supply through organic and non-organic sources based micro-protein feed production(Pikaar et al., 2017); (2) a revolution in grasslands through vegetation greening and fodder production through grassland restoration to replace imported ruminant animal products(Fang et al., 2016); and (3) a revolution in aquaculture through industrial-indoor-fish-plants and sustainable offshore marine production to boost aquatic production(Palma et al., 2019). Together these measures may have profound impacts on the Sustainable Development Goals in China and the countries from which it imports agricultural commodities.

In addition, new technologies in food production could also offer solutions for China, such as high-tech greenhouses for vegetable production to reduce demand for cropland, synthetic beef and meat-production technologies to reduce demand for grassland, and plant-based alternatives to meat made from beans and grain to reduce demand for animal feed. These technologies can help produce more food while limiting agricultural land expansion, reducing GHG emissions and pollution so as to achieve sustainable food production. All of these technologies are too expensive at present but may become more affordable in the future due to breakthroughs in technology and supplies of green energy.

Policies and recommendations

The report of the 19th National Congress of the Communist Party of China states that, "what we now face is the contradiction between unbalanced and inadequate development and the people's ever-growing need for a better life" (Xi, 2017). This is true for food and land-use systems, which face trade-offs between, for example, higher livestock production and the risk of high environmental pollution, or biodiversity loss or grassland degradation domestically and internationally. Since China is facing great pressures in terms of air and water pollution, in recent years, the central government has promoted several large projects to control haze in the North China Plain and the Yangtze River Delta, nonpoint source surface and ground water pollution, over-use of fertilizer and pesticides (Ministry of Agriculture of China, 2015b, 2015a; State Council of China, 2013). Moreover, a series of new policies have been implemented to shut down highly-polluting factories, reduce subsides for fertilizer manufacturing companies, limit transportation, increase the livestock manure recycling rate to substitute for fertilizer, implement the Non Livestock Production Zone, and enhance environmental protection without loosening the protection of cropland. (Ministry of Agriculture of China, 2015a, 2017; State Council of China, 2015) Meanwhile, President Xi has emphasized to the importance to reduce food wastage, with the "Empty the Plate" campaign, and announced that China will achieve Carbon Neutrality in 2060.

Therefore, we have witnessed the improvement of environmental protection, a decrease in fertilizer use, and increases of grain production in China. This indicates that China is on track to solve these tradeoffs, though large uncertainties remain due to climatic change and rapidly increasing demand for animal products.

To continue these advances, and to combat pollution, resources depletion and to achieve the SDGs, we recommend that the first priority for China be to take measures to improve the productivity of crop and livestock production without increasing inputs per unit (Cui et al., 2018; Ma et al., 2019). A series of policies, such as the circulation of rural land and rural land consolidation, are also needed to increase farm size and productivity. (Cui et al., 2018). We also recommend investing in micro-protein production, grassland management, and aquatic production to reduce China's reliance on imported feed protein and animal products, which may significantly reduce the potential negative impacts on other countries. Finally, reducing food waste and encouraging more moderate consumption of meat should also be considered by the central government to achieve the SDGs.

Limitations of the models and next step

At present, the FABLE Calculator is unable to account for the competition between urban land and cropland. Specifically, this means that that urban land only grows by 2% per year but does not impact other land use types. That may lead us to draw the erroneous conclusion that the agricultural redline policy is unnecessary when crop productivity is high, when, in reality, we have not accounted for cropland occupied by cities. However, if we give up the Cropland Protection Redline, we cannot ensure the protection of high productivity cropland that has ensured China's domestic food security. In addition, there was mismatch between our modeled GHG emissions, water use, food consumption with the historical data for China. This may be due to overestimations of the increase in crop and livestock productivity in the Sustainable Pathway, which may lead to lower land-use change when compared to our Current Trends Pathway. In addition, the FABLE Calculator does not account for nutrient management, which has large impacts on China's environment. Finally, biodiversity indexes are mostly based on land area, which does not capture the biodiversity by land use in a country.

Going forward we plan to address these limitations. First, by further calibrating the FABLE Calculator and matching the modeled results with historical changes. Second, by linking the model to nutrient management which enhances the prediction of demand for nitrogen and phosphorus fertilizers, and related environmental pollution. Third, by improving projections on the quality of diets by looking beyond energy intake to proteins, vitamins, and essential amino acids. Fourth and finally, by incorporating the aquaculture sector as it accounts for a great deal of the food produced in China and could contribute to the protection of ecosystems.

Finally, following the announcement of China's ambitious pledge to achieve carbon neutrality by 2060, the FABLE China team, in partnership with the Food and Land Use Coalition Platform in China, will seek to develop a long term pathway specifically focused on decarbonizing China's land sector.

Annex 1. List of changes made to the model to adapt it to the national context

- We have created a new scenario to ensure cropland area remains above 120 Mha, which reflect China's Cropland Protection Redline (Standing Committee of the National People's Congress, 2020).
- We have created a new scenario on afforestation to reflect the historical evolution of forest area and China's target to achieve 26% forest cover rate by 2050. (State Council of China, 2017a; National Forestry and Grassland Administration of China, 2016).
- We have collected protected area data, including natural reserves, national scenic areas, national geoparks and national forest park. Unfortunately, provincial-level protected areas are not included in the data, as many provinces did not build a standard geological database. This made it difficult for us to locate and identify their spatial scope (National Specimen Information Infrastructure, 2020).
- We have included the SSP1 and SSP2 crop productivity scenarios from the GLOBIOM model. For the crops that are included in the FABLE Calculator, but not included in GLOBIOM, we further reviewed statistic data and Ma et al. (2019) to complete the crop production scenario setting.
  - We referred to the increase rates in GLOBIOM-China and Ma et al. (2019) but not their absolute value as their data may come from different sources (for example Ma et al. (2019) used some data from National Bureau of Statistics) which may not match the FAO data used in FABLE Calculator.
  - First, we collected the crop productivity data in 2010 from FAOSTAT. Then for crops which are contained in GLOBIOM (wheat, sunflower, barley, cassava, corn, groundnut, millet, potato, and rice), we used the crop productivity increase rates from SSP1 and SSP2, which originated from Zhao et al.(n.d), as the productivity increase rates, respectively, of the Sustainable and Current Trends Pathways. For the crops which are not contained in GLOBIOM (soybean, vegetabless and fruits), we used the productivity increase rates from Ma et al. (2019) and FAO's historical data (2000-2010), as the crop increase rates, respectively, in the Sustainable and Current Trends Pathways. Finally, we multiplied the crop productivity data in 2010 and their increase rates to achieve their productivities in 2050.
- We have included a sustainable scenario on the evolution of imports for key commodities by reviewing annual reports that monitor the trade of agricultural products (Ma et al., 2019; FAO, 2020; Ministry of Agriculture and Rural Affairs of China, 2020).
- We identified the main imported and exported products, and important agricultural products for China to set a sustainable scenario which turns on importing more: soyabean (56%), cassava (68%), palm oil (98%), milk (20%), pork (10%), beef (10%), mutton (10%), corn (20%), and wheat (14%).
- We have used the SSP1 and SSP2 diet scenarios from GLOBIOM. For the food categories which are not covered in GLOBIOM, we have used the *Dietary guidelines for Chinese residents and the fat diet* (Chinese Nutrition Society, 2016).

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
The population is expected to reach 1,286 million by 2050 (SSP2). China implemented the "Two Child" policy in 2016, which has increased the annual birth rate in a short period. But we expect this will not change the long-term projections by UN towards to 2050, unless other policies are implemented. Based on National Bureau of Statistics of China (2020), Qi, Dai, & Zheng (2016) Jing, Wang, & Sun (2018) (SSP2 scenario selected)	The population is expected to reach 1,251 million by 2050 (SSP1). This is of high uncertainty in the future, as the central government has no such plan. However, when there is a continuous increase in education and income levels, the annual birth rate slightly decreases. Based on Brueckner & Schwandt (2015), Handa (2000) (SSP1 scenario selected)

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
We assume that there will be no constraint on the expansion of agricultural land beyond existing protected areas and under the total land boundary and that cropland will always remain higher than 120 Mha. Implementing the national policy of "cherish and use land rationally as well as give a true protection to the cultivated land" means that cultivated land should be more than 120 Mha.	Same as Current Trends

LAND Afforestation or reforestation target (1,000 ha)

Current Trends Pathway	Sustainable Pathway
We assume total afforested/reforested area will reach 249.6 Mha by 2050. Based on the central government's regular emphasis of the importance of afforestation and our national territorial plan, which clearly states that the forest cover rate should reach 24% by 2030. In addition, according to National forest management plan, the forest cover rate could reach 26% in 2050. Based on State Council of China (2017a) and National Forestry and Grassland Administration of China (2016)	Same as Current Trends

BIODIVERSITY Protected areas (1,000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.	We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.

PRODUCTION Crop productivity for the key crops in the country (in t/ha), here we show the productivity with the influence of RCP

Current Trends Pathway	Sustainable Pathway
By 2050, crop productivity (with the impacts of climate change) reaches: • 6.1 tonnes per ha for rice • 7.9 tonnes per ha for wheat • 7.8 tonnes per ha for corn We used the SSP2 crop productivity data from the GLOBIOM model. For several crops which are not included in GLOBIOM, we used historical productivity growth rates. Based on Zhao et al. (n.d.) and National Bureau of Statistics of China (2020)	By 2050, crop productivity (with the impacts of climate change) reaches: • 6.6 tonnes per ha for rice • 7.6 tonnes per ha for wheat • 9.1 tonnes per ha for corn We used the SSP1 crop productivity data from GLOBIOM model. For several crops which are not included in GLOBIOM, we used MA et al. (2019). Based on Zhao et al. (n.d.)

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

Current Trends Pathway	Sustainable Pathway
By 2050, livestock productivity reaches: • 110 kg per head for pig • 54 kg per head for beef cattle • 12 kg per head for sheep and goats These numbers are very close to the average animal productivity yearly growth rate in 2011-2018, according to Chinese statistics. Based on National Bureau of Statistics of China (2020)	By 2050, livestock productivity reaches: • 134 kg per head for pig • 78 kg per head for beef cattle • 15 kg per head for sheep and goats Taking the United States as the reference point, there are still large gaps in livestock productivity. Pig and poultry productivity are expected to increase by 20% compared to 2010. For beef cattle, dairy, sheep, goat and layer, the increase rate is assumed to be 40%. Based on Ma et al. (2019)

PRODUCTION Pasture stocking rate (in animal units/ha pasture)

Current Trends Pathway	Sustainable Pathway
By 2050, the average ruminant livestock stocking density is 0.37 TLU/ha per ha. As 2019 is almost the end of 13th five-year plan, the targets are almost achieved, so we believe the trend will also be the same as the Sustainable Pathway. Based on National Development and Reform Commission of China (2015, 2016)	By 2050, the average ruminant livestock stocking density is 0.35 TLU/ha per ha. Pasture-livestock balance is a long-term goal of animal production development and the government encourages rest grazing, rotational grazing, and high ambitious targets, which are set in "The 13th five-year plan for grassland protection, construction and utilization in China" Based on National Development and Reform Commission of China (2016) and National Bureau of Statistics of China (2020)

PRODUCTION Post-harvest losses

Current Trends Pathway	Sustainable Pathway
Remains constant. At present, there is no clear policy to address this issue.	By 2050, the share of production and imports lost during storage and transportation reduced by 20%. According to Ma et al. (2019), food loss and food waste would be reduced by 20% through a combination of new technologies, improved facilities, and education.

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway
By 2050, the share of total consumption which is imported is: • 1% by 2050 for pork • 4% by 2050 for beef • 10% by 2050 for milk • 80% by 2050 for soybean In this pathway, we still regard food security as an important target, the priority is self-sufficient, so the import is stable and export share keep constant. Based on The State Council Information Office of China (2019)	By 2050, the share of total consumption which is imported is: • 10% by 2050 for pork • 10% by 2050 for beef • 21% by 2050 for milk • 56% by 2050 for soybean Freer trade between China and other countries, agricultural product which is not the staple food and has low comparative effectiveness for China can depend more on other countries (i.e. milk and palm oil). As for soybean, we assumed imports would be 30% lower since, according to the FABLE Calculator's results, when we keep cropland higher than 120 Mha, we are able to plant more crops to increase China's self-sufficiency for soybean. Based on Ma et al. (2019)

TRADE Evolution of exports for key exported products (1,000 tons)

Current Trends Pathway	Sustainable Pathway
E4 for export By 2050, the volume of exports is: • 261 tonnes by 2050 for tea • 158 tonnes by 2050 for tobacco • 343 tonnes by 2050 for orange • 584 tonnes by 2050 for onion • 6078 tonnes by 2050 for vegetable_other Food security is a major governmental objective, so the self-sufficiency is prioritized. Therefore, exports remain constant, meaning that China's agricultural product trade deficit remains large. Based on The State Council Information Office of China (2010, 2019)	**E1 for export** By 2050, the volume of exports is: • 967 tonnes by 2050 for tea • 474 tonnes by 2050 for tobacco • 1030 tonnes by 2050 for orange • 1752 tonnes by 2050 for onion • 18233 tonnes by 2050 for vegetable_other Developing comparative advantages to further export agricultural products (e.g. tea, vegetables, and water products) can not only help to achieve sustainable goals in global level, but also to decrease China's trade deficit in agricultural products. Based on Ministry of Agriculture and Rural Affairs of China, (2020) and Thow & Nisbett (2019)

FOOD Average dietary composition (daily kcal per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 2,855 kcal and is: • 1196 kcal for cereals • 368 kcal for pork • 53 kcal for other red meat • 80 kcal for milk • 230 kcal for vegetable and fruit Using the SSP2 diet scenario from the GLOBIOM model. For the categories which are not included in GLOBIOM, we used the FABLE Calculator's scenario transitioning to a Western-style diet. Based on Zhao et al. (n.d.)	By 2030, the average daily calorie consumption per capita is 2,789 kcal and is: • 1185 kcal for cereals • 356 kcal for pork • 50 kcal for other red meat • 75 kcal for milk • 256 kcal for vegetable and fruit Using the SSP1 diet scenario from the GLOBIOM model. For the categories which are not included in GLOBIOM, we used the FABLE Calculator's scenario transitioning to a Western-style diet. Based on Zhao et al. (n.d.) and Chinese Nutrition Society (2016)

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
By 2030, the share of final household consumption which is wasted at the household level remains constant. At present, there is no clear policy to address this issue.	By 2030, the share of final household consumption which is wasted at the household level decreases by 20%. According to Ma et al. (2019), food loss and food waste would be decrease by 20% through a combination of new technologies, improved facilities, and education.

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
By 2050, biofuel production accounts for: • 15.4 Mt of corn production • 2.8 Mt of wheat production At present, biofuel policy in China is not clear	Same as Current Trends

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway

RCP 6.0
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m^2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect

	Yield shift between 2000-2050	
	Yield shifter (irrigation)	Yield shifter (rainfed)
Corn	0.93	0.89
Rice	0.9	0.9
Soyabean	0.92	0.91
Wheat	1	1.02

Based on NOAA (2020)

Sustainable Pathway

RCP 2.6
By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m^2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect

	Yield shift between 2000-2050	
	Yield shifter (irrigation)	Yield shifter (rainfed)
Corn	1	1.01
Rice	0.95	0.95
Soyabean	0.99	0.97
Wheat	1.02	1.07

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland<50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
0	Rock and Ice	5,662.07	20.30	71.80	24.40	75.60	15.48	99.40
232	Hainan Island monsoon rain forests	1,557.01	10.60	40.50	21.40	78.60	273.10	50.40
236	Jian Nan subtropical evergreen forests	66,407.70	5.50	22.60	8.30	91.70	21,901.72	51.40
249	Mizoram-Manipur-Kachin rain forests	1.55	-	68.00	-	-	0.01	100.00
256	Northern Indochina subtropical forests	14,730.88	7.20	31.60	9.20	90.80	2,393.34	72.80
259	Northern Triangle subtropical forests	4.76	-	88.60	-	-	-	
268	South China-Vietnam subtropical evergreen forests	18,461.27	2.70	9.80	9.20	90.80	9,697.20	34.60
306	Eastern Himalayan broadleaf forests	1.26	-	100.00	-	-	-	
307	Northern Triangle temperate forests	0.06	-	100.00	-	-	-	
309	Eastern Himalayan subalpine conifer forests	71.17	-	89.40	-	-	1.12	100.00
642	Guizhou Plateau broadleaf and mixed forests	27,013.86	10.90	8.60	31.20	68.80	13,054.51	51.90
643	Yunnan Plateau subtropical evergreen forests	24,087.38	4.00	12.70	6.30	93.70	5,169.23	69.10
653	Central China Loess Plateau mixed forests	36,043.46	6.80	9.60	18.60	81.40	14,055.21	46.70
656	Changbai Mountains mixed forests	4,612.25	13.70	70.40	16.00	84.00	489.80	56.80
657	Changjiang Plain evergreen forests	43,870.74	5.80	15.20	16.60	83.40	28,964.30	15.30
659	Daba Mountains evergreen forests	16,867.79	16.10	16.70	28.40	71.60	6,890.10	41.20

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
667	Huang He Plain mixed forests	43,457.09	2.60	4.40	13.90	86.10	35,860.66	5.80
669	Manchurian mixed forests	35,701.55	10.00	51.90	13.50	86.50	9,709.24	39.10
673	Northeast China Plain deciduous forests	23,190.93	3.80	6.40	16.20	83.80	17,325.62	17.40
677	Qin Ling Mountains deciduous forests	12,360.19	10.10	30.90	18.20	81.80	3,275.00	48.40
680	Sichuan Basin evergreen broadleaf forests	9,833.61	2.00	0.70	15.70	84.30	8,383.45	15.10
684	Tarim Basin deciduous forests and steppe	5,459.54	2.40	68.20	1.90	98.10	359.62	28.00
690	Altai montane forest and forest steppe	1,699.32	10.60	88.10	11.10	88.90	71.80	45.30
693	Da Hinggan-Dzhagdy Mountains conifer forests	15,146.50	6.30	91.70	6.40	93.60	264.87	76.80
696	Helanshan montane conifer forests	2,474.11	13.70	49.30	18.80	81.20	386.54	38.60
697	Hengduan Mountains subalpine conifer forests	9,964.12	19.90	56.30	23.10	76.90	610.98	78.40
702	Northeast Himalayan subalpine conifer forests	4,096.27	30.10	86.60	33.10	66.90	62.24	97.70
704	Nujiang Langcang Gorge alpine conifer and mixed forests	7,842.75	38.50	60.00	41.20	58.80	473.47	88.50
705	Qilian Mountains conifer forests	1,668.98	22.70	70.60	25.10	74.90	149.36	91.70
706	Qionglai-Minshan conifer forests	8,039.45	20.90	58.10	26.40	73.60	938.61	77.30
709	Tian Shan montane conifer forests	1,282.45	6.80	30.20	14.90	85.10	228.16	51.80
710	East Siberian taiga	32.37	-	92.30	-	-	-	

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
724	Altai steppe and semi-desert	219.51	0.10	15.70	0.20	99.80	79.12	41.50
726	Daurian forest steppe	266.36	5.20	42.20	12.30	87.70	6.75	98.70
728	Emin Valley steppe	4,598.05	2.80	27.40	7.20	92.80	786.30	32.80
734	Mongolian-Manchurian grassland	57,820.23	7.20	21.40	20.60	79.40	14,085.58	48.40
740	Tian Shan foothill arid steppe	871.13	-	6.80	0.10	99.90	531.64	20.70
741	Amur meadow steppe	5,292.45	11.00	27.60	22.20	77.80	3,975.65	10.10
742	Bohai Sea saline meadow	1,128.32	6.90	26.50	14.40	85.60	464.30	31.00
743	Nenjiang River grassland	2,325.17	2.60	26.10	5.00	95.00	1,649.06	23.80
746	Suiphun-Khanka meadows and forest meadows	1,822.99	25.60	25.80	41.60	58.40	1,139.38	13.00
748	Yellow Sea saline meadow	529.16	38.90	39.40	95.60	4.40	411.73	3.50
749	Altai alpine meadow and tundra	1,587.39	13.10	87.00	15.00	85.00	96.22	71.60
750	Central Tibetan Plateau alpine steppe	62,979.43	43.40	85.90	42.20	57.80	916.55	92.20
751	Eastern Himalayan alpine shrub and meadows	8,791.06	23.90	72.90	26.50	73.50	108.76	98.10
754	Karakoram-West Tibetan Plateau alpine steppe	2,822.47	3.60	74.10	3.90	96.10	7.70	96.50
759	North Tibetan Plateau-Kunlun Mountains alpine desert	37,525.98	15.00	88.30	16.20	83.80	136.90	90.20
760	Northwestern Himalayan alpine shrub and meadows	90.96	-	93.60	-	-	0.36	100.00
761	Ordos Plateau steppe	21,595.10	4.20	8.30	21.50	78.50	5,389.52	70.00
762	Pamir alpine desert and tundra	3,355.48	-	41.00	-	-	21.89	95.40

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
763	Qilian Mountains subalpine meadows	7,339.41	33.20	89.90	32.30	67.70	190.57	93.30
765	Southeast Tibet shrublands and meadows	46,184.76	31.50	78.30	34.80	65.20	4,304.21	80.30
767	Tian Shan montane steppe and meadows	19,357.17	5.70	46.20	8.00	92.00	2,438.09	48.50
768	Tibetan Plateau alpine shrublands and meadows	27,272.96	27.20	83.60	28.80	71.20	1,340.50	93.70
769	Western Himalayan alpine shrub and meadows	3,521.03	20.40	91.80	19.60	80.40	34.53	94.80
770	Yarlung Zanbo arid steppe	5,958.75	34.60	47.60	39.90	60.10	151.12	90.30
808	Alashan Plateau semi-desert	45,714.08	6.10	75.60	5.40	94.60	1,928.23	50.40
824	Eastern Gobi desert steppe	10,414.71	0.40	23.60	0.80	99.20	292.77	39.20
827	Junggar Basin semi-desert	23,927.79	2.30	41.30	3.00	97.00	2,903.40	17.20
835	Qaidam Basin semi-desert	19,247.18	9.10	87.80	10.00	90.00	89.17	87.50
843	Taklimakan desert	74,353.46	10.10	61.80	13.50	86.50	4,386.31	20.20

Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm – milimeters

Mm^3 – million cubic meters

Mt – million tons

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Colombia

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Colombia. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including the Ministry of Environment and Sustainable Development (MADS), the Ministry of Agriculture and Rural Development (MADR), the National Planning Department (DNP) and the Food and Land Use Coalition for Colombia (FOLU-Colombia), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Colombia's Nationally Determined Contribution (NDC) and Forest Reference Emission Level (FREL) treat the FABLE domains. According to the Government of Colombia, the country has committed to reducing its GHG emissions by 20% by 2030 compared to the projected business-as-usual (BAU) scenario for 2030 (Gobierno de Colombia, 2017). This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include reducing deforestation by 39% with

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and FREL

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2018)	2010 2030	224 335	2030	20% reduction compared to projected BAU scenario by 2030	Agriculture, land use and forestry, energy, industrial processes, and waste	Y	N	N	Water, deforestation
FREL (2016)	-	51.6 (UNFCCC, 2020)	-	-	Agriculture, land use and forestry	Y	N	Y Forest and No Forest map for 2020 Y Deforestation risk map for 2022 at subnational level	Deforestation

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

respect to NDC baseline, implementing the Nationally Appropriate Mitigation Action -NAMA- (MADS, 2017), including intervention on 3.2 Mha for the implementation of sustainable actions for livestock production, restoring 17,000 hectares per year of disturbed areas, establishing commercial forest plantations, and implementing cocoa plantations in areas previously occupied by grasslands. Under its current commitments to the UNFCCC, Colombia does not mention biodiversity conservation.

Table 2 provides an overview of the targets included in the latest National Biodiversity Strategies and Action Plan (NBSAP) from 2017 (MINAMBIENTE, 2017), as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. By gradually reducing deforestation and increasing carbon stocks via restoration, the NBSAP contributes to both biodiversity and climate objectives.

Table 2 | Overview of the NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(I.5) **By 2020, 2025 and 2030, Colombia will have 0.2Mha, 0.5Mha and 1Mha respectively, under restoration in areas defined as susceptible by the National Restoration Plan: Ecological Restoration, Rehabilitation and Reclamation of Disturbed Areas.**	**GHG EMISSIONS:** Zero or negative global GHG emissions from LULUCF by 2050 **BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(I.6) **Deforestation rates will be progressively reduced from 120,000ha/yr to 50,000ha/yr by 2020, from 50,000ha/yr to 25,000ha/yr by 2025 and from 25,000/yr to 10,000ha/yr by 2030. The reduction will be focused on deforestation *hotspots* identified by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM).**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(III.4) **By 2020, Colombia will apply eco-efficiency principles based on the integrated management of biodiversity and its ecosystem services to 0.3Mha intended for agricultural production. By 2025, an additional 0.6Mha will be incorporated.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(III.5) **By 2020, sustainable production systems that combine production and conservation actions to generate local development will be identified. Sustainable production systems will be rolled out in municipalities that are highly biodiverse and affected by the armed conflict.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Colombia.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 51.1 million in 2020 to 62.8 million in 2050), constraints on agricultural expansion, limiting deforestation by 2030, a medium afforestation target of 1 Mha by 2035, an 18% increase in the extent of protected areas by 2050, low productivity increases in the agricultural sector, a constant share of internal consumption being imported, and an increase in exports of banana, coffee, and raw sugar (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to slowing population growth, gradually curbing deforestation to less than 10,000 hectares per year by 2030 (CBD, 2020), implementing Colombia's defined National Agricultural Frontier (40.1 Mha) to limit further agricultural expansion (MADR-UPRA, 2018), increasing afforestation efforts via implementation of the National Restoration Plan (MINAMBIENTE, 2015), and increasing terrestrial protected areas in compliance with Aichi Target 11. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for rice and corn, (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to higher economic growth, a transition to more sustainable diets, higher livestock and crop productivity, higher exports, and lower food waste (see Annex 2). This corresponds to a future based on the implementation of ambitious policies that would also see considerable progress with regards to: (i) Colombia's increased productivity and competitiveness through the sustainable use of natural capital and the promotion of social inclusion, compatible with climate policies such as the Green Growth Policy (DNP, 2019b); (ii) increasing productivity for prioritized crops (i.e. rice, corn, potato, sugar cane for panela[2], and avocado) as a result of national production management plans (POPs) (UPRA, 2015); (iii) increasing livestock productivity in line with mitigation measures (e.g. sustainable livestock) (Pinto-Brun, 2016); (iv) diversifying exports and destinations for crops and livestock, and; (v) reducing food waste in line with Colombia's Policy for Preventing Food Waste and Loss -Law 1990, 2019- (Congreso de Colombia, 2019). With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

2 The word "panela" in Spanish-speaking Latin American countries refers to unrefined whole cane sugar. It is a solid product obtained by boiling and evaporating sugarcane juice.

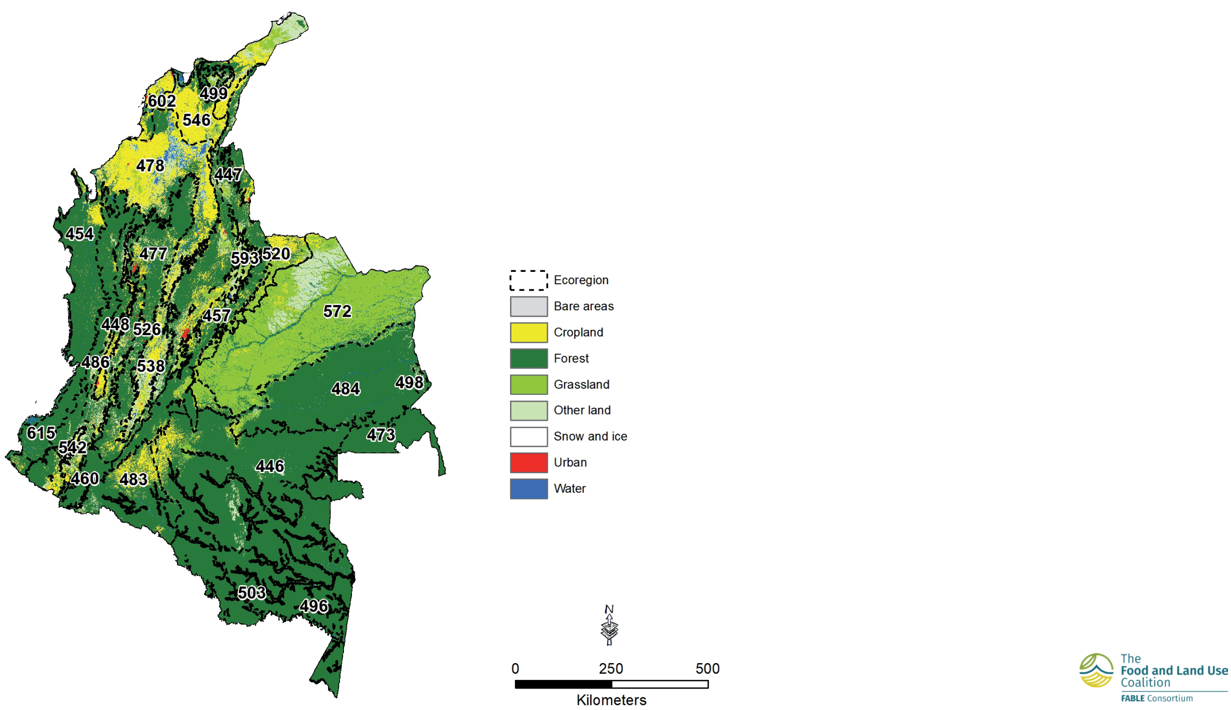
Land and Biodiversity

Current State

In 2010, Colombia was covered by 4% cropland, 35% grassland, 55% forest, 0.2% urban and 6% other natural land (FAO, 2020). Most of the agricultural area is located in the north (Caribbean region), northeast (The Plains or *Los Llanos* region), and in the inter-Andean valleys of the Magdalena and Cauca rivers. Forest can be mostly found in the south, as part of the Amazon region, and in the west towards the Pacific Ocean (Map 1). Finally, other natural lands, in particular grasslands, are located in the east as part of *Los Llanos* region. Land-use change related to agricultural expansion mainly for livestock production has historically been the main factor contributing to ecosystem fragmentation and biodiversity loss in Colombia (Etter, McAlpine, & Possingham, 2008). In 2012, the Ministry of Environment designed the National Policy for the Integral Management of Biodiversity and its Ecosystem Services. The policy aims to integrate conservation and production, especially for land-use activities.

We estimate that land where natural processes predominate[3] accounted for 57% of Colombia's terrestrial land area in 2010 (Map 2). The 503-Solimões-Japurá[4] moist forests hold the greatest share of land where natural processes predominate, followed by 484-Negro Branco moist forests and 446-Caquetá moist forests (Annex 4). Across the country, while 12 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



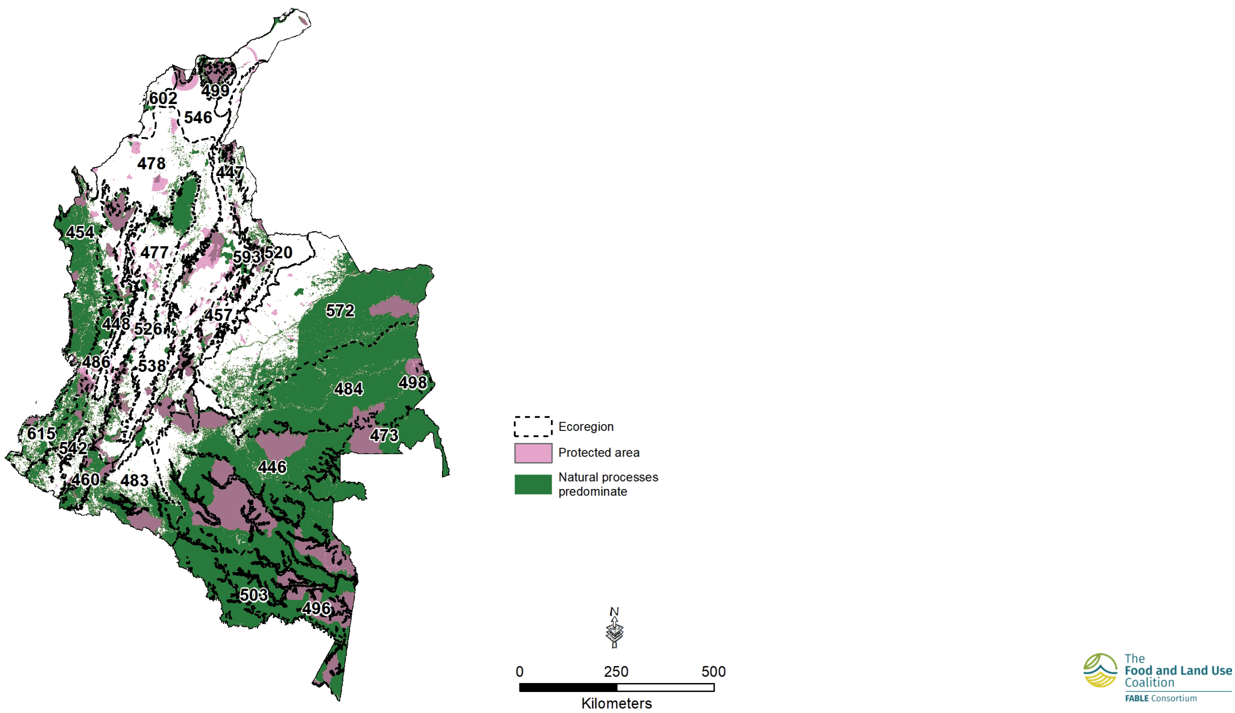
Notes: Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

3 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".
4 Solimões-Japurá moist forests, Negro Branco moist forest, and Caqueta moist forest are ecoregions with land in more than one country (e.g. Colombia, Brazil, and Venezuela). For this reason, their names do not necessarily correspond to geographical referents in Colombia, except for Caqueta. Within Colombia, these three ecoregions are spatially contiguous and belong to the Amazon region in the southern half of the country.

22% of land where natural processes predominate is formally protected. This indicates that *paramo* areas in northern Colombia (Santa Marta and Andean), dry forests in the Sinu Valley and Apure-Villavicencio, and montane forests in Santa Marta and the Cordillera Oriental are likely to remain important in the future. *Paramo* areas are important not only for biodiversity, but due to their role in regulating water supply for human activities in urban centers and in the countryside. Dry forests are one of the most endangered ecosystems in Colombia (Pizano & García, 2014). In this sense, forests such as those located in the Cauca Valley and Patia Valley are at high risk due to increased pressure from human activity. This tension also affects moist forests in Choco-Darien and natural grasslands in *Los Llanos*. It is worth noting that Choco-Darien is one of the most biodiverse regions in the world (WWF-Colombia, 2014).

Approximately 60% of Colombia's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in the 484-Negro-Branco moist forests, followed by 503-Solimões-Japurá moist forests, and 572-Llanos. They are all located in the east and southeast. The regional differences in the extent of biodiversity-friendly cropland can be explained by regional production practices and prevailing landscape conditions. For instance, remnants of natural vegetation in the Andes mountains are scattered and usually located in areas where agricultural activities are not always possible (e.g. steep slopes). Additionally, land plots tend to be small, numerous, and used for different activities, generating landscapes that are heavily transformed and heterogeneous. In contrast, in low-lying areas like the Llanos, crop fields tend to be large and surrounded by heterogeneous natural landscapes (e.g. natural grasslands mixed with riparian forests). Such conditions tend to increase the natural vegetation associated with croplands.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note: Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

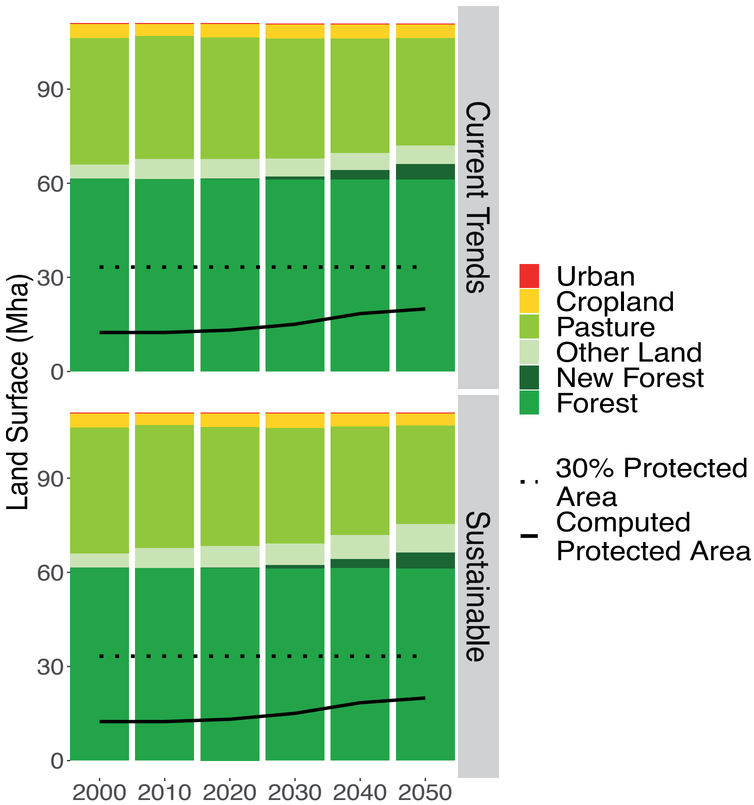
2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including the prevention of deforestation by 2030 (in line with the agricultural frontier), afforestation or reforestation of 1 Mha by 2035 (in line with the National Restoration Plan), and an increase in protected areas from 11% of the total land in 2000 to 18% in 2050 (see Annex 2). For the Sustainable Pathway, assumptions on agricultural land expansion, reforestation, protected areas were not changed. These assumptions were based on existing policies that were designed within the last five to ten years and are set to be implemented in the medium to long-term with ambitious sustainable targets. Their implementation is still in early stages, therefore it is too soon to assess their performance and consider any additional increase in their targets, particularly for policies addressing agricultural land expansion and afforestation.

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in cropland and new forest area and a decrease in other natural land and pasture areas. This trend continues over the period 2030-2050: pasture area further decreases and new forest area increases (Figure 1). The expansion of the planted area for sugar cane, coffee, and rice explains 71% of total cropland expansion between 2010 and 2030. For sugar cane, 51% of expansion is explained by an increase in the export of raw sugar and 48% by an increase in domestic consumption. For coffee, 73% of expansion is due to an increase in exports and 27% by an increase in domestic consumption. Finally, for rice, 65% results from an increase in domestic consumption and 24% from an increase in demand for animal feed. Pasture decline is mainly driven by the increase in ruminant density per hectare and livestock productivity per head over the period 2020-2030. Between 2030-2050, pasture areas continue to decrease. This is explained by a decline in the consumption of red meat, leading to a reduction in the average food intake per capita, and an increase in livestock productivity.

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

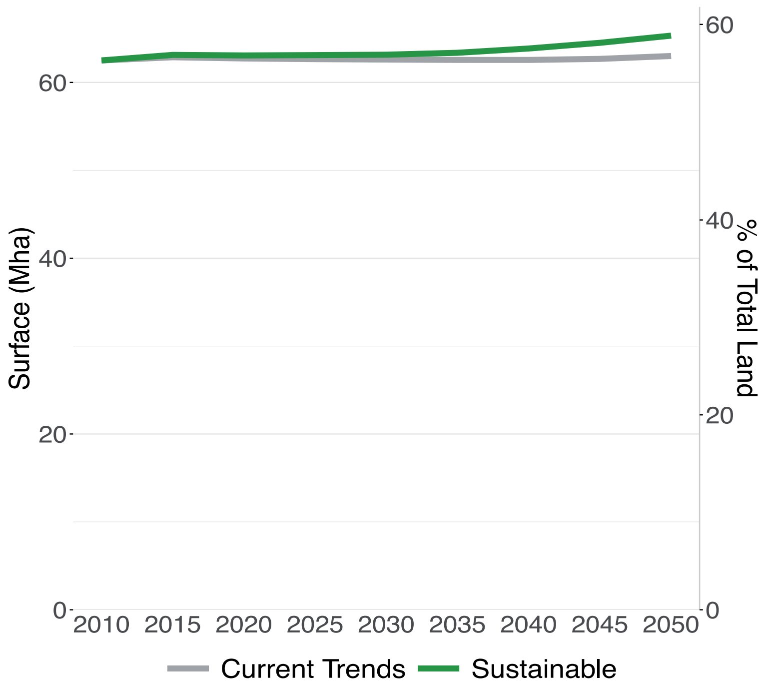


Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and IDEAM (2010) for protected areas for years 2000, 2005 and 2010.

This results in an expansion of land where natural processes predominate by 0.2% by 2030 and by 0.8% by 2050 compared to 2010, respectively.

Compared to the Current Trends Pathway, the overall evolution of land cover in Colombia is similar in the Sustainable Pathway. However, we observe two main differences. First, the pasture area is 2.8 Mha lower in 2050. Increases in productivity per head and ruminant density, as well as changes in diets (i.e. reduction in red meat consumption) are the main contributing factors to this change. Second, and similarly, the cropland area is slightly lower (0.6 Mha) in 2050. This result is due to the assumptions of increased crop productivity to respond to growing demand and the prevention of further agricultural expansion. Additional contributing factors to these two changes include reductions in food waste and the shift towards a more healthy and sustainable diet. This leads to a 4.5% increase in the area where natural processes predominate between 2010 and 2050 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate



GHG emissions from AFOLU

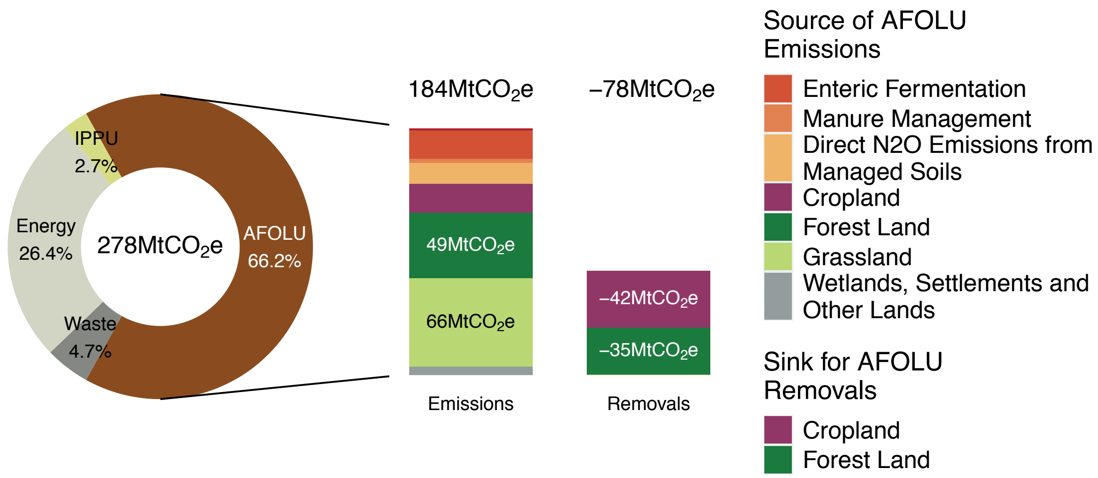
Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 66% of Colombia's total emissions in 2010 (Figure 3). Grassland is the main source of AFOLU emissions, followed by forest land, and enteric fermentation. This can be explained by the following factors: (i) conversion of natural forests into grasslands (*deforestation*) due to land grabbing, illicit crops and extensive cattle ranching (MINAMBIENTE & IDEAM, 2017); (ii) conversion of natural forests into secondary vegetation (*degradation*) caused by selective and illegal logging, among other factors (Meyer et al., 2019); and (iii) beef and milk production from bovine cattle. As for removals, the main contributing factor between 2000 and 2010 was the increase in the area used for commercial plantations and permanent crops like oil palm (Gobierno de Colombia, 2017).

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 48 Mt CO_2e/yr in 2030, before reaching 1 Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock is the largest source of emissions (53 Mt CO_2e/yr) while land-use change acts as a sink (-60 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for crops (6%) while land-use change consolidates its role as a sink (from -16 Mt CO_2e/yr to -60 Mt CO_2e/yr). In comparison, the Sustainable Pathway leads to a reduction in GHG emissions from AFOLU GHG by 25.2 Mt CO_2e/yr compared to the Current Trends Pathway by 2050 (Figure 4). The potential for emissions reduction under the Sustainable Pathway is dominated by a reduction in GHG emissions from land-use change (39%),

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2010



Note. IPPU = Industrial Processes and Product Use
Source. Tercera comunicación nacional de Colombia a la Convención Marco de las Naciones Unidas sobre Cambio Climático [Third National Communication of Colombia to the United Nations Framework Convention on Climate Change] (Gobierno de Colombia, 2017)

biofuels (39%) and livestock (20%) (Figure 5). The most important drivers of this reduction are the increases in livestock productivity and ruminant density which result in a decrease in the expansion of pasture areas; and the increase in biofuel production to include more ethanol (from sugar cane) and biodiesel (from oil palm) in the national fuel mix.

Compared to Colombia's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute to as much as 35% of its total GHG emissions reduction objective by 2030. Such reductions could be achieved through policy measures that increase livestock productivity, promote the transition to a more healthy and sustainable diet, and increase biofuel production. An increase in livestock productivity coupled with a shift in diets (i.e. reducing the consumption of red meat) should reduce pressure on existing natural areas for agricultural expansion. By reducing the expansion of agricultural land, new forest land should increase, enhancing the latter's role as a sink for sequestering carbon. These measures are of particular relevance when considering options for NDC enhancement and for other transversal policies including Colombia's Green Growth Policy, the National Development Plan, among others.

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

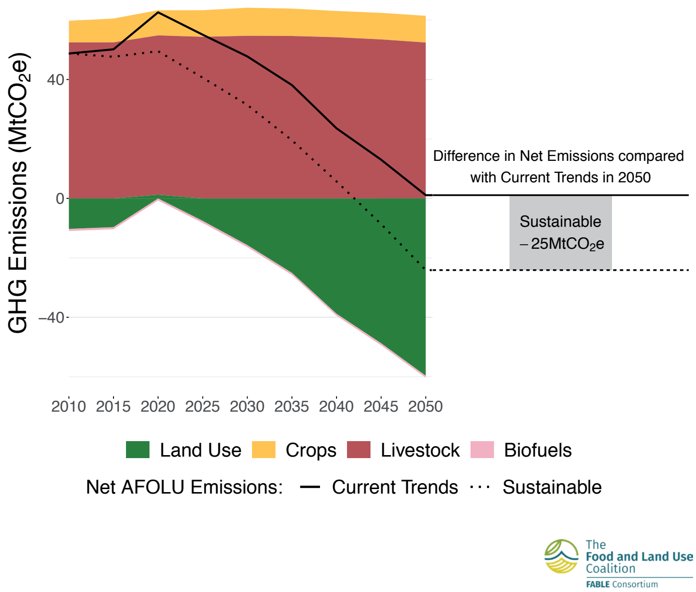
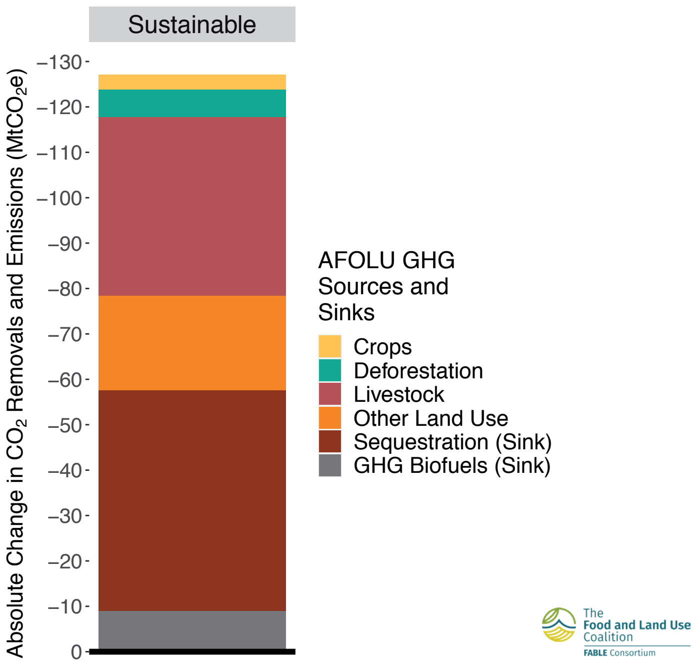


Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

Undernutrition

11% of the population was undernourished in 2010. This share decreased to 5% in 2017 (FAO, 2019).

13% of children under 5 stunted and 1% were wasted in 2010 (FAO, 2019).

Micronutrient Deficiency

8% of women and 8% of children (5-12 years) suffered from anemia in 2010, which can lead to maternal death (Instituto Colombiano de Bienestar Familiar [ICBF], 2010).

Overweight/ Obesity

56% of the population is overweight and 21% obese (WHO, 2016), 57% of adults and 24% of children (5-12 years), were overweight or obese in 2015. These shares have increased since 2010 (ICBF, 2015).

Disease Burden due to Dietary Risks

15% of deaths are attributable to dietary risks (Institute of Health Metrics and Evaluation, 2019).

8% of the population suffers from diabetes (WHO, 2016) and 30% from cardiovascular diseases (WHO, 2018), which can be attributable to dietary risks.

Table 3 | Daily average fats, proteins and kilocalorie intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,621 (2,072)	2,777 (2,092)	2,530 (2,092)	2,934 (2,084)	2,437 (2,084)
Fats (g) (recommended range)	82 (58-87)	80 (62-93)	81 (56-84)	79 (65-98)	80 (54-81)
Proteins (g) (recommended range)	59 (66-229)	61 (69-243)	58 (63-221)	64 (73-257)	58 (61-213)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

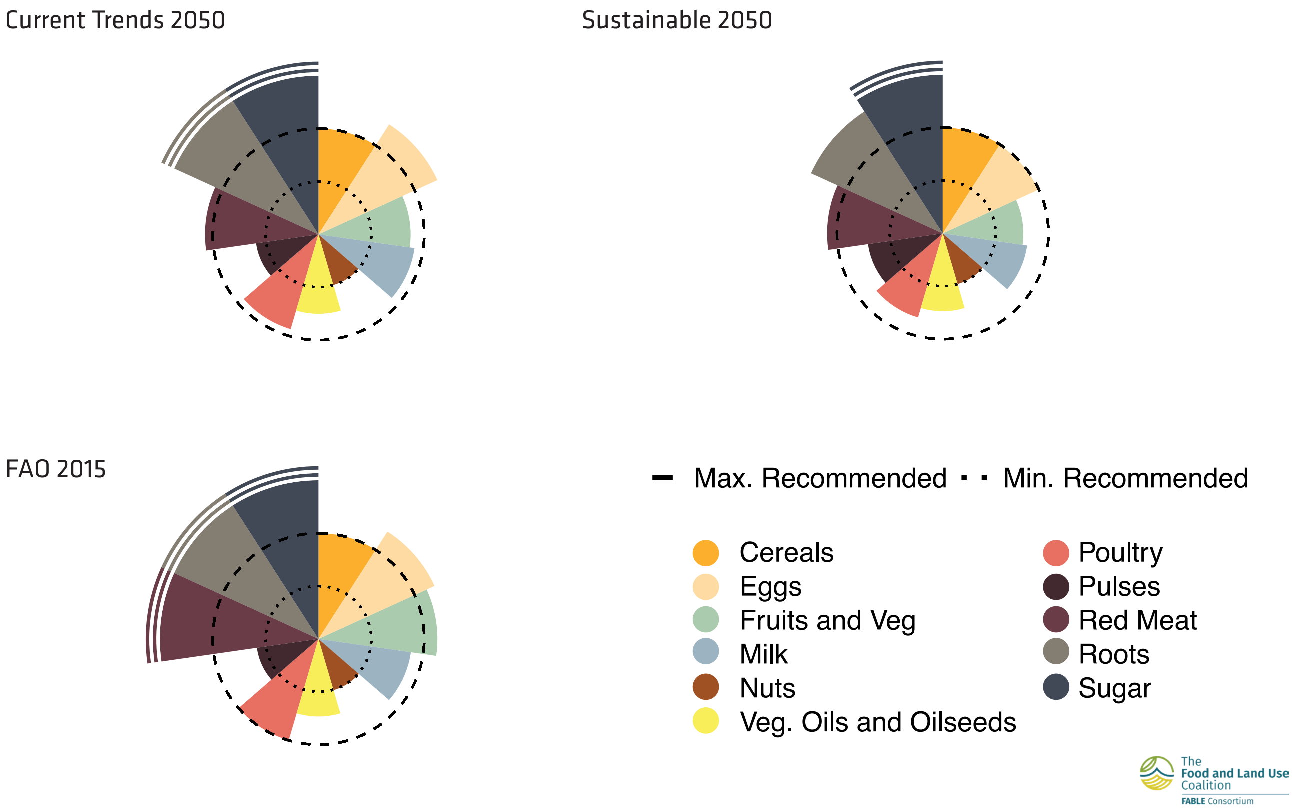
Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 33% higher in 2030 and 41% higher in 2050 (Table 3). The current average intake is mostly satisfied by cereals, sugar, vegetable oils, fruits and vegetables, and roots (80%). In turn, animal products (i.e. milk, red meat, poultry, eggs, and pork) represent 16% of the total calorie intake. We assume that the consumption of animal products, and in particular milk, will increase by 15% between 2020 and 2050. The consumption of beverages and spices, roots, sugar, eggs, and poultry will also increase while red meat and pork consumption will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), roots, sugar, red meat, and eggs are currently over-consumed while nuts are at the minimum recommended level. By 2050, this overconsumption of roots and sugar continue to increase while, in contrast, the consumption of red meat will decrease (Figure 6). Moreover, fat and protein intake per capita exceeds the dietary reference intake (DRI) in 2030, before falling below in 2050. This can be explained by an increase in the consumption of vegetable oils (i.e. oil palm and soy oil) and a decrease in the consumption of red meat, pork, and pulses (Figure 6).

Under the Sustainable Pathway, we assume that diets will transition towards a more healthy and sustainable diet. The ratio of the computed average intake over the MDER increases to 21% in 2030 and then decreases to 17% in 2050 under the Sustainable Pathway. Compared to the EAT-Lancet recommendations, the consumption of sugar, roots, and red meat remain outside the recommended range with the consumption of eggs within the recommended range in 2050 (Figure 6). Moreover, the fat and protein intake per capita exceeds the DRI in 2030 before falling below in 2050. Compared to the Current Trends Pathway, there is also a moderate improvement in the fat intake per capita but the protein intake still remains higher than the recommended level.

The following measures will be particularly important to promote a shift to more healthy and sustainable diets: updating the current national nutritional guidelines, providing information on the nutritional contents of food, promoting alternatives to animal-based foods, and applying economic incentives to deter the consumption of unhealthy foods.

The current national guidelines state that up to one-third of healthy diets should incorporate the consumption of animal-based food products (ICBF & FAO, 2015). These guidelines have been considered unsustainable as they only focus on health and disregard the sustainable dimension of food consumption (Blanco-Murcia & Ramos-Mejia, 2019). In addition, enhanced information on nutritional content via improved labels could help consumers make better-informed choices, including identifying unhealthy foods with high-sugar content (Cabezas-Zabala, Hernandez-Torres, & Vargas-Zarate, 2016). Additional measures include the promotion of plant-based food alternatives to partially substitute meat consumption. For instance, a higher consumption of pulses such as red beans and lentils, could be an alternative since they already form part of the Colombian diet (Blanco-Murcia & Ramos-Mejia, 2019). Finally, implementing economic incentives such as taxes on the consumption of unhealthy food could also help consumers choose healthier options (Cecchini, Sassi, Lauer, Guajardo-Barron, & Chisholm, 2010; Lake & Townshend, 2006).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of roots indicate that the average kilocalorie consumption of this food category is significantly higher than the maximum recommended.

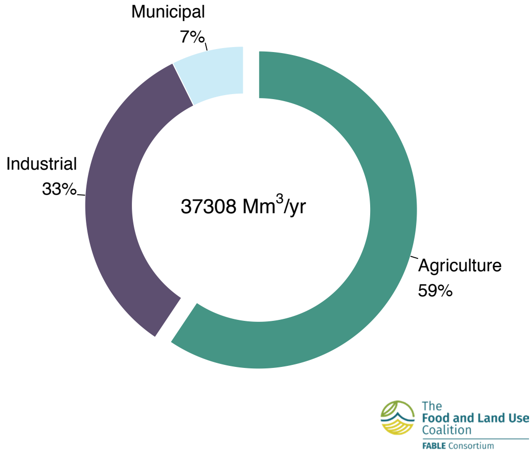
Water

Current State

Colombia is under the influence of the El Niño Southern-Oscillation (ENSO) and the latitudinal migration of the Intertropical Convergence Zone (ITCZ) (Poveda, 2004)m with an average annual precipitation of 2,888 mm (IDEAM , 2019). The rainy seasons are from March to May and October to November for regions with two rainy periods; and from May to September for regions with only one rainy season. The agricultural sector accounted for 59% of total water withdrawals in 2016 (Figure 7; IDEAM, 2019). Moreover, in 2014, 11% of the agricultural land was equipped for irrigation, representing 21% of estimated-irrigation potential (Perfetti et al., 2019). The three most important irrigated crops, rice, sugar cane, and oil palm accounted for 30%, 20%, and 19% of the total harvested irrigated area. Rice is mostly used for domestic consumption, while a sizeable portion of raw sugar is exported (27% in 2015).

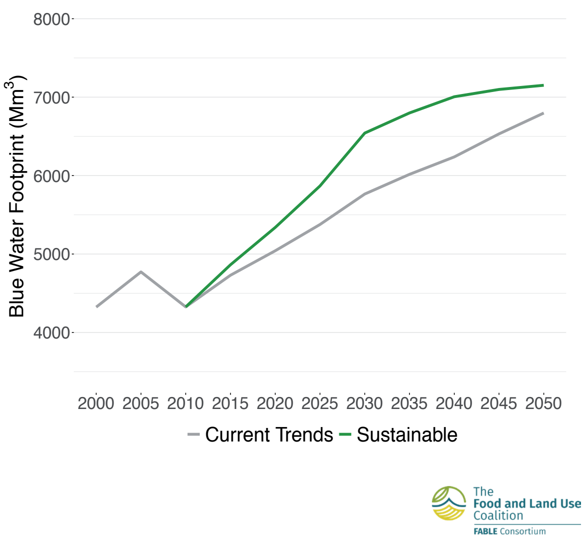
Despite the high-water availability at the country level, water use pressure indicators have reached critical levels, especially for the Magdalena and the Caribbean basins. According to the National Water Study (IDEAM, 2019), the blue water footprint increased by 11% between 2012 and 2016. For its part, the index of water pressure on ecosystems (IWPE) reflects that close to 37% of the units called hydrographic subzones (HSZ) present a highly critical situation (IDEAM et. al., 2019). At the same time, extreme climate variability is a factor that can potentially exacerbate the pressure on water resources.

Figure 7 | Water withdrawals by sector in 2016



Source. Adapted from AQUASTAT Database (FAO, 2017)

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000–2015 (4,323 and 4,730 Mm^3/yr), before reaching 5,765 Mm^3/yr and 6,798 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with sugarcane, plantain, and rice accounting for 41%, 23%, and 15% of computed blue water use for agriculture by 2050[5]. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture reaches 6,542 Mm^3/yr in 2030 and 7,151 Mm^3/yr in 2050. This is explained by an increase in the provision of infrastructure for irrigation. This allows a reduction of the blue water use in agriculture even though the production of sugarcane and plantain increases compared to the Current Trends Pathway to satisfy higher exports.

5 We compute the blue water footprint as the average blue fraction per ton of product times the total production of this product. The blue water fraction per ton comes from Varón-Cardenas & Garcia-Nuñez (2019). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

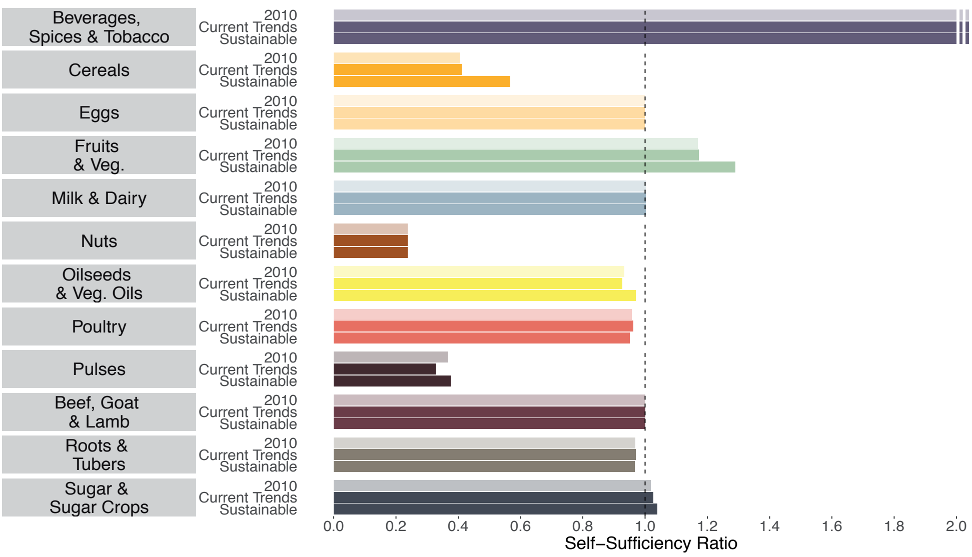
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Colombia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Self-sufficiency levels in Colombia have decreased from 94% in 2002 to 88% in 2010 (MINSALUD, 2015). This decline is due to the economic policies implemented in the early 90s, free trade agreements, and changes in dietary patterns, triggering increased demand for animal products like pork and chicken, and therefore, increasing demand for animal feed products.

Under the Current Trends Pathway, we project that Colombia will remain self-sufficient in beverages, spices and tobacco, eggs, fruits and vegetables, milk and dairy, vegetable oils, poultry meat, beef, roots and tubers, and sugar in 2050 (Figure 9). Colombia is highly dependent on imports of cereals, nuts, and pulses to satisfy domestic consumption, a dependency that will remain stable until 2050. Similarly, under the Sustainable Pathway, Colombia remains self-sufficient for most products except cereals, nuts, and pulses in 2050.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for beverages, spices and tobacco, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

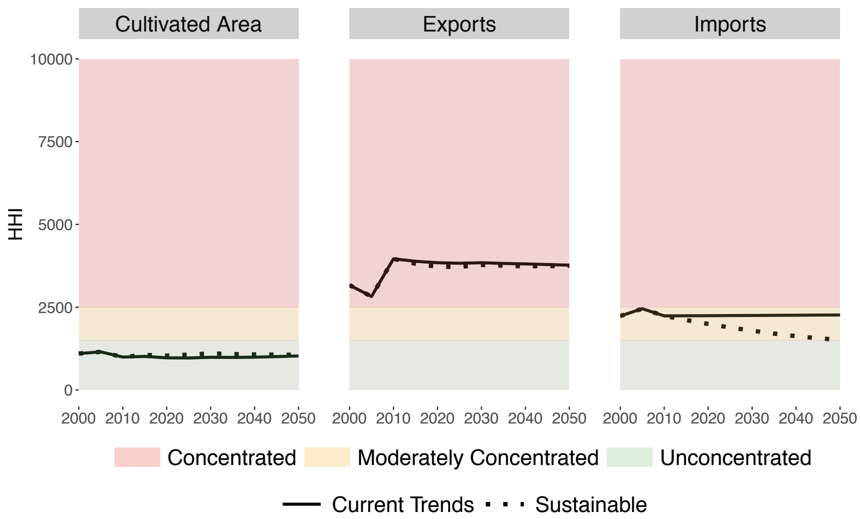
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

In 2010, the HHI indicates a low concentration in Colombia's cropland area, a moderate concentration in crop imports and a high concentration in crop exports (Figure 10). Six crops represent 65% of the cultivated area with shares of total cropland area varying between 10 and 17%: by order of importance these are corn, coffee, sugarcane, plantain, and rice. For imports, two crops, corn and wheat, represent 63% of the total volume of imported crops. Finally, Colombia exports few crops of which banana, coffee, and sugar represent 95% of the total volume of exported.

Under the Current Trends Pathway, we project high and medium concentration of crop exports and imports, respectively, and a low concentration in the range of crops planted in 2050, trends which stabilize over the period 2010–2050. This indicates a low level of diversity for exports, a moderate level for imports, and a high diversity across the national production system. These trends remain relatively similar under the Sustainable Pathway, with the exception of imports which have lower levels of concentration, indicating higher levels of diversity (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

The Colombian government recognizes the need for using a multi-sectoral and science-based approach for decision-making on food and land use systems. This approach has been central in the process to formulate national policies (NP), including the ***NP on climate change*** (in charge of the NDC), the ***NP on the integral management of biodiversity and its ecosystem services*** (in charge of the NBSAP targets) among others[6]. With this multisectoral approach, the government aims at promoting policy actions that allow for the simultaneous fulfillment of the objectives and targets of various policies (synergies), reducing potential conflicts between them. These medium- to long-term policies have been formulated within the last 5-10 years and seek, among others, to achieve balances between agricultural production and environmental protection. In this sense, they are largely consistent with the holistic approach proposed by the FABLE Consortium and have been incorporated into our modeling tools.

In general, our results are consistent with the multi-sectoral and comprehensive spirit of these existing policies on climate change and biodiversity (see *Climate and Biodiversity Strategies and Current Commitments*). On the one hand, these results are coherent with the objectives under which these policies have been formulated. Both the NDC and NBSAP have, respectively, converging policy actions and targets for reducing deforestation to reduce emissions and to protect biodiversity and ecosystem services. On the other hand, our results point out possible intervention points for additional or complementary measures that could be included within existing or prospective policies. This is the case of sustainable production systems that aim at increasing or maintaining productivity while fostering conservation since sustainable production systems are also part of the NDC (e.g. sustainable livestock) and NBSAP targets for Colombia.

Assumptions on agricultural expansion, including *no deforestation by 2030, afforestation and increase in protected areas* - both consistent with the NDC and NBSAP - determine to a large extent the following patterns in the Current Trends and Sustainable Pathways by 2050: a relatively constant proportion of forests and cropland areas, an increase in new forest areas, and a reduction in pasture areas. Increases in new forest areas and reductions in pasture areas in the Sustainable Pathway can also be traced to a dietary changes and increases in productivity that contribute to preventing agricultural expansion. Both deforestation prevention and forests expansion have synergistic positive effects on reducing emissions and conserving biodiversity. First, by avoiding emissions from deforestation and, second, by contributing to maintaining areas where natural processes predominate through preserving forests. In this sense, the FABLE Calculator captures aspects that are at the core of climate change and biodiversity policies in Colombia.

However, we note that for the Current Trends Pathway, the category *other land* may potentially be negatively affected, particularly by 2030. This category includes areas that may not be under protection and are not well represented in the system of protected areas (e.g parts of Los Llanos ecoregion). This indicates a possible point to consider as part of the NP on biodiversity in anticipation of the post-2020 CBD target. An additional aspect to consider when revising or preparing NPs are the main drivers of deforestation in Colombia, including land grabbing, illicit crops, infrastructure, mining, extensive livestock, and others (MINAMBIENTE & IDEAM, 2017). Most of these factors reflect the social, economic, and environmental complexities of Colombia over the past twenty years, including the periods of internal conflict and the post-conflict. These factors are not explicitly represented in the FABLE Calculator, the modeling tool used for this analysis. In consequence, part of the emissions related to land-use change may not be well represented.

Regarding potential intervention points, we have identified that changes in agricultural yields in the Sustainable Pathway, in particular for livestock, have important effects on reducing expansion (i.e. decreases in the pasture areas). This is a very relevant aspect for Colombia's 2018 policy on the agricultural frontier of (MADS, 2018). Currently, there is a mismatch between areas suitable for agriculture and livestock production and the actual areas used for those purposes within the frontier. For instance, Colombia has around 13.9 Mha of land suitable for agriculture but only 28.6% of agriculture is located on this land. In contrast, livestock production occupies more than 30 Mha, far above the area suitable for that purpose, or 17.6% of the agricultural frontier. This situation negatively impacts Colombia's agricultural productivity (Perfetti et al., 2019). In

6 Other multisectoral NPs include the agricultural frontier, the Green Growth policy, the policy on Water Resources Management.

this sense, sustainable land use that takes into account the lands most suitable for certain production types, and considers technological development, GHG emissions, water use, and biodiversity should result in increasing productivity and reducing the need for agricultural expansion in natural areas. Sustainable livestock, one of the country's NAMAs, is an example. It aims at simultaneously targeting increases in livestock productivity, carbon capture, and biodiversity conservation, among others. This mitigation measure was not included in the assumptions for this analysis, but harbors the potential for future improvements in the FABLE Calculator for Colombia.

Another potential intervention point identified from our results is diets. Like other emerging economies with a growing middle class, Colombia is experiencing an increasing trend in the consumption of products of animal origin and sugar. Results from the Current Trends Pathway are consistent with this pattern, in particular for products such as eggs, poultry, and milk. In contrast, for the Sustainable Pathway, in which we analyze a transition to a healthier and more sustainable diet, our results show that it is possible to maintain the energy requirements of the population and indirectly achieve positive effects on land use (i.e. contribute to limiting agricultural expansion). However, a dietary transition faces a series of barriers in Colombia and would require several policy interventions to address: i) the official national nutritional guides, which encourage the consumption of products of animal origin as part of a healthy diet but do not take into account questions of sustainability, ii) limited information on meat substitutes and on the nutritional quality of food, iii) the absence of economic instruments to disincentivize the consumption of unhealthy foods (e.g. foods with high sugar content). These barriers represent an opportunity to foster interaction with stakeholders, providing a holistic view of the relationships between food systems and land-use. Such a holistic view must underscore that in addition to being healthy, food must be sustainable as well.

The topics described above constitute a reference for continuing the process of improving our modeling tool and for interacting with stakeholders. In the first case, the model currently assumes total water availability will meet crop demand. However, in addition to climate change effects, climatic variability phenomena, including El Niño Southern Oscillation (ENSO), can affect crop yields in the short term (5-7 years) (IDEAM et al., 2019). These impacts are most evident for those rainfed dependent crops and, to a lesser extent, on irrigated crops. Additionally, competition for water use is critical in areas that have the greatest impact on agricultural GDP, such as the Magdalena river basin (IDEAM et al., 2019). Therefore, including the cumulative effects of climate change, climate variability, and pressure on water resources as restrictions for production in the model should produce a greater impact on the productivity of the agricultural sector.

In terms of stakeholder interaction, our results highlight the opportunity of establishing contact with institutions involved in developing the nutritional guidelines for the country, including the Ministry of Health and supporting bodies. This, in addition to the already established interactions with other stakeholders (i.e. the Ministry of Environment, Ministry of Agriculture, and other supporting bodies). Also, there is an opportunity to participate in the upcoming process for updating the National Policy on Water Resources Management and its associated planning instruments (e.g. Watershed Strategic Plans).

Finally, the current COVID-19 crisis and the trend in self-sufficiency indicators present a potential risk for Colombia's food security. This is particularly the case for the production of animal-based protein (i.e. pork, chicken, and eggs), which relies heavily imports of cereals such as corn. Historically, production costs at the national level for cereals have not been competitive enough to be supplied domestically. However, it could be expected that local food production will be promoted to reduce dependence on imports over the medium term, at least for those products whose domestic production is economically feasible.

Annex 1. List of changes made to the model to adapt it to the national context

- Some FAO values have been replaced with official data from Statistical Yearbooks of the Ministry of Agriculture (MADR, 2019), National Water Study (IDEAM et al., 2019), and other sources such as Fedepalma, Fenalce, Asocaña, and Cenicafé.
- Protected Areas data for 2010 were replaced by data from the Colombian Environmental Information System (SIAC).
- Oil Palm was selected as the commodity for biofuel production and national projections by 2050 were added, in accordance with Colombia National Energy Plan: Energetic vision 2050 by Energy-Mining Planning Unit (UPME, 2015).
- A table with the productivity ranges to 2050 was added: three (low, average, and high) ranges were considered according to the Statistical Yearbooks of the Ministry of Agriculture (MADR-UPRA, 2018), and other sources such as Fedepalma, Fenalce, Asocaña, and Cenicafé. These minimum and maximum values are used if the initial projected productivities were below or above these bounds.
- Soybean-cake and rice were added to imported products that can be modified through alternative scenario selection (for the other commodities, independently of the selected scenario, imports are computed with the 2010 share of the internal consumption which was imported times the internal demand). On the other hand, coffee, fruit_other [avocado], and cocoa were added to the export products that can be modified through scenarios.
- The water fraction value was updated for corn, oil palm, banana, rice, and sugar cane crop products using official statistics instead of Hoekstra and Mekonnen values.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)	
Current Trends Pathway	**Sustainable Pathway**
The population is expected to reach 62.8 million by 2050. Based on expected declining rates in population change, fertility, and international migration, as well as expected increases in access to education and urbanization (UN DESA, 2019). (SSP2 scenario selected)	Same as Current Trends.

LAND Constraints on agricultural expansion	
Current Trends Pathway	**Sustainable Pathway**
We assume that deforestation will be halted beyond 2030. Based on full implementation of the Integral strategy for controlling deforestation and managing forests. This is this REDD+ strategy for Colombia that includes measures to reduce deforestation and forest degradation and contributes to compliance of Colombia's binding commitments to the Paris Agreement by 2030 (MINAMBIENTE, 2017; MINAMBIENTE & IDEAM, 2017).	Same as Current Trends/
LAND Afforestation or reforestation target (1000 ha)	
We assume total afforested/reforested area to reach 1 Mha by 2035. Based on the target of existing National Restoration Plan formulated in 2015 (MINAMBIENTE, 2015). The plan is one of the implementing instruments for the National Policy on Biodiversity and the integral management of its ecosystem services (MINAMBIENTE, 2017). The policy is aligned with several international agreements under the CBD and UNFCCC (UNFCCC; MADS, 2012) and complementary initiatives such as the Bonn Challenge.	Same as Current Trends.

BIODIVERSITY Protected areas (1000 ha or % of total land)	
Current Trends Pathway	**Sustainable Pathway**
Protected areas increase. By 2050 they represent 18% of total land. Based on Colombia's commitment to comply with Aichi Target 11 by 2020: 17% of total land (terrestrial) protected (REDPARQUES, Proyecto IAPA, & Pronatura, 2018).	Protected areas increase. By 2050 they represent 18% of total land. Based on Colombia's commitment to comply with Aichi Target 11 by 2020: 17% of total land (terrestrial) protected (REDPARQUES et al., 2018). An update of the policy for the National System of Protected Areas SINAP is expected. One of the goals is to increase ecosystem representativity in the system of protected areas (WWF-Colombia, 2019). Such increases would imply further increases in protected areas. However, no official targets have been set yet.

PRODUCTION Crop productivity for the key crops in the country (in %)

Current Trends Pathway

The relative changes (%) in productivity between the base year and 2050 for key crops are as follows:
- 35% for cocoa
- 28% for plantain
- 17% oil palm fruit

We assume that the productivity growth rate remains stable, as observed between 2000-2010, based on statistics from the Ministry of Agriculture (MADR-UPRA, 2018). By 2050, the agricultural sector achieves moderate technology adoption and low to medium investment in science, technology, and innovation.

For oil palm, we assume it will regain the productivity level that existed before the arrival of the so-called bud rot (pudrición de cogollo) and lethal wilt (marchitez letal). These phytosanitary issues have led to serious productivity declines in several oil palm areas in Colombia. We assume that by 2030, phytosanitary problems are finally overcome. Therefore, a return to higher yields is anticipated.

Considering the above, the BAUGrowth scenario was selected.

Sustainable Pathway

The relative changes (%) in productivity between the base year and 2050 for key crops are as follows:
- 319% for corn
- 35% for rice
- 71% for oil palm fruit

Based on expected improvements in productivity for corn, included as part of the Corn for Colombia: 2030 Vision (Maíz para Colombia: vision 2030) (CIAT & CIMMYT, 2019). For rice, based on (UPRA, 2019), we assume that adoption of the Productive Management Plan for this sector is high, closing the productive gaps in Colombia. Finally, for oil palm, Colombia expects to achieve the initially projected productivity levels included in the document Vision of Palm Growing for the year 2020 (FEDEPALMA, 2000). The formulation of the plan occurred before the emergence of phytosanitary problems (i.e bud rot and lethal wilt) in Colombia.

Considering the above, the HighGrowth scenario was selected.

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

Current Trends Pathway

The relative changes (%) in productivity between the base year and 2050 for key livestock products are as follows:
- 18.8% per head for beef
- 0.0% per head for pork
- 96.7% per head for chicken

Based on the same productivity growth achieved during the last two decades. Overall, this productivity growth was due to the implementation of livestock systems with higher technological packages (e.g. with irrigation systems and genetic improvement) coupled with better management practices (FEDEGAN, 2019). Also, the country is aiming to increase sustainable livestock production practices that are consistent with improvements in productivity (Pinto-Brun, 2016). The latter is part of the Nationally Appropriate Mitigation Actions (NAMAs) and contribution to Colombia's commitments under the Paris Agreement.

For pork, the yield values indicate a negative trend between 2000 and 2010. We assume that the yield stabilizes in 2015 and remains constant until 2050.

Sustainable Pathway

The relative changes (%) in productivity between the base year and 2050 for key livestock products reach:
- 18.8% per head for beef
- 227% per head for pork
- 164% per head for chicken

Based on a more ambitious implementation of livestock systems with higher technological and better management practices. In the case of pork and chicken, the increases in productivity are also encouraged by an increasing demand for this type of protein.

PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

Current Trends Pathway

By 2050, the average ruminant livestock stocking density is 0.5 TLU/ha. Based on the same trend in productivity growth achieved during the last two decades for the livestock sector in Colombia. Overall, growth in productivity occurred by implementing livestock systems with higher technological packages (e.g. irrigated systems and genetic improvement), coupled with better management practices (FEDEGAN, 2019).

Sustainable Pathway

By 2050, the average ruminant livestock stocking density is 0.5 TLU/ha. Based on the increased ambition of implementing higher technological packages for livestock production, including irrigated systems and genetic improvement coupled with better management practices (FEDEGAN, 2019).

PRODUCTION Post-harvest losses

Current Trends Pathway

By 2050, the share of production and imports lost during storage and transportation is 40%. Based on the study of the National Planning Department (DNP, 2016). The study focuses on waste and loss of food in Colombia.

Sustainable Pathway

By 2050, the share of production and imports lost during storage and transportation is reduced compared to 2010. Based on the expected effects of implementing the recently enacted *policy for preventing food waste and loss.* The policy covers not only consumption and household level but other components in the system (e.g. production, storage, processing, distribution).

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway

The share of total consumption which is imported is:
- 88 % by 2050 for soybean
- 97 % by 2050 for barley
- 65 % by 2050 for sorghum

According to official statistics, Colombia imports a high volume of cereals to satisfy internal feed demand. Wheat, barley, and approximately 70% of corn have been imported during the last decades (DANE, 2019). Except for corn, it is highly probable that this trend continues in the future. Colombia is unable to produce most cereals at a competitive cost compared to production costs in other latitudes where soil and climatic conditions allow for a more efficient crop production.

Sustainable Pathway

The share of total consumption which is imported is:
- 88% by 2050 for soybean
- 97% by 2050 for barley
- 65% by 2050 for sorghum

In both the Current Trends and Sustainable Pathways, we selected the same stable import scenario.

TRADE Evolution of exports for key exported products (tonnes)

Current Trends Pathway

The volume of exports is:
- 2,092.8 tonnes by 2050 for sugar raw
- 1,699 tonnes by 2050 for banana
- 685 tonnes by 2050 for coffee

Banana. According to FAO, world production for banana has been increasing at a rate of 3.5% per year over the last 30 years. In Colombia, production for the same period has been increasing at a rate of 4.3% per year. Most of the production in Colombia is intended for export. In 2018, Colombia sent bananas to 31 countries around the world.

Coffee. Over the past ten years, coffee exports have been increasing significantly. Between 2000 and 2019, Colombian coffee exports increased by 84% (DANE, 2019). In the long term, the coffee sector will have to face the impacts of the effects of climate change. According to the results of some studies carried out by the Coffee Research Center, CENICAFE, a redistribution of the coffee production areas is likely. At the same time, it concludes that the adaptation of genotypes, spatial arrangements of shade and cultivation, nutrient dynamics, and water must be included into the research agenda. The sustainability of the coffee sector in Colombia will largely depend on the success of these research efforts.

Sugar raw. Raw sugar exports have been decreasing since 2005. Between 2005 and 2019, the volume of exported raw sugar has decreased by 37% due to biofuel production (DIAN, 2020). Historically, the production of sugar cane (raw material for sugar production) is concentrated in southwest Colombia (70% of the country's total area; MADR, 2018). We assume that the production of sugar cane expands to other territories due to the increase in demand. Currently, the Colombian Orinoquía registered around 26.6 kha in 2019 (13% of the total area of the country; MADR-UPRA, 2018).

Sustainable Pathway

The volume of exports is:
- 2,791.3 tonnes by 2050 for banana
- 2,340.4 tonnes by 2050 for sugar raw
- 822.5 tonnes by 2050 for coffee

Based on the same assumptions as on the Current Trends Pathway with a higher export goal.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2050, the main changes in average dietary composition per capita regarding 2020 are an 87% increase in beverages and spices, growth in the consumption of roots and sugar by 32% and 16%, respectively, and a decrease in the consumption of red meat by 30% and 23% for pork. Based on the National Plan on Food and Nutritional Security (PNSAN) 2012-2019 (Gobierno de Colombia, 2013). The PSAN is the implementation instrument for the National Policy on Food and Nutritional Security -CONPES 113/2008 (DNP, 2008a). Additionally, the current National Development Plan 2018/2022 aims at improving the nutritional state of the Colombian population (DNP, 2019a).	By 2050, the key changes in average dietary composition per capita regarding 2020 are a significant increase in the consumption of nuts (288%), a rise in the consumption of pulses and fish rise by 60% and 50%, respectively, and a reduction in the consumption of red meat (28%), sugar (27%), and roots (26%). Based on the partial implementation of the recommendations of the EAT-*Lancet* Commission Report on Food, Planet, and Health, (Willett et al., 2019) which encourages the change towards healthy eating that is compatible with the environment.

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
By 2030, the share of food wasted at consumption level (including household) is 16 %. Based on the study of the National Planning Department on waste and loss of food in Colombia (DNP, 2016). Policies targeting food waste at the household level remain scarce and the extent of the problem is not well known. Therefore, we assume the same share as in 2010.	By 2030, the share of final household consumption which is wasted at the household level is reduced compared to 2010. Based on the expected effects of implementing the *policy for preventing food waste and loss* of 2019. The policy is still in the formulation process but is expected to define specific targets, policy instruments, and monitoring processes. Its implementation during the medium to long-term should lead to a significant reduction in the share of food wasted. It is worth mentioning that the policy targets not only food waste at the household level but waste and loss for other sectors in the country. Therefore, we assume a reduced share compared to 2010.

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
By 2050, biofuel production accounts for: • 233.4kt of sugar cane production • 298.2kt of oil palm production Based on the stability in the fuel mix percentages for both ethanol (from sugarcane) and biodiesel (from palm oil). These percentages have remained relatively stable over the last several years (around 10%; DNP, 2019a; UPME, 2019).	By 2050, biofuel production accounts for: • 261.9kt of sugar cane production • 969.5kt of oil palm production Based on the full implementation of CONPES 3510/2008 on Policy Guidelines for promoting Sustainable Production of Biofuels in Colombia (DNP, 2008b). These guidelines constitute the basis for achieving 20% biofuels in the fuel mix.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[7]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
611	Amazon-Orinoco-Southern Caribbean mangroves	273.3	49.9	62.3	70.6	29.4	31.6	61
520	Apure-Villavicencio dry forests	2464.6	4.3	6.5	62	38	501.0	61.2
446	Caqueta moist forests	17195.0	28.9	90.2	31.9	68.1	436.0	74.2
447	Catatumbo moist forests	674.4	10.1	26.9	36.9	63.1	103.2	68.9
526	Cauca Valley dry forests	736.1	1.8	1.4	7.8	92.2	337.2	53.2
448	Cauca Valley montane forests	3212.7	12.5	19.3	31.4	68.6	296.8	87.6
449	Cayos Miskitos-San Andrés and Providencia moist forests	3.4	4.7	100	4.7	95.3	0.2	100
527	Central American dry forests	0.5	21.8	22.2	50.9	49.1	0.0	
454	Chocó-Darién moist forests	6003.3	7	73.2	7.6	92.4	211.1	70.8
457	Cordillera Oriental montane forests	5919.8	20.8	28.6	61.2	38.8	428.6	84.8
460	Eastern Cordillera Real montane forests	1092.9	22.7	84.3	25.9	74.1	20.9	89.3
461	Eastern Panamanian montane forests	87.6	40.3	94.9	38.5	61.5	1.1	96
602	Guajira-Barranquilla xeric scrub	2766.9	5.6	8.3	25.3	74.7	932.4	48.8
466	Guianan piedmont moist forests	1.9	0	78.7	0	0	0.0	
469	Iquitos várzea	30.3	45.3	55.7	56.4	43.6	0.0	100
473	Japurá-Solimões-Negro moist forests	3397.4	24.1	99.1	24.3	75.7	1.9	96.4
572	Llanos	15374.2	4.5	53.1	7	93	169.4	90.7

7 TThe share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Colombia

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
538	Magdalena Valley dry forests	1968.0	2.4	3.9	42.7	57.3	528.3	66.7
477	Magdalena Valley montane forests	10528.9	14.6	25	31.9	68.1	868.5	88.9
478	Magdalena-Urabá moist forests	7690.8	7.5	7.9	30.1	69.9	2995.6	45
483	Napo moist forests	4033.1	10.4	54.8	19	81	512.3	74.3
484	Negro-Branco moist forests	9769.9	4.8	95.4	4.7	95.3	36.4	98.1
593	Northern Andean páramo	1431.1	47.6	53.2	75.4	24.6	13.0	94.6
486	Northwest Andean montane forests	4920.7	15.7	54.6	26.2	73.8	267.9	91
542	Patía valley dry forests	227.6	0.1	23.2	0.3	99.7	29.8	94.3
496	Purus várzea	3025.4	25.4	95.3	26	74	4.9	79.1
498	Rio Negro campinarana	313.7	16.2	99.1	16.3	83.7	0.0	100
499	Santa Marta montane forests	479.6	45.5	70.9	63.7	36.3	5.8	99.7
594	Santa Marta páramo	124.6	97.5	100	97.5	2.5	0.0	100
546	Sinú Valley dry forests	2501.3	10.8	7.8	69.2	30.8	1372.2	41.9
503	Solimões-Japurá moist forests	7265.7	21.3	99	21.4	78.6	2.0	96.6
615	South American Pacific mangroves	557.7	26.3	75.4	29.1	70.9	2.2	86.7
505	Southwest Amazon moist forests	0.4	0	0			0.0	100
513	Venezuelan Andes montane forests	3.8	0	0			1.1	61.2
516	Western Ecuador moist forests	237.3	1.1	28.1	1.5	98.5	24.8	96.7

Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm – millimeters

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Ethiopia

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how advancing a sustainable food and land-use system can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Ethiopia. It presents two pathways for Ethiopia's food and land-use system for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand of food at national and global levels. We developed these pathways in consultation with national stakeholders, including experts from the National Integrated Land Use Policy and Plan Project Office and the Ministry of Agriculture, and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, & Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical climate change adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity in potential land use.

Table 1 summarizes how Ethiopia's Nationally Determined Contribution (NDC) treats the FABLE domains. According to its NDC, Ethiopia has committed to reducing its GHG emissions by 64% by 2030 compared to a business-as-usual (BAU) scenario. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include improving crop and livestock production practices and protecting and re-establishing forests for their economic and ecosystem services. Moreover, under its current commitments to the UNFCCC, Ethiopia mentions biodiversity conservation. In particular, it aims to develop biodiversity movement corridors in areas where most land has already been cultivated (Federal Democratic Republic of Ethiopia, 2015).

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in the current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2015)	BAU 2030	145	2030	64% reduction	energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	Y	N	Land-use change and forestry

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source. Federal Democratic Republic of Ethiopia (2015)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020) which are related to at least one of the FABLE Targets. This includes five of the eighteen National Biodiversity Targets from 2016-2020 (Ethiopian Biodiversity Institute, 2015). In comparison with the FABLE Target of zero net deforestation by 2030, the NBSAP aims to increase forest cover from 15% to 20%.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE Targets

NBSAP Target	FABLE Target
(Target 10) **By 2020, the contribution of biodiversity and ecosystem services, including climate change adaptation and mitigation, is improved through increasing forest cover from 15% to 20% of the country**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(Target 4) **By 2020, habitat conversion due to expansion of agricultural land is halved from the existing rate of about 10% per year.** (Target 7) **By 2020, area cover of ecologically representative and effectively managed protected areas are increased from 14% to 20%.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(Target 9) **By 2020, in situ conservation sites for important species and breeds are increased and the standards of the existing in situ conservation are improved.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(Target 10) **By 2020, the contribution of biodiversity and ecosystem services, including climate change adaptation and mitigation, is improved through an increased designated total area of wetlands from 4.5% to 9.0% and doubling the areas of restored degraded lands.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in lines with the FABLE Targets, for the food and land-use system in Ethiopia.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 112 million in 2020 to 170 million in 2050), no constraints on agricultural expansion, a low afforestation target (7 Mha by 2050), medium productivity increases in the agricultural sector, an evolution towards a diet higher in meat, milk, sugar, and fat (in order to meet recommended fat consumption levels), and high GDP growth (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to achieving economic development and meeting Ethiopia's Nationally Determined Contributions. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to lower population growth, higher afforestation (15 Mha), higher agricultural productivity, an evolution towards a diet higher in meat, milk, sugar, and fat (in order to meet recommended fat consumption levels), and lower agricultural land expansion (see Annex 2). This corresponds to a future whereby policy measures are enacted to meet the Bonn Challenge and that would also see considerable progress with regards to improving forest cover. With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

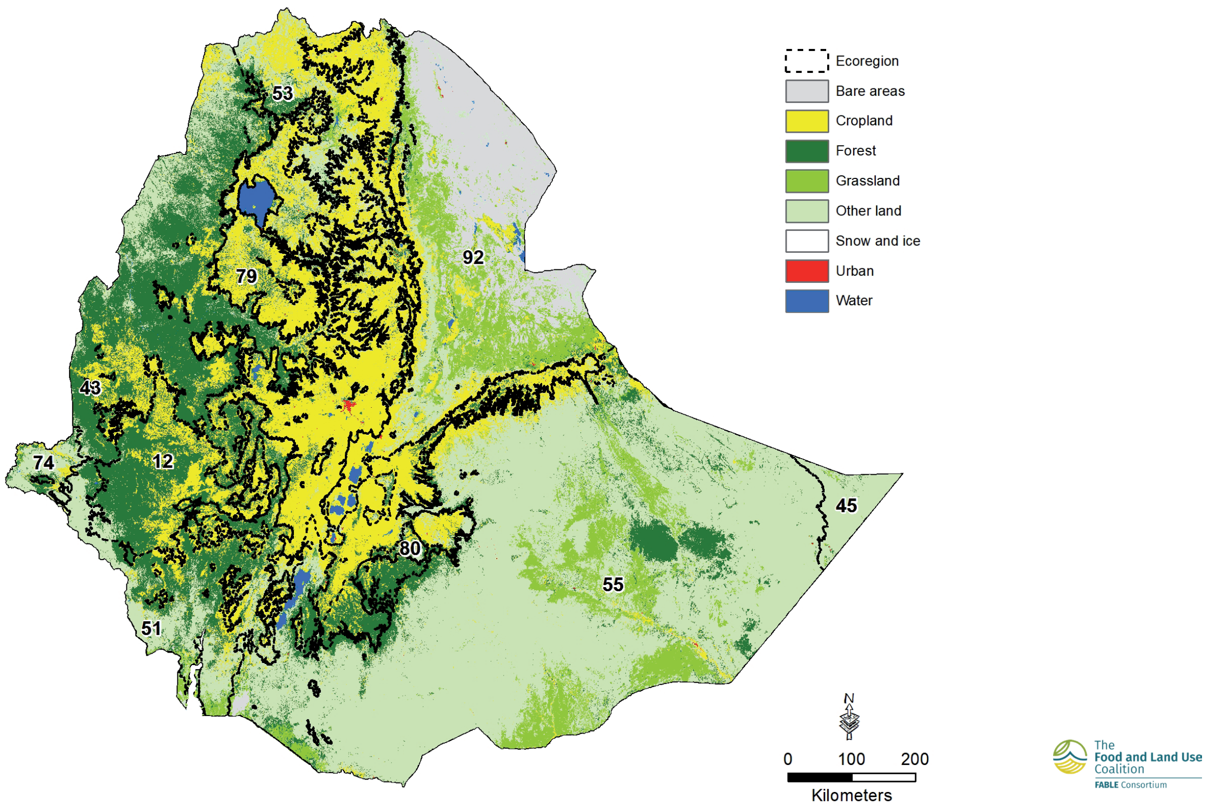
Land and Biodiversity

Current State

In 2010, Ethiopia's land was comprised of 14% cropland, 21% grassland, 13% forest, 0.1% urban, and 52% other natural land FAOSTAT (FAO, 2020). Most of the agricultural land area is concentrated in the central highland part of the country and to some extent spreads to the eastern and western parts of the country, while forest and other natural land are mostly found in the western and, to some extent, the southern, regions (Map 1). While demographic change is an indirect cause of biodiversity loss in Ethiopia, habitat conversion, unsustainable utilization of biodiversity resources, invasive species, replacement of local varieties and breeds, climate change, and pollution are the main direct threats (Ethiopian Biodiversity Institute, 2014).

We estimate that land where natural processes predominate[2] accounted for 23% of Ethiopia's terrestrial land area in 2010 (Map 2 and Table 3). The 80-Ethiopian montane moorlands hold the greatest share of land where natural processes predominate, followed by 74-Sudd flooded grasslands and 12-Ethiopian montane forests (Table

Map 1 | Aggregated land cover types and ecoregions



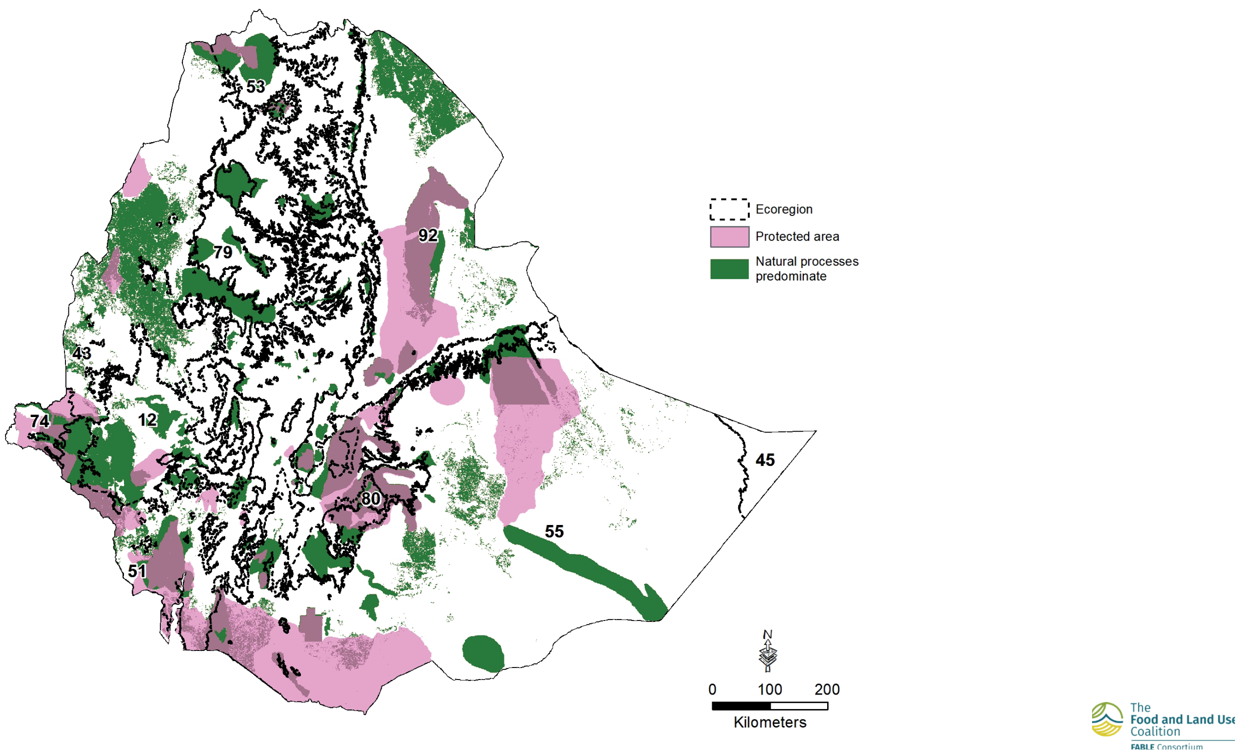
Note. Correspondence between original ESACCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3. The numbers on the map indicate landcover categories listed in Table 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

3). Overall, the 17.5% of protected areas is below the national target of increasing ecologically representative and effectively managed protected areas from 14% to 20% by 2020 (Ethiopian Biodiversity Institute, 2015). While 43-East Sudanian savanna and 51- Northern Acacia-Commiphora bushlands and thickets ecoregions are at or a bit higher than 14%, 11-Ethiopian montane forests, 45-Horn of Africa xeric bushlands, 53- Sahelian Acacia savanna, and 79- Ethiopian montane grasslands and woodlands ecoregions are still below 14%. The remaining ecoregions are well above 20% (Table 3). Across the country, while 20 Mha or 17.5% of land is under formal protection, falling short of the 30% zero draft CBD post 2020 target, only 23.2% of land where natural processes predominate is formally protected. The unprotected areas where natural processes predominate include parts of Ethiopia's highlands, which also form part of the Eastern Afromontane hotspot, as well as forested areas in the south and southwest. These areas are important areas for biodiversity conservation but are under threat due to sustained rates of deforestation, resettlement, and commercial farming (USAID, 2008), and could be prioritized for future protection.

Approximately 56.5% of Ethiopia's cropland was in landscapes with at least 10% natural vegetation in 2017. These relatively biodiversity-friendly croplands are most widespread in 50-Masai xeric grasslands and shrublands, followed by 51-Northern Acacia-Commiphora bushlands and thickets and 74-Sudd flooded grasslands. The regional differences in the extent of biodiversity-friendly cropland can be explained by farming intensity, which is much lower in the aforementioned ecoregions.

Map 2 | Land where natural processes predominate, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates areas under protection and where natural processes predominate overlap. The numbers on the map indicate landcover categories listed in Table 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

Ecoregion		Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Cropland as share of eco-region (%)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
12	Ethiopian montane forests	6810.1	11	40.6	15.2	84.8	2206.7	32.4	57.8
43	East Sudanian savanna	21716.2	14.1	34.8	23.4	76.6	3271.5	15.1	68.6
45	Horn of Africa xeric bushlands	1329.2	0	0	0	0	3.8	0.3	29.2
50	Masai xeric grasslands and shrublands	180.7	80.9	37.7	88.1	11.9	3.0	1.7	99.4
51	Northern Acacia-Commiphora bushlands and thickets	8.5	15.8	2	15.1	84.9	0.4	4.7	97.5
53	Sahelian Acacia savanna	3371.3	7.4	24.8	29.6	70.4	1235.2	36.6	62.1
55	Somali Acacia-Commiphora bushlands and thickets	41933.6	21.8	15.5	41.2	58.8	1001.3	2.4	71.7
74	Sudd flooded grasslands	990.4	66.6	42.6	64.2	35.8	119.4	12.1	72.4
79	Ethiopian montane grasslands and woodlands	19660.2	8.5	15.7	43.1	56.9	9889.1	50.3	50.4
80	Ethiopian montane moorlands	1572.9	32.1	46.9	65.4	34.6	540.7	34.4	60.4
92	Djibouti xeric shrublands	15963.3	23.2	27.2	43.3	56.7	1748.6	11.0	51.6

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

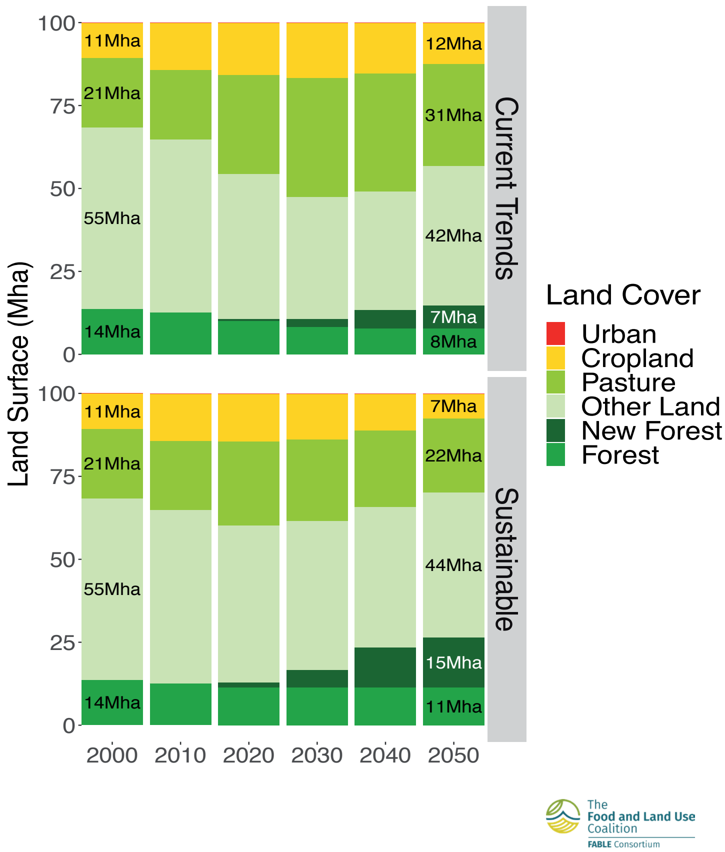
3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway will result in an additional 7 Mha of reforested or afforested land and an additional 31 Mha of pastureland by 2050.

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase of pasture and cropland area and a decrease in forest and other land areas; this pathway does not consider important elements of Ethiopia's biodiversity targets and would lead to the loss of another third of its remaining natural, biodiversity-rich native forests. This trend inverts slightly over the period 2030-2050: pasture and cropland area decrease and new forest and other land area increase (Figure 1). The expansion of the planted area for vegetable, sorghum, and corn explains 45% of total cropland expansion between 2010 and 2030. The increase of vegetable production is mainly driven by food demand. For sorghum, 50% of expansion is due to an increase of feed whereas the remaining 30% and 20% of the expansion are due to increases in the share of sorghum (for food and non-food uses). Where the non-food uses of sorghum include use of sorghum for seed and other use (other non-biofuel, non-food uses). Finally, for corn, 59% of the expansion results from an increase in food and 39% an increase of feed, and the remaining 2% is due to increases in non-food use (1%) and food waste (1%). Pasture expansion is mainly driven by the increased demand for milk, beef, and mutton. As a result, even though livestock productivity per head increases, ruminant density per hectare of pasture remains constant over the period 2020-2050. Between 2030-2050, decreases in the area of pastureland could be explained by increases in productivity for the livestock sector and a slowdown in

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

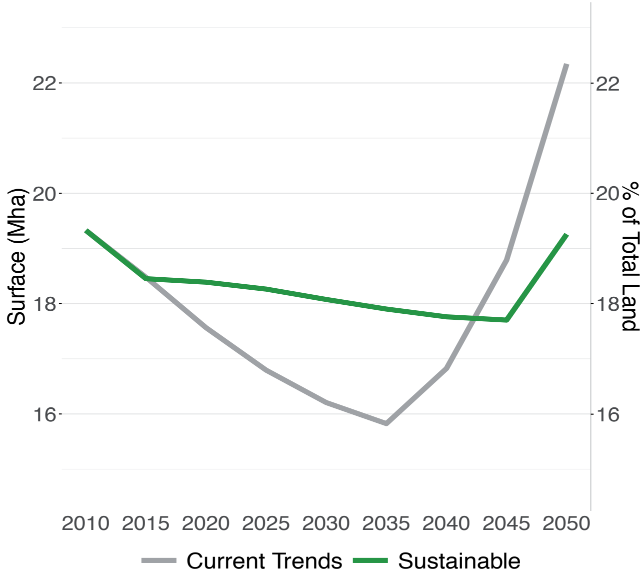


Source: Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000.

population growth. This results in a 16% reduction of land where natural processes predominate by 2030 and an expansion of land where natural processes predominate by 15.6% by 2050 compared to 2010, respectively. The Sustainable Pathway will result in no agricultural land expansion and in an additional 15 Mha reforested or afforested land after 2045.

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Ethiopia in the Sustainable Pathway: (i) deforestation per year is much lower between 2015 and 2050 and the Current Trends Pathway deforestation rate mimics this rate only in the period 2035-2050, (ii) agricultural land expansion is restricted, (iii) new forest increases sharply, and (iv) cropland extent decreases after 2030. In addition to the differences in assumptions regarding land-use planning, these differences compared to the Current Trends Pathway are explained by a lower population growth rate. Among other things, this leads to a relatively low expansion in cropland area. This in turn leads to the stabilization in the area where natural processes predominate, which stops declining by 2045 and increases by 9% between 2045 and 2050. The increases in natural land are greater under the Current Trends Pathway after 2040. This is due to the fact that, under the Sustainable Pathway, reforestation occurs on other natural land, which causes the natural land area to decrease (only increases in natural land are counted as increasing land where natural processes predominate). If the new forest is implemented in a way that supports biodiversity, land where natural processes predominate would, in fact, be greater under the Sustainable Pathway (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate



GHG emissions from AFOLU

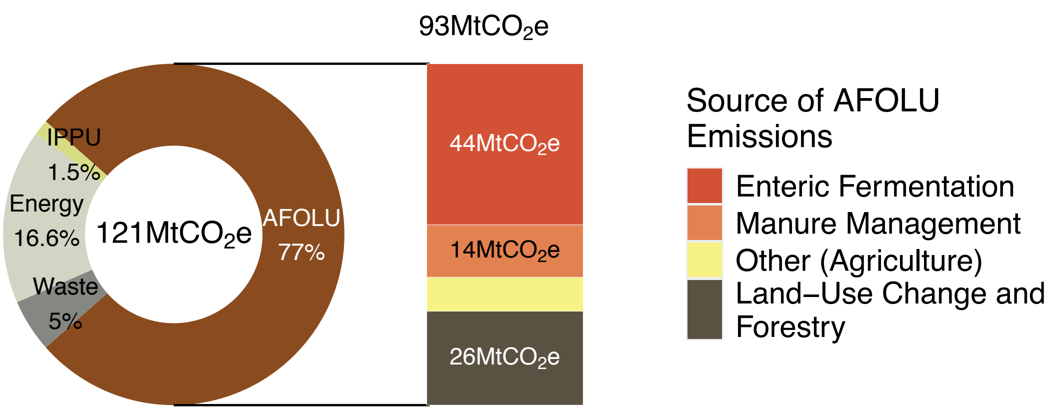
Current State

Direct GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) accounted for 77% of total emissions in 2013 (Figure 3). Enteric fermentation is the principal source of AFOLU emissions, followed by land-use change and forestry. This can be explained by the large number of cattle in Ethiopia (FAO, 2017b).

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU increase to 171 Mt CO_2e/yr in 2030, before dropping to 123 Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock is the largest source of emissions (127 Mt CO_2e/yr) while land converted to forest acts as a sink (-6 MtCO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for agriculture (5%), while a reduction is computed for land-use change from reforestation (-900%), deforestation (100%) and loss of other natural land (100%) (Figure 5).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2013



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

In comparison, the Sustainable Pathway leads to a 31% reduction in GHG emissions from AFOLU by 2050 (Figure 4). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from the livestock sector, which is a result of reduced livestock productivity leading to lower pasture demand. The lower population growth and the halting of agricultural land expansion, which has resulted in lower feasible consumption, are the most important driver of this reduction.

Compared to Ethiopia's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute an additional 20% of its total GHG emissions reduction objective by 2030, as outlined in its NDC. Such reductions could be achieved by improving livestock productivity (an area that has not yet received sufficient attention in policy circles), supporting family planning measures, and implementing the Bonn Challenge. These measures could be particularly important when considering options for NDC enhancement.

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

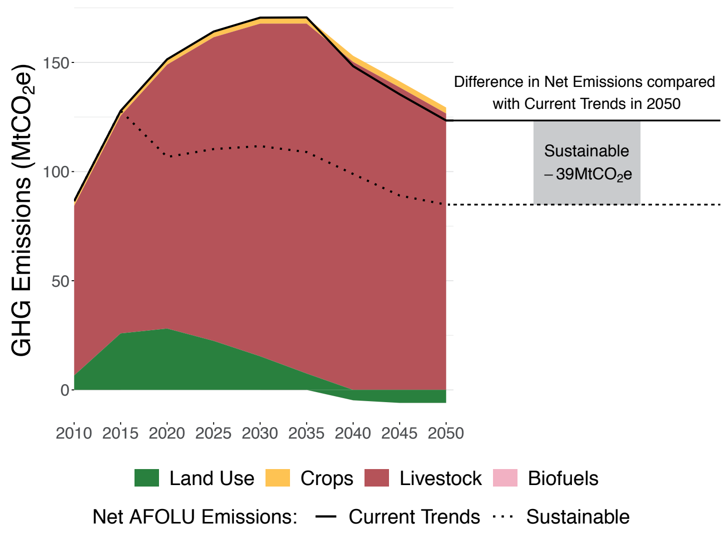
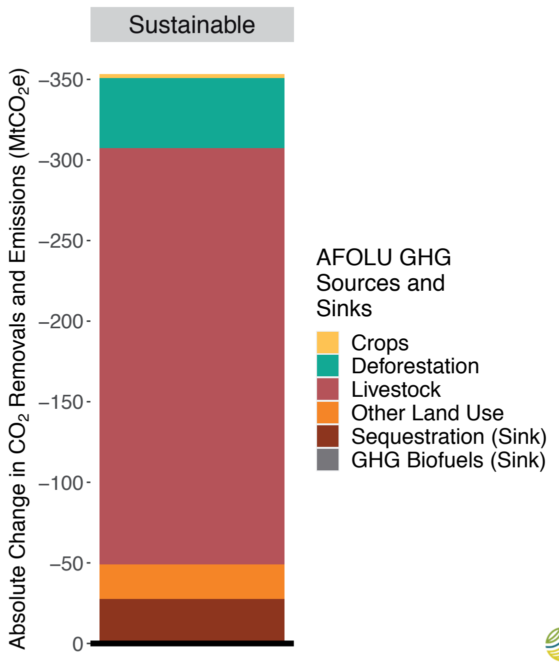


Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

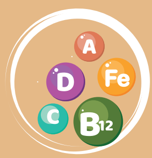
Current State

The "Triple Burden" of Malnutrition

Undernutrition

20.6% of the population was undernourished in 2016-2018. This share has decreased since 1999-2001 (Global Nutrition Report, 2020).

38.4% of children under 5 stunted and 9.9% wasted in 2016 (FAO, 2020).



Micronutrient Deficiency

24% of women of reproductive age, between 15-45 years, and 56.9 % of children aged 6-59 months suffer from anemia (<11.0g/dl) in 2016, which can lead to maternal death (CSA & ICF, 2017).

3.4% of women of reproductive age, between 15-45, are deficient in vitamin A (EPHI, 2016), which can notably lead to blindness and child mortality, and 51.8% are deficient in iodine, which can lead to developmental abnormalities (EPHI, 2016).

Overweight/ Obesity

1% of adults were obese in 2016. These shares have increased since 2000 (CSA & ICF, 2017).

4.6% of adults and 1% of children were overweight in 2016. The share of overweight adults has marginally increased

since 2000, while the share of overweight children has remained stable (CSA & ICF, 2017).

Disease Burden due to Dietary Risks

14.5% of deaths are attributable to dietary risks, or 3,856 deaths per year (per 100,000 people) (Melaku et al., 2018).

5.8% of the male and 5% of the female population suffer from diabetes and 31.7% of the female and 28.8% of the male population from cardiovascular diseases (raised blood pressure), which can be attributable to dietary risks (Global Nutrition Report, 2020).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,044 (1938.5)	2,197 (2,020)	2,134 (2,020)	2,232 (2,067)	2,218 (2,067)
Fats (g) (recommended range	25 (45-68)	47 (49-73)	44 (47-71)	52 (50-74)	50 (49-74)
Proteins (g) (recommended range	77 (51-179)	84 (55-192)	80 (53-187)	86 (56-195)	84 (55-194)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

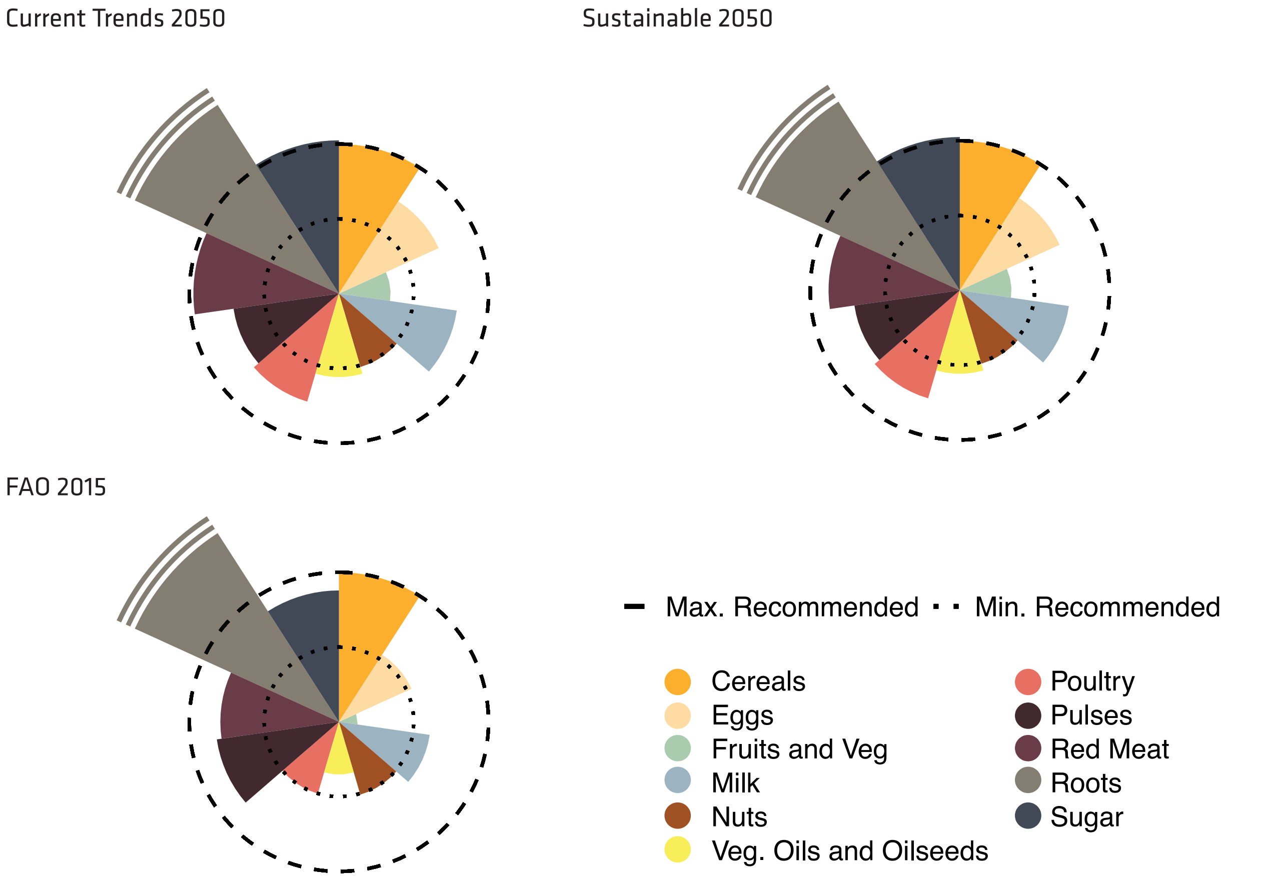
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 9% higher in 2030 and 8% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals, roots and tubers, and animal products, the latter representing 9% of total calorie intake. We assume that the consumption of animal products, and in particular milk, will increase by 45% between 2020 and 2050. The consumption of fruits and vegetables, meat, eggs, poultry, sugar, and nuts will also increase while cereals, pulses, and root crop consumption will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), roots, cereals, and sugar are over-consumed while animal fat, nuts as well as fruits and vegetables are under-consumed in 2050. Although the consumption of fruits and vegetables show some improvement compared to the baseline, it will remain below the minimum recommended level in 2050 (Figure 6). Moreover, fat intake per capita is inferior to the dietary reference intake (DRI) in 2030 and exceeds the dietary reference intake in 2050. On the other hand, protein intake per capita exceeds the dietary reference intake both in 2030 and 2050. This can be explained by an increase in the consumption of animal products like milk, eggs, and fish (Figure 6).

Under the Sustainable Pathway, we assume that diets will transition towards those higher in meat, milk, sugar, and fat. The ratio of the computed average intake over the MDER increases to 6% in 2030 and 7% in 2050 under the Sustainable Pathway. Compared to the EAT-*Lancet* recommendations, only the consumption of roots remains outside of the recommended range with the consumption of eggs and vegetable oils and oilseeds within the recommended range in 2050 (Figure 6). Moreover, while the fat intake per capita is inferior to the dietary reference intake (DRI) in 2030, the protein intake per capita exceeds the DRI in 2030. However, neither the fat nor protein intake per capita show improvement compared to the Current Trends Pathway.

Transforming the livestock sub-sector towards a higher productivity system and at the same time limiting the adverse environmental impact from intensification will be particularly important to promote this shift in diets (Gebru et al., 2018). In general, government commitments towards improving healthy diets and improving nutrition is reflected in several policy documents, including the Growth and Transformation II (GTP II), the Seqota Declaration, and the National Nutrition Program II (NNP II) (FDRE National Planning Commission, 2016; Federal Democratic Republic of Ethiopia, 2015, 2016). In the Seqota declaration, the government expresses its commitment to end hunger and undernutrition by 2030. Similarly, in the NNP II, it states its objectives of reducing stunting from 40% to 26% by 2020 as well as to reduce chronic undernutrition among women of reproductive age from 27% to 16% by 2020. The Ministry of Agriculture and Natural Resources' "Nutrition Sensitive Agriculture Strategic Plan" document also indicates the government's commitment to the NNP II targets and the need to revise agricultural sector policies and strategies with a nutrition lens (FDRE Ministry of Agricultural and Natural Resource and FDRE Ministry of Livestock and Fishery, 2016).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



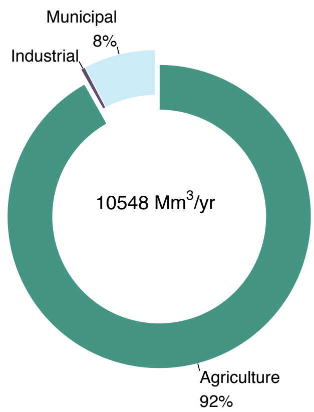
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings) i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of roots indicate that the average kilocalorie consumption of this food category is significantly higher than the maximum recommended.

Water

Current State

Ethiopia is characterized by three climatic zones of tropical rainy, temperate rainy, and dry climate with 848 mm average annual precipitation that mostly occurs between July and September (FAO, 2005; Kidanewold, Seleshi, & Melesse, 2014). The agricultural sector represented 92% of total water withdrawals in 2016 (Figure 7; FAO, 2017a). Moreover, in 2002, 4% of agricultural land was equipped for irrigation, representing 7% of estimated-irrigation potential (FAO, 2005). The three most important irrigated crops, corn, cotton, and sorghum, account for 18%, 14%, and 9% of the total harvested irrigated area. These crops are mostly used for domestic consumption - Ethiopia exported only 1% of corn, 7% of cotton, and 0.1% of sorghum in 2017 (ITC, 2020).

Figure 7 | Water withdrawals by sector in 2005 and 2016

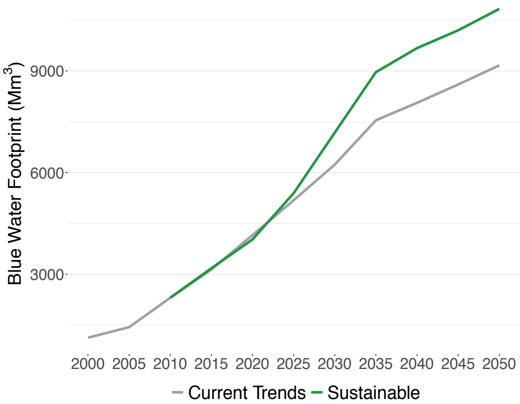


Notes. Agriculture data: 2016, municipal: 2005, industrial: 2005
Source. Adapted from AQUASTAT Database (FAO, 2017a)

Pathways and Results

Under the Current Trends Pathway, annual blue (irrigation) consumptive water use increases between 2000-2015 (1,128 Mm^3/yr and 3,142 Mm^3/yr), before reaching 6,237 Mm^3/yr and 9,165 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with vegetables, soybean, and banana accounting for 49%, 22%, and 7% of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Pathway, the agricultural blue water footprint reaches 7,181 Mm^3/yr in 2030 and 10,832 Mm^3/yr in 2050. This is explained by climate change impacts on water used for irrigation.

Figure 8 | Evolution of the water footprint in the Current Trends and Sustainable Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

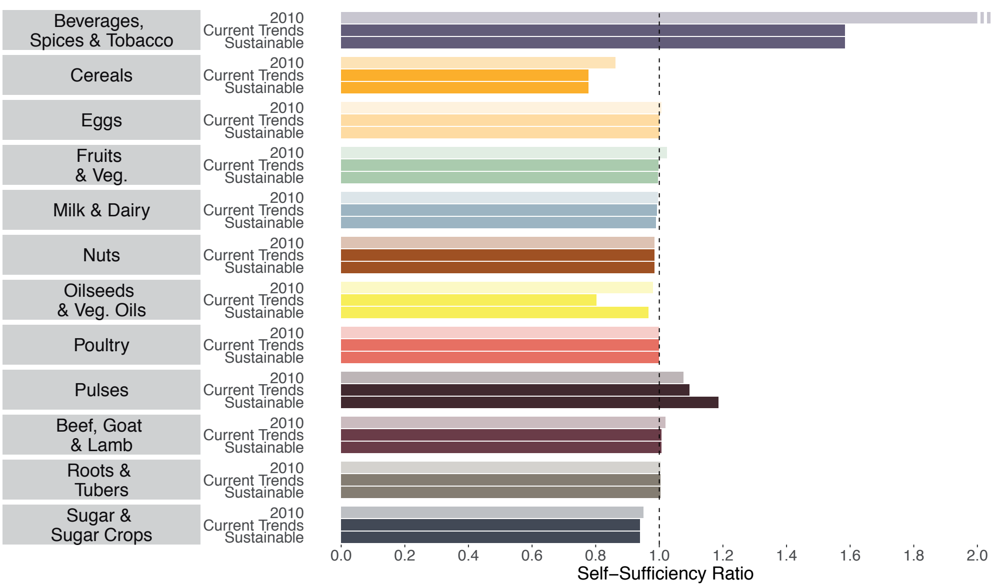
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Ethiopia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Currently, Ethiopia depends on imports of certain food products including wheat, cooking oil, sugar, and sugar products. This is mainly due to the rapidly increasing population size, increasing economic growth and development, which involves dietary changes, and traditional production systems that depend heavily on rain-fed agriculture. Studies (Tesfaye et al., 2018) show that Ethiopia has a self-sufficiency rate of less than one and that the country needs to boost its crop productivity to become more self-sufficient in the future.

Under the Current Trends and Sustainable Pathways, we project that Ethiopia would be self-sufficient in beverages, spices and tobacco, pulses, fruits and vegetables, egg, nuts, and roots and tubers in 2050, with self-sufficiency by product group remaining stable for the majority of products from 2010 – 2050 (Figure 9). It is most dependent on imports of cereals, oilseeds, and vegetable oils as well as sugar and sugar products to satisfy domestic consumption, a trend that will increase until 2050 (Figure 9). This is mainly explained by the growing population and changes in diets.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for beverages, spices and tobacco, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

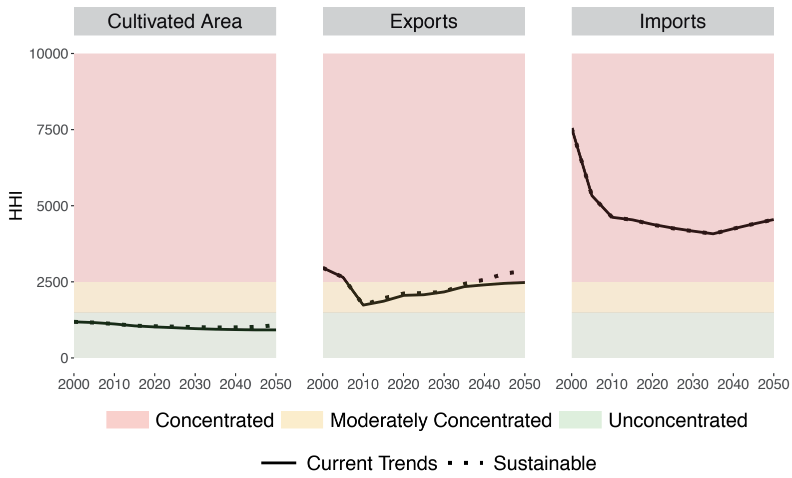
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, a moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Although the five major cereals (teff, wheat, maize, sorghum, and barley) account for about three-quarters of the total area cultivated, Ethiopia's crop production system tends to be relatively unconcentrated thanks to its widely varying agroecological conditions. Cereals account for 74% of the total cultivated area, while pulses and oilseeds account for 12% and 7%, respectively (Taffesse, Dorosh, & Gemessa, 2012). Although Ethiopia's exports are generally concentrated among a few agricultural products, particularly coffee, crop exports are likely to diversify as oilseeds and pulses also happen to be important export items. Ethiopia's crop imports, on the other hand, are likely to be highly concentrated due to its heavy reliance on imports of wheat, which, according to Gebreselassie, Haile, and Kalkuhl (2017), comprises the single most important imported food crop.

Under the Current Trends Pathway, we project a high concentration of crop imports, moderate levels of crop exports, and a low concentration in the range of crops planted in 2050, trends which stabilize over the period 2010 - 2050. This indicates high levels of crop diversity across the national production system, moderate levels of concentration in exports, and low levels of crop diversity in imports. Under the Sustainable Pathway, we project high concentration of crop exports and imports and low concentration in the range of crops planted in 2050, indicating high levels of diversity across the national production system and low levels of diversity across imports and exports (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

Important policy areas in Ethiopia's pathway towards sustainable development are identified in the Climate Resilient Green Economy Strategy (CRGE) and development plans (GTPs). The CRGE, which came into effect in 2011 and remains in force until 2030, is the main document that guides Ethiopia's Nationally Determined Contribution (NDC). It covers both the adaptation and mitigation objectives of the government (Federal Democratic Republic of Ethiopia, 2011).The second GTP, which is the current development plan ending this year (2019/20), will be followed by the Ten-Year Perspective Development Plan (TYPDP) in 2021. The TYPDP, which will be implemented between 2020 and 2030, has an ambitious growth target and a climate-resilient green economy as one of its pillars (*Ethiopian Monitor*, 2020). With its plans and strategies, the government aims to achieve a high economic growth rate while maintaining a low level of emissions. This requires identifying green economy opportunities and needs the support of development partners for its full realization.

Under the Current Trends Pathway, constructed based on Ethiopia's ambitious planned improvement in per capita income and the expected population growth rate, our results show that Ethiopia's per capita consumption of fats, which is below the recommended level, will increase rapidly. This will increase the demand for food and for animal-based production in particular. Assuming the continuation of previously observed growth in crop productivity, our results show that agricultural land will expand at the expense of forest and other natural lands. This result indicates that Ethiopia will struggle to simultaneously achieve the development plan, meet the food demand of its growing population, and, as stipulated in its NDC, keep its GHG emissions at a low level while protecting biodiversity without the concerted technical and financial support of development partners. The feasibility of expanding agricultural land at the expense of other lands is questionable at best. This is due to political, social, cultural, and developmental challenges that will make the free expansion of agricultural land impractical. Moreover, studies indicate that cropland expansion is reaching its limit in the highlands, which has traditionally been an important area for crop production (Schmidt & Thomas, 2018).

Therefore, we developed an alternative Sustainable Pathway with enhanced crop productivity, slower population growth, and restrictions on the expansion of agricultural land. Under this pathway, Ethiopia can better reconcile the demand for land and food. Focusing on increases in productivity and slower population growth will lead to desirable development and GHG emissions outcomes. For example, under such a pathway, it will be possible to increase the forest cover to meet the targets of the ambitious Bonn Challenge by 2050. This underlines the need to have a clear and well-thought-out land use plan and policies, as well as institutions with a land-use mandate at both at the federal and regional levels. However, such a development trajectory will require significant investment to raise productivity and the efficient use of resources. For example, small-scale irrigation with high water use efficiency can be used towards boosting production of vegetables and fruits, diversifying crop production, providing increased access to healthy diets for the growing urban population.

One limitation of the above analysis is that it only applies to the national level despite the well-known regional differences within Ethiopia. Ethiopia is geographically diverse and follows a federal governance arrangement with nine regional states. The challenges in one region may differ from those in others. Therefore, it will be important to introduce an analysis of regional differences within the FABLE framework and have a more granular assessment of the food and land-use system that can inform sectoral plans. Yet another challenge that is disrupting the food and land use system and not covered in the above analysis is the recent outbreak of COVID-19. In particular, supply chain distribution is already impacting fresh vegetable commodities and international trade. The food systems in low-income countries, with limited storage facilities and contact intensive marketing systems, are highly vulnerable and require attention. The implication of adjustments in farming decisions as a result of COVID-19 may also have far-reaching consequences that need to be analyzed using the FABLE framework. Going forward, we will endeavor to fill these gaps and promote the use of FABLE's analytical framework to the relevant stakeholders with the aim of supporting knowledge-based policy making in Ethiopia.

Annex 1. List of changes made to the model to adapt it to the national context

- We have separated Teff which is a staple crop in Ethiopia. In FAOSTAT (FAO, 2020), it is considered as other cereals.
- We have included a high economic growth scenario as per governmental plans.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
UN's low growth scenario was selected, whereby the total population size reaches 170 million by 2050. Based on the UN's population projection database (UNDP, 2015). The primary source of population data is the census, which was conducted in 1994 and 2007. Accordingly, the average population growth rate was close to 2.5% per year between 1994 and 2007 – corresponding to the two census periods (CSA, 2013). However, this rate is expected to decrease.	SSP1 scenario, which influences demographics in the direction that is supposed to improve the sustainability of the food and land use system, was selected. According to this scenario, Ethiopia's population will reach 154 million by 2050

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
Free expansion of productive land under the total land boundary is selected as the current pathway scenario for land. Although there is little room for further expansion of agricultural land in the highlands of Ethiopia, where the majority of crop production in the country takes place, there is potential to expand cropland activities in the low lands (Schmidt & Thomas, 2018). Concerning pastureland, the grey literature identifies the rise in rangeland enclosures (Fekadu Beyene, 2009; Napier & Desta, 2011). Moreover, since we are not aware of any efforts that aim to limit agricultural land expansion, we assume that free land expansion will be closer to what is likely to happen in the current pathway.	For the sustainable scenario, we assume no productive land expansion beyond the 2010 value. This is assumed to be consistent with limited availability of land for further expansion of agricultural land in the highland areas of the country as indicated in Schmidt & Thomas (2018). Although there is some land in the low lands that can potentially be used for agricultural expansion, that there might be political as well as infrastructural constraints that holds back the country from doing so thus far. Schmidt & Thomas (2018) also indicate the difficulty of expanding agricultural land in the lowlands as these areas are characterized by a relatively higher risk of disease as well as more erratic and limited rainfall.

LAND Afforestation or reforestation target (1000 ha)

Current Trends Pathway	Sustainable Pathway
Ethiopia's NDC Target is 7 Mha by 2030 (FDRE National Planning Commission, 2016). In line with this, we assume that Ethiopia will achieve this target by 2050.	Afforestation/reforestation target in line with the Bonn Challenge commitment. Specifically, considering the commitment towards a Climate Resilient Green Economy that Ethiopia outlined in 2011 and the afforestation pledge it has made, we have taken Ethiopia's Bonn challenge commitment targeting 15 Mha for afforestation by 2020 (Pistorius, Carodenuto, & Wathum, 2017). This is extremely ambitious and we assume that the country will achieve this target by 2050.

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
No expansion of protected areas beyond the current extent, which means keeping the share of protected areas at 20% of total land. Given the increasing population pressure and the resulting habitat conversion, unsustainable utilization of biodiversity resources, climate change, pollution, etc. that threaten protected areas, we assume restricted expansion of protected areas (Ethiopian Biodiversity Institute, 2014; USAID, 2008).	Expansion of protected areas in the future, increasing share of protected areas to 21% of total land area from its current level of 20%.

PRODUCTION Crop productivity for the key crops in the country (in t/ha)	
Current Trends Pathway	**Sustainable Pathway**
We assume the same crop yield growth as in 2000-2010.	We assume higher crop yield growth compared to 2000-2010. The reason for assuming high crop productivity growth is based on Ethiopia's currently relatively low cereal productivity base (Taffesse et al., 2012) and significant improvements that took place after 2010 - following the government's focus on agricultural transformation through various programs such the agricultural growth program (World Bank, 2017), which showed a 16% improvement in yield in five years (between 2011 and 2016). In GTP II period (2015/2016-2019/2020) the government aims to sustain the achievements in crop productivity obtained in the GTP I period (2010/2011-2014/2015) (FDRE Ministry of Finance and Economic Development, 2010; FDRE National Planning Commission, 2016).
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)	
We assume higher yield growth for livestock than what is observed for 2000-2010. Specifically, we assume an increase in productivity rate of 200%, 100%, and 70% if the annual growth rate in the period 2000-2010 is negative, between 0% and 1%, and greater than 1%, respectively. This is because of the renewed interest among policymakers and development partners towards the livestock sector, as well as the low level of current productivity. Ethiopia's cattle meat production of 14 kg per standing head is lower than neighboring countries like Kenya (21 kg per standing head) and milk production is even less productive 72.5 kg per standing head compared to Kenya's 194.74 kg per standing head (Shapiro et al., 2015).	Same as Current Trends
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)	
We assume no change in the management of permanent pasture area, leading to pasture degradation in some cases. The baseline (2010) livestock density value used in our scenario is 1.58 TLU/ha. Tilahun & Schmidt (2012) report a livestock density value of 0.3 TLU/ha, excluding camel and donkey.	Same as Current Trends
PRODUCTION Post-harvest losses	
We assume a reduction in the proportion of food that is wasted. We have assumed a reduced (50%) share of food waste compared to 2010 as many development partners are looking at food waste as a possible area of intervention (Federal Democratic Republic of Ethiopia, 2011).	Same as Current Trends

TRADE Share of consumption which is imported for key imported products (%)	
Current Trends Pathway	**Sustainable Pathway**
We assume increased import shares for wheat following the pattern of imports in the country (Olana et al., 2018). As is also indicated in Olana et al. (2018), Ethiopia's wheat imports have been growing rapidly and are expected to increase in the future given the high population growth and improvements in living standards in the country, which in turn is likely to lead to higher demand for wheat products.	Same as Current Trends
TRADE Evolution of exports for key exported products (1000 tons)	
We assume increases in exports in the future. Specifically, we assume that exports will be multiplied by 1.5 by 2050. This assumption is consistent with the GTP II's target of increasing agricultural export revenue as a share of GDP by 2.9 percentage points (FDRE National Planning Commission, 2016)	Same as Current Trends

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)	
Current Trends Pathway	**Sustainable Pathway**
Here we selected the fat diet scenario which implies a higher share of meat products, oil, and sugar in the total food intake. This is assumed to be consistent with the assumption of high yield growth for livestock than what is observed for 2000-2010 as well as government's target of increasing the production and consumption of animal source foods in the five year period between 2016-2020 (FDRE Ministry of Agricultural and Natural Resource and FDRE Ministry of Livestock and Fishery, 2016).	Same as Current Trends
FOOD Share of food consumption which is wasted at household level (%)	
We have assumed a reduced share of food loss compared to 2010. This assumption is made as many development partners are looking at food waste as a possible area of intervention (Federal Democratic Republic of Ethiopia, 2011).	Same as Current Trends

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
We assume no change, which implies stable biofuel demand as in 2010.	Based on OECD_AGLINK scenario which makes projections until 2028 that remain stable afterward. Accordingly, biofuel use is assumed to increase for wheat, corn, sugarcane, and soy oil, by a factor of about 3.34 - 7.91 over the period 2015-2050. This is consistent with studies that report increased use of biofuel in Ethiopia (Ferede, Gebreegziabher, Mekonnen, Guta, & Levin, 2015; Teka, 2007).

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland<50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm - millimeters

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Finland

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Finland. It presents two pathways for food and land-use systems for the period 2020-2050: *Current Trends and Sustainable*. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including from the Ministry of Agriculture and Forestry, the Central Union of Agricultural Producers and Forest Owners (MTK), and the Natural Resources Institute Finland (Luke), and modeled them with FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019) and the DREMFIA agricultural sector model (Lehtonen, 2015). See Annex 1 for more details on the adaptation of the FABLE Calculator to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Finland's NDC treats the FABLE domains. According to the NDC, Finland has committed to reducing its GHG emissions by 40% by 2030. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include soil carbon sequestration, measures relating to the use of peatlands, and the handling and treatment of manure. Under its current commitments to the UNFCCC, Finland does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
(EU) NDC (2016)	1990	71.2	2030	At least 40% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Forests

Note. "Total GHG Mitigation" and "Mitigation Measures related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019), except for the GHG emissions baseline, which comes from Statistics Finland (Statistics Finland, 2020)
Source. EU (2016)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the national biodiversity targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2013, as listed on the CBD website, which are related to at least one of the FABLE Targets (CBD, 2020). In comparison, the national protected land area target falls clearly below the global FABLE Target, while the significantly negative GHG emissions from Finland's LULUCF sector (Statistics Finland, 2020) is compatible with the national target on carbon stocks and the FABLE Target of zero or negative LULUCF emissions.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(5) **By 2020, the loss of all natural habitats has been halted, and the degradation and fragmentation of natural habitats have been significantly reduced.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(7) **By 2020, areas under agriculture, aquaculture and forestry are managed and utilised sustainably, ensuring the conservation of biodiversity**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(14) **By 2020, ecosystems that provide essential services, including services related to water, health, livelihoods and well-being, are restored and safeguarded, taking into account socioeconomic and cultural considerations**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(15) **Finland participates in global efforts to restore at least 15 per cent of degraded ecosystems**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(11) **By 2020, Finland's network of protected areas and the measures applied to conserve biodiversity in the use of other areas together cover at least 17 per cent of the terrestrial environments and inland waters of the country, and 10 per cent of coastal and marine areas**	**BIODIVERSITY:** At least 30% of global terrestrial area protected by 2030
(15) **By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks have been enhanced through conservation and restoration**	**GHG EMISSIONS:** Zero or negative global GHG emissions from LULUCF by 2050

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Finland.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by low population growth from 5.5 million inhabitants in 2020 to 5.9 million in 2050, minimal agricultural expansion in line with historical trends, a low afforestation target, no change in the extent of protected areas, moderate productivity increases in the agricultural sector (low increase in crop yields, moderate increase in livestock productivity, and a significant increase in labor productivity on livestock farms), no change in diets, and no change in agricultural policy (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to changes in farm structure, growth in farm size, and agricultural labor productivity (Lehtonen, Niskanen, Karhula, & Jansik, 2017). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. We assume that trends in technological change continue and that adaptation to climate change is moderate. Consequently, climate change challenges to crop production (Hakala, Hannukkala, Huusela-Veistola, Jalli, & Peltonen-Sainio, 2011) are sufficiently addressed to avoid crop yield losses and a small (5-10%) increase in crop yields is gradually attained by 2050 (Tao et al., 2015). Our model includes the corresponding climate change impacts on crop yields by 2050 for wheat, barley, oats, oilseeds, potatoes, peas, sugarbeet, and forage grass (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to slightly higher crop yields and significantly decreased consumption of livestock-based foods (see Annex 2). A significant decrease in the consumption of livestock-based foods would lead to declining area for pasture and feed production, half of which would be forested by 2050. Protected areas and population growth would remain unchanged compared to the Current Trends Pathway. This corresponds to a future based on responsible consumer behavior, strategic adaptation to climate change, and market changes at the farm and food-industry levels, also incentivized by effective climate policy. Consequently, higher crop yields aided by new crop cultivars adapted to longer and warmer growing seasons (+10-20% between 2020-2050, which is consistent with Tao et al., 2015) and reduced demand for feed crop production would free up farmland not used in agriculture. Afforestation of a part of this farmland, as well as greenhouse gas mitigation in peatlands, provide opportunities for GHG mitigation (Aakkula et al., 2019; Koljonen et al., 2020). Structural change in agriculture including growth in farm size and increases in labor productivity development also remain unchanged as compared to the Current Trends Pathway. With the other FABLE country teams, we embed this pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

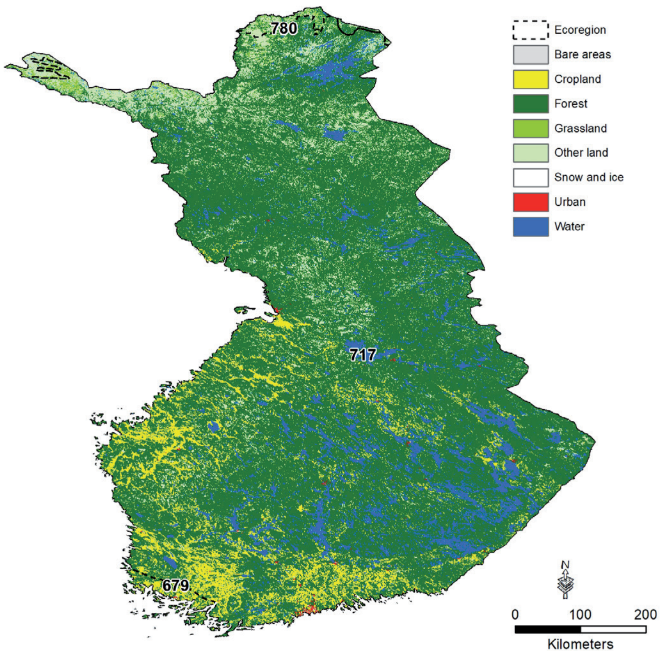
Land and Biodiversity

Current State

In 2015, Finland was covered by 74% forest land, 7% cropland, <1% grassland, <1% urban, and 19% other natural land. Most of the agricultural area is located in southern and western parts of the country while forest and other natural land can be mostly found in central, eastern and northern Finland (Map 1). Challenges to biodiversity in Finland include the gradual decline in biodiversity in managed forests and croplands. These concerns are addressed by Finland's National Biodiversity Strategy and Action Plan (Ministry of Environment, 2020).

We estimate that land where natural processes predominate[2] accounted for 61% of Finland's terrestrial land area in 2015 (Map 2). The ecoregion 780-Scandinavian Montane Birch forest and grasslands hold the greatest share of land where natural processes predominate, followed by 717-Scandinavian and Russian taiga and 679-Sarmatic mixed forests (Table 3). Across the country, while 5Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 17% of land where natural processes predominate is formally protected. This indicates that managed forests, which dominate land use in ecoregions 717-Scandinavian and Russian taiga and 780-Scandinavian Montane Birch forest and grasslands are also likely to play an important role for biodiversity conservation in the future. The National Biodiversity Strategy and Action Plan (Ministry of Environment, 2020) outlines actions to ensure the improved protection of these at-risk areas.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



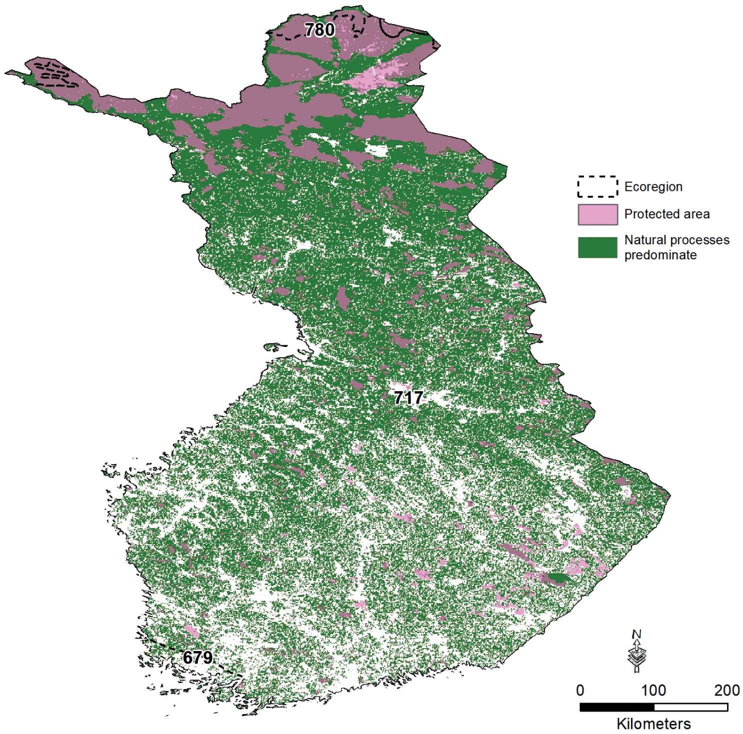
Note. Correspondence between original ESACCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Finland

Approximately 56% of Finland's cropland was in landscapes with at least 10% natural vegetation in 2015. These relatively biodiversity-friendly croplands are most widespread in ecoregion 717-Scandinavian and Russian taiga, followed by 780-Scandinavian Montane Birch forest and grasslands and 679-Sarmatic mixed forests. The regional differences in the extent of biodiversity-friendly cropland can be explained by the share of low intensity grass forage production.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km^2 (%)
679	Sarmatic mixed forests	360	2.2	36.2	2.7	97.3	127.8	55.1
717	Scandinavian and Russian taiga	32 444	12.6	63.5	16.9	83.1	2485.0	55.9
780	Scandinavian Montane Birch forest and grasslands	381	78.2	97	79.1	20.9	0.03	100

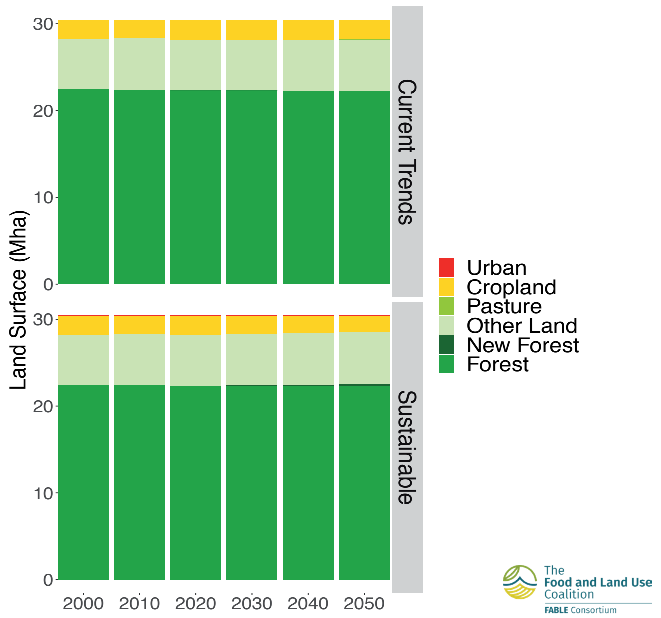
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no changes in diets, a small increase in population, and no expansion of agricultural land beyond 2010 levels. There is no planned afforestation and reforestation. Protected areas remain unchanged at 5Mha, representing 16% of total land cover (see Annex 2).

By 2030, we estimate little change in land cover in the Current Trends Pathway. This is due to little to no change in diets and population growth, which leads to stable agricultural production. We also assume that agricultural policy incentives influencing crop allocation and cultivated land area will remain close to current levels, even though the real value of farm payments will gradually decrease as the European Union (EU) and national agricultural budget is unlikely to increase (Lehtonen & Niemi, 2018). All available farmland will not

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

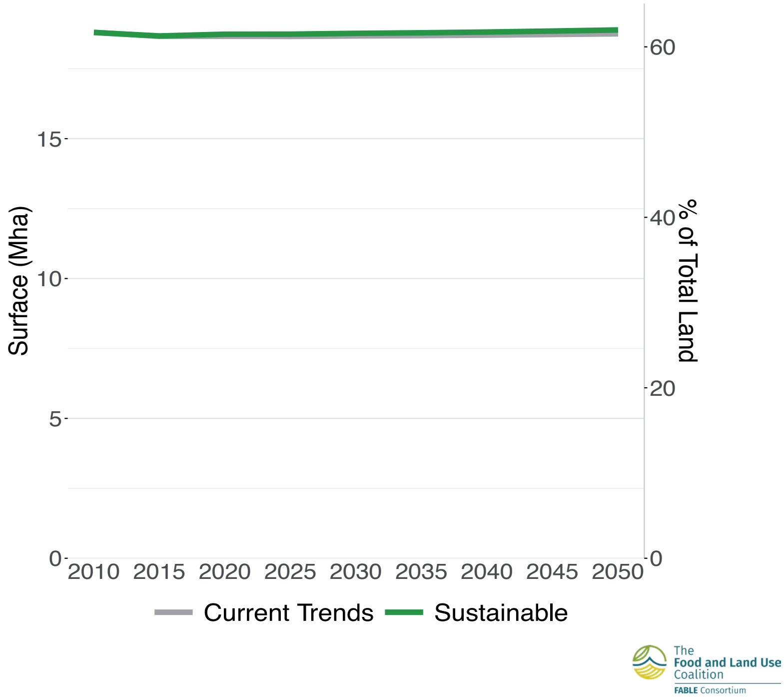


Source: Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000.

3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

be used for production as areas will be set aside for the purpose of accessing significant farm payments. Thus, the farm payments keep all farmland in cultivation and the cropland area changes very little, if at all. In addition, forest land area may decrease slightly due to urban expansion. These trends remain stable over the period 2030-2050 (Figure 1).

Figure 2 | Evolution of the area where natural processes predominate



In the Sustainable *Pathway*, assumptions on reduced consumption of livestock-based foods and increased crop yields result in decreasing demand for farmland. Increasing demand and production of protein crops (e.g. peas and oilseeds) utilize only a fraction of the land area freed up from livestock feed production. Decreased farm support per hectare, and animal, also result in decreasing utilized agricultural land. The main assumption that affects land use is climate policy which incentivizes afforestation. Thus 0.2Mha of cropland (9% of cropland area in 2015) is afforested over the period 2020-2050. Protected areas do not change (see Annex 2).

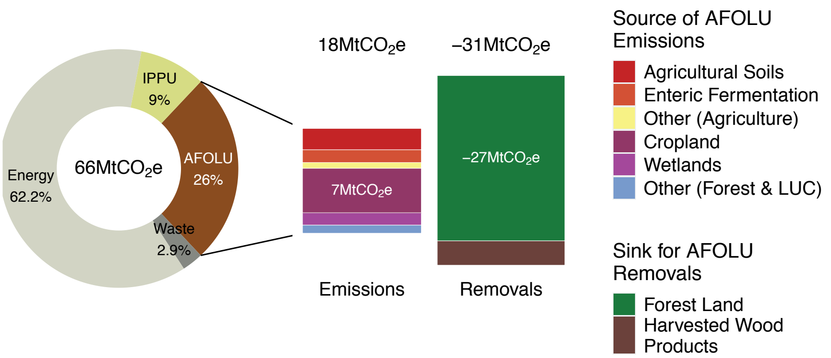
Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Finland in the Sustainable Pathway: (i) impact on agricultural land, (ii) impact on afforested land. This leads to a small (1%) increase in the area where natural processes predominate by 2050. While this may be considered negligible, the negative direction of change is clearly reversed (Figure 2). Achieving a significant increase in the areas in which natural processes predominate is challenging to realize as they already cover 93% of land area (74% forest land and 19% other natural land). Agricultural area decreases by 9% through afforestation in the Sustainable Pathway, but this contributes to a small change in overall land use since agricultural land currently represents only 7% of land area. Increasing the combined share of forest land and other natural land close to 95-100% of land area would mean a significant change or downscaling of human activities.

GHG emissions from AFOLU

Current State

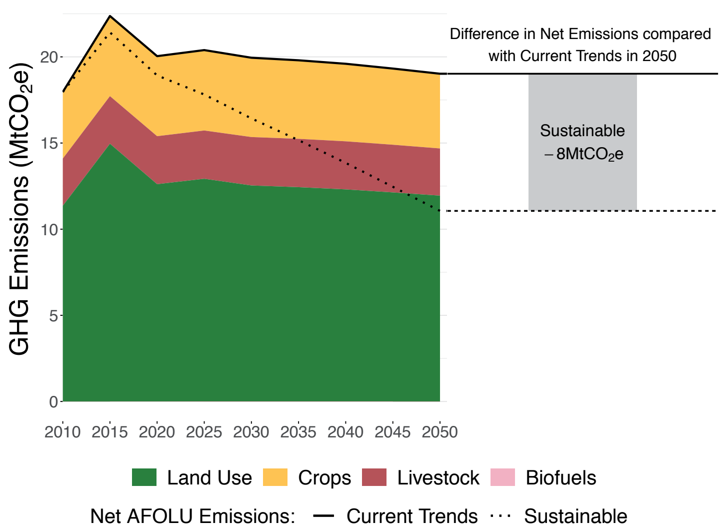
Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 26% of total emissions in 2015 (Figure 3). Agricultural soils (especially CO_2 from peatlands) is the principle source of AFOLU emissions, followed by cropland (N_2O emissions) and enteric fermentation (CH_4). This can be explained by the fact that peatlands account for 11% of cultivated lands, which produce more than 50% of Finland's GHG emissions for agriculture (Statistics Finland, 2020). Large areas of peatlands with thick layers of peat were converted to croplands between 1918-1940 and 1945-1960 due to 36,000 farm families losing their farms, lands, and homes in the Second World War (Kotta, 2017). A large share of peatlands has been kept in agricultural use because of their importance for agriculture and rural livelihoods, especially in remote rural areas with few alternative sources of income. Peatlands are often well suited for grass forage cultivation for dairy and beef production but less suited for crop production. Older investments in dairy and beef production in peatland areas maintain peatland soils in their agricultural production, especially if there are few incentives or possibilities to shift production to mineral soils (Lehtonen, Peltola, & Sinkkonen, 2006; Regina

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2015



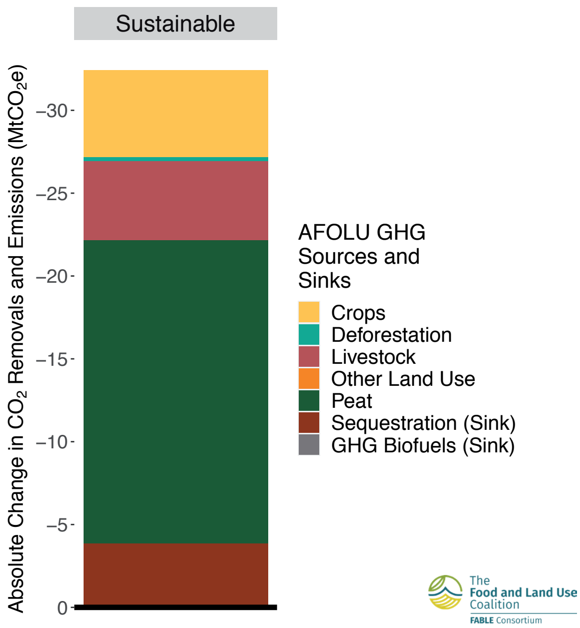
Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Figure 4 | Potential AFOLU emissions reductions by 2050 by trajectory compared to Current Trends



et al., 2015). Emissions from croplands (feed crop production requiring inorganic fertilizers) and enteric fermentation are also significant since agriculture in Finland (Statistics Finland, 2020) is traditionally based on livestock, and especially dairy and beef production, because of the difficult climate and natural conditions for crop production in large parts of the country (Niemi & Väre, 2019). Approximately 70% of agricultural land is used for animal feed production (OSF, 2020). Hence livestock production, directly or indirectly, is the main driver of GHG emissions.

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Pathways and Results

Under the Current Trends Pathway, the fluctuation of the GHG emissions calculated using the FABLE Calculator in Figure 4 is because of the technicalities in the calculation procedure. However, there is a small 5% decrease in GHG emissions 2020-2050 with the strongest relative reduction computed for crops (-6%). This small change in GHG emissions is understandable since there is little change in production and land use in the Current Trends Pathway (Figure 4). In 2050, organic soils (peatlands used in agriculture and forestry) is the largest source of emissions (12.4 Mt CO_2e/yr), crops are the second largest with 4.4 Mt CO_2e/yr, and livestock is the third largest with 2.7 Mt CO_2e/yr. Land use change in agriculture acts as a small sink (-0.4 Mt CO_2e/yr).

In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by -42% in the period of 2020-2050 compared to the Current Trends Pathways (Figure 4). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from organic soils, crops and livestock. Furthermore, there is a significant carbon sink (-1.4 Mt CO_2e in 2050) in land use change due to the afforestation of 200 kha of agricultural land which is no longer needed for agricultural production due to decreased demand and production of livestock products. The most important drivers of this very significant 42% emission reduction are the changes in diets, especially decreases in red meat consumption, and the consequential decreases in feed (cereals and forage grass) production on organic soils.

Compared to Finland's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute to as much as 28% of its total GHG emissions reduction objective by 2050. Such reductions could be achieved through the following policy measures: decreasing agricultural production on organic soils (share of peatlands out of all agricultural land decreasing from 10.5% to 7.9%; -140 000 ha), promoting diet changes so that more protein crops and fish, but less red meat and dairy products, are consumed, and incentivizing afforestation of agricultural land (with mineral soils) for carbon sequestration. These measures could be particularly important when considering options for NDC enhancement (Table 1) and the ambitious national policy target of a carbon neutral Finland 2035 and carbon negative one soon thereafter (Government of Finland, 2019, 2020).

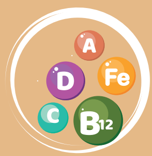
Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

<2% of the population undernourished in 2016. (Statistics Finland, 2017).



Micronutrient Deficiency

25% of the population are deficient in vitamin A and D; 20% of men are deficient on vitamin C and riboflavin (Valsta et al., 2018).

More than 50% of women are at the risk of deficiency of iron, not necessarily deficient (Valsta et al., 2018).

Overweight/ Obesity

26% of the population, and 25% of adults and 22% of children were obese in 2017. These shares have increased since 2011 (Koponen, Borodulin, Lundqvist, Sääksjärvi, & Koskinen, 2018).

67% of the population, and 62% of women and 72% men were overweight in 2017. These shares have increased since 2011 (Koponen et al., 2018).

Disease Burden due to Dietary Risks

65% of men and 50% of women are reported to have increased blood pressure, at least slightly, which increases risks to cardiovascular diseases. Increased blood pressure is often attributable to dietary risks (Koponen et al., 2018).

15% of men and 10% of women suffer from diabetes. 60% of people over 30 years old have increased cholesterol levels, partly attributable to dietary risks. 14% of men and 7% of women older than 50 years suffer from cardiovascular diseases, which can be caused by dietary risks (Koponen at al. 2018). Cardiovascular diseases were the immediate cause of death in 36% (equally for men and women) of all deaths in Finland 2017 (Statistics Finland, 2017).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,805 (2,087)	2,788 (2,077)	2,677 (2,078)	2,787 (2,078)	2,607 (2,078)
Fats (g) (recommended range	120 (62-94)	119 (62-93)	105 (59-89)	119 (62-93)	92 (58-87)
Proteins (g) (recommended range	96 (70-245)	95 (70-244)	93 (67-234)	95 (70-244)	89 (65-228)

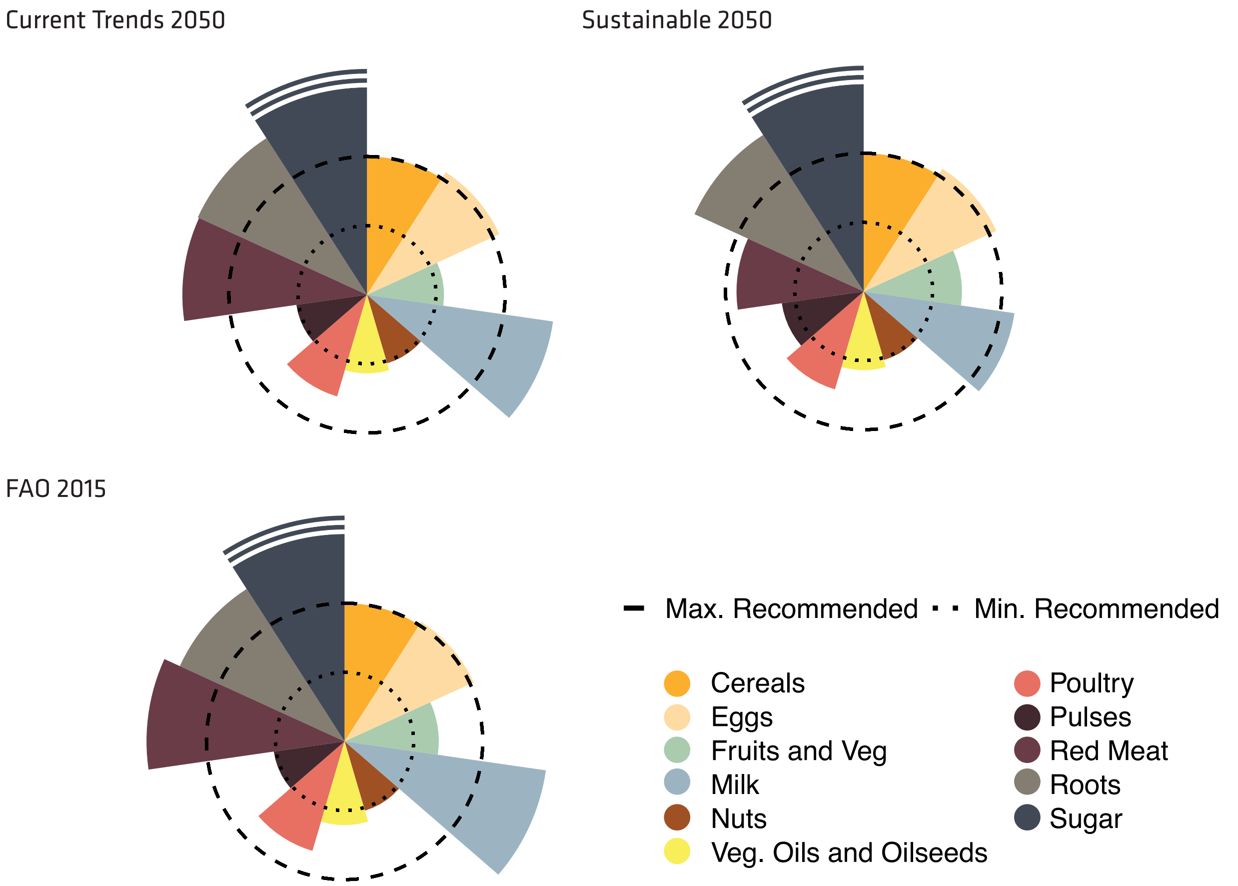
Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 34% higher in both 2030 and 2050 (Table 4). The current average intake is mostly satisfied by cereals and animal products, especially dairy products and meat. We assume that the consumption of animal products, as well as other food categories, will stay the same between 2020 and 2050. Compared to the EAT-Lancet recommendations (Willett et al., 2019) animal products, especially red meat, white meat and dairy products are over-consumed while fruits and vegetables, pulses and nuts are in the lower range of recommended intake (Figure 6). Moreover, while fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050, protein intake remains within the recommended range.

Under the Sustainable Pathway, we assume that diets will transition towards fruits and vegetables and protein crops, and away from red meat and dairy products. The ratio of the computed average intake over the MDER decreases to 29% in 2030 and 25% in 2050 under the Sustainable Pathway. Compared to the EAT-Lancet recommendations (Willett et al., 2019), the consumption of sugar, dairy products, and roots is high and still remains outside of the recommended range of consumption. However, fruit and vegetable consumption has increased, and red meat consumption has decreased and is now within the recommended range (Figure 6). The fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and also slightly in 2050, nevertheless showing significant improvement compared to the Current Trends Pathway (Table 4). Increased consumer guidance and information will be particularly important to promote this shift in diets.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



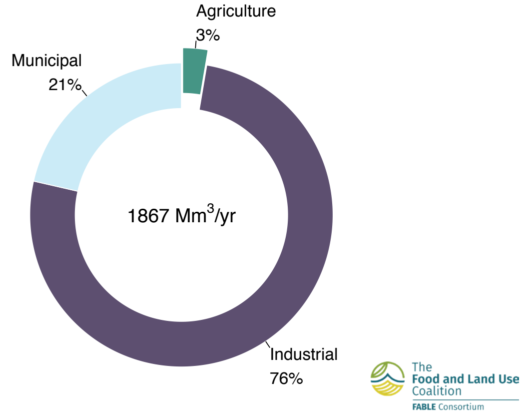
Notes. These figures are computed using the relative distances to the minimum and average recommended levels (i.e. the rings), therefore the different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring.

Water

Current State

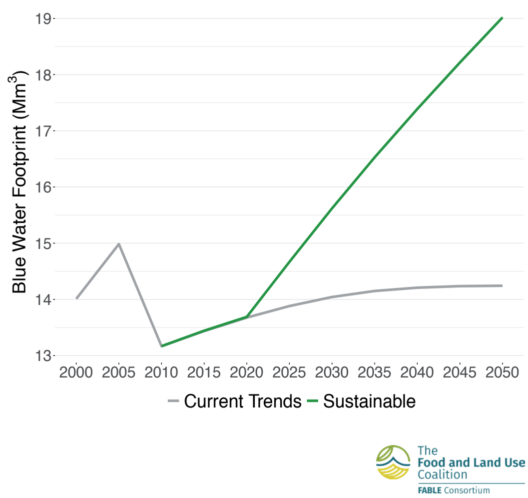
Finland, located in northern Europe between the 60th and 70th parallel north latitudes, is characterized by relatively harsh climatic conditions from an agricultural point of view. The growing season, which ranges from early to late May to late August or September with temperature sums of 900-1600 degree days, is suitable for a limited number of crops. Winter wheat, winter rye, grain legumes, and winter oilseed rape are cultivated in southern parts of the country (Peltonen-Sainio et al., 2013) but crop production is dominated by spring cereals such as barley and oats for animal feed (OSF, 2020). Annual precipitation, which averages between 550-700 mm, is clearly higher than annual evapotranspiration. However, early summer drought (from May to June) often limits crop yields since a large part of annual precipitation occurs over the period August to December (Ministry of the Environment and Statistics Finland, 2017; Tao et al., 2015). Nevertheless, irrigation is mostly limited to horticulture and seed crop production. The agricultural sector represented 3% of total water withdrawals in Finland (OSF, 2018) (Figure 7). Moreover, in 2016, 2.5% of agricultural land was equipped for irrigation, almost half of which is for potato, representing a small fraction of estimated-irrigation potential (OSF, 2018). Irrigation, either sprinkler or drip irrigation, was used in open air vegetable and berry production and in greenhouse production (OSF, 2018). The most exported crops (oats, wheat, and barley) are not irrigated, thus their annual production and export volumes are highly variable due to weather conditions affecting crop yields.

Figure 7 | Water withdrawals by sector in 2016



Source. Adapted from AQUASTAT Database (FAO, 2017)

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



Pathways and Results

Under the Current Trends Pathway, annual blue water use remains stable between 2000-2015 (14 and 13 Mm^3/yr), before plateauing at 14 Mm^3/yr between 2030 and 2050, respectively (Figure 8), with vegetables and potato production accounting for most of the computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Pathway, blue water footprint in agriculture reaches 16 Mm^3/yr in 2030 and 19 Mm^3/yr in 2050, respectively. This increase in blue water use is due to the increasing vegetable production. However, drip irrigation (see Annex 2) improves the water-use efficiency of irrigation (Pajula & Triipponen, 2003).

4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account

Resilience of the Food and Land-Use System

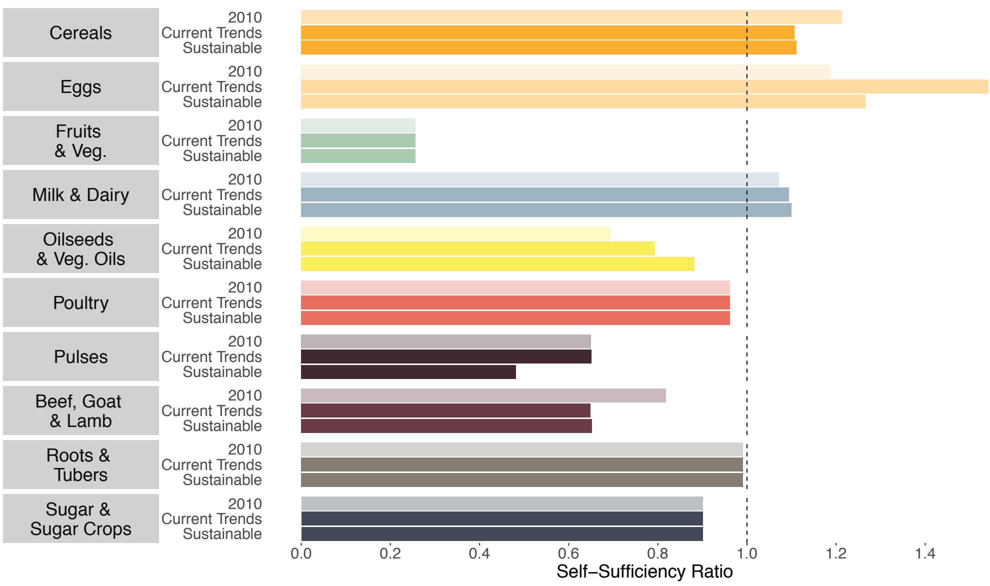
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Finland's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

In Finland, 70-80% has been used as a proxy for self-sufficiency of food, as in the recent COVID-19-related food-security discussion (Niemi, 2020; Pihlanto, 2020). Providing an exact estimate of food self-sufficiency is challenging because of the large differences in the share of domestic production out of consumption per product, the shares of which vary over different years due inter-annual fluctuations in imports and, for example, annual crop yields (Niemi, 2020; Niemi & Väre, 2019; OSF, 2020). Very recently, Finland was ranked the 5th best country in terms of food security in the world. One key reason was the high share of domestic ingredients used in foods consumed in Finland (The Economist, 2020).

Under the Current Trends Pathway, we project that Finland would be self-sufficient in cereals, eggs, and dairy in 2050, almost self-sufficient in poultry, roots and tubers, with self-sufficiency decreasing in beef but increasing only in oilseeds, with the other products staying constant from 2010 to 2050 (Figure 9). The product groups for which Finland depends the most on imports to satisfy internal consumption are fruits and vegetables and pulses. This dependency will remain rather stable until 2050. Under the Sustainable Pathway, by 2050, Finland remains self-sufficient in cereals, eggs, and dairy, and almost self-sufficient in poultry, roots and tubers, as in the Current Trends Pathway. However, Finland would be less self-sufficient in pulses and nuts because of increasing consumption and unfavorable climatic conditions to grow these crops.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

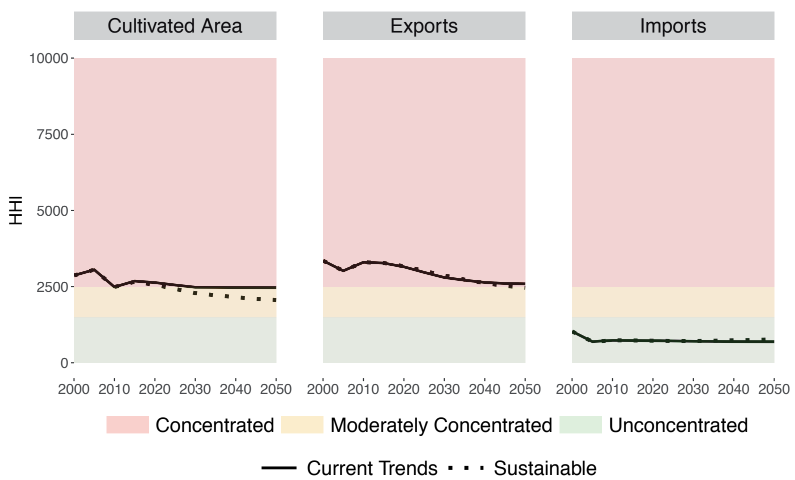
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, sec. 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

In Finland, crop production has been and is currently dominated by cereals and grass forage production for feed (OSF, 2020), crop exports have been heavily dominated by barley, oats and wheat, depending on the weather and harvest conditions affecting the crop yields (OSF, 2019a, 2019b), while crop imports are less concentrated since a large number of crops, especially fruits and vegetables, are imported (OSF, 2019b).

Under the Current Trends Pathway, we project the high concentration of crop exports to continue although to decrease gradually. This is due to excess production of cereals not being very profitable in a country where crop yields are lower than in most other countries in Europe. We also project low concentration of imports to continue. These trends show rather low diversity and low competitiveness of crop production over the period 2010-2050. In contrast, under the Sustainable Pathway, we project slowly increasing diversity of crop production since cereals production for feed will decrease and vegetable and oilseed production will increase. This change is slow but significant up to 2050. Increased diversity of crop production and reduced monocultures also support slightly higher crop yields per hectare in the Sustainable Pathway compared to the Current Trends Pathway. Diversity of crop imports will also stay high in the Sustainable Pathway since fruits and vegetable consumption increases. Consumption and imports of nut and pulse crops also increase slightly. Diversity of exports only increases slightly in the Sustainable Pathway, compared to the Current Trends Pathway (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

The outcomes of the two pathways, Current Trends and Sustainable, clearly show that even without drastic changes in diets, productivity, food trade, land use, or GHG abatement, gradual and consistent changes in the same direction will cause very large changes in the entire Finnish agriculture and food system. The key driving force in this development is food consumption. If there is lower demand for animal products and increased demand for fruits and vegetables and protein crops, producers will have no option but to follow. Sustainable production practices are another key point that must be ensured, specifically productivity increases need to be attained with improved utilization of production inputs. This requires improved quality of agricultural soils (e.g. water retention and soil pH), improved crop protection and crop rotation, which can be promoted by, for example, more diversified crop production which may also improve biodiversity and resilience at the farm level. Large scale, often monocultural, cultivation of feed crops in highly specialized farms in specialized production regions would diminish with decreased demand for animal-based foods. Instead, protein crops as well as expanding fruit and vegetables production could diversify land use both at farm and regional scale.

Nevertheless, large scale, efficient, and productive livestock farms and related production chains are also needed in the future as the consumption of livestock products is unlikely to rapidly decrease. Instead, 50-70% of current demand and production may remain close to year 2050. Animal products have clear advantages in human nutrition, especially for children and elderly people, because of, for example, iron, zinc, vitamins B12 and D, as well as calcium and selenium, all of which are not easily obtained from purely vegetarian or vegan diets. However, decreasing the consumption of animal-based foods would have positive health effects for many people in Finland since high cholesterol and blood pressure as well as cardiovascular diseases are often linked to high saturated fat intake. Reasonable volume of advanced and more sustainable livestock production with more efficient and accurate input use is also useful for maintaining soil quality and biodiversity with the means of rotational grasslands, including high nature valued biotopes, and advanced manure management. Animal farms can also produce biogas for energy and utilize more effective nutrient recycling.

Our results suggest that decreased animal production is needed for large scale land use change necessary for the effective reduction of GHG emissions from agriculture. A large part of GHG emissions originate from croplands while relatively less coming from enteric fermentation of animals and manure management, even though decreasing methane and nitrous oxide from animal production is also important. Reduced livestock production would nevertheless decrease feed demand and overall level of fertilization and nitrous oxide emissions from soils. Specific measures for decreasing GHG emissions from organic soils prove to be effective in reducing greenhouse gas emissions. With decreased demand for livestock products, all peatlands currently under cultivation are not needed in agricultural production, thus part of them could be rewetted, afforested, or even abandoned, resulting in significant GHG emission reductions per ha. Decreased cultivation area of feed crops would also free up some mineral soils. Afforesting these mineral soils can produce a significant reduction in GHG emissions over long run, though much less per hectare than from organic soils. More accurate accounting for peatlands and their productivity and GHG emissions could improve the analysis significantly when finding cost-effective approaches for long-run sustainability. In addition, we do not account for other environmental effects, such as possible nutrient leaching to watercourses. These, however, require more specialized studies.

Our results suggest that all these changes together may contribute up to a 42% reduction in AFOLU emissions by 2050. The key driver to launch this kind of change are more climate-, environment-, and health-conscious consumer behaviors. To obtain these reductions, it is not necessary for all people to become vegans but many must halve their consumption of livestock products. It is also important that the land-use changes and productivity developments described in this chapter have the opportunity to be effectively realized. This requires investments in agricultural research and development. In addition, to obtain the required large-scale changes in agriculture, economic incentives for change are pivotal. Productivity does not increase without effort. However, the costs linked to this or other large-scale changes in agriculture are not analyzed in this study.

There also have to be sufficient incentives for farmers to implement effective land use changes and other means of decreasing GHG emissions. For example, lost farm subsidies due to afforestation, re-wetting peatlands, and lost incomes due to changes in production practices (diversification or reduction of fossil-based inputs) should be compensated, at least partly, for farmers who need to find profitable and feasible alternatives already in the near future. Launching this change and seeing the long-run big picture of these developments is the main challenge for policymakers as well as for the society at large.

Annex 1. List of changes made to the FABLE Calculator to adapt it to the Finnish context

- Extended possible feed types to typical Finnish feeds
- Included feed efficiency scenarios: possible to increase or decrease the required feed per TLU
- Extended productivity shifters to product-specific multipliers
- Extended import and export scenarios to product-specific scenarios
- Included a custom extension to take peatland soil emissions in agriculture into account

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)	
Current Trends Pathway	**Sustainable Pathway**
The population is expected to reach 5.9 million by 2050. Based on Statistics Finland (2015). (SSP2 scenario selected)	The population is expected to reach 5.9 million by 2050. Based on Statistics Finland (2015). (SSP2 scenario selected)

LAND Constraints on agricultural expansion	
Current Trends Pathway	**Sustainable Pathway**
We assume no expansion of agricultural land beyond 2010 agricultural area levels. This is because cultivated farmland area has remained stable since 2000 (OFS, 2020). We assume that there will be no expansion of the agricultural land on existing protected areas.	Same as Current Trends.
LAND Afforestation or reforestation target (1000 ha)	
We assume that deforestation will not be fully halted beyond 2030. However, the rate of deforestation remains very small (Aakkula et al., 2019). We did not take afforestation into account in this pathway (no afforestation scenario selected).	We assume that deforestation will be halted and afforestation of unused farmland results in slightly increased forest area beyond 2030. We assume total afforested/reforested area to reach 0.2 Mha by 2050. (LowCarbon scenario selected)

BIODIVERSITY Protected areas (1000 ha or % of total land)	
Current Trends Pathway	**Sustainable Pathway**
Protected areas remain stable: by 2050 they represent 16% of total land.	Same as Current Trends.

PRODUCTION Crop productivity for the key crops in the country (in t/ha)	
Current Trends Pathway	**Sustainable Pathway**
By 2050, crop productivity reaches: • 3.4 tonnes per ha for barley • 3.3 tonnes per ha for oat • 3.7 tonnes per ha for wheat Based on Tao et al. (2015)	By 2050, crop productivity reaches: • 3.6 tonnes per ha for barley • 3.5 tonnes per ha for oat • 3.9 tonnes per ha for wheat Based on Tao et al. (2015)
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)	
By 2050, livestock productivity reaches: • 11,000 kg milk per head for dairy cows • 360 kg per head for cattle bulls • > 30 piglets per sow Based on food industry expert consultations.	Same as Current Trends.
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)	
By 2050, the average ruminant livestock stocking density is less than 1 TLU/ha. Based on Lehtonen et al. (2017)	Same as Current Trends.
PRODUCTION Post-harvest losses	
By 2050, the share of production and imports lost during storage and transportation is only slightly reduced.	By 2050, the share of production and imports lost during storage and transportation is reduced by 20% Based on Silvennoinen et al. (2015)

TRADE Share of consumption which is imported for key imported products (%)	
Current Trends Pathway	**Sustainable Pathway**
By 2050, the share of total consumption which is imported is: • 50% for cheese • 35% for beef • 10 % for poultry Based on Lehtonen (2015)	Same as Current Trends.
TRADE Evolution of exports for key exported products	
By 2050, the volume of exports is: • Significantly decreased for cereals • Slightly increased for dairy products • Remained unchanged for other products Based on Lehtonen (2015)	Same as Current Trends.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita: • remained unchanged for animal products • remained unchanged or slightly increased for fruits and vegetables • remained at low levels for pulses and nuts (expert opinion)	By 2030, the average daily calorie consumption per capita is: • decreased significantly for animal products • increased significantly for fruits and vegetables • increased moderately for pulses and nuts Based on Saarinen et al. (2019)

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
By 2030, the share of final household consumption which is wasted at the household level is unchanged. Based on expert opinion	By 2030, the share of final household consumption which is wasted at the household level is decreased moderately. Based on Silvennoinen, Heikkilä, Katajajuuri, & Reinikainen (2015)

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
By 2050, biofuel production is at a small scale and based on few biogas plants utilizing manure and excess forage grass biomass as input. Based on Niemi & Hären (2020)	By 2050, biofuel production is at a moderate scale and based on few biogas plants utilizing manure and excess forage grass biomass as input. Based on Niemi & Väre (2020)

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO2 fertilization effect. The results are similar to the ones by Tao et al. (2015)	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO2 fertilization effect. The results are similar to the ones by Tao et al. (2015)

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tonness

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Germany. It presents three pathways for food and land-use systems for the period 2020-2050: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition (referred to as "*Current Trends*", "*Sustainable*", and "*Sustainable* +" in all figures throughout this chapter). These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways benefitting from consultations with national stakeholders and experts, including from the Chamber of Agriculture in Lower Saxony (Landwirtschaftskammer Niedersachsen), the Farmers' Association North East Lower Saxony (Bauernverband Nordostniedersachsen), the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (Nds. Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz), the Lower Saxony Ministry of Food, Agriculture and Consumer Protection (Nds. Ministerium für Ernährung, Landwirtschaft und Verbraucherschutz), the Lower Saxony Ministry for the Environment, Energy, Building, and Climate Protection (Nds. Ministerium für Umwelt, Energie, Bauen und Klimaschutz), Greenpeace Hamburg, and the German Federation for the Environment and Nature Conservation Lower Saxony (BUND Niedersachsen) as well as interviews with farmers in the context of the Integrative modeling lab on agricultural adaptation in North Germany (IMLAND), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how the European Union's (EU) NDC, which applies to Germany, and Germany's Long Term Low Emissions and Development Strategy (LT-LEDS) address the FABLE domains. According to the LT-LEDS, Germany has committed to reducing its GHG emissions by at least 55% by 2030 and by 80 to 95% by 2050 compared to 1990. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include substantial reductions in surplus nitrogen and ammonia emissions, increasing the share of organically farmed land to 20% by 2030 (from 6.3% in 2014), and optimizing the next reform of the EU Common Agricultural Policy (CAP) and its elements in light of their effectiveness for climate change mitigation under the principle of "public funds for the public good" (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit [BMUB], 2016). Under its current commitments to the UNFCCC, Germany mentions biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and LT-LEDS

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
(EU) NDC (2016)	1990	1,249	2030	At least 40% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Forests
LT-LEDS (2016)	1990	1,248	2030 / 2050	At least 55% / 80 to 95% GHG emissions reduction	Economy-wide (Energy, buildings, transport, industry, agriculture, other)	Y	Y	N	food security, water, forests

Note. "Total GHG Mitigation" and "Mitigation Measures related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source: EU (2016) for the NDC, UNFCCC (2020) for GHG inventory data, and EU (2020) for the LT-LEDS

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. In comparison with FABLE targets, German NBSAP Targets are on the whole less precise and ambitious.

Table 2 | Overview of the latest NBSAP Targets in relation to FABLE Targets

NBSAP Target	FABLE Target
10% of public woodland allowed to develop naturally	**DEFORESTATION:** Zero net deforestation from 2030 onwards
Initiative for more wilderness in Germany	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
Improve the conservation status of species and habitats	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present three alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Germany.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by a small population decline (from 81.86 million inhabitants in 2020 to 78.91 million in 2050), significant constraints on agricultural expansion, no afforestation target, no change in the extent of protected areas (37.7% of total land in 2010), medium productivity increases in the agricultural sector, and a slow reduction of the share of food wasted by consumers to 50% compared to 2010 levels by 2050. Furthermore, we assume an evolution towards a slightly more flexitarian diet, expressed through a cultural shift towards 10% vegetarians and 1.5% vegans, as well as a reduction in average overall caloric intake by 10% and by 50% in sugar and fat intake, respectively (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regard to crop and livestock productivity, as projected from historical data trends, food waste, and dietary changes, as targeted by current policies, and slow popularity growth of plant-based diets, especially among younger generations (Bundesministerium für Ernährung und Landwirtschaft [BMEL], 2018b, 2019a, 2019d, 2020a; Drenckhahn et al., 2020). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, soybeans, and wheat (see Annex 2).

Our Sustainable Medium Ambition Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to a slight population growth instead of a decline (from 82.2 million inhabitants in 2020 to 82.4 million in 2050) due to SSP1-associated improvements in overall human wellbeing and mortality. Furthermore, we assume a higher extent of protected areas (from 37.7% of total land in 2010 to 42% in 2050), higher productivity increases in the agricultural sector, a quicker pace of the 50% reduction in the share of consumer food waste, and a stronger cultural shift towards a more flexitarian diet, with an increasing number of vegetarians (20%) and vegans (2%) by 2050 as well as a 30% reduction in overall average caloric and a 50% reduction in sugar and fat intake. The restrictions on agricultural expansion and the low national afforestation target are the same for both the Current Trends Pathway and the Sustainable Medium Ambition Pathway (see Annex 2). This corresponds to a future based on policies that favor a shift to plant-based diets, such as carbon prices in the agricultural sector and agro-environmental subsidies, large investments into research and development of technologies improving agricultural productivity, information campaigns about food waste as well as support for food-saving initiatives, and treating biodiversity protection of similar importance as climate change. This future would also see considerable progress with regard to GHG emission mitigation and land-use, due to the reduction in required resources. With the other FABLE country teams, we embed this Sustainable Medium Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Our Sustainable High Ambition Pathway represents a future in which politicians and society follow the Sustainable Medium Ambition Pathway but put even more effort into changing the dietary culture in Germany. The target diet would rely mostly on plants, increasing especially the share of legumes and nuts, while (often drastically) reducing animal products and reducing overall average caloric intake by about 30% in comparison to 2010, effectively working towards the EAT-*Lancet* diet, as defined by (Willett et al., 2019). The pathway corresponds to the highest boundary of feasible action. Compared to the Sustainable Medium Ambition Pathway, we assume that this future would lead to a greater reduction of consumed animal products. The diet change is the only difference between the Sustainable Medium Ambition and Sustainable High Ambition Pathway, all other scenarios are the same (see Annex 2). As in the Sustainable Medium Ambition Pathway, we embed this Sustainable High Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

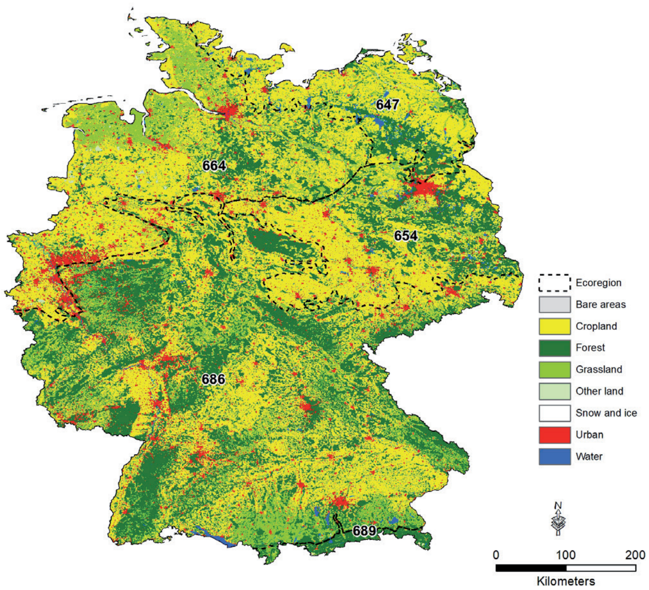
Land and Biodiversity

Current State

In 2010, Germany was covered by 36% cropland, 14% grassland, 32% forest, 7% urban, and 11% other natural land. While agriculture is an important sector in all German regions, agricultural areas are especially prevalent in the north and the east. Similarly, forests and other natural land can be found everywhere in Germany, but they are especially dense in areas not suited for intensive agriculture, such as mountainous regions in the center and south (Map 1). The loss of biodiversity, and especially insects, is a core issue for biodiversity policies in Germany, which has at its disposal a range of measures, such as incentivizing insect-friendly agriculture, investing in research and development of digital agricultural technologies that may increase biodiversity protection, and reducing the expansion of land used for housing and transport to net-zero by 2050 (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit [BMU], 2019a).

We estimate that land where natural processes predominate[2] accounted for 19% of Germany's terrestrial land area in 2010 (Map 2). The 689-Alps conifer and mixed forests hold the greatest share of land where natural processes predominate, followed by 647-Baltic mixed forests and 654-Central European mixed forests (Table 3). Across the country, while 13.1Mha of land is under formal protection, meeting the 30% zero-draft CBD post-2020 target, only 67.9% of land where natural processes predominate is formally protected. This indicates that large parts of German forests will stay important in the future, especially since there is low risk of deforestation in general in Germany, even without formal protection. However, German forests may increasingly face other issues, such as the changing climate resulting in more severe droughts and storms, more frequent and more severe forest fires, and novel and

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



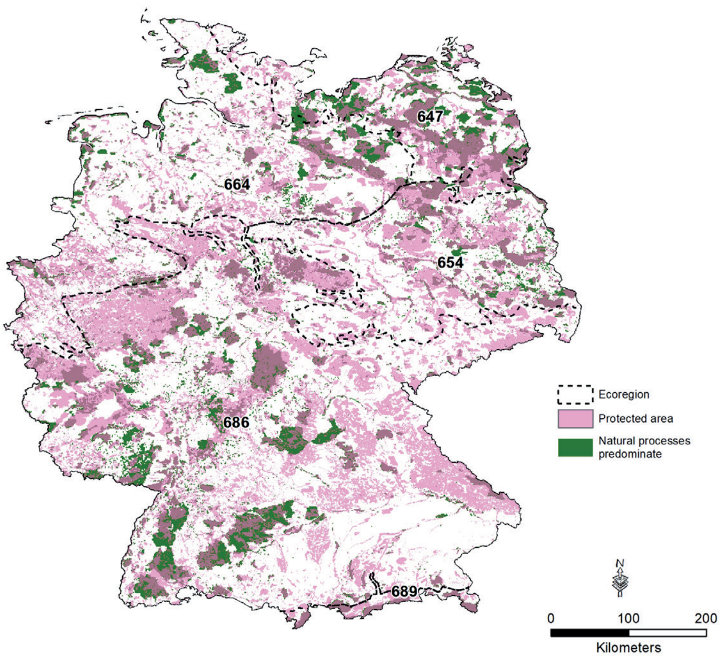
Notes. Correspondence between original ESACCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

stronger pests. To counteract these problems, policies increasing forest protection and reforestation have been put into action (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz [BMELV], 2011; BMEL, 2019b).

Approximately 36% of Germany's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in 689-Alps conifer and mixed forests, followed by 686-Western European broadleaf forests and 664-European Atlantic mixed forests. The regional differences in the extent of biodiversity-friendly cropland can be partly explained by less intensive, more traditional agricultural practices, as seen in the Alps.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Notes. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within $1km^2$ (%)
647	Baltic mixed forests	3113.7	43.5	37.3	68.1	31.9	1826.1	29.0
654	Central European mixed forests	4881.2	37.2	18.4	75.2	24.8	2755.7	24.9
664	European Atlantic mixed forests	7750.2	29.0	16.9	62.8	37.2	4142.8	35.4
686	Western European broadleaf forests	19472.0	39.0	18.2	66.9	33.1	7392.5	42.2
689	Alps conifer and mixed forests	345.2	61.9	37.9	95.5	4.5	6.8	90.7

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

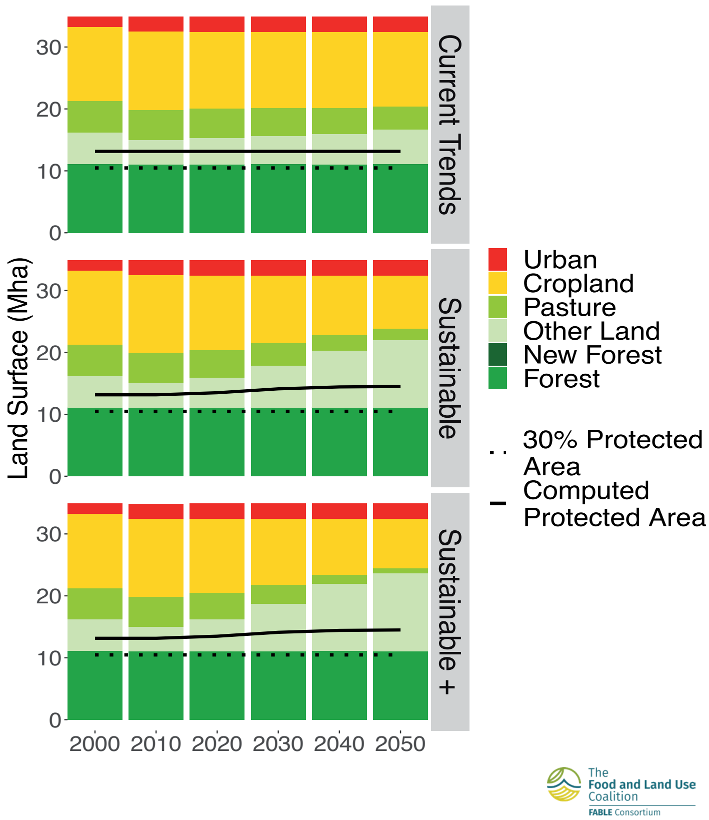
Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including constraints on the expansion of agricultural land beyond its current area, no planned afforestation, with reforestation limited to keeping net-zero forest loss, and protected areas remaining at 13.2Mha, representing 37.7% of total land cover (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in other natural land area and a decrease in pasture area. This trend remains stable over the period 2030-2050: other natural land area will further increase at the expense of pasture area (Figure 1). Pasture reduction is mainly driven by an increase in milk consumption and a decrease in beef consumption while livestock productivity per head increases and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, the further decrease of pasture area and the corresponding increase in other natural land area is explained by a continued increase in livestock productivity outweighing the growing demand for milk. This results in an expansion of land where natural processes predominate by 10% by 2030 and by 26% by 2050 compared to 2010, respectively (Figure 2).

In the Sustainable Medium Ambition and Sustainable High Ambition Pathways, assumptions on protected areas have been changed to reflect discussions beyond the Aichi biodiversity targets, EU-wide recognition of the importance of ecosystem services, and highly ambitious targets, such as the "Nature Needs Half" initiative (Drenckhahn et al., 2020; European Commission, 2011; *Germany - Nature Needs Half,* n.d.). The main assumptions include net-zero forest loss, constraints on the expansion of agricultural land beyond its

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

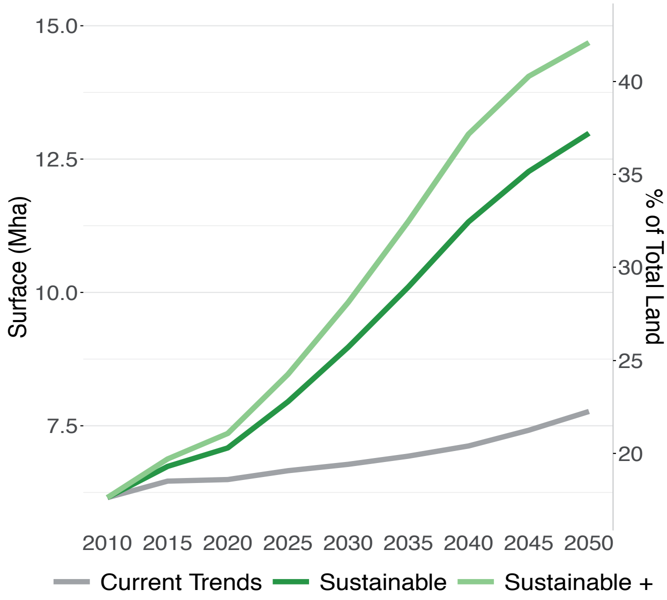


Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Area (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

current area, and protected areas increase from 37.7% of total land in 2010 to 42% in 2050, including at least 50% protected area in each ecoregion (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Germany in the Sustainable Medium Ambition and Sustainable High Ambition Pathways: (i) cropland steadily decreases starting in 2025, (ii) pasture area decreases even more, especially between 2020–2050, and (iii) other natural land area increases accordingly to the loss in agricultural area), where all of these effects are stronger in the Sustainable High Ambition Pathway compared to the Sustainable Medium Ambition Pathway. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by dietary shifts that reduce the amount of pasture-intensive animal products consumed, such as milk and beef, while also reducing overall caloric intake, including from crop products, and higher increases in crop and livestock productivity. This leads to an increase in the area where natural processes predominate: the area increases by 111% between 2010 and 2050 in the Sustainable Medium Ambition Pathway and by 139% in the Sustainable High Ambition Pathway, creating 37% and 42% of total land in Germany where natural processes predominate, respectively (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate

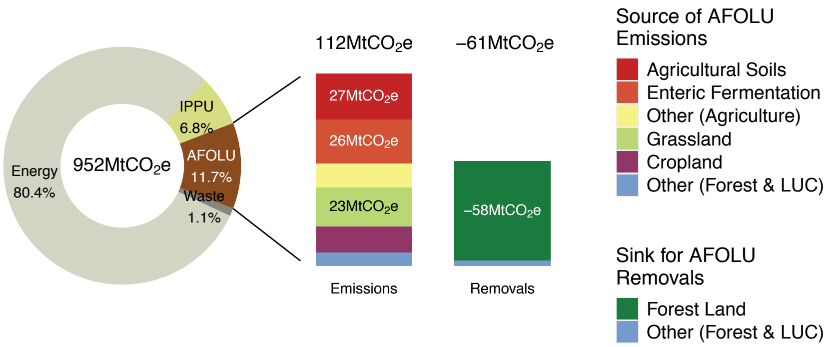


GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 11.7% of total emissions in 2017 (Figure 3). Agricultural soils are the principal source of AFOLU emissions, followed by enteric fermentation, grassland, cropland, and manure management. This can be explained by the large number of dairy cattle in Germany as well as both storage and intensive application of manure and other fertilizers. Furthermore, large shares of German agricultural land are drained and degraded peatlands. These lands are often very productive, but also sources of a significant amount of the GHG emissions from the German agricultural sector (Tiemeyer et al., 2020; Umweltbundesamt [UBA], 2018).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2017

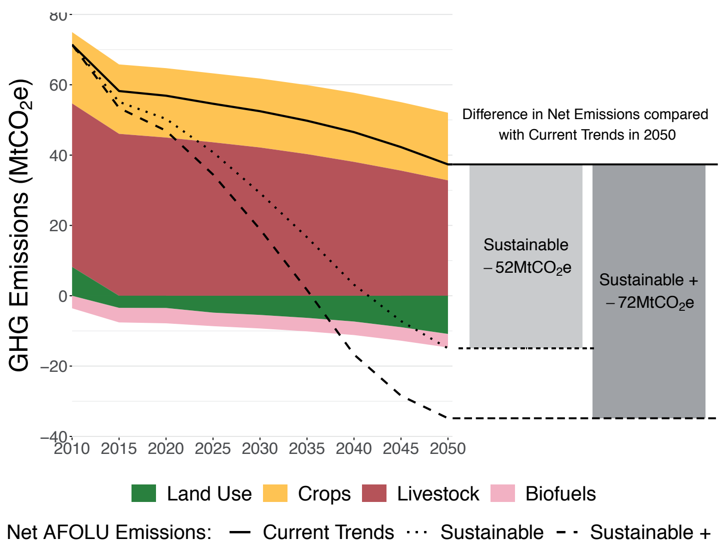


Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 52.5 Mt CO_2e/yr in 2030, before declining further to 37.4 Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock is the largest source of emissions (33 Mt CO_2e/yr) while biofuels and sequestration act as sinks (-4 Mt CO_2e/yr and -11 Mt CO_2e/yr, respectively). Over the period 2020-2050, the strongest relative decrease in GHG emissions is computed for livestock (-27%)

Figure 4 | Potential AFOLU emissions reductions by 2050 by trajectory compared to the Current Trends Pathway

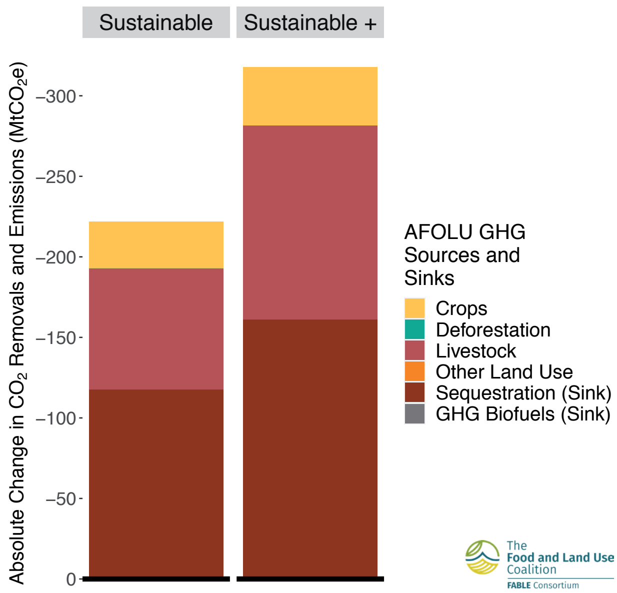


while sequestration sees the strongest relative increases (179%).

In comparison, the Sustainable Medium Ambition Pathway leads to a reduction of AFOLU GHG emissions by an additional 140% and the Sustainable High Ambition Pathway to a reduction by an additional 193% compared to the Current Trends Pathway (Figure 4) emission levels by 2050. The potential emissions reductions under the Sustainable Medium Ambition Pathway is dominated by a reduction in GHG emissions from livestock. The assumed diet change towards a more plant-based lower-calorie diet and the increasing livestock productivity are the most important drivers of this reduction. Under the Sustainable High Ambition Pathway, GHG emissions from livestock are further reduced thanks to further, more ambitious changes in diet assumptions (Figure 5).

Compared to Germany's commitments under UNFCCC (Table 1), our results show that beyond the Current Trends Pathway contributions AFOLU could contribute to as much as 7% of its total GHG emissions reduction objective by 2030 under the Sustainable High Ambition Pathway. Such reductions could be achieved through policy measures, such as incentivization and advertisement of a more plant-based and overall more sustainable diet, e. g. by extending carbon pricing to all sectors and removing subsidies counteracting these price effects, and higher investments into research and development, allowing for sustainable intensification, higher yield efficiency, and higher crop resilience to pests and climate. The positive effects of such policies may be further increased by extending current reforestation policies to afforestation of land freed up due to consumption changes These measures could be particularly important when considering options for NDC enhancement. AFOLU is, by far, the sector with the smallest amount of emissions, but still contributes tens of millions of tonnes CO_2e which these policies may help to reduce even further than currently planned, as far as potentially achieving sectoral net negative emissions by 2050. Considering the shared EU goal of at least 40% domestic GHG emissions reduction by 2030, such

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



a sector emissions pathway would either slightly reduce pressure in other sectors, enabling easier transitions, or allow for even more ambitious reductions overall, such as Germany's national climate action plan 2050, targeting GHG emissions reductions of overall at least 55% and about 30% in the agricultural sector by 2030–which is barely met by the Current Trends Pathway, while the Sustainable Medium Ambition and Sustainable High Ambition Pathways go beyond it.

Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

Less than 2.5% of the population was undernourished in 2017. This share is estimated based on EU shares and has likely been this low for several decades (FAO et al., 2019).

1.7% of children under 5 stunted and 0.3% wasted in 2016 (Schienkiewitz et al., 2018).

Micronutrient Deficiency

16.3% of women of reproductive age (15–49) and 12.4% of children under 5 suffer from anemia in 2016, which can lead to maternal death (WHO, 2017a, 2017b)

27% of school-age children were deficient in iodine in 1999, which can lead to developmental abnormalities (WHO, 2006).

Overweight/ Obesity

54% of adults were overweight in 2014, including 18.1% of adults who were obese. These shares have increased since 1999 (Schienkiewitz et al., 2017).

15% of children between 3 and 17 were overweight in 2016, including 6% of children between 3 and 17 who were obese. These shares have stayed the same since 2005 (Kurth & Schaffrath Rosario, 2007; Schienkiewitz et al., 2018).

Disease Burden due to Dietary Risks

0.2% of adult deaths are attributable to dietary risks (cardiovascular diseases, diabetes mellitus type 2, neoplasms), or 162 deaths per year (per 100,000 people) (Afshin et al., 2019).

8.5% of the population suffered from diabetes (type 2) in 2015, and 10% from cardiovascular diseases in 2010, which can be attributable to dietary risks (Robert Koch-Institut & Destatis, 2015; Tönnies et al., 2019).

Table 4 | Daily average fats, proteins, and kilocalories intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways in 2030 and 2050

	2010	2030			2050		
	Historical Diet (FAO)	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition
Kilocalories (MDER)	3,175 (2,106)	3,012 (2,083)	2,800 (2,083)	2,831 (2,083)	2,812 (2,079)	2,189 (2,079)	2,276 (2,079)
Fats (g) (recommended range)	135 (71-106)	129 (67-100)	122 (62-93)	128 (63-94)	116 (62-94)	96 (49-73)	112 (51-76)
Proteins (g) (recommended range)	94 (79-278)	94 (75-264)	84 (70-245)	87 (71-248)	100 (70-246)	69 (55-192)	77 (57-199)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014).For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

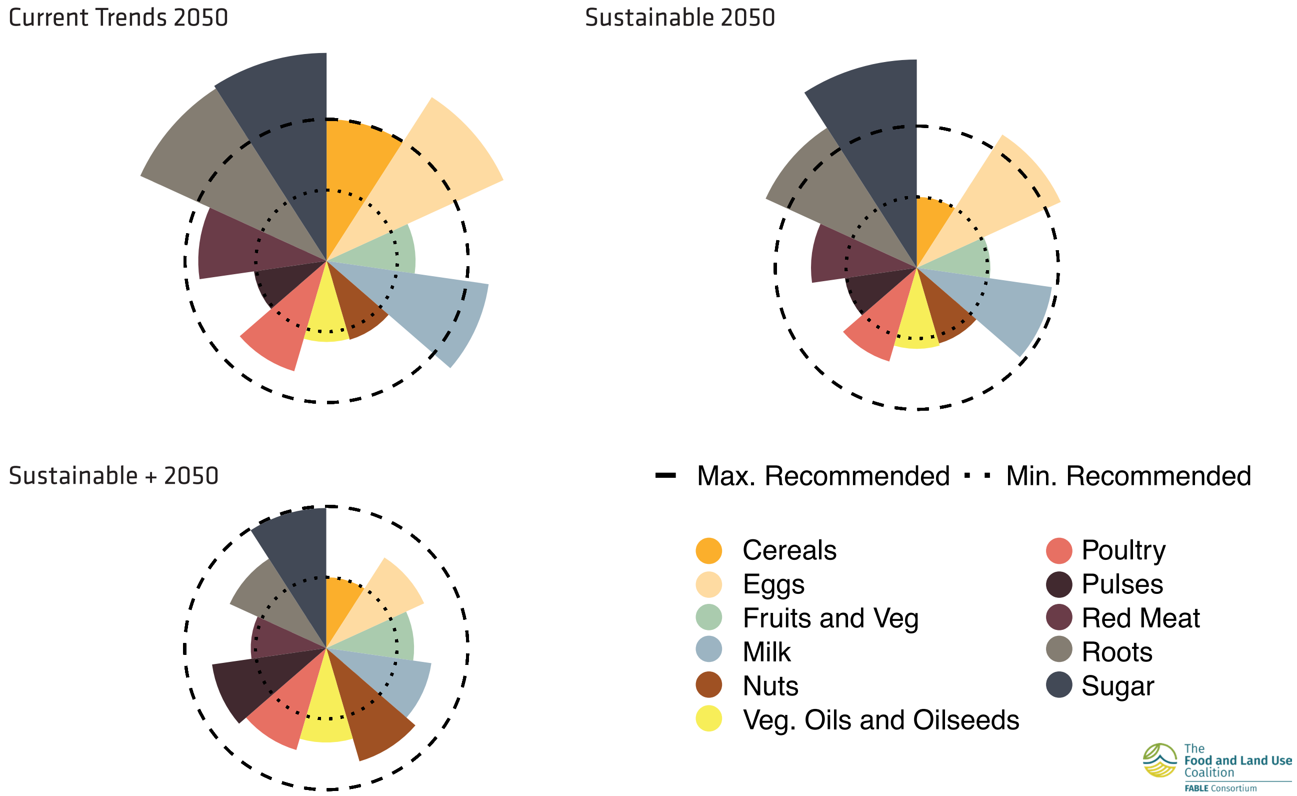
Requirement (MDER) at the national level, our computed average calorie intake is 45% higher in 2030 and 35% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals, oilseeds and vegetable oils, sugar, milk, pork, and animal fats. Animal products currently represent 28% of the total calorie intake. In general, we assume that the share of consumption of animal products will increase by 11% and, specifically, that the relative share of consumption of milk and eggs will increase by 12% between 2020 and 2050. The consumption of cereals, fruits and vegetables, roots, pulses, and nuts will also increase while the consumption of oilseeds and vegetable oils, sugar, pork, poultry, red meat, and animal fat will decrease. Compared to the EAT-*Lancet* recommendations (Willett et al., 2019), eggs, roots, milk, and sugar are over-consumed in 2050 (Figure 6). Moreover, despite a reduction between 2020-2050, fat intake per capita exceeds the dietary reference intake (DRI) in both 2030 and 2050, while protein stays within the reference range. This can be explained by a decline in the consumption of animal fats, and oilseeds and vegetable oils.

Under the Sustainable Medium Ambition Pathway, we assume that diets will transition towards a more plant-based diet with reduced overall caloric intake. Similar assumptions are made under the Sustainable High Ambition Pathway, where the target diet is even closer to the EAT-Lancet recommendations. The ratio of the computed average intake over the MDER decreases to 34% in 2030 and 5% in 2050 under the Sustainable Medium Ambition Pathway, and 36% in 2030 and 9% in 2050 under the *Sustainable High Ambition Pathway*.

Compared to the EAT-Lancet recommendations, only the consumption of eggs, roots, and sugar remains outside of the recommended range (albeit to a smaller degree compared to the Current Trends Pathway), while the consumption of milk is within the recommended range under the Sustainable Medium Ambition Pathway. Under the Sustainable High Ambition Pathway, all calculated product groups are within the recommended range in 2050 (Figure 6). Moreover, while the fat intake per capita still exceeds the DRI in 2030, it shows some improvement compared to the Current Trends Pathway.

Incentives, such as carbon pricing, restrictions on additives, and information campaigns on both personal and planetary benefits of such diet changes will be particularly important to promote this shift in diet. Regarding other sectors, similar mechanisms are already in place, foremost the EU Emissions Trading System (EU ETS), covering currently about 45% of all EU GHG emissions, as well as a more recent national pricing system covering German emissions from heating and transportation. AFOLU emissions, on the other hand, are currently not covered despite experts pushing for such a policy expansion. The recent political movement towards an animal welfare label, the adoption of the NutriScore food label, and the start of a campaign to reduce sugar and fat in convenience food highlight possible ways of restricting and informing about unhealthy products (BMEL, 2018a, 2018b, 2019c; BMUB, 2016; BMU, 2019b; Drenckhahn et al., 2020).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



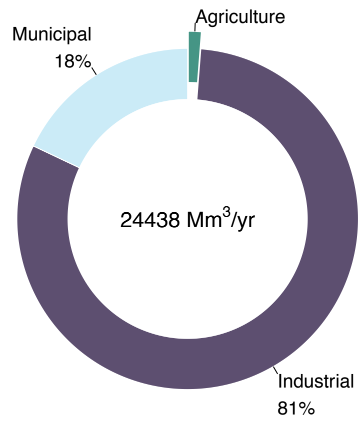
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings) i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring.

Water

Current State

Germany is characterized by a moderate climate, without any prolonged periods of extreme heat or cold (which tend to occur more in the continental south and east) and more maritime climate in the coastal regions and the northwest with 700mm average annual precipitation that occurs all year long and peaks in the period May–August. The agricultural sector represented 1% of total water withdrawals in 2016 (FAO, 2017; Figure 7). Moreover, in 2015, 100% of agricultural land was equipped for irrigation, representing 100% of estimated-irrigation potential. The three most important irrigated crops, corn, sugar beet, and potatoes, account for 25%, 19%, and 12% of total harvested irrigated area. Germany exported 11% of corn, 17% of potatoes, and 0.4% of sugar beet produced in 2017 (FAO, 2020).

Figure 7 | Water withdrawals by sector in 2016

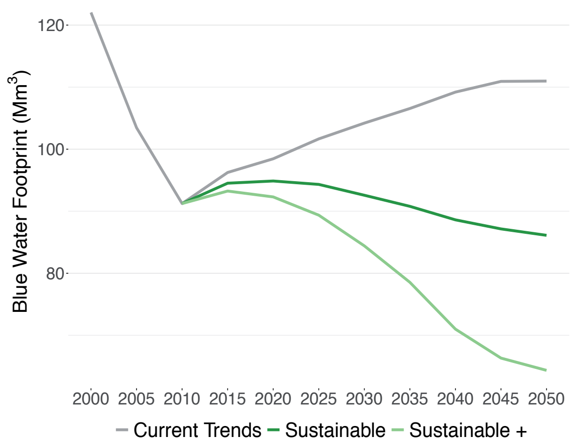


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use decreases between 2000-2015 (122 and 96.2 Mm^3/yr), before increasing to 104.2 Mm^3/yr and 111 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with potato accounting for 90% of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Medium Ambition Pathway, the blue water footprint in agriculture reaches 92.6 Mm^3/yr in 2030 and 86.1 Mm^3/yr in 2050, respectively. Under the Sustainable High Ambition Pathway, the blue water footprint further decreases to 64.3 Mm^3/yr in 2050. This is explained by changes in the produced amounts of water-intensive crop products, foremost potatoes, due to a decline in internal food demand due to diet changes. This effect is even more pronounced in the Sustainable High Ambition Pathway, where potato production decreases.

Figure 8 | Evolution of blue water footprint in the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

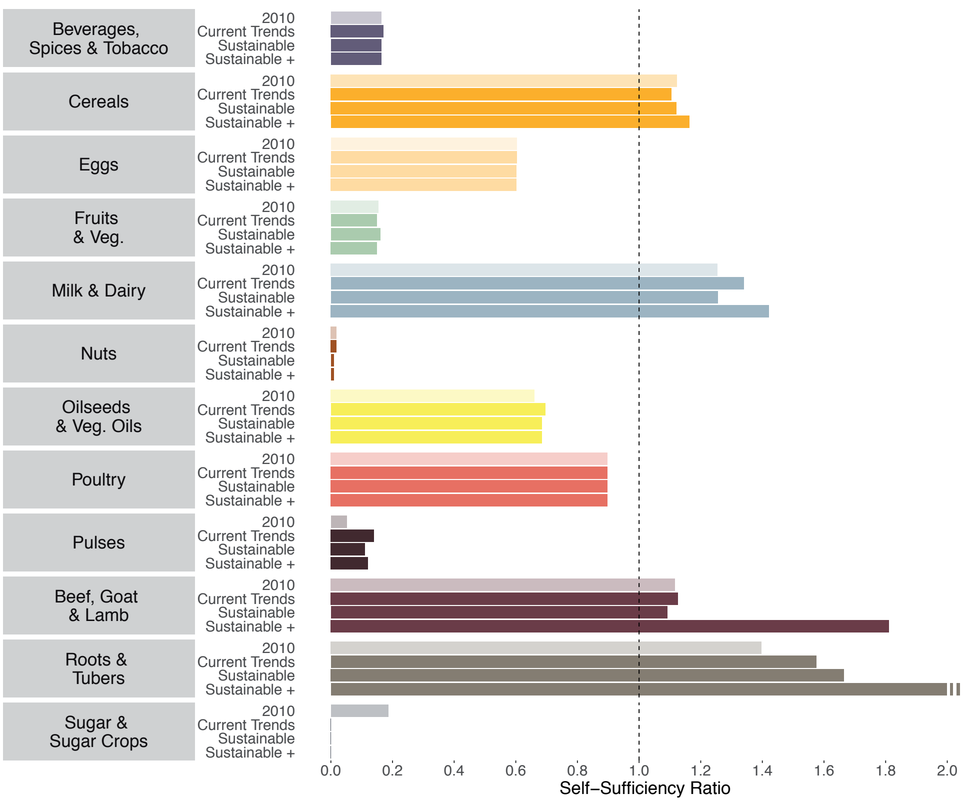
Resilience of the Food and Land-Use System

The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Germany's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Germany has a strong agricultural sector, taking up roughly half of all its land. Despite this size, it is reliant on imports for a variety of products, especially feed for its livestock. That is both because of its large livestock sector but also because of land-use conflicts between crops for biofuel, food, and feed. On the other hand, many imports are provided by European neighbors and, in most situations, being part of the EU may increase Germany's resilience, even though this would not strictly be considered self-sufficiency.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right of this figure, as seen for roots and tubers, indicate a high level of self-sufficiency for these categories.

Under the Current Trends Pathway, we project that Germany would be self-sufficient in cereals, milk and dairy, beef, goat and lamb, and roots and tubers in 2050, with self-sufficiency by product group increasing for the majority of products from 2010–2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are nuts, fruit and vegetables, pulses, sugar and sugar crops, and beverages, spices and tobacco and this dependency will remain stable for most products, increase for pulses, and decrease for sugar and sugar crops until 2050. Despite changes in internal demand, the overall self-sufficiency differs neither in the Sustainable Medium Ambition Pathway nor the Sustainable High Ambition Pathway to a large degree. This is despite notable increases in self-sufficiency in the Sustainable High Ambition Pathway regarding beef, goat and lamb, and roots and tubers since Germany was completely self-sufficient in these two groups even before the increase while product groups below self-sufficiency show little to no change.

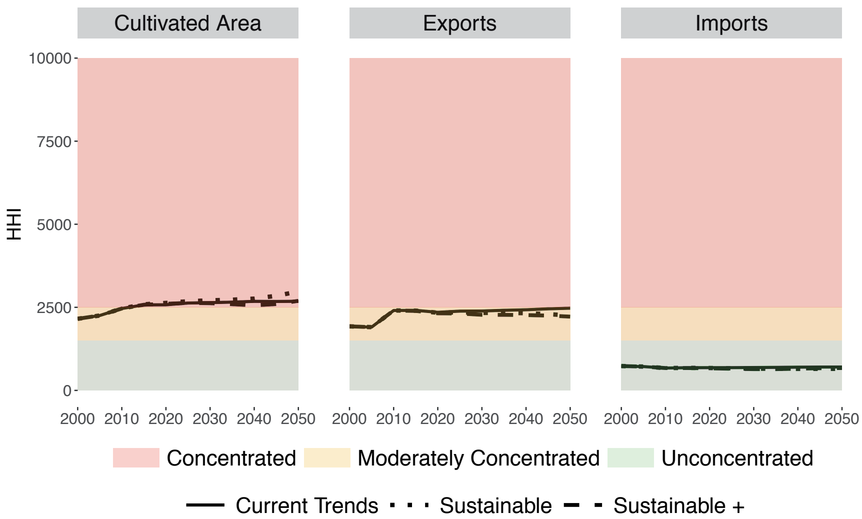
Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



According to the HHI, the planted crop area in 2010 is moderately concentrated and follows a trend towards high concentration. Similarly, exports are moderately concentrated bordering on highly concentrated in 2010 after a rapid spike in the previous years. Imports, on the other hand, diversified even further in the years 2000–2010 and were very unconcentrated.

Under the Current Trends Pathway, we project medium concentration of crop exports and crops planted in 2010 and low concentration of imports. Exports concentration rises slowly towards the upper limit of medium concentration between 2020–2050, concentration of crops planted rises slightly to a high concentration and levels off between 2030–2050, and the concentration of imports remains constant at very low concentration levels between 2020–2050. This indicates low levels of diversity across the national production system and exports, while imports seem to be highly diversified. Similarly, under both the Sustainable Medium Ambition Pathway and the Sustainable High Ambition Pathway, we project medium concentration of crop exports, low concentration of imports, and a high concentration in the range of crops planted in 2050, indicating low levels of diversity across the national production system and exports, but high levels of diversity across imports (Figure 10). This is explained by the large focus on a few strong export products, such as wheat and beef, while Germany imports low quantities of a large variety of goods. Similarly, few crops are grown in large amounts for feed, food, or biofuel, leading to highly concentrated cropland, which further concentrates with increasing internal demand towards crops, such as cereals.

Discussion and Recommendations

While many scenarios went into the German FABLE Calculator, the assessment in this chapter and especially the comparison of the Sustainable Medium Ambition and Sustainable High Ambition Pathways show very clearly that some scenarios have far more impact than others on German transformation pathways towards fewer greenhouse gas emissions and improved biodiversity protection in the AFOLU sector. According to these model results, it seems very clear that enhancing policies that move the populace towards a more plant-based diet may have overall very positive impacts. This comes as no surprise since such policies have been assessed thoroughly in the past, for example in the context of the EAT-Lancet recommendations referenced in this model (Willett et al., 2019).

However, advances to encourage a more plant-based diet by, for example, pushing for a "meatless Thursday" (also known as Veggie Day) were met with very vocal opposition in the past, despite the objectively low impact such a policy would have had on any single person's life (BÜNDNIS 90 / DIE GRÜNEN, 2013; „Der Veggie Day teilt das Land", 2013; „Neue Forsa-Umfrage", 2013; Infratest dimap, 2013).

Less controversial approaches may include information campaigns, such as food labels that inform about health and sustainability benefits, or the lack thereof, of certain products. The current move towards implementing the NutriScore system in Germany and the recent implementation of a new animal welfare label may be the first steps in this direction (BMEL, 2018a, 2019c). Furthermore, instead of removing meat options once per week from public canteens, as suggested for the "veggie day", policies encouraging or enforcing a food option in line with the EAT-*Lancet* recommendation in every canteen may be met with less opposition, keeping meat available while also creating more opportunities for people to experience "planetary health" options. Removing incentives, such as subsidies, and extending carbon price mechanisms to include the agricultural sector to internalize environmental damages will also have a nudging effect. Similarly, projected health costs could be internalized. Such pricing mechanisms and labels would need to be applied to all products of course, including imports from outside the European Union to counteract carbon leakage effects (Drenckhahn et al., 2020).

A second important driver of a more sustainable future is technological development. The productivity increases—both in crops and in livestock—assumed in these pathways positively shape the future. Such developments are not guaranteed, but Germany is a rich country well known for its engineers and ingenuity, able to invest in research and development of new technologies, increasing yield, land and water efficiency, and resilience. Using, for example, advanced robotics for precision farming may have positive impacts on farming cost and biodiversity protection due to a focused application of a reduced amount of pesticides, allowing for sustainable intensification. Furthermore, robotic farmhands may be a response to the current COVID-19 crisis and the resulting lack of field workers. To increase adoption rates, such technologies must not only be available but also tailored to farmers' needs (Knierim et al., 2019). Both the EU and Germany are working towards such developments by incentivizing and supporting research (BMEL, 2018c; Standing Committee on Agricultural Research & Directorate-General for Research and Innovation [European Commission], 2013). Vertical farming may reduce the required land for farming and increase yield efficiency (O'Sullivan et al., 2020). In the future, lab-grown meat may be both cheaper and more sustainable than farm-grown options as well—while also solving the ethical dilemma of consuming meat (Bryant & Barnett, 2018).

However, these assumptions are very optimistic in the FABLE Calculator. While Germany has the resources to invest in such developments, its populace has also shown that it is skeptical towards modern agricultural technologies and processes, such as genome editing, potentially holding back important developments

(BMEL, 2019e). The current political target to increase organic farming to 20% of all agricultural land in Germany by 2030 may have a positive effect on local biodiversity but may reduce yield efficiency and thus increase the need for farmland, potentially resulting in overall more pressure on protected areas and a worse footprint per yield tonne (Seufert et al., 2012). However, there are many policies in place and being put in action that will likely have direct positive effects on Germany's biodiversity, e. g. financially incentivizing sustainable farming (BMU, 2019a). Germany also already protects a large share of its land, going beyond the Aichi Target of 17%, albeit still falling short of the very ambitious 50% target formulated by some (*Germany - Nature Needs Half,* n.d.). While there is little political movement towards protection on this level, scientific advisors push in this direction (Drenckhahn et al., 2020).

By design, the model focuses on specific sectors important for sustainable development, while completely or in large parts ignoring others, such as energy, building, and industry, which combined are responsible for over 70% of Germany's greenhouse gas emissions. While there are targets and policies for all sectors, the reduction targets are far steeper for these three (both in absolute and relative numbers). In turn, agricultural emissions as well as reduction targets are lower than in any other sector (up to 34% reduction by 2030 compared to 1990 emissions). This imbalance may be due to the already large investments in the German "Energiewende", keeping the spotlight on the energy and related sectors, while AFOLU policies currently focus on smarter fertilizer application and carbon sequestration. (BMUB, 2016; BMU, 2019b). So, while the modeled and suggested policies' impact might be relatively small in the broader context of German GHG emissions, they may be able to drastically improve the AFOLU sector's footprint beyond current targets and even help to turn it into an overall carbon sink.

As with all models, there are of course caveats. While the model provides insights and trends, more thorough debugging is necessary. Currently, historical data and model calculations do not always align, including extreme outliers in a few cases. Furthermore, important aspects of the German sustainability and climate debate may need to be better reflected in this model, such as the importance of organic soils as carbon storage and emission source. The organic farming target, too, needs to be reflected in yield, land, and emission calculations. Furthermore, due to the way reforestation and afforestation are currently planned, it is only reflected as net-zero forest loss in the model. However, seeing how much land is freed up as "other natural land" due to the changing internal demand, it may make sense to assume active afforestation for Germany. Lastly, biofuel and biogas scenarios need to properly reflect current political targets and alternatives.

Our next steps will be to implement these changes in the FABLE Calculator and to create a second model to confirm our findings and assess the trade-offs and necessary balances between different SDGs in Germany.

Annex 1. List of changes made to the FABLE Calculator to adapt it to the German context

- Increased the threshold on urban land to prevent the “erasure” of German cities since more than the normally allowed 3.5% of total land are urban land in Germany
- Set up a new way to calculate food waste assumption, aligning reported annual food waste per capita and food waste share assumptions from the original calculator
- Expanded the food loss assumptions to include pork and milk

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
The population is expected to reach 78.9 million by 2050 based on SSP2 (global "middle of the road" sustainability narrative) assumptions regarding rich OECD countries: medium fertility, medium mortality, medium migration, medium education Based on Kc & Lutz (2017).	The population is expected to reach 82.4 million by 2050 based on SSP1 (global "taking the green road" sustainability narrative) assumptions regarding rich OECD countries: medium fertility, low mortality, medium migration, high education Based on Kc & Lutz (2017).	Same as Sustainable Medium Ambition Pathway

LAND Constraints on agricultural expansion		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
We assume no expansion of agricultural land beyond 2010 agricultural area levels. Based on BMEL (2020b).	Same as Current Trends Pathway	Same as Current Trends Pathway
LAND Afforestation or reforestation target (1000 ha)		
We expect net-zero forest loss due to reforestation focus on damaged trees. Based on BMU (2019b).	Same as Current Trends Pathway	Same as Current Trends Pathway

BIODIVERSITY Protected areas (1000 ha or % of total land)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Protected areas remain stable: by 2050 they represent 37.7% of total land. As German levels are already relatively high, there is little movement towards higher levels.	Protected areas increase: by 2050 they represent 42% of total land, corresponding to at least 50% protection of each ecoregion. Based on Drenckhahn et al. (2020); *Germany - Nature Needs Half* (n.d.)	Same as Sustainable Medium Ambition Pathway

PRODUCTION Crop productivity for the key crops in the country (in t/ha)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
By 2050, crop productivity reaches: • 492.6 tonnes per ha for tomatoes • 75.5 tonnes per ha for sugarbeet • 40.0 tonnes per ha for potatoes Based on own calculations using data from (FAO, 2020).	By 2050, crop productivity reaches: • 696 tonnes per ha for tomatoes • 89.5 tonnes per ha for sugarbeet • 75.7 tonnes per ha for potatoes Based on own calculations using data from (FAO, 2020). Assumptions are more optimistic to reflect both the necessity and the general German capability to improve productivity.	Same as Current Trends Pathway
PRODUCTION Livestock productivity for the key livestock products in the country (in kg/head of animal unit)		
By 2050, livestock productivity reaches: • 9,500 kg per head for cattle • 4,100 kg per head for chickens • 1,500 kg per head for pigs Based on own calculations using data from (FAO, 2020).	By 2050, livestock productivity reaches: • 12,400kg per head for cattle • 6,300kg per head for chickens • 1,900kg per head for pigs Based on own calculations using data from (FAO, 2020). Assumptions are more optimistic to reflect both the necessity and the general German capability to improve productivity.	Same as Sustainable Medium Ambition Pathway
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)		
By 2050, the average ruminant livestock stocking density is 2.52TLU/ha per ha.	Same as Current Trends Pathway	Same as Current Trends Pathway
PRODUCTION Post-harvest losses		
By 2050, the share of production and imports lost during storage and transportation is the same as in 2010 (NoChange scenario selected)	By 2050, the share of production and imports lost during storage and transportation is reduced by 50%. Analogous to (BMEL, 2019d)	Same as Sustainable Medium Ambition Pathway

TRADE Share of consumption which is imported for key imported products (%)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
Imports are only affected intrinsically, as no specific policy changes are implying otherwise.	By 2050, in response to changing internal demand, the share of total consumption which is imported is: • 71% by 2050 for SoyCake.	Same as Sustainable Medium Ambition Pathway
TRADE Evolution of exports for key exported products (tonnes)		
By 2050, the volume of exports is only affected intrinsically, as no specific policy changes are implying enforced export volumes.	By 2050, in response to changing internal demand, the volume of exports is: • 4,509,000 tonnes by 2050 for milk • 741,000 tonnes by 2050 for pork • 116,000 tonnes by 2050 for beef	Same as Sustainable Medium Ambition Pathway

Germany

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
By 2030, the average daily calorie consumption per capita is 3,064 kcal and is: • 815 kcal for cereals • 308 kcal for milk • 303 kcal for red meat Based on BMEL (2018b, 2019a, 2020a): 10% kcal reduction by 2050 compared to 2010, with 50% kcal reduction from sugar and fat, and a slight decrease in relative meat consumption.	By 2030, the average daily calorie consumption per capita is 2,842 kcal and is: • 725 kcal for cereals • 274 kcal for milk • 262 kcal for red meat Based on BMEL (2018b, 2019a, 2020a): 30% kcal reduction by 2050 compared to 2010, 50% kcal reduction from sugar and fat, and a stronger decrease in relative meat consumption.	By 2030, the average daily calorie consumption per capita is 2,886 kcal and is: • 737 kcal for cereals • 236 kcal for milk • 207 kcal for red meat Based on Willett et al. (2019).

FOOD Share of food consumption which is wasted at household level (%)		
By 2030, the share of final household consumption which is wasted at the household level is between 0 and 11%, depending on the product group. Based on BMEL (2019d).	By 2030, the share of final household consumption which is wasted at the household level is between 0 and 7%, depending on the product group. Based on BMEL (2019d).	By 2030, the share of final household consumption which is wasted at the household level is between 0 and 7%, depending on the product group. Based on BMEL (2019d).

BIOFUELS Targets on biofuel and/or other bioenergy use (kt)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
No expansion of biofuel crop area beyond 2028 OECD projections. By 2050, biofuel production accounts for: • 1,673kt of rape oil production • 781kt of wheat production • 7kt of corn production Based on UBA (2013)	No expansion of biofuel crop area beyond 2028 OECD projections. By 2050, biofuel production accounts for: • 1,673kt of rape oil production • 781kt of wheat production • 7kt of corn production Based on UBA (2013)	No expansion of biofuel crop area beyond 2028 OECD projections. By 2050, biofuel production accounts for: • 1,673kt of rape oil production • 781kt of wheat production • 7kt of corn production Based on UBA (2013)

CLIMATE CHANGE Crop model and climate change scenario		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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India

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in India. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts[1], including from WRI India, the Council on Energy, Environment and Water, The Energy and Resources Institute, and implemented them within a global partial equilibrium model—the Model of Agricultural Production and its Impact on the Environment—MAgPIE (Dietrich et al., 2019; Lotze-Campen et al., 2008; Popp et al., 2017). See Annex 1 for more details on adapting the model to the national context.

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Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how India's Nationally Determined Contribution (NDC) and Forest Reference Emission Level (FREL) treat the FABLE domains. According to the NDC, India has committed to reducing the carbon emissions intensity of its GDP by 33–35% compared to 2005 levels by 2030. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include the National Initiative of Climate Resilient Agriculture (NICRA), National Mission on Sustainable Agriculture (NMSA), *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY), the Prime Minister's Micro-Irrigation Scheme, and measures to minimize residue burning and livestock intensification policies (Ministry of Environment, Forest and Climate Change, 2018). Under its current commitments to the UNFCCC, India mentions biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and LT-LEDS

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[2] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2017)	2005	n/a	2030	Reduce the emissions intensity of GDP by 33-35% by 2030	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	Y	N	Afforestation
FREL (2018)	2008	n/a	-	**-49.70 million CO_2e**	n/a	n/a	n/a	n/a	n/a

Note. The NDC "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Sources: UNFCC(2015), UNFCC(2018)

2 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2014 (NBSAPs received since COP10), as listed on the CBD website (CBD, 2020) which are related to at least one of the FABLE Targets. This NBSAP includes 12 National Biodiversity Targets from 2010-20. In comparison with the FABLE targets on biodiversity and deforestation, the NBSAPs targets are similar, in particular on protecting a minimum share of terrestrial land to support biodiversity conservation and zero net deforestation.

Table 2 | Overview of the NBSAP targets in relation to FABLE targets

NBSAP Target	Global FABLE Target
(5) By 2020, measures are adopted for sustainable management of agriculture, forestry and fisheries.	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(6) Ecologically representative areas on land and in inland waters, as well as coastal and marine zones, especially those of particular importance for species, biodiversity and ecosystem services, are conserved effectively and equitably, on the basis of PA designation and management and other area-based conservation measures and are integrated into the wider landscapes and seascapes, covering over 20% of the geographic area of the country, by 2020	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways in line with the FABLE Targets for food and land-use systems in India, Current Trends and Sustainable. The Sustainable Pathway is a high ambition path to meet national sustainability objectives. Our underlying assumptions for both pathways are in the line of Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2014) (Figure 1). We assume SSP2 parameterization for the Current Trends Pathway and a storyline that builds on SSP1 (e.g. dietary shifts beyond SSP1) for the Sustainable Pathway, including greenhouse gas mitigation efforts and dietary changes (Figure 2) (see Annex 2 for more details on the underlying assumptions).

Figure 1 | Shared Socio-economic pathways (SSPs) from O'Neill et al., (2014)

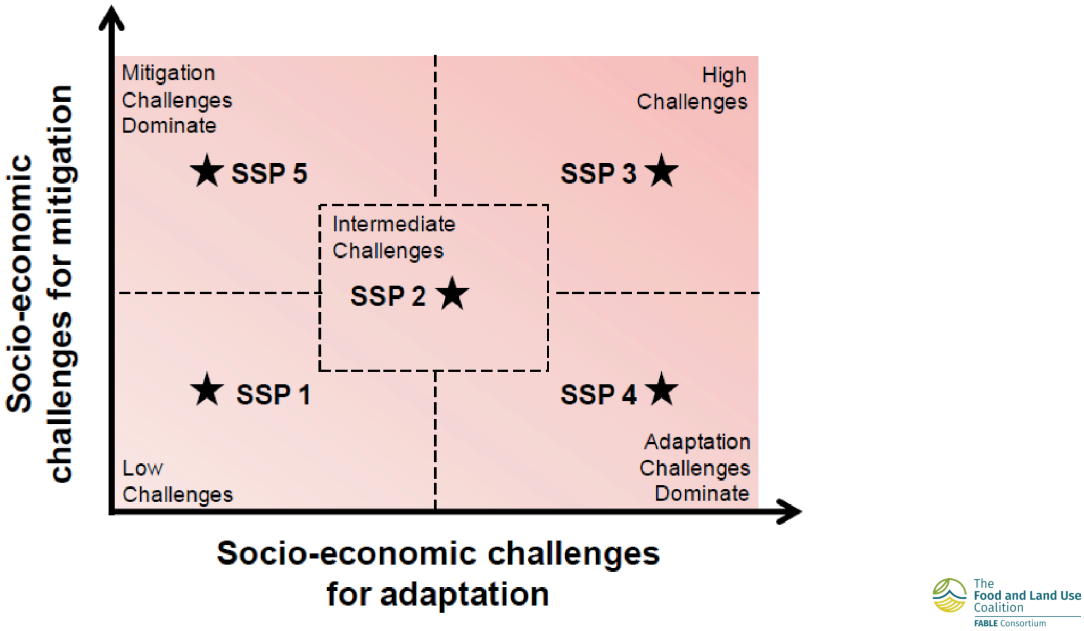
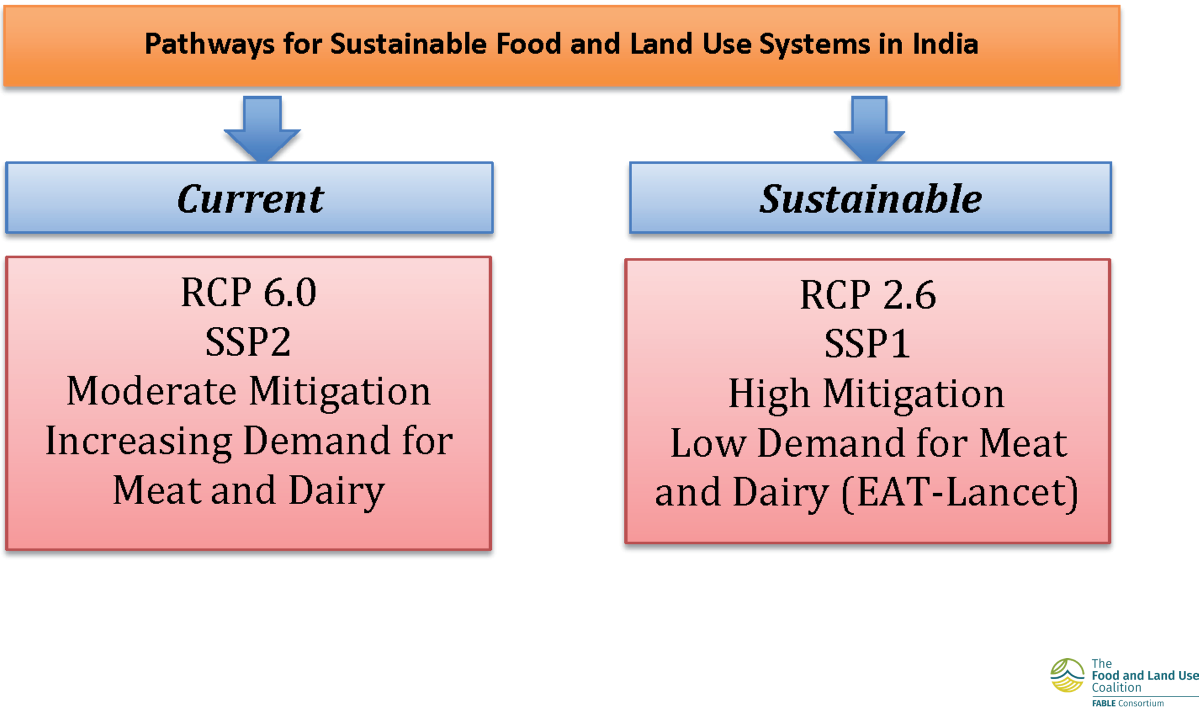


Figure 2 | Description of main assumptions underlying the Current Trends and Sustainable Pathways



Our Current Trends Pathway corresponds to the medium boundary of feasible action. It is characterized by medium population growth (from 1,389 million in 2020 to 1,734 million in 2050), significant constraints on agricultural expansion, a medium afforestation target (21 Mha by 2030) with no change in the extent of protected areas, moderate increases in crop productivity, an evolution towards a diet with relatively high consumption of animal-based products (O'Neill et al., 2017), and other important assumptions (see Annex 2). This corresponds to a future based on current policies and historical trends that would also see moderate population growth and increasing demand for food, moderate growth and lower inequality, stronger nutrition requirements and changes in dietary patterns that follow increases in income, continuous improvements in technologies to increase yields and the high use of fertilizers to increase productivity, moderate mitigation activity to cope with climate change with low enforcement of environmental protection and low targets of renewables and first generation biofuels. These factors underpinning the Current Trends Pathways are based on country level historical trends and current policies and practices (FAO, 2019; Forest Survey of India, 2019; Government of India, 2015; Indian Council of Agricultural Research, 2015; Ministry of Agriculture & Farmers Welfare, 2018; Ministry of Agriculture and Farmer's Welfare, 2017; National Council of Applied Economic Research, 2015). Moreover, as with all FABLE country teams, we embed these Current Trends Pathways in a global GHG concentration trajectory that would lead to a radiative forcing level of 6.0 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. We assume a moderate water-use efficiency scenario under this pathway along with climate change impact (RCP 6.0) Our model includes the corresponding climate change impacts on crop yields by 2050 for cereals, oil crops, sugar crops, fruits and vegetables and for all crops simulated within the model (see Annex 2).

Our Sustainable Pathway represents a future in which substantial efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to higher afforestation targets and lower population growth (see Annex 2). This corresponds to a future based on India's pledges under international commitments such as the Paris Agreement, Bonn Challenge, and Aichi Targets, as well as other aspirational targets to reach higher production of renewables and biofuels with more efficient technologies and transition towards healthy diets (i.e. according to recommendations of the EAT-*Lancet Commission*) (Willett et al., 2019) that would also see considerable progress with regards to the achievement of sustainable development goals. We assume a higher water-use efficiency scenario under this pathway along with climate change impact (RCP 2.6). Therefore, we include environmental flow requirements in our model assumptions that reserve a certain fraction of water for environmental purposes and that are not available for agricultural activities. We also assume that the interest rate and technological cost will be low in line with SSP1, which leads to higher crop yields. These pledges and targets are the major factors underpinning our Sustainable Pathway and are in line with national targets to achieve the Sustainable Development Goals (Borah, Bhattacharjee, and Ishwar, 2017; Ministry of New and Renewable Energy, 2018; Ministry of Statistics and Programme Implementation, 2020; Ministry of Environment, Forest and Climate Change, 2018). With the other FABLE country teams, we embed this Sustainable Pathway in biophysical drivers consistent with a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

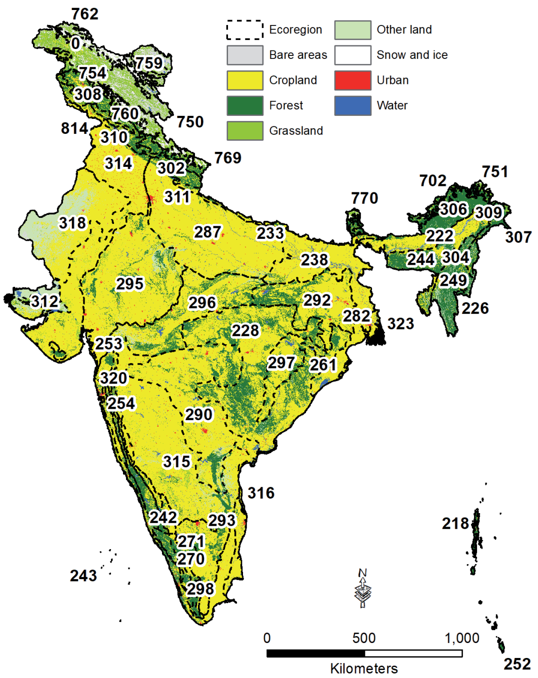
In 2010, India was covered by 67% cropland, 5% grassland, 19% forest, 1% urban land, and 4% other natural land. Most of the agricultural area is located in northern and western India while forest and other natural land can be mostly found in the southwest and east (Map 1). In a developing economy with a growing population and a focus on economic development, impacts can be seen on the increasing pressure on biodiversity. Habitat loss, degradation, invasive alien species, over exploitation of fisheries and increasing incidence of forest fires are some of the major biodiversity threats in India (Ministry of Environment and Forests, 2014).

We estimate that land where natural processes predominate[3] accounted for 12% of India's terrestrial land area in 2010. The 770-Yarlung Zanbo arid steppe holds the greatest share of land where natural processes predominate, followed by the 307-Northern Triangle temperate forests and the 751-Eastern Himalayan alpine shrub and meadows (see Annex 4). Across the country, while 18.2 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, protected land where natural processes predominate is mainly located along the southwestern coast. In contrast, the last remaining patches of land where natural processes predominate in the north and east of the country lie unprotected and are at risk of losing their biodiversity if action is not taken to better protect these areas (Map 2).

Approximately 15% of India's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in forested northern regions including the 226-Chin Hills-Arakan Yoma montane forests, 750-Central Tibetan Plateau alpine steppe, and 307-Northern Triangle temperate forests. These ecoregions have relatively small areas of cropland intermixed with natural vegetation, while cropland dominates landscapes in many other ecoregions of India, pushing natural vegetation to the margins. The regional differences in the extent of biodiversity-friendly cropland can be explained by cropping intensity (Ministry of Agriculture and Farmer's Welfare, 2016).

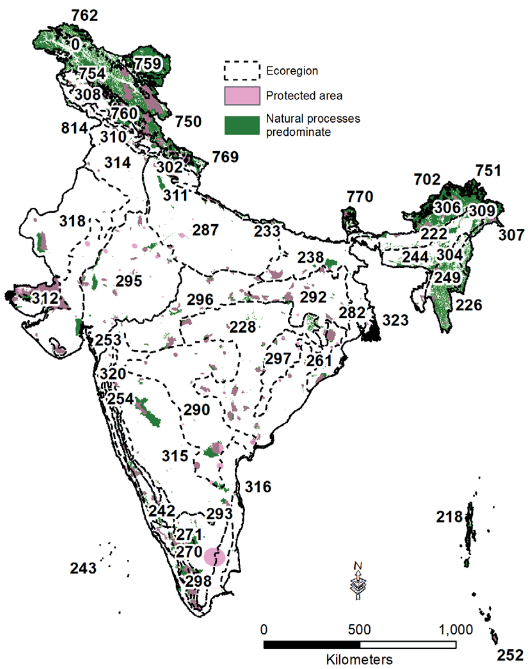
3 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)
Notes: Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.

Map 2 | Land where natural processes predominate, protected areas and ecoregions in 2010



Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)
Note: Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.

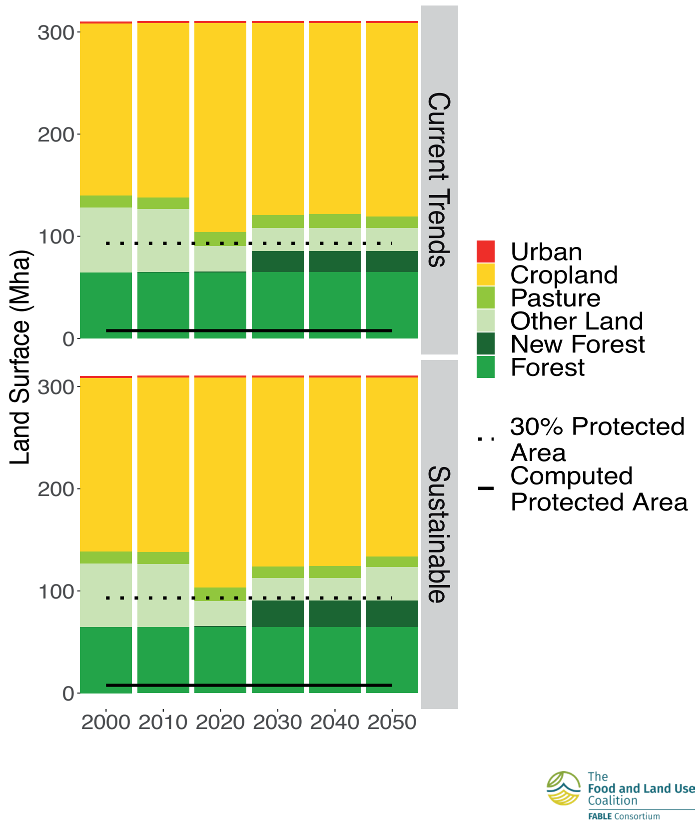
Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions: deforestation will be halted beyond 2005 and the expansion of agricultural land into natural forests is halted. Agricultural land can be increased by converting other natural vegetation areas that have lower carbon densities compared to natural forests. Moreover, 21 Mha are reforested or afforested by 2030, and protected areas remain at 181,404 km2, representing 6% of total land cover in 2050 (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result in an increase in the forest cover area and a decrease of other land areas. Decreases in other land occurs due to cropland area expansion between 2010 and 2025, after which other land remains stable. Forest area remains stable until 2025, increases between 2025 and 2030, before stabilizing (Figure 3) due to our assumption to achieve the Bonn Challenge target for India (21 Mha by 2030). The expansion of the planted area for corn and soybean explains 99% of total cropland expansion between 2010 and 2025. For corn, the expansion is largely explained by an increase in feed use. For soybean, the expansion is primarily due to an increase in exports of soybean. The marginal pasture expansion between 2010 to 2035 is driven by the increase in demand for livestock products, in particular dairy products. Between 2030-2050, the increase in forest area is explained by actions to meet afforestation targets set under the Bonn Challenge (Borah et al., 2017). There is no change between 2000 and 2050 in the area of land where natural processes predominate, which is explained by cropland or pasture area expansion and stabilization, respectively.

In the Sustainable Pathway, assumptions on agricultural land expansion remain similar to the Current Trends Pathway, except for an additional afforestation assumption that includes 26 Mha of new forest area by 2030 based on the revised Bonn Challenge target

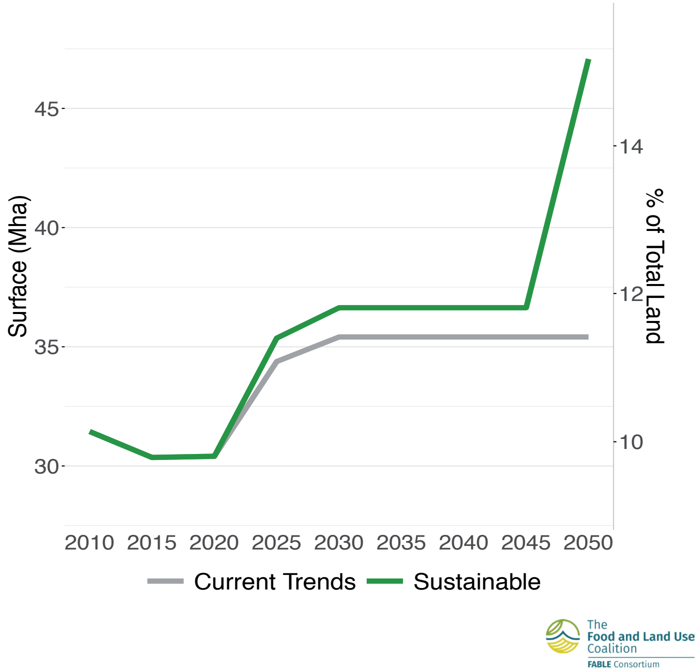
Figure 3 | Evolution of area by land cover type and protected areas under each pathway



Sources. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas data (UNEP-WCMC & IUCN, 2020) for 2020 for India. Protected areas remain constant at 6% of the total land area (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in India in the Sustainable Pathway: (i) a decrease in the loss of natural land, (ii) a moderate increase in agricultural land, and (iii) an increase in afforested land. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by cropland expansion and afforestation targets. Under the Current Trends Pathway, natural processes increase by 1.5% between 2010 and 2030, then stabilize. Under the Sustainable Pathway, land where natural processes predominate increases by 1.8% between 2010 and 2030, stabilizes until 2045, then sharply increases by a further 3% by 2050 (Figure 4).

Figure 4 | Evolution of the area where natural processes predominate



GHG emissions from AFOLU

Current State

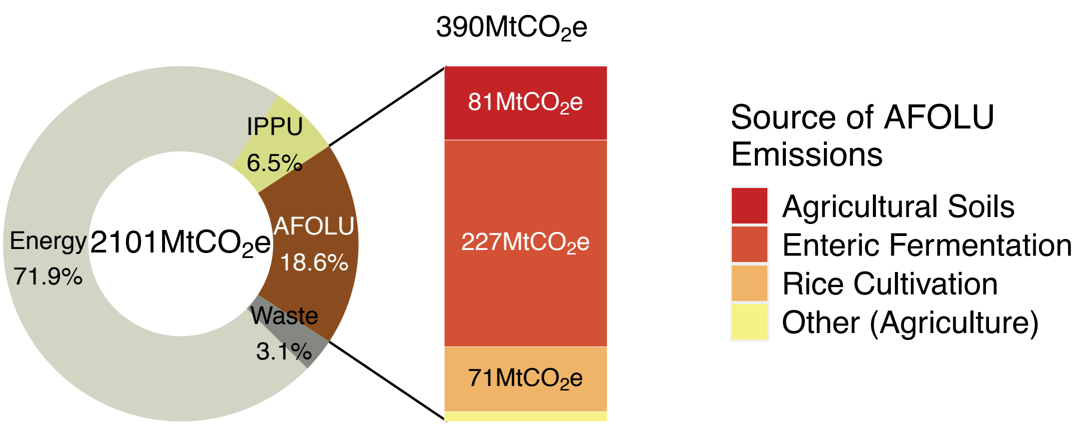
Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 18.6% of total emissions in 2010 (Figure 5). Enteric fermentation and field burning of agricultural residues is the principal source of AFOLU emissions, followed by agricultural soils, and rice cultivation.

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU increase to 1,140 Mt CO_2e/yr in 2030 before reaching 1,550 Mt CO_2e/yr in 2050 (Figure 6). In 2050, enteric fermentation is the largest source of emissions (1,067 Mt CO_2e/yr), while emissions from other land-use change act as a sink (13 Mt CO_2e/yr). Over the period 2020–2050, the strongest relative increase in GHG emissions is computed for enteric fermentation (170%), while a reduction is computed for emission from rice cultivation (-40%).

In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by 300% in 2050 compared to the Current Trends Pathway (Figure 6). The potential emissions reductions under the Sustainable Pathway are dominated by a reduction in GHG emissions from the livestock sector. Our assumptions related to diets (EAT-Lancet recommendations) under the Sustainable Pathway, which assume a reduction in demand for livestock products and other assumptions in line with an SSP1 narrative, are the most important drivers of this reduction.

Figure 5 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2010



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Compared to India's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute moderately to the total GHG emissions reduction objective by 2030 (reducing the emissions intensity of GDP by 33% to 35% by 2030 compared to 2005 levels). Such reductions could be achieved through policies to promote a strong shift in diets, improvements to the livestock feeding system, meeting afforestation targets, and increasing bioenergy production. Such policies could be particularly important when considering targets to create an additional carbon sink of 2.5 to 3 billion tonnes of CO2 equivalent through afforestation/reforestation by 2030 as per India's commitment to UNFCCC (INDC, 2015). The National Biofuel Policy (2018) in particular relates to India's new biofuel targets (Ministry of New and Renewable Energy, 2018) which is also important to meet India's commitment to UNFCCC.

Figure 6 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

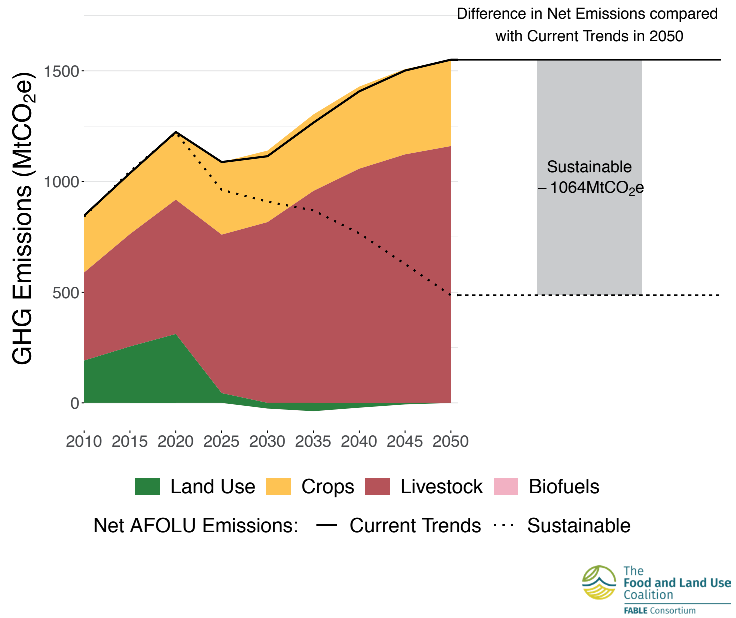
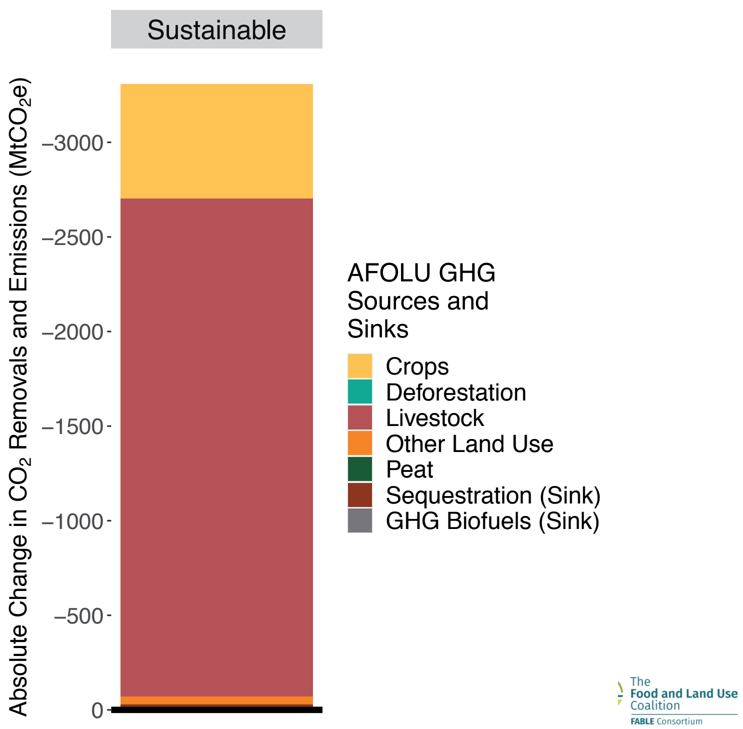


Figure 7 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

The “Triple Burden” of Malnutrition

Undernutrition

14.5% of the population undernourished in 2019. This share has decreased since 2005 (von Grebmer et al., 2019).

38.4% of children under 5 stunted and 21% wasted in 2016 (Indian Institute of Population Sciences, 2016).

Micronutrient Deficiency

50.1% of women and 57.3% of children suffer from anemia in 2016, which can lead to maternal death (NLIS, 2018).

5% of pregnant women were deficient in vitamin A (Akhtar et al., 2013), which can notably lead to blindness (West, 2002) and child mortality, and 34% of the population is deficient in iodine, which can lead to developmental abnormalities (Andersson, Karumbunathan, & Zimmermann, 2012).

Overweight/ Obesity

3.9% of adults and 2% of children were obese in 2016. These shares have increased since 2005 (Global Health Observatory, 2018).

19.7% of adults and 6.8% of children, were overweight in 2016. These shares have increased since 2005 (Global Health Observatory, 2018).

Disease Burden due to Dietary Risks

20.8% of deaths are attributable to dietary risks, or 152.77 deaths per year (per 100,000 people) (Global Burden of Disease Collaborative Network, 2018).

Table 4 | Daily average fats, proteins and kilocalorie intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,097 (2,181)	2,260 (2,252)	2,286 (2,281)	2,325 (2,255)	2,272 (2,284)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

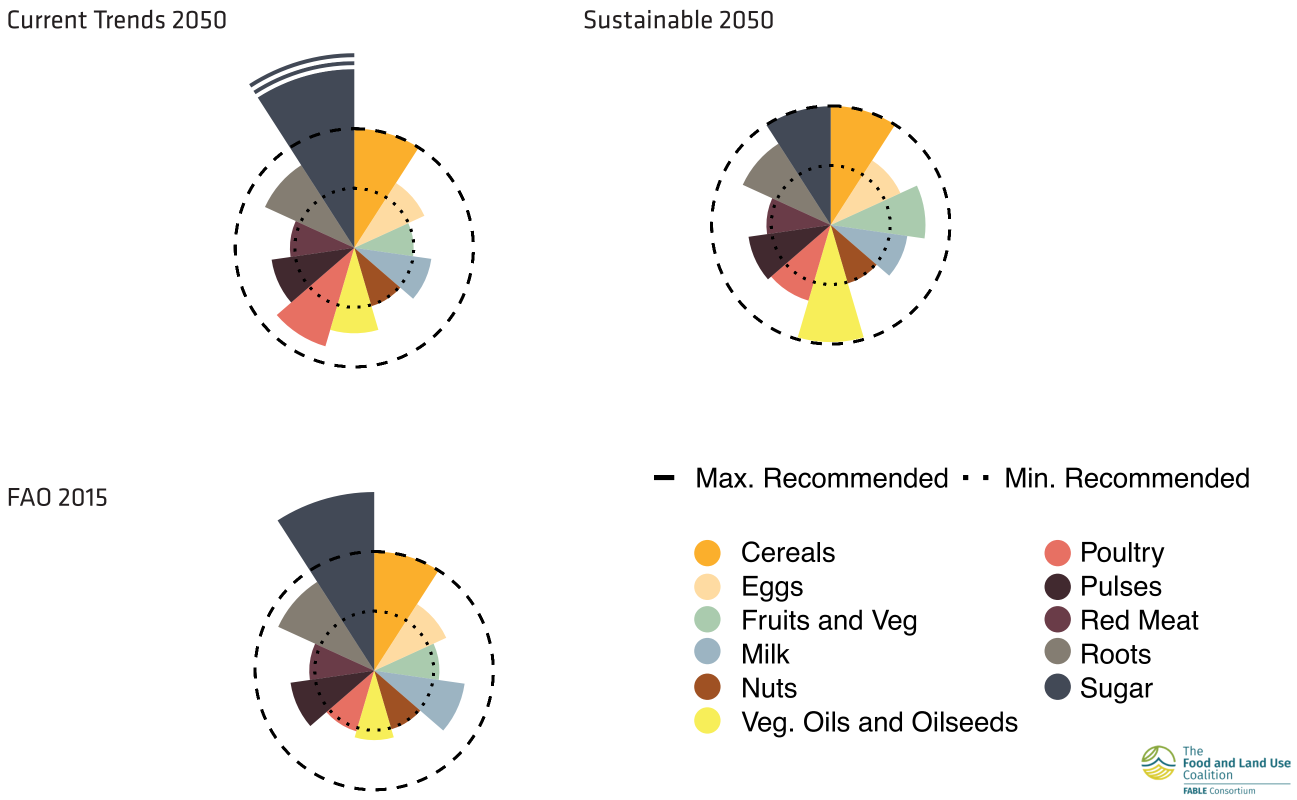
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 0.3% higher in 2030 and 3% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals, sugar and oils, and animal products, which represent 13% of the total calorie intake. We assume that the consumption of animal products will increase by 57% and by 106% for poultry meat between 2020 and 2050. The consumption of dairy, sugar, fruits and vegetables, and nuts will also increase while the consumption of oil crops, cereals, and pulses will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), which is in line with the assumptions of our Sustainable Pathway, only sugars are over-consumed whereas no products are under-consumed (Figure 8).

Under the Sustainable Pathway, we assume that diets will transition towards EAT-Lancet recommendations. The ratio of the computed average intake over the MDER increases to 0.3% in 2030 and decreases to 0.4% in 2050 under the Sustainable Pathway.

India's changing food demand landscape partially promotes the transition to healthy food systems. While we find that, on average, the number of food groups consumed by Indian households has increased from 8.8 (out of 12 food groups) to 9.7 between 1990 and 2012 in rural India and from 9.3 to 9.5 in urban India (Pingali, Aiyar, Abraham, & Rahman, 2019), there is still a need to reduce the over-dependence on certain food groups, particularly ultra-processed foods, sugars and cereals, to achieve overall dietary diversity as recommended by our Sustainable Pathway (EAT-*Lancet* recommendations). A shift from the current over-dependence on the consumption of cereals, which is rooted in existing regulatory reforms that highly subsidize the production and consumption of cereals, towards a focus on diversifying the food basket to include more fruits, vegetables, nuts, and pulses will be important to achieve the EAT-*Lancet* dietary recommendations. The gap between current Indian diets as compared to EAT-*Lancet* recommendations calls for public health and nutrition policies that address malnutrition as well as agricultural, trade, and consumer awareness policies. With an aim to address broader societal context, these policies shall aim to affect the accessibility, acceptability, and affordability of healthier dietary options in India (Sharma, Kishore, Roy, & Joshi, 2020).

Figure 8 | Comparison of the computed daily average kilocalorie intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar indicate that the average kilocalorie consumption of this food category is significantly higher than the maximum recommended.

Water

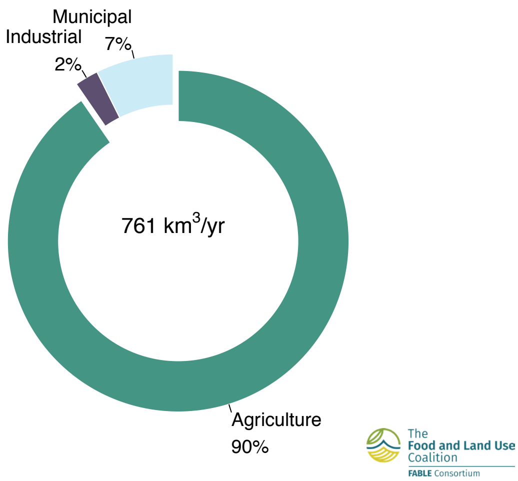
Current State

India is characterized by tropical monsoon climate with unreliable rainfall and 1,183 mm average annual precipitation that mostly occurs between June and September. The agricultural sector represented 90% of total water withdrawals in 2010 (Figure 9; FAO, 2017). Moreover, in 2013, 70.4 Mha of agricultural land was equipped for irrigation, representing 50% of estimated irrigation potential (FAO, 2017). The three most important irrigated crops, rice, soybean, and pulses, account for 26%, 15%, and 7% of total harvested irrigated area. India exported 61% of soybean, 23% of cotton lint and 6% of rapecake in 2020.

Pathways and Results

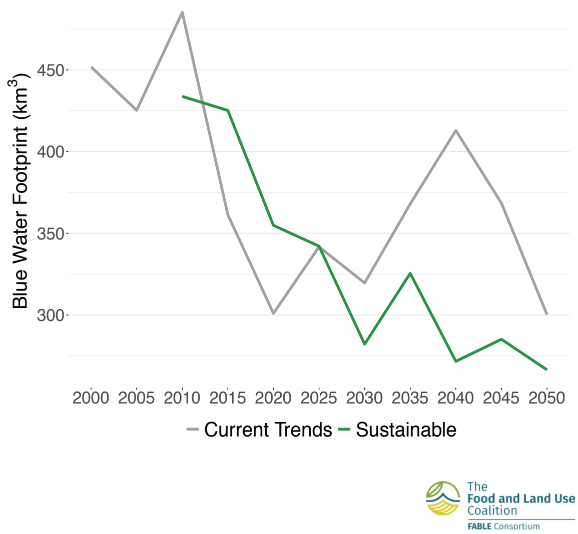
Under the Current Trends Pathway, annual blue water use decreases between 2000 and 2015 (685 km^3/yr and 547 km^3/yr), before reaching 484 km^3/yr and 455 km^3/yr in 2030 and 2050, respectively (Figure 10), with rice, wheat and chicken accounting for 37%, 23%, and 12% of computed blue water use for agriculture by 2050. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture reaches 427 km^3/yr in 2030 and 403 km^3/yr in 2050, respectively. This is explained by accounting for environmental-flow-protection policies as well as climate change impacts in the MAgPIE model (see Annex 2), which leads to an 11% decrease in water withdrawals in agriculture by 2050 and changes in the production of rice, wheat, and raw sugar due to a decline in internal food demand as well as demand for biofuels. Water withdrawal values in the model do not fully reflect underground water use for agricultural production which was beyond the scope of this analysis.

Figure 9 | Water withdrawals by sector in 2010



Source. Adapted from AQUASTAT Database (FAO, 2017)

Figure 10 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



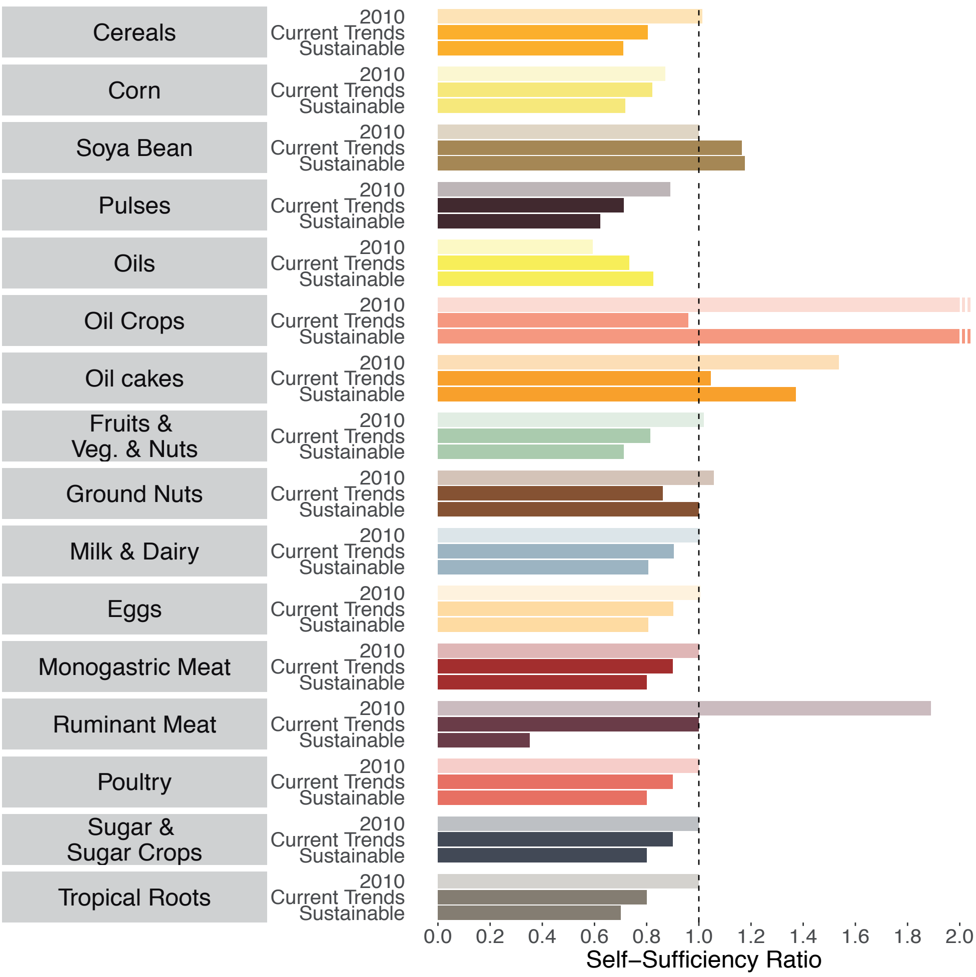
Resilience of the Food and Land-Use System

The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge India's resilience to agricultural trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

According to the historical data (2010), India is self-sufficient for the major food categories, such as cereals, fruits and vegetables, nuts, oilseeds and vegetable oils, soya bean, ruminants, eggs, sugar and sugar crops, oil crops, mild and dairy, fruits, vegetables and nuts and poultry meat. Self-sufficiency is low for corn and oils.

Figure 11 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for beverages, spices and tobacco, nuts, oilseeds and vegetable oils, indicate a high level of self-sufficiency in these categories.

Under the Current Trends Pathway, we project that India would be self-sufficient in pulses, fruits vegetables and nuts, and ruminant meat in 2050, with self-sufficiency by product group remaining stable for the majority of products between 2010 and 2050 (Figure 11). The product groups for which India depends the most on imports to satisfy internal consumption are roots and tubers, poultry meat, milk and dairy, sugar and sugar crops, and eggs. According to our projections, this dependency will decline until 2050. In contrast, under the Sustainable Pathway, India's self-sufficiency remains stable overall, with full self-sufficiency for pulses, fruits and vegetables, ruminant meat, and nuts but with a further decline in the self-sufficiency for roots and tubers, dairy, and sugar crops by 2050. This is explained by changes in the volume of imports and exports, productivity, and change in diets.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Figure 12 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)

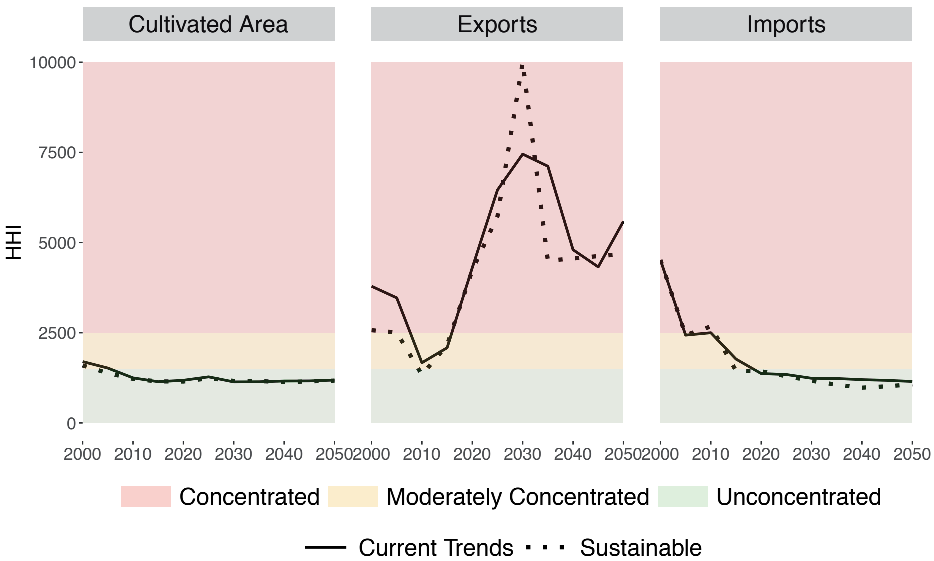


Figure 12 shows that the planted area is quite diverse in 2010 and that imports and exports are, respectively, moderately and highly concentrated during the historical period 2010 to 2015.

Under the Current Trend Pathways, we project moderate concentration in crop exports between 2010 to 2015 and a high concentration between 2020 to 2050. Crop imports are moderately concentrated during the period 2010-2020 and unconcentrated between 2020-2050. The range of crops planted is projected to experience low concentration, a trend which is stable over the period 2010 - 2050. This indicates high levels of diversity across the national production system and imports and low diversity across exports. Similarly, under the Sustainable Pathway, we project a high concentration of crop exports, and low concentration of crop imports and in the range of crops planted in 2050. Sustainable scenarios do not change the diversification patterns of crops despite the range of different assumptions. This is explained by several changes in the assumptions related to population, diets, crop productivity, biofuel policy, among the pathways.

Discussion and Recommendations

To explore viable ways to sustainably transform food and land-use systems in India, this study developed Current Trends and Sustainable Pathways using the global land systems model MAgPIE. The differences between these two Pathways are meant to help stakeholders and policy makers to better understand the differences between current trajectories and potential future trends of sustainable indicators to support the setting of national targets and monitor their progress. We hope our results can be useful in developing a framework of policy actions that aim to achieve several international commitments for climate mitigation and forest conservation, such as the Paris Agreement, the Convention on Biological Diversity, the Sustainable Development Goals, and the Bonn Challenge. For example, our analysis projects an emission reduction of 1064 Mt CO_2e per year under the Sustainable Pathway compared to Current Trends Pathway by 2050. This reduction is primarily due to our assumptions of a transition towards healthy diets, an improvement in livestock production systems (including the feed basket content), an afforestation target of 26 Mha by 2030, and others, which are in line with SSP1. Moreover, we find the livestock sector would be the major contributor towards these emissions reductions. Finally, the inclusion of the national biofuel mandate (Ministry of New and Renewable Energy, 2018) in our analysis, shows the impact on land-use dynamics and the potential for bioenergy crop use to meet India's blending targets.

Relevant and suitable policy transformations are required if the goals identified under the Sustainable Pathway are to be reached. For example, the successful implementation of the National Biofuel Policy of 2018 will be important in bringing about an increase in bioenergy crops which have implications on overall water use for production as well as GHG emissions. Similarly, our results indicate significant policy implications for ensuring the country's food security. The national Public Distribution System provides subsidized grains (rice and wheat) to economically disadvantaged segments of the population (up to 75% of rural population and 50% of urban population) under the National Food Security Act of 2013. However, the focus on cereals wards off the relevance of other nutritionally rich food products that shall help improve the dietary diversity of the Indian population. According to our projections, dietary shifts towards healthy diets will promote the advancements towards Sustainable Development Goals and thereby imply significant changes in the NFSA to include nutritionally rich foods such as pulses too.

From our analysis, focus on balanced diets can be brought out with the support of varied production of crops and livestock, while limiting the impact of this shift on water-use. About 90% of India's water use is dedicated to agricultural production, with rice and poultry production responsible for the largest blue water footprint. Under the Current Trends Pathway, the consumption of livestock products and cereals is expected to increase - in line with historical trends and rising household incomes, thereby placing additional pressures on land-use systems. While in the past, Indian diets have relied on cereals and a greater share of plant-based proteins, India currently faces a triple-burden of malnutrition, with high incidences of both under-nutrition and obesity in the population. High production and consumption of ultra-processed foods, sugars, and cereals leaves little room for protein and fiber-rich foods in the food basket. In the Sustainable Pathway, we assume that future dietary requirements will move towards plant-based nutrients, in line with the recommendations of EAT-*Lancet* Commission. These recommendations encourage lower consumption of animal products combined with greater consumption of fruits and vegetables. Our results point towards large environmental benefits from a shift to these healthier diets and that it may be possible to do so without expanding the cropland cover.

We conducted our analysis and assumptions with the dynamic, global partial-equilibrium MAgPIE model, which we have applied to India. Using a global modeling framework for a regional analysis has certain advantages and disadvantages. In terms of advantages, there is a benefit to building on an existing global model when no national land-system model with a comparable scope exists. In particular, our model includes many processes that are likely superior to static assumptions, even though they are only parametrized through international datasets. These include dynamic feed baskets, endogenous technological change, fertilization management, and emissions accounting. Finally, a global model might be better suited to account for international drivers such as trade, or for long-term trajectories of Indian land systems and how they compare to trajectories in other countries. On the other hand, using a global model for regional analysis also has its downsides. Firstly, as the input data is required on a global scale, more comprehensive and detailed data that may exist on the national scale cannot be easily incorporated into the model. For example, the MAgPIE model accounts for irrigation efficiency as a global weighted average of water losses from source to field ("conveyance efficiency times management factor") from Rohwer, Gerten, and Lucht (2007), which means we must use the same irrigation efficiency for India for both Current Trends and Sustainable Pathways. Similarly, water demand for crop production in the model is endogenously calculated based on irrigated cropland and livestock production and considers only blue water during the crop growing period. The current model framework accounts for lower water demand for agriculture overall as model validation and improvements in the model were beyond the scope of this exercise. Also, our findings on dietary patterns and consumption remain restricted to the national level as we are unable to account for sub-national and regional variations in dietary patterns across the country. In addition, the simulated processes were chosen based on their relevance for the global food system and may neglect important dynamics of high relevance for national food systems. For example, processes that may drive dietary patterns in India, such as religious affiliation, are not explicitly accounted for.

Moving ahead, while our analysis and assumptions have greatly benefitted from input from various stakeholders, we aim to continue to improve our assumptions to generate specific and actionable results through continued stakeholder engagement. Our Sustainable Pathway is already including highly ambitious targets for healthy diets, sustainable agricultural practices, and low emission targets. Through additional assumptions, we will be able to address additional sustainability objectives at national level are relevant for our stakeholders. In the present context of Covid-19, the focus on food systems and supply chains has become all the more relevant for policy makers and the general public.

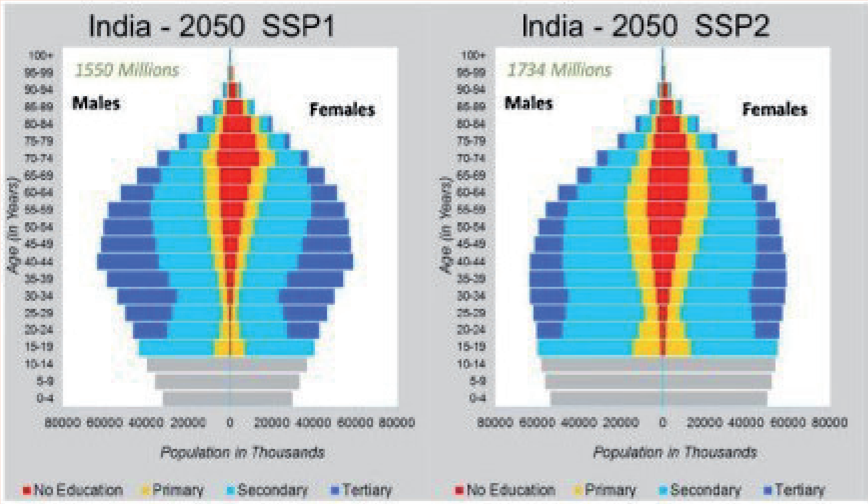
Annex 1. List of changes made to the model to adapt it to the national context

- MAgPIE is a recursive dynamic cost-minimization model of global land systems. The model simulates crop production, land-use patterns, water use for irrigation, and carbon stock changes at a spatial resolution of 0.5° × 0.5°. An additional feature of this model is the inclusion of international trade between defined world regions A detailed description of the modeling framework can be found in (Dietrich et al., 2019). The technical model description of the used version 4.1 is available at https://rse.pik-potsdam.de/doc/magpie/4.1/.
- MAgPIE uses spatially explicit biophysical information from the global gridded crop and hydrology Lund–Potsdam–Jena managed Land (LPJmL) model (Bondeau et al., 2007).
- To adapt the model in order to analyze options for sustainable food and land-use systems in India, we first conducted a validation process to tailor the model to national-level context and policies (e.g. improvement in productivity of pastures and grazelands).
- We have created two pathways “Current Trends” and “Sustainable” by setting the narratives around the Shared Socioeconomic Pathways (SSPs). Under the Current Trends, our assumptions are in line with SSP2, which is considered “Middle of the Road”, and for the Sustainable Pathway, our assumptions are in line with SSP1 which defines “Sustainability – Taking the Green Road” scenario (O’Neill et al., 2014; Popp et al., 2017; c.f. the underlying assumptions behind the scenarios in Section 10, Annex 2).
- In the Sustainable pathway, we have implemented the biofuel mandate of a 20% blending target in petrol and 5% in biodiesel according to India’s New Biofuel Policy (Ministry of New and Renewable Energy, 2018).
- For the purpose of FABLE Scenathon, we have implemented an exogenous trade setting for the trade adjustment of select commodities. The Scenathon (or “scenario marathon”) is an iterative process in which the FABLE country teams adjust their assumptions and pathways to ensure balanced trade flows and to aim towards achieving the global FABLE Targets.
- To convert the MAgPIE output to be compatible with the other FABLE models participating in the Scenathon we have disaggregated MAgPIE commodity groups into the FABLE Calculator commodity group by calculating the historical shares of each commodity within their respective product group by using FAOSTAT data for 2010 and 2015.
- We have implemented the FABLE biodiversity targets of “No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate” and “Protected areas cover at least 30% of global terrestrial land by 2030” by using evolution in the land cover category.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
The population is expected to reach 1.73 billion by 2050 based on our underlying assumption of SSP2 parameterization (Kc & Lutz, 2017). Currently, India's population is 1.31 billion and it is expected to reach approximately 1.4 billion by 2022. The projection suggests that India's population will continue to grow for several decades up to 1.5 billion in 2030 and 1.8 billion in 2050 (UN DESA, 2015).	The population is expected to reach 1.55 billion by 2050 based on our underlying assumption of SSP1 parameterization. The SSP1 parameterization is in line with more sustainable pathways that assume that investments in health and education will accelerate the demographic transition, leading to a relatively low world population (Kc & Lutz, 2017). Research indicates that under the SPP1 scenario for India, female education levels will be higher along with lower assumed education-specific fertility rates, thereby resulting in much lower birth rates.



Population of India by age, sex and educational attainment under SSP1 and SSP2 scenario (Source: Kc and Lutz, 2017).

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable High Ambition Pathway
We assume that deforestation will be halted beyond 2005. The assumption is based on several national policies that have been implemented (e.g. the Indian Forest Act and Indian Forest Conservation Act) and based on historical trends (FAO, 2020). Therefore, no agricultural land expansion into natural forests is allowed. Agricultural land can be increased by converting other natural vegetation areas that have lower carbon densities than natural forests. Areas under the industrial forestry sector are assumed to be constant and therefore cannot be converted into other land uses.	Same as Current Trends

LAND Afforestation or reforestation target (1,000 ha)

Current Trends Pathway	Sustainable High Ambition Pathway
We assume total afforested/reforested area will reach 21 Mha by 2030. These assumptions are based on India's Bonn Challenge Commitment (2014) whereby India has pledged to restore 13 Mha of degraded and deforested land by 2020, and an additional 8 Mha by 2030. According to Borah et al., 2017 India has brought an area of 9.8 Mha under restoration since 2011, meaning that work to restore these landscapes is already underway.	We assume total afforested/reforested area will reach 26 Mha by 2030. This assumption is based on India's additional commitment of 5 Mha in line with the existing Bonn Challenge commitment (2014). This new commitment was announced by the Government of India at the UN Summit in 2019 (Prime Minister's Office, 2019).

BIODIVERSITY Protected areas (% of total land)

Current Trends Pathway	Sustainable Pathway
We assume that protected areas remain stable until 2050: by 2050 they represent 6% of total land. Indian protected areas were computed using the data from World Database on Protected Areas (UNEP-WCMC & IUCN, 2020). The assumptions are in line with India's commitment to the CBD.	Same as Current Trends

BIODIVERSITY Crop productivity for the key crops (in t DM /ha)

Current Trends Pathway

By 2030, crop productivity reaches:

- 4.5 tonnes DM per ha for rice
- 1.9 tonnes DM per ha for corn
- 6.7 tonnes DM per ha for soybean

We assume a moderate increase in crop productivity compared to 2010. This dynamic change in crop productivity is based on our assumptions of medium technological costs and medium interest rates (7%) that influence investments in yield-increasing technologies. The assumed investment horizon is provided by the interest rate, which is a risk-accounting factor associated with investment activities (Dietrich, Schmitz, Lotze-Campen, Popp, & Müller, 2014; Wang et al., 2016). Along with technological change, the change in crop yield is also driven by high use of fertilizers due to the underlying SSP2 parameterization and yield growth is proportional to the growth in fertilizers use (Valin et al., 2013; Mogollón et al. 2018). The elasticity of variable input including fertilizer use with respect to echnological change is 1.00 (Fricko et al., 2017) which means moderate use of yield improving technologies together with moderate use of fertilizer.

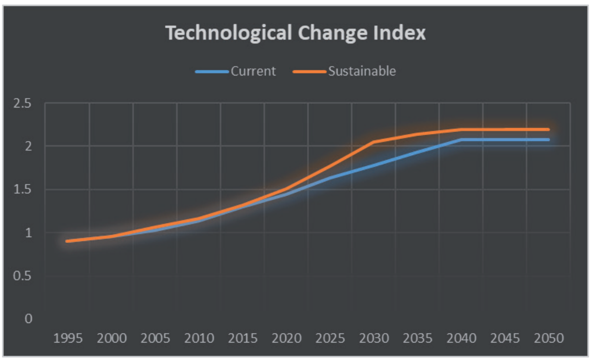
Sustainable Pathway

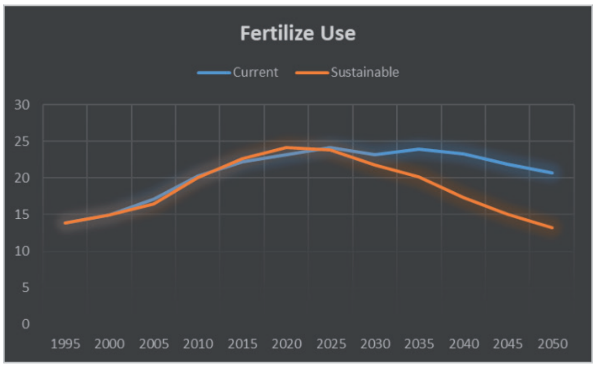
By 2030, crop productivity reaches:

- 6.5 tonnes DM per ha for rice
- 2.5 tonnes DM per ha for corn
- 7.8 tonnes DM per ha for soybean

We assume a high increase in crop productivity compared to 2010. This dynamic change in crop productivity is based on our assumptions of low technological costs and lower interest rates (4%). The assumed investment horizon is provided by the interest rate, which is a risk-accounting factor associated with investment activities (Wang et al., 2016). In addition, due to underlying SSP1 parameterization the yield growth is proportional to the growth in fertilizer use (Mogollón, Beusen, van Grinsven, Westhoek, & Bouwman, 2018; Valin et al., 2013). The elasticity of variable input including fertilizer use with respect to technological change is 0.75 (Fricko et al., 2017) which means high use of yield improving technology and low use of fertilizer.

Our assumptions are based on National Council of Applied Economic Research (2015) that suggests that due to technological innovation and diffusion through institutional arrangements, growth in yields will be high in the coming decades. In addition, several subsidies will reduce the cost of technologies and increase economies of scale. The study suggests that the area expansion for several cereal crops including wheat is going to be weak and that production and growth will mostly be driven by yield increases.





Difference in fertilizer use under the Current Trends (SSP2) and Sustainable pathways (SSP1)

BIODIVERSITY Livestock productivity

Current Trends Pathway	Sustainable Pathway
We assume that by 2050, livestock productivity moderately increases based on improvements in feed basket content and livestock production systems. Following the methodology of (Wirsenius ,2000) feed conversion (total feed input per product output in dry matter) and feed baskets (demand for different feed types per product output in dry matter) are derived by compiling system-specific feed energy balances. To facilitate projections of feed conversion and feed baskets, we create regression models with livestock productivity annual production per animal in tonne fresh matter/animal/year as a predictor, which permits the construction of livestock feeding scenarios. Currently, feeding scenarios are derived based on exogenous livestock productivity scenarios consistent with the storylines of the Shared Socioeconomic Pathways (Weindl et al., 2017). We assume an SSP2 storyline which implies moderate growth in livestock productivity and related changes in feed baskets (Fricko et al., 2017,). Based on National Council of Applied Economic Research (2015), the increase in income levels, population, and urban space, as well as the increased use of livestock products will expand the production of livestock products in coming decades. Despite a major dependency on cereals, rising protein consumption will necessitate increasing livestock and dairy production. To meet the domestic protein demand, the Government of India is focusing on livestock intensification systems to improve yields in animal products (Planning Commission, 2012).	By 2050, livestock productivity increases at a higher rate compared to 2010 based on the improvement in feed baskets and livestock production systems. The feed conversion calculation is same as described in the Current Trends Pathway. We assume an SSP1 storyline which implies high growth in livestock productivity and related changes in feed baskets (Fricko et al., 2017). The extent to which growth in livestock production can be accelerated will depend on how technology, institutions, and policies address constraints facing the livestock sector. Production growth dependent on larger animal stocks is not sustainable in the long run, due to adverse effect on the carrying capacity of land and available resources; hence, future growth in production should essentially come from improvements in productivity. This will require overcoming feed and fodder scarcity and improvements in the delivery of animal health and breeding services. A key driver of growth will be the generation and dissemination of yield-enhancing and yield-saving technologies (Ministry of Agriculture and Farmer's Welfare, 2017).

BIODIVERSITY Pasture stocking rate

Current Trends Pathway	Sustainable Pathway
By 2050, the average ruminant livestock stocking density per hectare will be higher compared to 2010 as we assume higher yields of pastureland. Several initiatives were taken to improve livestock feeding systems because, by 2025, India is likely to experience a fodder deficit of about 65% for green fodder and 25% for dry fodder (Indian Council of Agricultural Research, 2015; Ministry of Agriculture and Farmer's Welfare, 2017; Planning Commission, 2012).	Same as Current Trends

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway
By 2050, the share of total consumption which is imported is: • 17% for corn • 14% by 2050 for groundnut • 10% by 2050 for poultry meat	By 2050, the share of total consumption which is imported is: • 28% by 2050 for corn • 21% by 2050 for dairy • 21% by 2050 for poultry meat

TRADE Evolution of exports for key exported products (1,000 tonnes)

Current Trends Pathway	Sustainable Pathway
By 2050, the volume of exports is: • 9,037 tonnes by 2050 for soybean • 3,409 tonnes by 2050 for fibers • 2,428 tonnes by 2050 for cotton lint Based on our assumption of 10% trade liberalization for secondary and livestock products in 2030, 2050, 2100 and 20% for crops.	By 2050, the volume of exports is: • 7,747 tonnes by 2050 for soybean • 1,4370 tonnes by 2050 for oils cake • 195 tonnes by 2050 for cotton lint Based on our assumption of 10% trade liberalization for secondary and livestock products in 2030, 20% in 2050, 2100 and 20% in 2030, 30% in 2050, 2100 for crops.

FOOD Average dietary composition (daily kcal per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 2,260 kcal and is: • 1,207 kcal from crops • 363 kcal from livestock products • 626 from secondary products Our assumption is in the line with the SSP2 parameterization which assumes moderate consumption growth and an increasing share of livestock products in the dietary mix (Fricko et al., 2017). We assume that expected rise in per capita income, commercialization, and urbanization will cause a shift from main staples to high-value products, for example livestock products in India (Alae-Carew et al., 2019; Ritchie, Reay, & Higgins, 2018; Rosegrant, Leach, & Gerpacio, 1999), and substantial increases in projections for vegetable oils and sugar (Alexandratos, Nikos & Bruinsma, Jelle, 2012; Carriquiry et al., 2010)	By 2030, the average daily calorie consumption per capita is 2,286 kcal and is: • 1,170 kcal from crops • 385 kcal from livestock products • 668 kcal from secondary products We implemented a transition to a sustainable and healthy diet into the model's internal calculations of food demand, which are designed for long-term scenarios of food intake, dietary composition, body mass index distribution, body height and food waste. The food demand model is established based on a regression analysis with historical data to estimate consumption patterns using only changing GDP and population levels over time as drivers (Bodirsky et al., 2015; Dietrich et al., 2019). For the Sustainable Pathway we assume a linear convergence during the period 2020 and 2050 from model-internal calculations using the SSP1 parametrization of dietary patterns shifting according to recommendations for a healthy and sustainable diet described by the EAT-Lancet Commission (Springmann, 2019; Springmann et al., 2018).

FOOD Share of food consumption which is wasted at household level (%)

By 2030, the share of final household consumption which is wasted at the household level is 20%. This value is based on an exogenous food waste target that is approximately half of that of high-income countries. These exogenous values are derived from FAO historical data and calibrated to FAO Food supply values globally. In India, since food loss is mainly determined by the loss of fruits and vegetables during transportation and retail, we assume a moderate reduction in food loss and waste by 2050 under the SSP2 scenario (Fricko et al., 2017) as there is little available information on food waste at the household level.	By 2030, the share of final household consumption which is wasted at the household level is 10%. This value is based on an exogenous food waste target that is approximately a quarter of that of high-income countries. These exogenous values are derived from FAO historical data and calibrated to FAO Food supply values globally. Under the SSP1 scenario, we expect a more sustainable use of food at the household level owing to changes in consumer behavior, better storage facilities, and improved education and awareness (Stehfest et al., 2019) as there is little available information on food waste at the household level.

BIOFUELS Targets on biofuel and/or other bioenergy use (Mt DM/Year)

Current Trends Pathway	Sustainable Pathway
By 2050, biofuel production accounts for: • 79.63 Mt DM/year of sugarcane production • 2.39 Mt DM/year of corn production • 28.97 Mt DM/year of temperate cereal production Based on our assumption that the demand for bioenergy will increase up to 2030 and remain stable thereafter. Energy demand is defined as total demand for first-generation bioenergy, which is mainly determined by public policy measures, and rises to about 6 EJ of final energy globally in 2030 and 0.5 EJ of final energy for the South Asian Region in 2030 (Lotze-Campen et al., 2014). India's average blending rate for ethanol in gasoline is expected to reach a record 5.8%, up from a previous record 4.1% in 2019 and considerably higher than historical levels. A surplus sugar season coupled with a stronger incentive to convert excess sugar to ethanol has helped oil-marketing companies procure upwards of 2.4 billion liters in 2019 (Aradhey, 2019)	By 2050, biofuel production accounts for: • 540 Mt DM/year of sugarcane production • 33.91 Mt DM/year of corn production • 39.13 Mt DM/year temperate cereal production Based on the implementation of India's New Biofuel Policy, 2018. The policy proposes an indicative target of 20% blending of ethanol in petrol and 5% blending of biodiesel in diesel by 2030. Under these scenarios, we assume that the demand for ethanol will increase from 0.4 PJ/yr to 788 PJ/yr over the period from 2015 to 2030 and to 1838 PJ/yr in 2050. To meet the biodiesel mandate we assume that the demand for vegetable oils will also increase from 0.84 PJ/yr to 292 PJ/yr over the period from 2015 to 2030 and to 680 PJ/yr in 2050 with a continued increase after 2030. In our scenario we assume that demand will stabilize between 2030 and 2050 (Ministry of New and Renewable Energy, 2018)

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model LPJmL (Bondeau et al., 2007; Müller & Robertson, 2014).	By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model LPJmL (Bondeau et al., 2007; Müller & Robertson, 2014).

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland<50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
0	Rock and Ice	1981.607	27.1	63.4	33.5	66.5	4.582	93.3
218	Andaman Islands rain forests	514.522	5	68.8	6.3	93.7	11.262	91.2
222	Brahmaputra Valley semi-evergreen forests	5656.174	5.2	18.3	22.7	77.3	3688.655	25.3
226	Chin Hills-Arakan Yoma montane forests	15.518	0	72.5	0	0	0.188	100
228	East Deccan moist deciduous forests	34174.77	4.9	6.3	72.4	27.6	18539.109	26.2
233	Himalayan subtropical broadleaf forests	576.101	15.9	35.4	42.9	57.1	366.055	12.5
238	Lower Gangetic Plains moist deciduous forests	14617.61	3.1	6.4	45.4	54.6	12571.004	4.4
242	Malabar Coast moist forests	3471.677	3.6	3.8	30.5	69.5	1246.106	59.5
243	Maldives-Lakshadweep-Chagos Archipelago tropical moist forests	0.839	0	0		0	0.063	9.5
244	Meghalaya subtropical forests	4168.236	1.1	18.4	3.8	96.2	684.712	40.1
249	Mizoram-Manipur-Kachin rain forests	5822.178	4	49.6	7.6	92.4	470.292	47.3
252	Nicobar Islands rain forests	144.538	52.9	92.3	56.7	43.3	11.954	72.3
253	North Western Ghats moist deciduous forests	4830.426	4.9	6.7	65.1	34.9	2345.098	41
254	North Western Ghats montane rain forests	3100.352	17.2	24.1	62.5	37.5	607.07	69.3
261	Orissa semi-evergreen forests	2222.441	7.1	10.1	64	36	1760.293	10.4
270	South Western Ghats moist deciduous forests	2382.368	27.8	40.2	57.7	42.3	1022.4	31

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
271	South Western Ghats montane rain forests	2268.59	26.5	39.4	55.1	44.9	357.942	67.6
282	Sundarbans freshwater swamp forests	676.522	3.5	1.7	87	13	540.533	6.2
287	Upper Gangetic Plains moist deciduous forests	26367.93	1.3	2.3	38	62	24317.115	3.3
290	Central Deccan Plateau dry deciduous forests	24067.43	4.1	4.7	56.2	43.8	19066.507	11.2
292	Chhota-Nagpur dry deciduous forests	12269.22	6	6.8	80.2	19.8	8670.922	16
293	East Deccan dry-evergreen forests	2526.867	1.7	2.4	52.9	47.1	2241.722	7
295	Khathiar-Gir dry deciduous forests	26737.79	4.2	5.4	56.9	43.1	21266.776	13.2
296	Narmada Valley dry deciduous forests	17025.68	4.5	6.4	66.9	33.1	10854.944	26
297	North Deccan dry deciduous forests	5844.994	2.8	3.5	64.9	35.1	3870.024	20.1
298	South Deccan Plateau dry deciduous forests	8243.186	9.1	6.4	19.5	80.5	6469.961	9.7
302	Himalayan subtropical pine forests	3937.36	4.4	6.7	54.1	45.9	783.475	70.2
304	Northeast India-Myanmar pine forests	964.412	0	45.9	0.1	99.9	17.115	97.4
306	Eastern Himalayan broadleaf forests	5130.547	9.5	77.2	11.9	88.1	112.362	66.7
307	Northern Triangle temperate forests	6.379	0	98.8	0	0	0.068	100
308	Western Himalayan broadleaf forests	4664.288	6	17.6	29.3	70.7	876.715	64.2
309	Eastern Himalayan subalpine conifer forests	1265.683	5.8	90.7	6.3	93.7	12.141	93.7
310	Western Himalayan subalpine conifer forests	666.904	21.9	48.5	43	57	53.213	81.1
311	Terai-Duar savanna and grasslands	1193.908	9.8	13.7	65.2	34.8	734.683	20.4

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
312	Rann of Kutch seasonal salt marsh	2395.042	78.9	74.6	93.9	6.1	167.378	63
314	Aravalli west thorn scrub forests	24441.65	2	3.9	37.3	62.7	20837.085	9.8
315	Deccan thorn scrub forests	33804.62	2.8	4.6	26.1	73.9	29566.782	11.1
316	Godavari-Krishna mangroves	642.768	13.6	21.1	53.1	46.9	415.004	15.1
318	Thar desert	16029.25	2	3.4	56.4	43.6	6807.855	28.6
320	Indus River Delta-Arabian Sea mangroves	261.584	3.5	14.3	21.2	78.8	147.409	30.2
323	Sundarbans mangroves	378.45	38.7	35.8	97.7	2.3	160.833	4.7
702	Northeast Himalayan subalpine conifer forests	535.269	7.7	92.4	8.3	91.7	5.961	99.6
750	Central Tibetan Plateau alpine steppe	108.192	0	74.1	0	0	0.038	100
751	Eastern Himalayan alpine shrub and meadows	1257.011	11.1	98.5	11.3	88.7	16.171	99
754	Karakoram-West Tibetan Plateau alpine steppe	5172.01	26.6	74.1	34.8	65.2	41.834	92.1
760	Northwestern Himalayan alpine shrub and meadows	2457.337	21.5	73.3	27.5	72.5	68.208	95.4
769	Western Himalayan alpine shrub and meadows	1353.641	23.2	66.3	27	73	54.275	97.2
770	Yarlung Zanbo arid steppe	0.151	0	100	0	0	0	0
814	Baluchistan xeric woodlands	2.235	0	0	0	0	2.092	8.3

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

DM – Dry Matter

EJ – Exa Joule

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm – milimeters

Mm^3 – million cubic meters

Mt – million tonnes

PJ – Peta Joule

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Indonesia

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Indonesia. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. The Indonesian FABLE team developed and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Indonesia's NDC and Forest Reference Emission Level (FREL) treat the FABLE domains. According to the NDC, Indonesia has committed to reducing its GHG emissions by 29% by 2020 compared to 2010. This does include emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include enhanced actions to study and map regional vulnerabilities as the basis of an adaptation information system, strengthen institutional capacity and the promulgation of climate-change-sensitive policies and regulations by 2020, and implement a strategic approach predicated on 4 principles: 1) employing a landscape approach, 2) highlighting existing best practices, 3) mainstreaming the climate agenda into development planning, and 4) promoting climate resilience in food, water, and energy. Under its current commitments to the UNFCCC, Indonesia mentions biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and FREL

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2010	1.8 (2005)	2020	29% unconditional, 41% conditional	IPPU, Energy, Waste, Agriculture, Forestry and Land-use Change.	Y	Y	N	water, food, forests
FREL 2016	1990-2012	0.351 0.217	n/a	n/a	Deforestation and degradation Peat Decomposition	Y	N	N	n/a

Note. The NDC "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2017, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. The Indonesia Biodiversity Strategy and Action Plan strives to increase the awareness and participation of all national stakeholders to acknowledge the importance of biodiversity at the national and global levels over the long term (Bappenas, 2016). Links were made to map the national targets to the Aichi Targets,thus creating a connection to the Global FABLE Targets.

Table 2 | Overview of the NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(5) **Development of ex-situ conservation areas to protect local ecosystems**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(11) **Realization of sustainable maintenance and improvement of conservation areas**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(15) **Realization of conservation and restoration of degraded ecosystems in the region**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Indonesia.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 270 million in 2020 to 324 million in 2050), no constraints on agricultural expansion, a 2 Mha afforestation target, no change in the extent of protected areas, high productivity increases in the agricultural sector, and no change in diets (see Annex 2). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, rice, and soybean (see Annex 2).

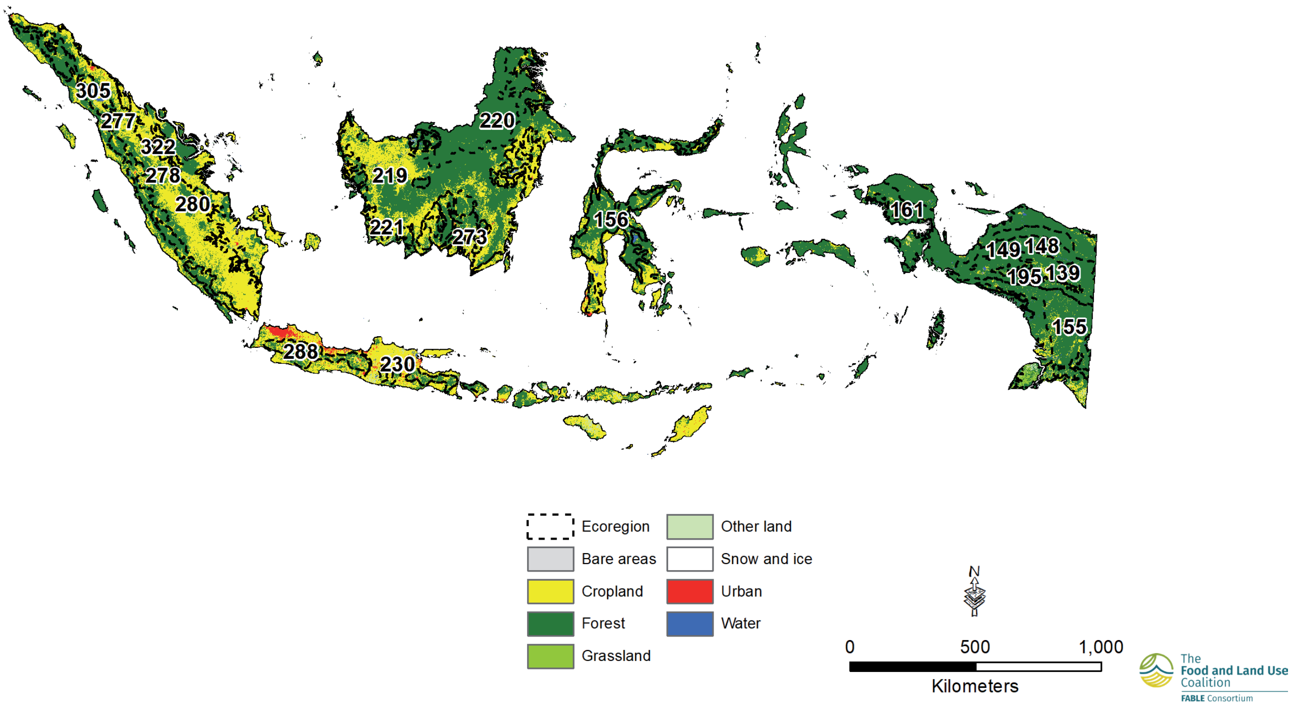
Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to greater expansion of protected areas by 2050, more constraints on agricultural expansion, and an increase in the afforestation target, set at 5 Mha (see Annex 2). This corresponds to a future based on the strong ambition of the Government of Indonesia to restrict land expansion by the moratorium on new permits/concessions on primary forest and peatland (Government of Indonesia, 2015) and to make considerable progress in sustainable forest management and biodiversity conservation measures (Bappenas, 2016). With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

In 2015, Indonesia was covered by 42% cropland, 4% grassland, 53% forest, 1% urban and 0.3% other natural land. Forest and other natural lands can be mostly found on Papua Island where 148-Northern New Guinea lowland rain and freshwater swamp forests dominates but can also be found in 140-Maluku Halmahera Rain Forest, 157-Sulawesi Montane Rain Forest, 219-Kalimantan Borneo Lowland Rain Forest, and 273-Freshwater Swamp Forests (Map 1). Whereas cropland can be found in 288-Java Western Java Montane Rain Forest, 280-Sumatera Sumatran Peat Swamp Forest, 278-Sumatran Lowland Rain Forest, and part of 156-Sulawesi lowland rain forest. Settlements and urban land are more centralized on Java Island where the most populated provinces are located (49 million people live in West Java). Indonesia currently faces challenges in managing data and information on biodiversity richness and its utilization, therefore data collection activities, including exploration and expeditions, are critically needed to uncover the existence of new species and the current state of others. For example, collected samples of mammal locations only cover about 26% of all Indonesian provinces, thus showing the urgency to increase coverage (Bappenas, 2016).

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

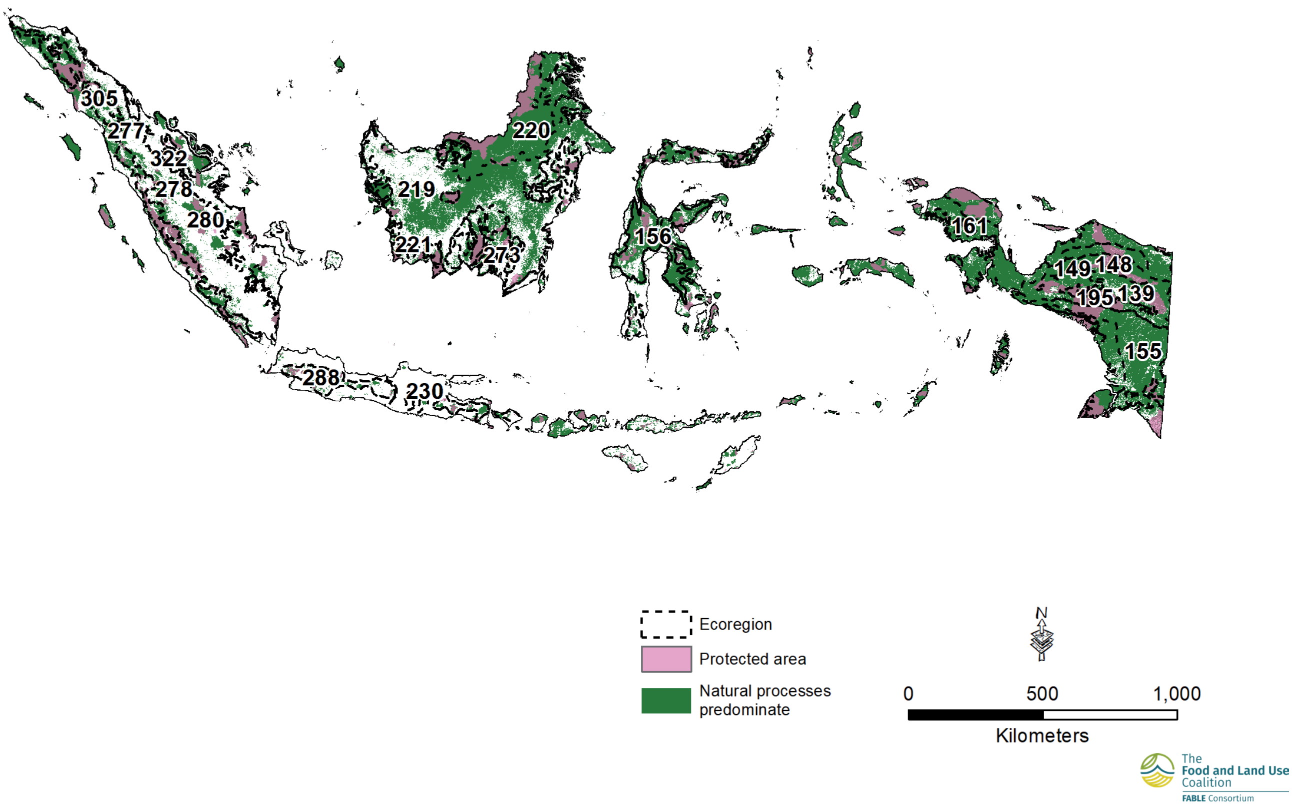


Notes: The correspondence between national land cover map classes and aggregated land cover classes displayed on the map and an overview of biodiversity indicators for the current state at the ecoregion level can be and can be found in Annexes 3 and 4, respectively .
Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – National Land Cover Map (KLHK, 2019)

We estimate that land where natural processes predominate[2] accounted for 55% of Indonesia's terrestrial land area in 2010 (Map 2). The 219-Borneo Lowland Rain Forest holds the greatest share of land where natural processes predominate, followed by 278-Sumatran Lowland Rain Forest and 156-Sulawesi Lowland Rain Forest (see Annex 4). Across the country, while 22 Mha of land is under formal protection (12% of total land), falling short of the 30% zero-draft CBD post-2020 target, only 21% of the land where natural processes predominate is formally protected. This indicates the urgency of preserving and better managing the above-mentioned ecoregions as pressure on the land system is increasing rapidly, specifically the impact of cropland expansion is imminent. For example, designated areas for a major rice production site include 156-Sulawesi Lowland Rain Forest of South Sulawesi.

Approximately 52% of Indonesia's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in 219-Borneo lowland rain forest, followed by 278-Sumatran Lowland Rain Forest and 156-Sulawesi Lowland Rain Forest (see Annex 4). The regional differences in the extent of biodiversity-friendly cropland can be explained by regional production intensity of, for example, paddy fields and rice in 156-Sulawesi Lowland Rain Forest, palm oil and coconut in 278-Sumatran lowland rain forest, and rubber and palm oil in 219-Borneo lowland rain forest.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note: Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

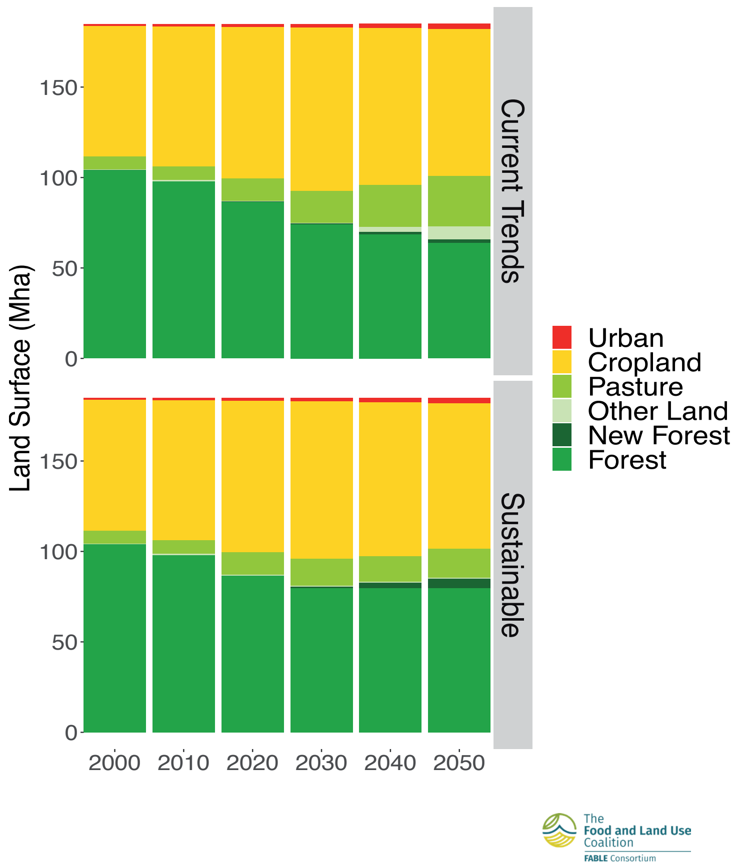
2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, 2 Mha of reforestation/afforestation by 2050 following the Bonn Challenge commitment, and protected areas remaining at 22 Mha, representing 12% of total land cover in 2050 (see Annex 2).

Historical deforestation in Indonesia decreased from 1 Mha in 2014-2015, to 0.43 Mha in 2015-2016, and 0.31 Mha in 2016-2017 (Kementerian Lingkungan Hidup dan Kehutanan, 2018). Our results show a higher average annual deforestation: 1.3 Mha between 2015-2020. By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase of cropland area, an increase in pasture area, and a decrease in forest area. Between 2015 and 2030, Forest area is estimated to decrease by 21%, totaling 74 Mha in 2030, resulting in an average annual deforestation of 1.3 Mha. For comparison, national scenarios in Indonesia's NDC used 0.8 Mha deforestation rate for the BAU Scenario over 2012-2030, and other national scenarios (CM1 unconditional / CM2 conditional) assume an annual rate of 0.3 Mha of deforestation (Minister of Environment and Forestry, 2017). Our results are explained by expansions in cropland (0.7 Mha per year) and pasture (0.5 Mha per year) in pasture expansion over the period 2015-2030. However, historically, pasture area has decreased in Indonesia, so this computed expansion of pasture area largely explains the overestimation of deforestation in our results.

Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Note. Other land includes bare soil, ice, and all land areas that do not fall into any of the other five categories
Source. Authors' computation based on National land cover map of Indonesia for the area by land cover type for 2000, (KLHK, 2019)

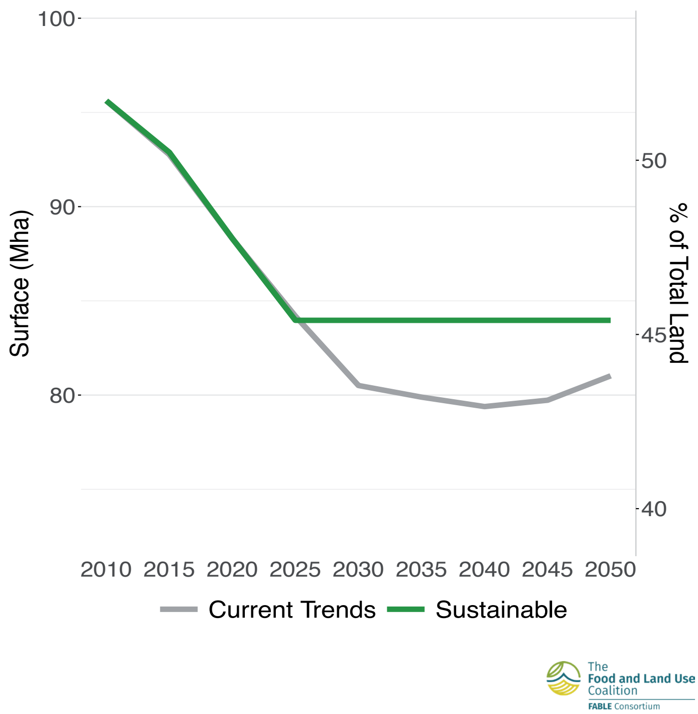
Over the period 2030-2050, computed cropland area decreases and grassland area further increases (Figure 1). The expansion of the planted area for oil palm fruit, rubber, and nuts explains 81% of total cropland expansion between 2010 and 2030: 37% from oil palm fruit, 29% from rubber, and 15% from nuts. For oil palm fruit, 81% of expansion is explained by an increase in palm oil exports and 19% by an increase of nonfood domestic consumption. For rubber, 96% of the expansion is due to an increase in exports. Finally, for nuts, most of the expansion results from an increase in internal demand for food. Pasture expansion is mainly driven by the increase in the domestic consumption of milk and red meat despite an increase in the cattle productivity per head over the period 2020-2030.

Between 2030-2050, the increase in pasture area is explained by a continued increase in the domestic consumption of milk and red meat coupled with the relative stabilization of cattle productivity. Over the same period, cropland reduction is explained by a decrease in the level of palm oil production combined with an increase in productivity of oil palm trees. Despite our initial assumptions of strong growth in exports, palm oil exports are cut by 8% in 2050 compared to 2030 after trade adjustment. This is due to global imports for palm oil only growing by 5% even though Malaysia also projected large increases in their palm oil exports, which led to a large over-estimation of palm oil exports globally. Moreover, the reduction in corn area is explained by the fact that we assume a very large increase in productivity that leads to land savings combined with continuously higher production. The same is true for rice though the assumed growth in productivity is lower. This results in a reduction of land where natural processes predominate by 16 % by 2030 and by 15% by 2050 compared to 2010, respectively (Figure 2).

In the Sustainable Pathways, assumptions on agricultural land expansion and reforestation have been changed to reflect the strong ambition of the Government of Indonesia to reduce deforestation under presidential instruction. The main assumptions include the prevention of deforestation by 2030 and 5.5 Mha reforestation/afforestation by 2050 (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Indonesia in the Sustainable Pathway: (i) 10 Mha of avoided deforestation between 2030 and 2050, (ii) a 1% increase in the total land where natural land processes predominate, reaching 45% in 2050, (iii) limiting pasture area expansion to 1.3 Mha between 2030 and 2050, and (iv) increasing reforested/afforested land. The prevention of deforestation is equivalent to preventing any agricultural expansion as the area classified as other natural land is already at the minimum (i.e. within protected areas in the model). Palm oil exports are further reduced compared to the Current Trends pathway due to lower international demand for palm oil in the Sustainable pathway. Additionally, increases in the productivity of rice also contributes to the differences between the *Current Trends* and *Sustainable* pathways. These changes lead to the stabilization in the area where natural processes predominate after 2025 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate

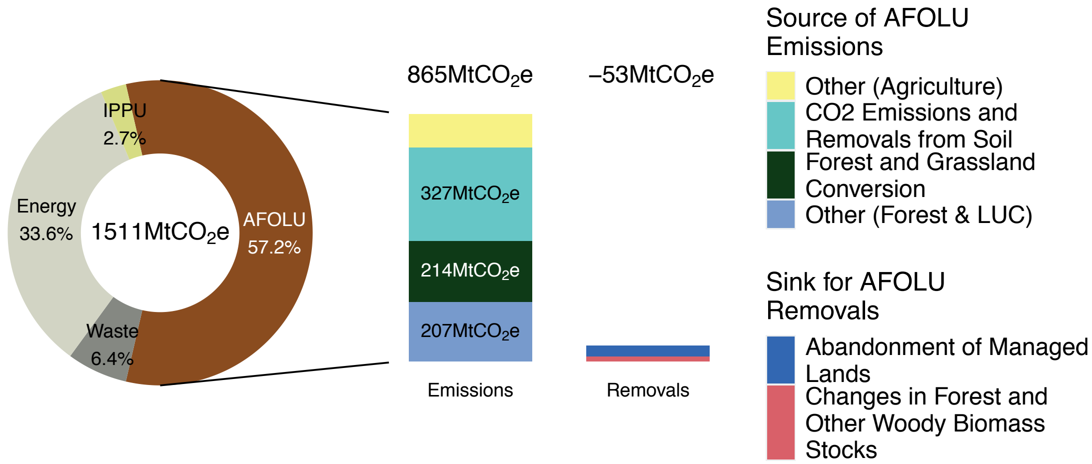


GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 57.2% of total emissions in 2012 (Figure 3). Forest and grassland conversion is the principle source of AFOLU emissions, followed by CO_2 emissions and removals from soil (peatland). This can be explained by oil palm estate expansion, rice cultivation, and rubber plantation expansion into forests, including on peatland between 1990 and 2000, the expansion of pulp and paper and sawn timber plantations after 2000, and transmigration policies and illegal logging (Margono et al., 2012).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2012



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from Indonesia's First Biennial Update Report (Republic of Indonesia, 2015)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU increase from 863 Mt in 2015 to 1,291 Mt in 2030 before decreasing to 989 Mt in 2050 (Figure 4). In 2050, land-use conversion is the largest source of emissions (602 Mt CO_2e/yr from deforestation and 527 Mt CO_2e/yr from peat in 2030) while land also acts as a small sink (-10 Mt CO_2e/yr in 2030). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for emissions from livestock and peat while emissions from deforestation decrease over time (-66%).

In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by 45% by 2050 compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Pathway are dominated by a reduction in GHG emissions from deforestation, peat, and livestock (Figure 5). Efforts on stopping deforestation by 2030 and changing diets are the most important drivers of this reduction. Indonesia's commitments under UNFCCC (Table 1) are to reduce total GHG emissions by 29% by 2030 and up to 41% compared to a BAU equivalent, or 522 Mt CO_2e/yr and 738 Mt CO_2e/yr, respectively. Our results show that AFOLU emissions could be reduced by 689 Mt CO_2e/yr by 2030 compared to BAU in 2030. This suggests that the reduction of GHG emissions AFOLU sector could allow for some increase of emissions in other sectors.

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends pathway

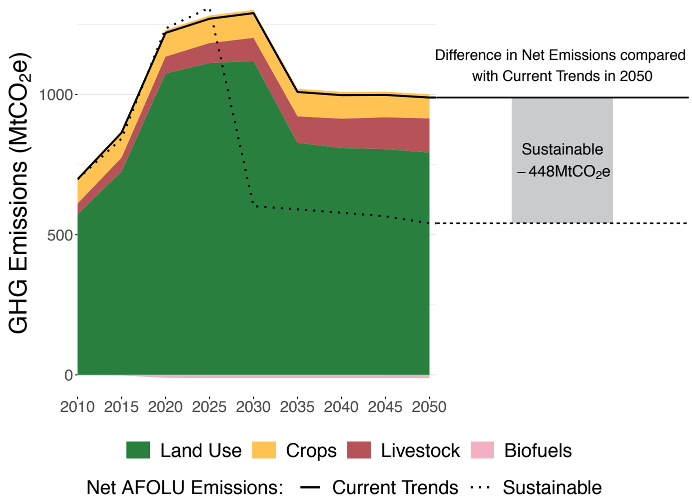
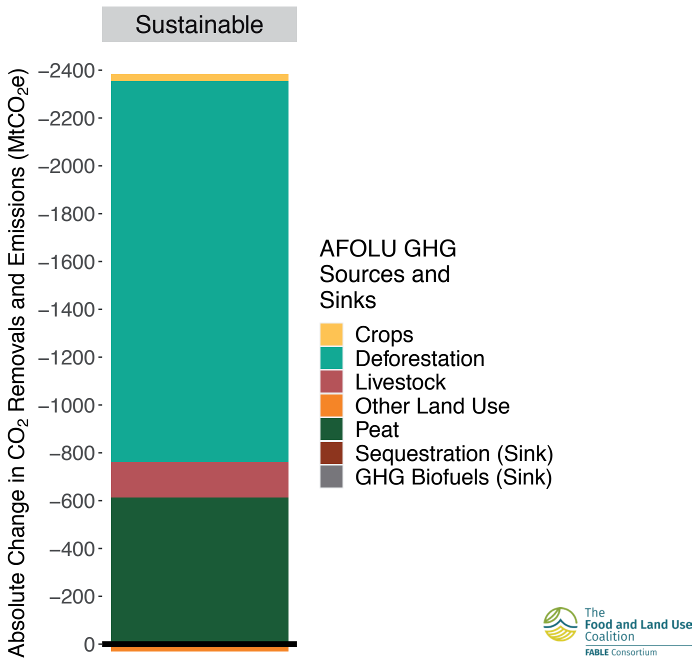


Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

Undernutrition

7.6% of the population undernourished in 2014 - 2016. This share has decreased since 2011 (FAO, 2017b).

36.4% of children under 5 stunted and 12.1% wasted in 2015 (UNICEF, 2017).

Micronutrient Deficiency

33% of women and 23% of children suffer from anemia in 2010, which can lead to maternal death (Institute for Health Metrics and Evaluation [IHME], 2020).

16.7% of the population are deficient in vitamin A (IHME, 2020), which can notably lead to blindness and child mortality, and 0.5% are deficient in iodine, which can lead to developmental abnormalities (IHME, 2020).

Overweight/ Obesity

28% of the population, and 11% of adolescent girls and 11% of adolescent boys were overweight in 2018 (Maehara et al., 2019). These shares have increased since 2015 (Harbuwono, Pramono, Yunir, & Subekti, 2018).

33% of adults and 9.4% of children, were overweight in 2014. These shares have increased since 1994 (Oddo, Maehara, & Rah, 2019).

Disease Burden due to Dietary Risks

14.1% of the population suffers from diabetes and 4.6% from cardiovascular diseases, which can be attributable to dietary risks (IHME, 2020).

Table 3 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,570 (2,058)	2,482 (2,080)	2,313 (2,080)	2,437 (2,084)	2,412 (2,084)
Fats (g) (recommended range)	50 (57-85)	57 (55-83)	52 (51-77)	66 (54-81)	64 (53-80)
Proteins (g) (recommended range)	57 (64-224)	62 (62-217)	59 (57-202)	68 (61-213)	67 (60-211)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

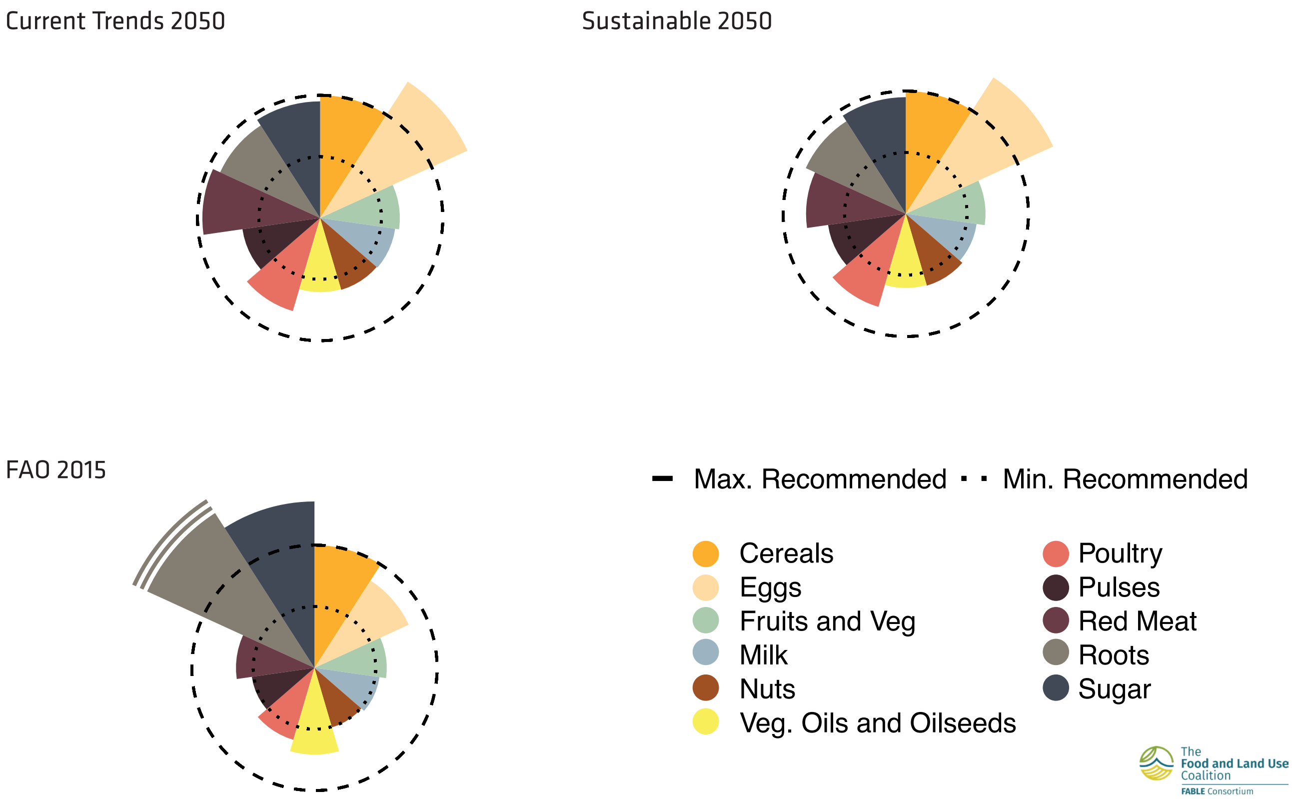
Pathways and Results

In both pathways, we base our diet scenarios on the historical energy consumption intake in 2017 as reported by the National Food Security Agency, which made these calculations following Indonesia's Targeted Food Pattern (PPH) (Satriani & Martianto, 2019). The PPH is composed of 9 food groups that we included in the FABLE Calculator in effort to provide more detailed dietary scenarios that reflect these groups. When the PPH value was not available for certain commodity groups, we took historical consumption data.

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 19% higher in 2030 and 17% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals, oil and fat, and fruit and vegetables. Animal products represent only 10% of the total calorie intake. We assume that the per capita kilocalorie consumption of animal products including fish, will increase by 68% between 2020 and 2050. The consumption of oil and fat, and nuts will also increase while cereals, sugar, and roots consumption will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), in 2015 roots consumption is above and cereals and sugar are close to the maximum recommended. By 2050, only eggs are over the maximum recommended, while cereals just reach the maximum limit (Figure 6). Moreover, there is an increasing demand for milk consumption but it remains within the recommended range.

Under the Sustainable Pathway, we assume similar diets compared to the Current Trends Pathway. However, compared to the Current Trends, the ratio of the computed average intake over the MDER decreases to 11% in 2030 and 15% in 2050. This is explained by the fact that in the Sustainable pathway we applied a zero deforestation policy after 2030. Since other natural land is already at the minimum level (i.e. only found within protected areas), agricultural land cannot expand after 2030. This penalizes livestock production in particular, and, in the absence of further productivity gains or increases in the imports of livestock products, the internal consumption for livestock products has to be reduced. Compared to the EAT-*Lancet* recommendations, the consumption of red meat is still within the recommended range and is now closer to the average recommended daily intake in 2050 (Figure 6). Moreover, the fat and protein intake per capita are in line with the dietary reference intake (DRI) in 2030, showing a slight decrease compared to the Current Trends Pathway but remaining within recommended boundaries (Figure 6).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of roots indicate that the average kilocalorie consumption of this food category is significantly higher than the maximum recommended.

Water

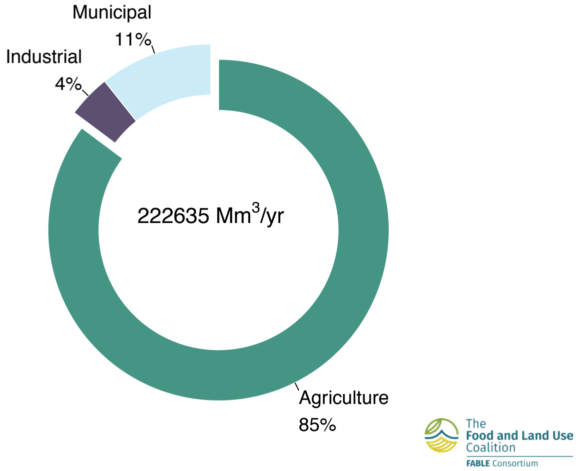
Current State

Indonesia is characterized by a tropical climate, with 2,702 mm average annual precipitation that mostly occurs between December to March. The agricultural sector represented 85.2% of total water withdrawals in 2016 (Figure 7). Moreover in 2013, 17% to 20% of agricultural land was equipped for irrigation. Irrigation water demand is estimated at 5,441 m^3/s (Asian Development Bank, 2016). Rice occupies 80% of total harvested irrigated area, with corn, groundnuts, soybean, and vegetables mostly accounting for the rest (AQUASTAT 2005).

Pathways and Results

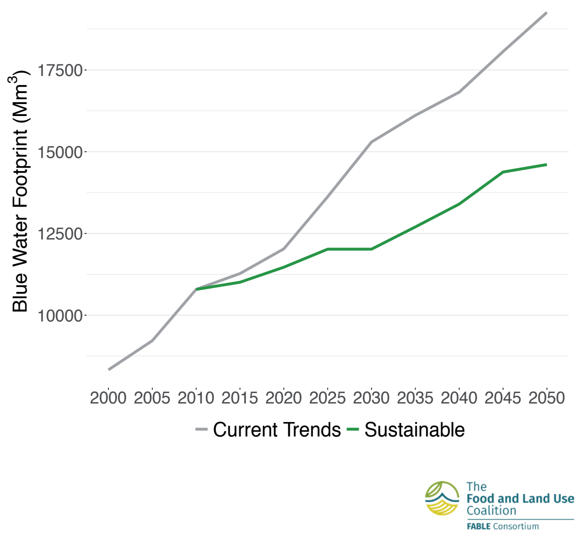
Under the Current Trends Pathway, blue water use increases between from 11,273 Mm^3/yr in 2015, to 15,297 Mm^3/yr and 19,261 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with rice, corn, and sugarcane accounting for 79%, 9%, and 6% of computed blue water use for agriculture by 2050[3]. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture reaches 12,019 Mm^3/yr in 2030 and 14,607 Mm^3/yr in 2050, respectively. We did not assume a change in the water efficiency, and the production level of the main irrigated commodities does not significantly change between the Current Trends and the Sustainable pathways. Therefore, this change is solely driven by the estimated impact of climate change on water demand: under the Current Trends pathway, we assume a higher concentration pathway than in the Sustainable pathway at the global level (RCP 6.0 vs RCP 2.6) (see Annex 2). According to the national average estimates from the GEPIC crop model using climate inputs from the climate model hadgem2, the per tonne irrigation water use would increase by more than 30% in 2050 compared to 2010 for corn and rice under the Current Trends pathway while it would stay constant for corn and only increase by 11% for rice.

Figure 7 | Water withdrawals by sector in 2016



Source. Adapted from AQUASTAT Database (FAO, 2017b)

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



3 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Koekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

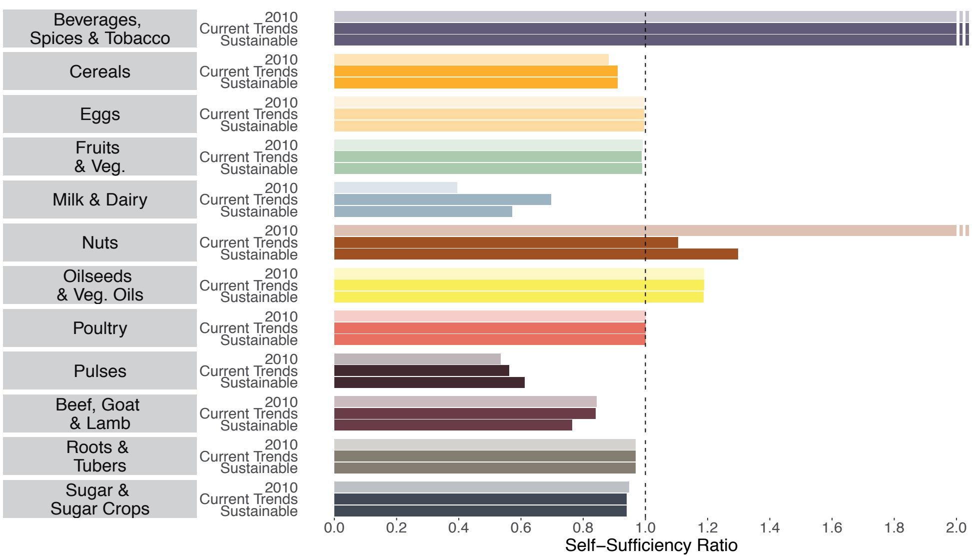
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Indonesia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

The 2012 Indonesian law on food regulates the pursuit of food security and self-sufficiency of certain key commodities, rice, maize, sugar, soybean, and beef.

Under the Current Trends Pathway, we project that Indonesia would be self-sufficient in eggs, fruits and vegetables, nuts, oilseed and vegetable oils, and poultry meat in 2050, with self-sufficiency by product group remaining stable for the majority of products from 2010 to 2050 (Figure 9). The product groups where Indonesia would depend the most on imports to satisfy internal consumption are cereals, milk and dairy, pulses, and red meat. By 2050, Indonesia would be 80% self-sufficient in cereals and red meat and less than 50% self-sufficient in pulses and milk and dairy. These trends are similar in the Sustainable Pathway, with the exception of milk and red meat, for which self-sufficiency would decrease, and pulses, for which it would increase, by 2050. Among the specific commodities for which Indonesia aims to achieve self-sufficiency (rice, maize, sugar, soybean, and beef), only soybean and sugar would not achieve this target by 2050. Finally, the self-sufficiency ratio for beef is reduced in 2050 by 12% in the Sustainable pathway. This is explained by the reduction in cattle production, which is due to stronger restrictions on the expansion of agricultural land.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for beverages, spices and tobacco and nuts, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

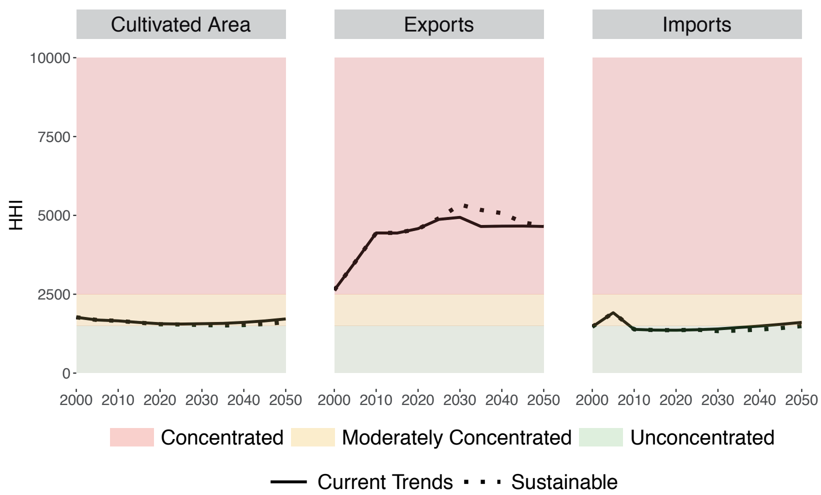
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

In 2010, 5 crops represented 79% of the cultivated area with shares of total cropland area varying between 2% and 15% for, by order of importance, rice, rubber, oil palm, corn, and coconut. For imports, four commodities (wheat, milk, soyabean, and soycake) represented 62% of the total volume of imported commodities. Finally, Indonesia exported low quantities of palm oil and rubber, two major commodities, which already represent 74% of the total volume of exported crops.

Under the Current Trends Pathway, we project high concentration of crop exports, a medium to low concentration of imports, and a medium to low concentration of planted crops in 2050, trends which slightly increase between 2010 and 2050. This indicates moderate to high levels of diversity across the national production system and for imports, but low diversity for exports. Under the Sustainable Pathway, our results remain similar to the Current Trends pathway, except for the projection of higher concentration of crop exports compared with the Current Trends pathway, in which they peaked between 2025 and 2045 (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

The Current Trends and Sustainable Pathways presented in this chapter show two alternative futures for land use and food systems in Indonesia. Under the Current Trends Pathway, we projected medium population growth (from 270 million in 2020 to 324 million in 2050), with no constraints on agricultural expansion, a 2 million hectare afforestation target, no change in the extent of protected areas, high productivity increases in the agricultural sector, and no change in diets. In contrast, under the Sustainable Pathway, there are significant efforts to adopt sustainable policies reflecting the strong ambition of the Government of Indonesia.

In terms of land and biodiversity, we find that under the Current Trends Pathway, deforestation will continue to increase in the future due to increases in cropland and pasture areas, while reforestation will be limited to 2 million hectares. In contrast, under the Sustainable Pathway, we assumed the implementation of zero-deforestation policies by 2030 and increased the reforestation target to 5.5 million hectares, which leads to a net gain in forested land after 2030 and an increase in total land where natural processes predominate.

Currently, Indonesia's agricultural sector is highly fragmented, it comprises large plantations, both state-owned and private enterprises, and small-scale farmers. Plantation areas are dominated by export commodities such as oil palm and rubber, while staple crops are dominated by rice, maize, and cassava. Low productivity issues for staple goods have been a major concern for Indonesia's food security and increasing crop productivity and cropping intensity are the main targets for the agricultural sector to reduce demand for land. Indonesia's agricultural policy aims to increase agricultural productivity (non-oil palm commodities) by 4% per year (LCDI, 2019). The low productivity of agricultural staple crops in Indonesia is due the large number of "petani gurem" or smallholder farmers with less than 0.5 hectares of land. One problem faced by smallholder farmers is agricultural land conversion to non-agricultural land. In addition, many smallholder farmers have to transition from a situation where they operate their own land to a one where they either rent or share ownership. Another problem that leads to low agricultural productivity is that many farmers still practice slash and burn (shifting cultivation) in forest areas, which contributes to forest loss and it is the main cause of land degradation.

Two government programs could be especially helpful to smallholder farmers in the future, the Tanah Objek Reforma Agraria (TORA) program and Social Forestry (SF). Under the TORA program, a community is provided legal certainty over land ownership. Farmers with legal ownership of land will have access to government subsidies, credit, and extension services for supporting their farming activities. Under the SF program, local communities can manage forest themselves, including for agroforestry or timber plantations. The government targeted approximately 4.1 million hectares of land distributed through the TORA program me and 12 million hectares of forest area for SF. These programs will contribute to increasing crop production.

In the Sustainable Pathway, there is a 45% reduction in GHG emission by 2050 that comes from reduced deforestation, well-managed peat, and improved livestock productivity. Restrictions on deforestation are the important drivers of this reduction in our model. The Mitigation Action and Emission Reduction Target in National Action Plan – Green House Gas (RAN-GRK) from the Indonesian government lists the following actions to reduce emissions in the agriculture and forestry sectors: (i) sustainable forestry, (ii) avoiding deforestation and degradation, (iii) reforestation, and (iv) land optimization (NDC, 2017). The realization of these actions will play a key role in reducing GHG emissions in Indonesia. Indonesia has taken a significant step towards a moratorium on new licences to protect primary forests and peatlands conversion. This moratorium provides legal rights of villagers, smallholders, and forest protection and provides the opportunity to undertake critical forest governance and agricultural and land-use reforms.

Our findings suggest that the implementation of no-deforestation policies might reduce food availability if not accompanied by other measures. The adoption of dietary changes that follow the national dietary guidelines of Indonesia might be part of the solution. The country's new Food Development Strategy for 2020-2024 also includes a national reduction strategy for food loss and waste. We will include these two components into our future analyses.

Water is also crucial to support food security. The climate change impact estimates that we used suggest that Indonesia might suffer from a reduction in precipitation under RCP 6.0 (Current Trends Pathway) leading to a large increase in water use for irrigation. While we have only used one crop model and one climate model in this analysis, we recognize that uncertainties related to future climate change may be large. We will complement our analysis with additional estimates from other crop and climate models to evaluate the level of confidence about future climate change impacts on agriculture in Indonesia.

The new regulation on water resources in Indonesia states its priorities to increase access for daily needs and estate crops agriculture (GoI, 2019). In the future, Indonesia may see increasing blue water usage to tackle its low crop productivity. Restoring critical watersheds and sources with regulation that controls water usage can lead to improved water efficiency in Indonesia.

Limitations were also recognized in our models. We are aware of the challenges on data collection and availability to build the scenarios and assumptions to complete the analysis of the FABLE Calculator. The implementation of One-Map policy of the Government of Indonesia may be of interest to feed into our future efforts in modeling the pathways for a sustainable land-use system that can support decision making on land reforms and agricultural developments in Indonesia.

Further improvements to our Sustainable Pathway will require exchange and knowledge sharing with others in the modeling community. In this light, the FABLE Indonesian team is building a community of practice on land-use modeling. This community of practice acts as a hub to create future opportunities for information exchanges, network building, and discussion around the FABLE domains. It brings together all modeling activities undertaken in Indonesia to support long-term strategies such as the LCDI and other sustainability objectives. Through these efforts, we will continue to further improve our analysis and ignite discussions on the modeling of food and land use systems to provide support to The Government of Indonesia. Due to the large heterogeneity of Indonesian landscapes and strong decentralization, in the future we would also like to adapt the FABLE Calculator to the sub-national level, including island-wide analyses. Through this, we can engage provincial level governments in developing a food and land component to various sustainable pathways.

Annex 1. List of changes made to the model to adapt it to the national context

- Making use of National Population Projection up to 2035, including comparing it with population projections.
- Using national land cover map of Indonesia, which has been aggregated to the FAO class land (KLHK, 2019)
- Taking GDP projections from the National Medium Term Development Plan (RPJMN) from Bappenas for Current Trends pathway
- Adapting the dietary scenario to the national context by drawing on data from the Indonesia Self-Sufficiency Institute
- Adding peat classification and ensuring that peat decomposition is taken into account.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
Estimated increase from 302.86 million people in 2035 to 323.57 million people in 2050. According to the national demographic projection, it is estimated that, in 2035, Indonesia will have 305.6 Million people. Scenario selected showed realistic percentage growth according to national statistics (Badan Pusat Statistik, 2018). (UN_InstantReplacement scenario selected)	Same as Current Trends. We consider no change because the current projections already meet the numbers of national projection until 2035 and are thus in line with national statistics.

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
No further regulation on land conversion in forestry area. Currently, there seems to be a low coordination between all stakeholders which creates a situation non-conducive to reform and enforcement of the regulation on palm oil moratorium (Anderson, Kusters, McCarthy, & Obidzinski, 2016). These scenarios describe the future of uncontrolled expansion.	High level of enforcement in forestry sector to target zero deforestation in 2030. Indonesia is increasing enforcement and building coordination between levels of governance and stakeholders creating less conflict on the regulation of moratorium of new permits or licenses in some types of forest area and peatland.

LAND Afforestation or reforestation target (1000 ha)

Current Trends Pathway	Sustainable Pathway
Afforestation/Reforestation target inline according to Bonn Challenge with 2 Mha forest replanted.	Indonesia's implementation on Land Restoration and Rehabilitation Target is enforced. Adding 5.5 Mha of rehabilitated land to natural habitat, including forest. According to RPJMN 2020 -2024 (Bappenas, 2019). This scenario assumes that forest and land rehabilitated target for 2020 is 5.5 Mha and 1.9 Mha would be achieved.

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
Total protected areas remain constant to 2050 at 22.5 Mha (Bappenas 2019).	The by-default assumption in the FABLE Calculator were used, which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.

PRODUCTION Crop productivity for the key crops in the country (in t/ha)	
Current Trends Pathway	**Sustainable Pathway**
Estimated productivity for key crops between 2015 and 2050: 1. Palm oil fruit: 17t/ha to 24 t/ha 2. Rice: 3,4t/ha to 4,8t/ha 3. Corn: 4.6t/ha to 16.7 t/ha 4. Soybean: 1.4t/ha to 2.2t/ha 5. Sugarcane: 61.7t/ha to 87.8t/ha Indonesia's national statistics reported productivity for selected commodities in 2015: 1. Rice: 5,152 t/ha 2. Corn: 4.84 t/ha 3. Soybean: 1,416 t/ha Differences with national data on production still remain, but estimated productivity captured national values of Indonesian data for selected commodities	Same as Current Trends The Current Trends pathways values of productivity for major crops in Indonesia, such as corn and soyabean, are in the range of national historical values, thus we opted to make no change on the productivity scenario.
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)	
Between 2015 and 2050, the productivity per head range: 1. Beef: 0.043 t/TLU to 0.044 t/TLU 2. Chicken: 0.282 t/TLU to 0.506 t/TLU 3. Milk: 2,175 t/TLU to 2,257 t/TLU	Same as Current Trends There are no official records of productivity projection in Indonesia between 2015 and 2050, but Indonesia's target on self-sufficiency mentions beef products. Increasing production and productivity of beef is included in The Ministry of Agriculture strategy to empower food sovereignty (Sulaiman, Subagyono, Soetopo, Sulihanti, & Wulandari, 2018)
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)	
The average livestock stocking density remains constant at 1.89 TLU/ha of pasture between 2015 and 2050. We assume no change for the pasture stocking rate scenario	Same as Current Trends We have not found national data for comparison. Therefore, we make assumptions that are in line with 6 Strategic Targets from The Ministry of Agriculture (The Ministry of Agriculture Republic of Indonesia, 2015) .
PRODUCTION Post-harvest losses	
We assume a 50% decrease in the share of post-harvest losses between 2010 and 2050 Based on the Ministry of Agriculture, which has set the following national targets on post-harvest loss of major crops: Rice: from 10.48% (baseline) to a 0.4 % decrease in 2019 Corn: from 4.81% (baseline) to a 0.9% decrease in 2019 Soyabean: from 14.7% (baseline) to a 1.3% decrease in 2019 Cassava: from 11.58% (baseline) to a 0.3% decrease in 2019 Decreasing the share of post-harvest loss through good handling practices was included in the Strategic Targets of Agriculture Development (Direktorat Pascapanen Tanaman Pangan, 2015)	Same as Current Trends The national targets on post-harvest losses are only available until 2019. Therefore, we assume a 50% decrease between 2010 and 2050, which is in line with national goals.

Indonesia

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway
The share of total consumption which is imported between 2015 and 2050: 1. For rice: a decrease from 1.58% to 0.85% 2. For corn: a decrease from 8.8% to 4.7% 3. For soyabean: an increase from 58.6% to 68.8% National Ambition in self-sufficiency of selected crops.	Same as Current Trends Values in Current Trends pathways captures the national ambition of reaching self-sufficiency in selected strategic crops.

TRADE Evolution of exports for key exported products (1000 tons)

Current Trends Pathway	Sustainable Pathway
The exported quantity increases between 2015 and 2050: 1. Palm Oil: from 24 Mt to 45 Mt 2. Rubber: from 2.8 Mt to 4 Mt Based on national data from the Ministry of Agriculture, in 2015 Indonesia exported 26.5 Mt of palm oil and 2.6 Mt of rubber. Increasing exports on major commodity such as palm oil and rubber is mentioned in national agendas (The Ministry of Agriculture Republic of Indonesia, 2015)	Same as Current Trends Different results showed in the calculation can be explained by the implementation of land scenarios.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
Indonesia's kcal consumption requirement (AKE) in 2018 is (in kcal/cap/day): Grains/rice: 1,315 Tubers: 53 Meat: 233 Oil and fat: 240 Oily fruit/seeds: 22 Nuts: 60 Sugar: 78 Vegetables and fruits: 113 Others: 52	Same as in Current Trends

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
Between 2015 and 2050, the share of final household consumption which is wasted decreases from 10% to 5%. There is no official record or research on food waste targets in Indonesia. We; nevertheless, assume increasing commitments from the government by 2050.	Same as Current Trends

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
Based on by-default OECD projections. Palm oil is still the major crop for producing biodiesel in Indonesia. According to the National Development Plan, biofuel by 2020, 2025 and 2050 are targeted to reach 7.7 MKL, 10.8 MKL, and 54.6 MKL (Metric Kilo Litre) respectively (Bappenas, 2019). Meanwhile. there is a strong regulation on blending (B30) that requires 30% blending of biodiesel with Diesel Oil to stimulate the renewable energy sector in Indonesia.	Same as Current Trends Currently, the given scenario reflects the ambition of Indonesia to increase the usage of biofuel nationally.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
We assumed a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m2 by 2100 (RCP 6.0). The model includes the corresponding climate change impacts on crop yields by 2050 as estimated with GEPIC crop model for corn, rice, and soybean.	We assumed a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)	National Land Cover Map
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)	Shrubs, Estate Crops,Swampy Shrubs, Dryland Agriculture, Mixed Dryland Agriculture, Paddy Field
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)	Primary Dryland Forest, Secondary Dryland Forest, Primary Mangrove Forest, Secondary Mangrove Forest, Primary Swamp Forest, Secondary Swamp Forest, Plantation Forest
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)	Settlements, Savanna/Grass, Transmigration
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)	Bare Land,Airport, Mining
Bare areas	Bare areas (200,201,202)	
Snow and ice	Snow and ice (220)	
Urban	Urban (190)	
Water	Water (210)	

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
136	Banda Sea Islands moist deciduous forests	690,6	15,1	74,8	18,3	81,7	134,9	60,7
137	Biak-Numfoor rain forests	257,1	18,6	72,6	23,8	76,2	18,8	73,4
138	Buru rain forests	849,0	0,8	68,5	1,1	98,9	186,9	61,9
139	Central Range Papuan montane rain forests	7.500,1	28,2	90,8	29,7	70,3	160,9	90,5
140	Halmahera rain forests	2.549,1	8,1	80,7	10,0	90,0	79,2	78,0
148	Northern New Guinea lowland rain and freshwater swamp forests	5.966,4	23,3	92,6	22,8	77,2	94,1	76,7
149	Northern New Guinea montane rain forests	1.666,7	20,4	94,0	20,2	79,8	24,2	57,1
151	Seram rain forests	1.879,0	10,6	79,8	13,3	86,7	128,7	74,0
154	Southern New Guinea freshwater swamp forests	5.037,1	17,0	87,2	19,1	80,9	267,2	77,4
155	Southern New Guinea lowland rain forests	7.582,8	7,1	90,6	7,8	92,2	301,1	78,9
156	Sulawesi lowland rain forests	11.323,5	7,3	45,9	14,8	85,2	3.559,2	42,4
157	Sulawesi montane rain forests	7.597,8	14,8	79,5	18,4	81,6	929,4	60,3
160	Vogelkop montane rain forests	2.166,4	57,0	95,8	58,6	41,4	13,7	89,0
161	Vogelkop-Aru lowland rain forests	7.433,3	8,9	88,9	9,2	90,8	163,9	76,7
162	Yapen rain forests	234,4	48,4	87,3	55,3	44,7	0,5	99,2
163	Lesser Sundas deciduous forests	3.838,1	7,6	42,1	17,0	83,0	1.495,6	52,9
165	Sumba deciduous forests	1.071,2	9,0	21,3	41,2	58,8	618,9	56,2

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
166	Timor and Wetar deciduous forests	1.819,5	5,2	28,4	15,6	84,4	977,7	55,7
188	Trans Fly savanna and grasslands	821,1	49,7	55,2	49,9	50,1	196,0	75,9
195	Papuan Central Range sub-alpine grasslands	978,5	62,0	98,1	62,8	37,2	6,5	97,1
217	New Guinea mangroves	1.992,8	28,4	81,0	29,9	70,1	16,4	72,6
219	Borneo lowland rain forests	29.176,0	2,9	54,3	4,7	95,3	4.823,9	63,2
220	Borneo montane rain forests	8.128,6	28,0	98,6	28,4	71,6	15,3	94,3
221	Borneo peat swamp forests	4.602,0	10,4	47,5	20,6	79,4	1.247,3	61,9
229	Eastern Java-Bali montane rain forests	1.591,2	7,4	26,2	22,5	77,5	487,5	69,9
230	Eastern Java-Bali rain forests	5.347,9	2,6	4,9	48,8	51,2	3.797,2	27,8
245	Mentawai Islands rain forests	598,3	30,9	90,7	33,7	66,3	4,8	92,7
265	Peninsular Malaysian rain forests	532,4	2,6	53,0	0,6	99,4	176,8	47,8
273	Southwest Borneo freshwater swamp forests	3.676,5	14,3	42,1	31,1	68,9	1.251,1	57,1
277	Sumatran freshwater swamp forests	1.802,9	3,9	11,7	28,0	72,0	1.117,8	44,0
278	Sumatran lowland rain forests	25.842,7	7,1	28,2	23,6	76,4	8.851,2	53,8
279	Sumatran montane rain forests	7.310,4	31,9	70,2	43,5	56,5	1.092,0	58,6
280	Sumatran peat swamp forests	8.760,2	7,7	23,4	30,5	69,5	4.179,5	46,6
281	Sundaland heath forests	7.593,8	9,8	35,9	25,1	74,9	2.603,2	53,9
288	Western Java montane rain forests	2.634,2	7,8	19,7	34,3	65,7	940,0	69,2
289	Western Java rain forests	4.150,5	2,0	4,7	38,3	61,7	2.057,5	35,6
305	Sumatran tropical pine forests	276,6	39,5	77,4	46,0	54,0	33,5	58,3

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
322	Sunda Shelf mangroves	2.678,8	12,0	39,1	24,8	75,2	738,2	58,5
136	Banda Sea Islands moist deciduous forests	690,6	15,1	74,8	18,3	81,7	134,9	60,7

Sources: ccountries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm – millimeters

Mm^3 – million cubic meters

Mt – million tonnes

t – ton

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Malaysia

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Malaysia. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways based on publicly available government reports and academic literature in consultation with national stakeholders and experts and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019).

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Malaysia's Nationally Determined Contribution (NDC), and Forest Reference Emission Level (FREL) treat the FABLE domains. According to the NDC, Malaysia has committed to reducing its **GHG emissions intensity of GDP** by 45% by 2030 compared to 2005. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include the Central Forest Spine (CFS) initiative, the Heart of Borneo (HoB) initiative, and expanding the implementation of good agricultural practices, intensifying research and development for improving agricultural production under the Eleventh Malaysia Plan. Under its current commitments to the UNFCCC, Malaysia does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially explicit planning in current NDC and FREL

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2005	288.7	2030	Reducing its GHG emissions intensity of GDP by 45% by 2030	Energy, Industrial Processes, Waste, Agriculture, Land Use, Land Use Change and Forestry (LULUCF)	Y	N	N	Forests, water, and food security
FREL (2019)	2005 - 2015	-205	2016 - 2025	Not Available	Deforestation, Sustainable Management Forest, and Conservation activities	N	N	N	Forests

Note. The NDC "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Sources. Malaysia (2016) for NDC and Malaysia (2019) for FREL

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020) which are related to at least one of the FABLE Targets. In comparison with FABLE Targets, the NBSAP targets identify specific areas of concern but tend not to set concrete targets.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE Targets

<table>
<tr><th>NBSAP Target</th><th>FABLE Target</th></tr>
<tr><td>(4)
By 2025, our production forests, agriculture production and fisheries are managed and harvested sustainably.</td><td>DEFORESTATION: Zero net deforestation from 2030 onwards</td></tr>
<tr><td>(6)
By 2025, at least 20% of terrestrial areas and inland waters, and 10% of coastal and marine areas, are conserved through a representative system of protected areas and other effective area-based conservation measures.</td><td>BIODIVERSITY: At least 30% of global terrestrial area protected by 2030</td></tr>
<tr><td>(4)
By 2025, our production forests, agriculture production and fisheries are managed and harvested sustainably.</td><td rowspan="3">BIODIVERSITY: No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate</td></tr>
<tr><td>(7)
By 2025, vulnerable ecosystems and habitats, particularly limestone hills, wetlands, coral reefs and seagrass beds, are adequately protected and restored.</td></tr>
<tr><td>(8)
By 2025, important terrestrial and marine ecological corridors have been identified, restored and protected.</td></tr>
</table>

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Malaysia.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 32.7 million in 2020 to 40.7 million in 2050), limited constraints on agricultural expansion, no afforestation target, medium productivity increases in the agricultural sector, and slow shifts in diets consistent with SSP2 (see Annex 1). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to shifting away from land exploitation to manufacturing and service sectors for economic growth. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for rice and corn (see Annex 1).

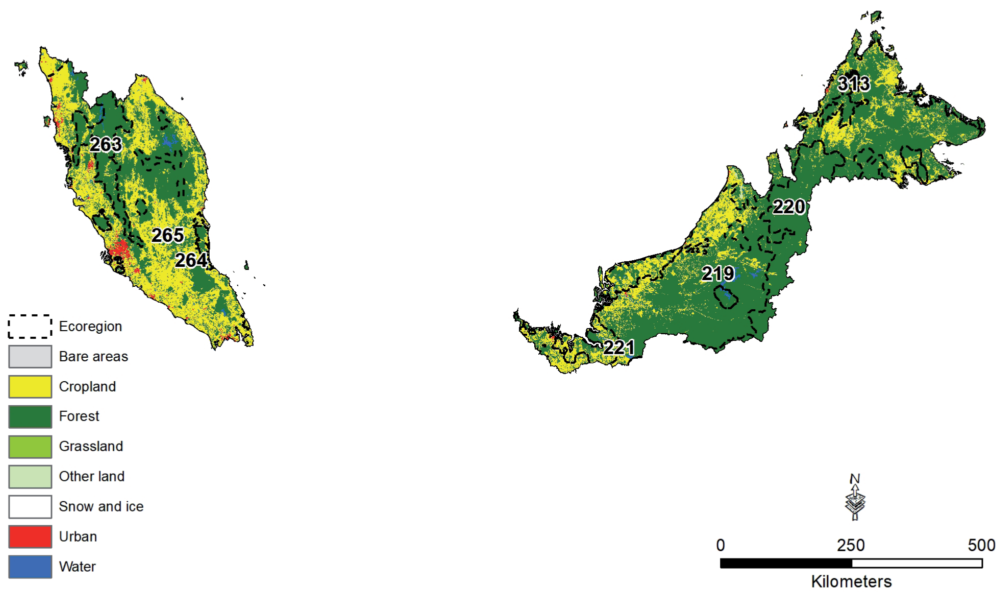
Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would have higher agricultural productivity and lower deforestation (see Annex 1). This corresponds to a future based on the successful implementation of various national technological and innovation policies that would also see considerable progress with regards to achievement in technological breakthrough, leading to lower dependence on primary agricultural expansion. With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

In 2012, Malaysia was covered by 66% forest, 21% cropland, 1% urban, and 12% other natural land as determined from the FABLE Calculator. Agricultural land is roughly evenly distributed in Peninsula Malaysia and more concentrated in the coastal regions of Sabah and Sarawak state. The largest contiguous forested zones are found in Sabah and Sarawak as well as the regions adjacent to the Taman Negara National Park and the Titiwangsa Mountain Range that runs on a North to South axis along the center of Peninsular Malaysia (Map 1). The primary threats to biodiversity in Malaysia have been the expansion of oil palm estates into forested zones (2.1.3 International Union for Conservation of Nature (IUCN) threat classification) and logging activities (5.3.2 IUCN threat classification).

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



Note. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 2.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

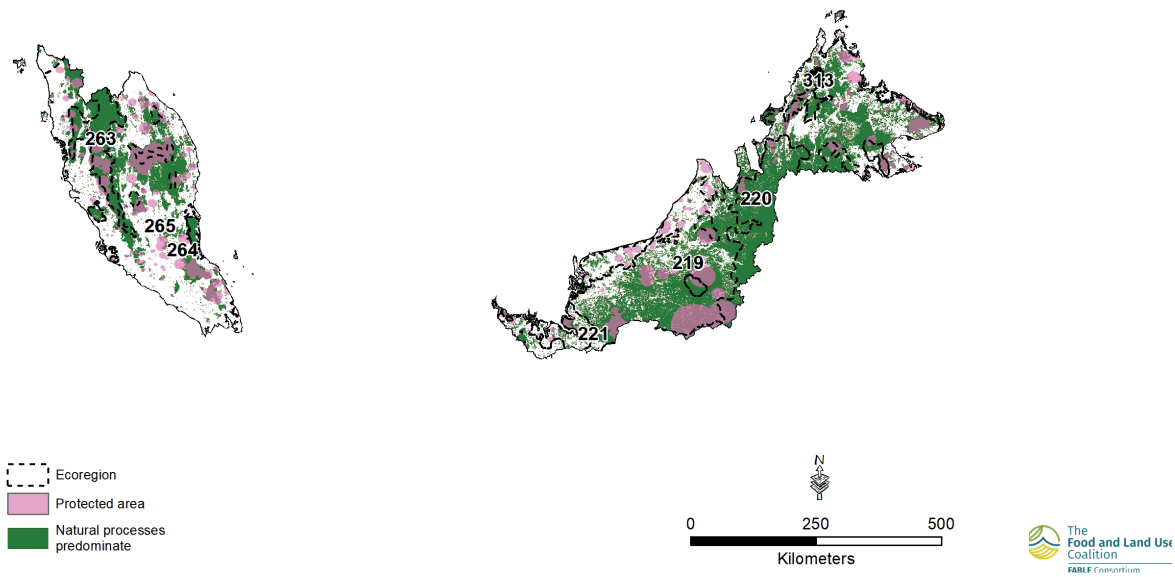
We estimate that land where natural processes predominate[2] accounted for 62% of Malaysia's terrestrial land area in 2010 (Map 2). The Southwest Borneo freshwater swamp forests in Sarawak holds the greatest share of land where natural processes predominate, followed by Peninsular Malaysian montane rain forests and Kinabalu montane alpine meadows in Sabah (Table 3). Across the country, while about 7 Mha of land are under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 25% of land where natural processes predominate is formally protected. The Borneo lowland rain forests and Borneo montane rain forests in Sabah and

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Sarawak are still at risk of logging and conversion to cropland. There have been recent positive tendencies though (Borneo Post Online, 2019): In Sarawak, the Chief Minister has committed to stop issuing new permits for new oil palm plantations. In Sabah, a jurisdictional approach has been adopted to achieve a state-wide RSPO certification by 2025, leveraging on existing laws and regulations (van Houten & de Koning, 2018). The commitment was brought to the State Cabinet in 2015 jointly by The Sabah Forestry Department, the Natural Resource Office, and LEAP (Land Empowerment, Animals, People), a civil society organization, and the RSPO secretariat.

Approximately 68.2% of Malaysia's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively "biodiversity-friendly" croplands, leaving some space for natural vegetation, are most widespread in Peninsular Malaysian rain forests, followed by Borneo lowland rain forests and Borneo peat swamp forests. The reason for regional differences in extent of "biodiversity-friendly" croplands is not known, but can potentially be explained by the requirement for suitable soil conditions for oil palm cultivation, which requires acidic, well drained alluvial soils where there are no extensive slopes exceeding 15% grade. In other words, oil palm grows less optimally on hilly terrain, which is where most of this natural vegetation is left to grow.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within $1km^2$ (%)
219	Borneo lowland rain forests	13,215	17.7	58.7	23.8	76.2	1,527	78.4
220	Borneo montane rain forests	3,823	16.4	87.6	17.9	82.1	90	82.4
221	Borneo peat swamp forests	1,901	19.0	26.2	20	80	467	72.7
263	Peninsular Malaysian montane rain forests	1,651	31.5	94.0	32.8	67.2	36	82
264	Peninsular Malaysian peat swamp forests	363	4.4	55.2	3.3	96.7	106	69.8
265	Peninsular Malaysian rain forests	10,921	17.1	33.3	30.6	69.4	3,544	64.2
268	South China-Vietnam subtropical evergreen forests	0	100.0	0.0			0	
273	Southwest Borneo freshwater swamp forests	1	1.0	100.0	1	99	0	100.0
281	Sundaland heath forests	57	24.8	31.3	15.6	84.4	16	71.8
284	Tenasserim-South Thailand semi-evergreen rain forests	240	9.2	21.3	23.3	76.7	140	20.8
313	Kinabalu montane alpine meadows	60	78.5	90.4	86.6	13.4	5	54.3
319	Indochina mangroves	0	0.0	0.0			0	
321	Myanmar Coast mangroves	42	0.0	82.9	0	0	3	93
322	Sunda Shelf mangroves	726	32.3	55.4	39.7	60.3	89	79.8

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

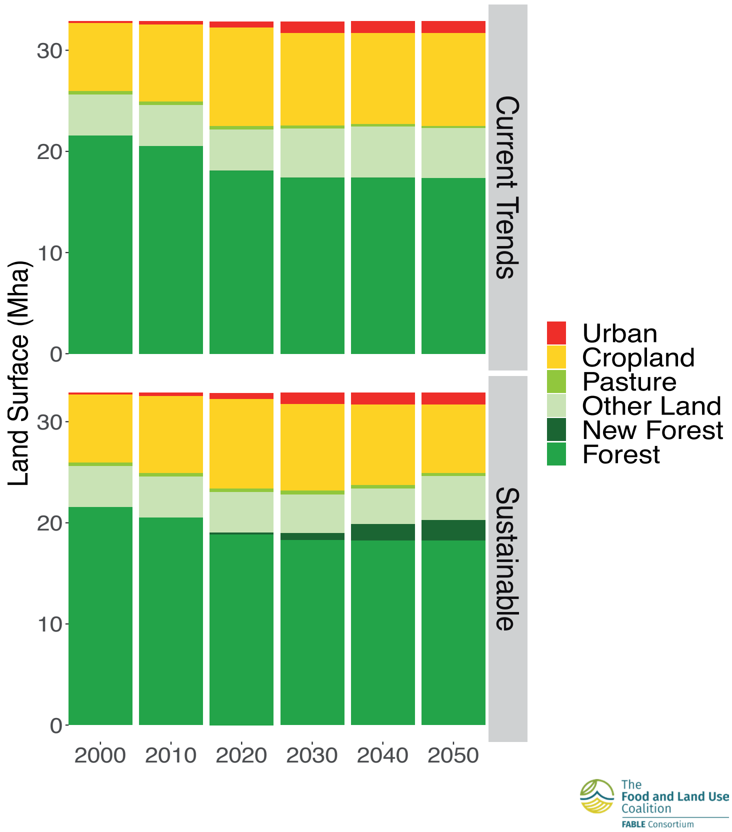
Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas and no afforestation by 2025 (see Annex 1).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase of cropland area and a decrease of forest area compared to 2000-2010. This trend will stop over the period 2030-2050: cropland area and forest area stabilize (Figure 1). The expansion of the planted area for oil palm, rice, and cocoa explains 98% of total cropland expansion between 2010 and 2030. For oil palm, most of the expansion is export-oriented, with about 4% of palm oil produced being consumed locally. For rice, the expansion is due to increasing local food demand. Finally, for cocoa, the expansion is due to increasing local food demand and increasing exports. Pasture expansion is mainly driven by the increase in internal demand while livestock productivity per head increases and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, main land cover change is explained by increased internal demand due to increase in average food intake per capita as well as increasing exports of palm oil products. This results in a reduction of land where natural processes predominate by -6% by 2030 and by -3.5% by 2050, both compared to 2010, respectively.

In the Sustainable Pathway, assumptions on deforestation and protected areas have been changed to reflect the Malaysian government's commitment

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

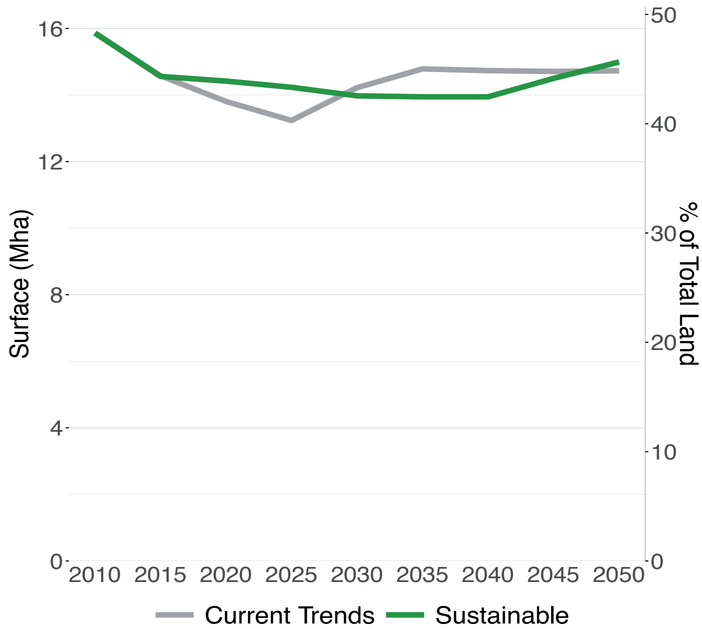


Source: Authors' computation based on ESA CCI (2017) for the area by land cover type for 2000.

to ban expansion of oil palm acreage beyond 6.5 Mha by 2023 (Yusof, 2019). The main assumptions include the prevention of deforestation by 2023 and constraints on the expansion of agricultural land beyond its current area (see Annex 1) (Ministry of Natural Resources and Environment, 2016).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Malaysia in the Sustainable Pathway: (i) complete halting of deforestation, (ii) reduction of loss of land where natural processes predominate, (iii) stabilization of agricultural land area, and (iv) no reforested/afforested land. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are mainly explained by stopping forest conversion to export-oriented oil palm plantations. This leads to a stabilization in the area where natural processes predominate: the area stops declining by 2035 and increases by 3% between 2045 and 2050 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate



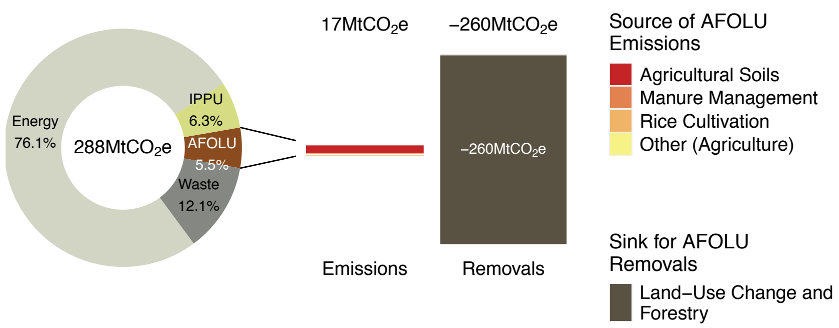
GHG emissions from AFOLU

Current State

The Agriculture, Forestry, and Other Land Use (AFOLU) sector is a critical component of the Malaysian plan to address climate change largely due to the extent of carbon sinks in the region such as forests and peatlands. The effort to balance economic concerns, food security, and the preservation of the country's vast carbon sinks remains a point of debate to this day. In particular, peatlands pose a unique challenge due to the lack of national data available.

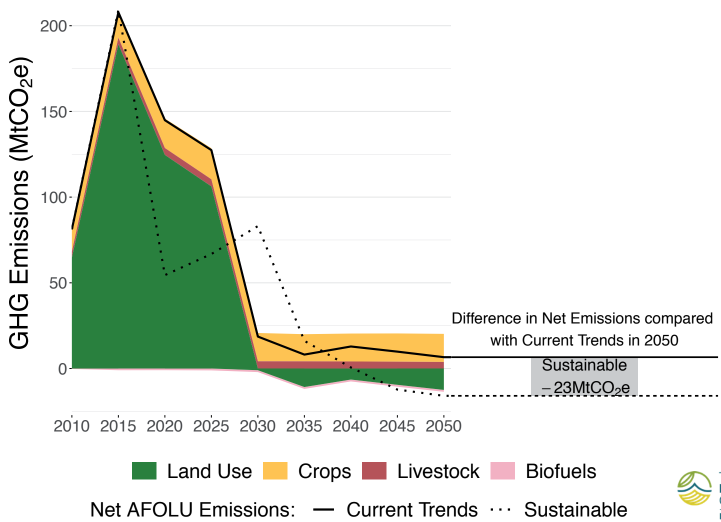
Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 5.5% of total emissions in 2011 (Figure 3). Agricultural soils are the principle source of AFOLU emissions, followed by manure management, rice cultivation, and field burning of agricultural residues. This can be explained by the projected increase in palm oil plantations to meet both external demand as well as fulfill domestic trade targets. This increase in planted area corresponds to increased fertilizer use which has historically contributed to increases in GHG emissions from the agricultural sector (Ministry of Energy, Science, Technology, Environment and Climate Change, 2018).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2011



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



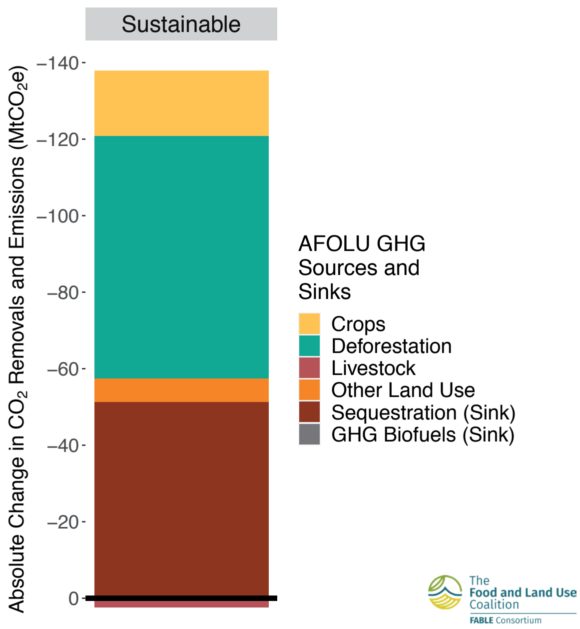
Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 18.6 Mt CO_2e/yr in 2030, before declining to 6.6 Mt CO_2e/yr in 2050 (Figure 4). In 2050, cropland is the largest source of emissions (16 Mt CO_2e per year) while there is also significant carbon sequestration from vegetation (-12.5 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for livestock (8%) while a reduction is computed for deforestation (110%).

In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by 341% (Figure 4). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from land-use change (Figure 5). The change in assumptions made for cropland expansion as well as afforestation targets are the most important drivers of this reduction.

Compared to Malaysia's commitments under UNFCCC (Table 1), our results show that the targets can easily be met even under the current trends scenario. This result could be particularly important when considering options for enhancing our future commitments in the subsequent NDCs. One particular criticism that can be made is the usage of GHG intensity per GDP to measure the target. This makes achieving the target much simpler as the GDP of the country is expected to grow steadily over the period and hence may present a much more positive view of the country's achievements than is warranted.

Figure 5 | Cumulated GHG emissions reduction computed over 2020–2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

Malaysia continues to be plagued by the burden of malnutrition and non-communicable diseases. While the data shows that Malaysia is largely on track by way of caloric, protein and fat consumption, its health outcomes remain poor. The prevalence of stunting and obesity among its population is high relative to other upper middle-income countries (UNICEF, 2018). Our analysis shows that there remain imbalances in Malaysian diets that need to be addressed, particularly the overconsumption of sugar, eggs, and poultry, and the under-consumption of nuts, pulses, fruits, and vegetables.

The "Triple Burden" of Malnutrition

Undernutrition	Micronutrient Deficiency	Overweight/ Obesity
2.5% of the population was undernourished in 2017. This share has decreased since 2008 (-4.2%) (World Bank, 2017).	35.5% of women (Institute for Public Health, 2015) and 6.6% of children under 12 suffer from anemia (Poh et al., 2013), which can lead to maternal death.	17.7% of adults, and 11.9% of children were obese in 2015 (Institute for Public Health, 2015). These shares have increased since 2006 (Institute for Public Health, 2006).
20.7% of children under 5 were stunted and 11.5% wasted in 2016 (Institute for Public Health, 2016).	2.5% of male and 4.5% of female children 5 years old and younger are deficient in vitamin A (Khor, 2005), which can notably lead to blindness and child mortality. 48.2% are deficient in iodine, which can lead to developmental abnormalities (Selamat et al., 2010).	30% of adults were overweight in 2015 (Institute for Public Health, 2015), and 10% of children were overweight in 2013 (Salleh, 2017). This share has increased since 2006 (Institute for Public Health, 2006).

Disease Burden due to Dietary Risks
73% of deaths are attributable to non-communicable diseases (NCDs) which are linked to dietary risks (Institute for Public Health, 2015), or approximately 364 deaths per year per 100,000 people (WHO, 2016).
17.5% of the population suffers from diabetes (Institute for Public Health, 2015) and 35% from cardiovascular diseases (Institute for Public Health, 2017), which can be attributable to dietary risks.

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,804 (2,085)	2,805 (2,092)	2,802 (2,092)	2,805 (2,096)	2,816 (2,096)
Fats (g) (recommended range	84 (62-93)	84 (62-94)	82 (62-93)	84 (62-94)	84 (63-94)
Proteins (g) (recommended range	78 (70-245)	78 (70-245)	78 (70-245)	78 (70-245)	78 (70-246)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

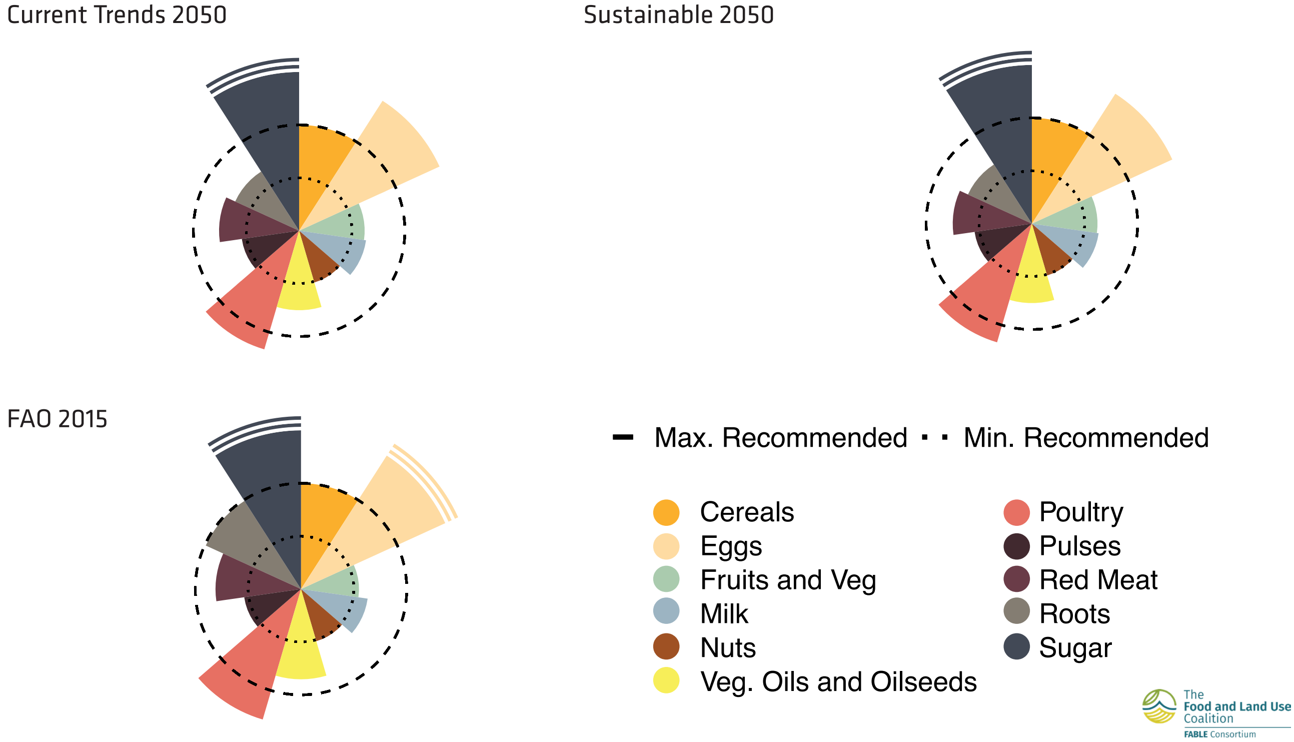
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 34.1% higher in 2030 and 33.8% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals and sugar, and animal products, which represent 18% of the total calorie intake. We assume that the consumption of animal products, animal fat, fish, fruits, and vegetables will increase, while oilseeds and vegetable oils, poultry, red meat, and roots consumption will decrease. Compared to the EAT-Lancet recommendations (Willett et al., 2019), sugar, eggs and poultry are over-consumed while nuts, pulses, fruits and vegetables are under-consumed in 2050 (Figure 6). The intake of fat and protein per capita are within the dietary reference intake (DRI).

Under the Sustainable Pathway, we assume that diets will transition towards SSP1 (Sustainability). The ratio of the computed average intake over the MDER increases to 33.9% in 2030 and 34.3% in 2050 under the Sustainable Pathway. Compared to the EAT-*Lancet* recommendations, only the consumption of eggs, poultry and sugar remains outside of the recommended range with the consumption of all the remaining categories are within the recommended range in 2050 (Figure 6). Moreover, the fat and protein intake per capita fall within the dietary reference intake (DRI) in 2030, showing no improvement compared to the Current Trends Pathway.

The National Plan of Action for Nutrition of Malaysia III (2016-2025) outlines a host of facilitating and enabling strategies (Ministry of Health, 2016) that will be particularly important to promote this shift in diets. Addressing nutritional deficiencies, obesity and other diet-related non-communicable diseases have been given due attention considering national health outcomes. With specific strategies targeted at women, children, and the general population, solutions range from awareness campaigns, to food fortification, to policies governing food advertising.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



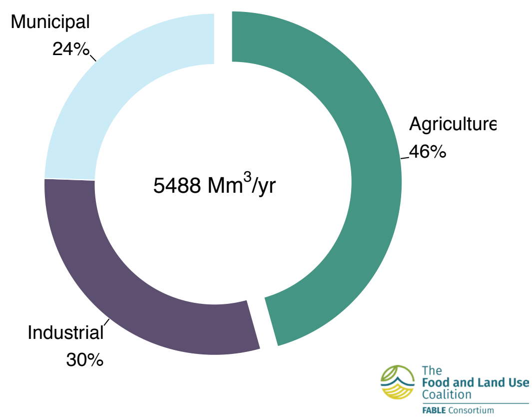
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and eggs indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

Malaysia is characterized by equatorial climate with high uniform temperatures with 2,875 mm (FAO, 2017) average annual precipitation that mostly occurs over the period of November – March and May – October (Zakaria, Craig, Ooi, & Thomas, 2020). The agricultural sector represented 46% of total water withdrawals in 2005 (World Bank, 2020; Figure 7). Moreover in 2009, 5.4% of agricultural land was equipped for irrigation (FAO, 2011). The three most important irrigated crops, rice, other vegetables, and other products, account for 87%, 11%, and 2% of the total harvested irrigated area, respectively.

Figure 7 | Water withdrawals by sector in 2005

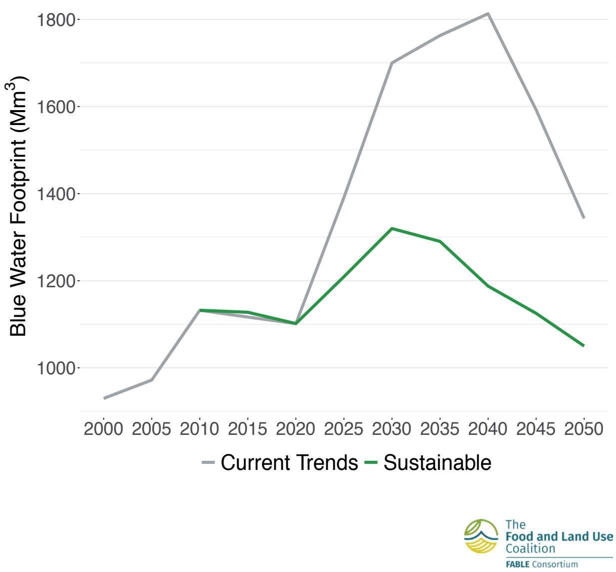


Source. Adapted from World Bank (2020)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000-2015 (930 Mm^3/yr and 1,117 Mm^3/yr), before reaching 1,700 Mm^3/yr and 1,343 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with rice accounting for 81% of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Pathway, blue water footprint in agriculture reaches 1,320 Mm^3/yr in 2030 and 1,050 Mm^3/yr in 2050, respectively.

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

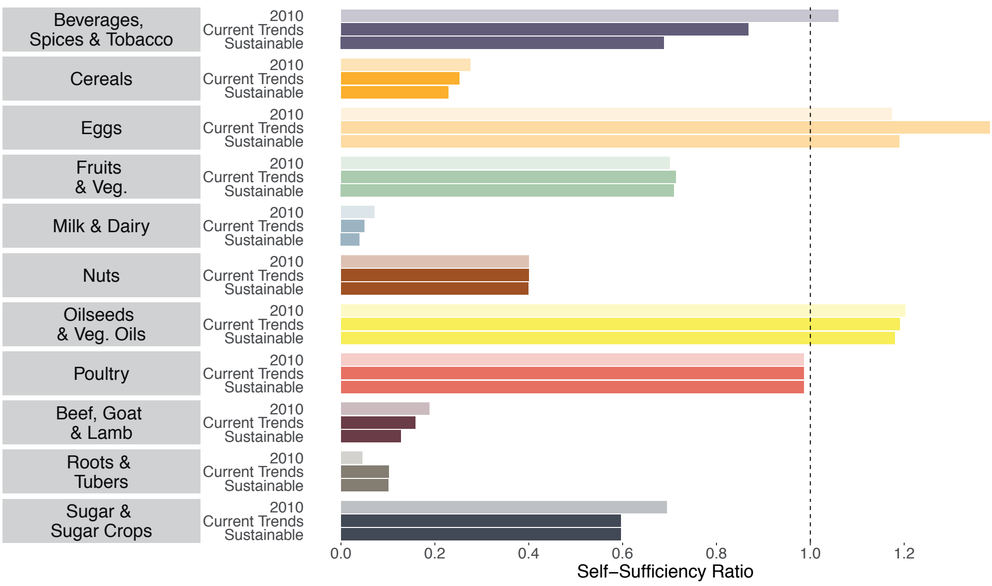
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Malaysia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Malaysia's level of self-sufficiency is low because key product groups such as cereals, milk and dairy, beef, goat, and lamb are significantly reliant on imports. Among cereals product groups, rice is a particularly important component since it was consumed by 89.8% of the population in 2014 (Ministry of Health, 2014). In 2010, 40% of rice was imported, hence a significant source of the population's energy source is dependent on external sources (FAO, 2013).

Under the Current Trends Pathway, we project that Malaysia would be self-sufficient in eggs, oilseeds, and vegetable oils in 2050, with self-sufficiency levels by product group remaining stable for most products from 2010 – 2050 (Figure 9). The product groups where the country depends on the most on imports to satisfy internal consumption are cereals, milk and dairy, beef, goat, and lamb and this dependency will continue until 2050. Similarly, under the Sustainable Pathway, Malaysia remains self-sufficient in eggs, oilseeds and vegetable oils, representing stable self-sufficiency levels. This is explained by Malaysia's food production system whereby production of wheat is not suitable to be grown locally, while milk, beef, mutton and lamb local production remains low despite numerous governmental initiatives, hence demand is expected to continue to significantly rely on imports (Sundaram and Gen, 2019).

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

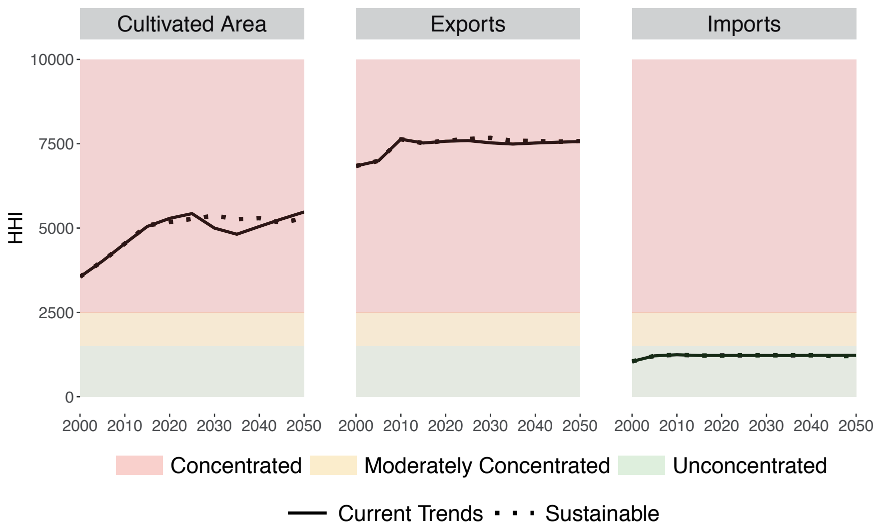
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

According to the HHI, Malaysia has a very high concentration of exports and planted area. This is because Malaysia's agriculture policy is highly skewed towards palm oil. In 2010, palm oil represented 55.8% of all crop exports measured by tonnage and 66.2% of all crop acreage (FAO, 2013). Malaysia's imports on the other hand are diversified. This means that Malaysia not only has low self-sufficiency, but Malaysia's low self-sufficiency applies to a wide variety of product groups.

Similarly, under the Current Trends and the Sustainable Pathways, we project high concentration of crop exports and low concentration of imports and high concentration in the range of crops planted in 2050, trends which increase over the period 2010 - 2050. This indicates low levels of diversity across the national production system and exports (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI).



Discussion and Recommendations

Since the beginning of 21st century, Malaysia has observed large-scale deforestation mainly in its Bornean states, i.e. Sabah and Sarawak. The land-use changes in both states mark an unprecedented, vivid example of land exploitation to jumpstart economic development. The changes began with rampant logging (legal and illegal) and were followed by the expansion of oil palm plantations. In 2000-2020, about 2.6 Mha of new oil palm plantations were established throughout Malaysia, with 0.5 Mha in Sabah and 1.3 Mha in Sarawak. The total land with oil palm plantations has almost doubled in the last 20 years, reaching almost 6 Mha in 2020 compared to 3.4 Mha in 2000. While the expansion of the cash crop has brought in significant revenue for the country, it also involved large-scale conversions of forests and peatlands which are rich in carbon stock and biodiversity.

Currently, the conventional exploitative land-based economy in Malaysia is facing a predicament: how to maintain economic growth without causing further environmental impacts and also repairing the damage done in the past. One of the benefits of the collaborative approach in FABLE has been to clearly demonstrate that all sectors are closely inter-related. Particularly for the case of Malaysia, changes in food consumption patterns and trade patterns can have significant impacts on domestic agricultural expansion and forested areas. Palm oil cultivation, in particular, has an outsized impact on forest cover, given the lack of other land cover types to convert from. Indeed, it can be seen using the FABLE Calculator tool that under the Current Trends Pathway that an increase in external demand for palm oil translates to rapid loss of forest cover before 2030, after which it is assumed that no further deforestation will occur. We modeled here a 116% increase in palm oil exports between 2000 and 2015 and can observe, as mentioned above, a loss of 2.6 Mha of forest cover (or 12% loss from 2000) within the same period; most of which can be attributed to palm oil expansion given no other major crop has seen such growth.

In recent years, palm oil has been the single largest crop export by tonnage for Malaysia (greater than 50%). From 1990 to 2010, palm oil production grew robustly at a rate of 3.1% per year, however in the Current Trends Pathway, we forecast that the annual growth for the 2010-2050 period will slow down to 1.8% per year, as global demand is anticipated to be much more tepid and exports are adjusted to follow import demand in the FABLE Calculator. A solution to the country's land exploitation dilemma begins by searching for **new sources of income to reduce the dependency on palm oil export**. From an environmental perspective, capping oil palm expansion would significantly avoid further forest loss in the country. On the contrary, extending palm oil plantations even more in order to increase exports would lead to more land use change, deforestation and biodiversity loss, and potentially excessive water consumption. A combination of coherent policies across ministries are needed to address the problems embedded in the AFOLU sector.

For the Sustainable Pathway, we estimate that the total global demand for palm oil, for the 2010-2050 period, will fall a further 8.4% per year vis-à-vis the Current Trends Pathway due to slower global population growth and increased productivity of local substitutes. This forecast follows closely with the trend of declining global demand for commodities, and the increasing wages of foreign laborers which makes Malaysia gradually lose its comparative advantage in furthering oil palm expansion. Therefore, our Sustainable Pathway is based on the assumptions that instead of clearing more land to produce more palm oil for a slowing demand, seeking new sources of revenues, such as investing more in downstream activities for high value-added products will be the focus of the land-based sectors. That is why we anticipate that there will be about 0.9 Mha more forests by 2050 in the Sustainable Pathway.

At a macro level, the country has been **transforming from an agriculture-based economy into a manufacturing and services centered economy**. In 1990, agriculture already decreased to 15% of GDP compared to 44% in 1960. The share further halved to 7% by 2018, with the services sector emerging as the most significant sector contributing 53% of GDP (World Bank, 2018). Moving forward, Malaysia - with its relatively small landmass - needs to enhance the skills of its workforce so that it can successfully transform its economy from developing status to advanced status, where growth and prosperity depend on human capital and ingenuity rather than wanton exploitation of land and nature.

However, the country may have to rethink its land-use strategy, especially considering **reinventing its model of food supply-demand**. In 2018, Malaysia's food import bill was 50 billion MYR, and our food trade deficit totaled 18.6 billion MYR in 2016 (Murad, 2020). Despite repeated calls to increase Malaysia's self-sufficiency levels, government initiatives to reach those targets have continually fallen short. New and innovative approaches to local food production will need to be developed. Given the rapid urbanization trend across the whole country, urban farming may potentially address food security as well as create new business opportunities. Food security policies should do more than just address "dietary energy undernourishment", but also be oriented towards micronutrient deficiencies and diet related non-communicable diseases. Lastly, while there has been growing awareness of the scale of Malaysia's food waste problem, a more multisectoral approach must be implemented to optimize our food systems, including supply chain efficiency and consumer behaviors, rather than viewing it purely in terms of solid waste management.

It is, however, important for policymakers to realize that utility-based development strategies with wealth creation as the center of policymaking may prevent further degradation but are likely inadequate to repair the previous environmental damage. **Effective restoration strategies** need to be put in place on top of the previously mentioned actions. Some areas, however, should be given top priority to conservation. For example, restoring riparian buffers are necessary not only to mitigate land conversion impacts on biodiversity and water quality but also to ensure long-term viability of agricultural activities by slowing rates of riverbank erosion and lateral channel migration. Also, restoring patches of degraded land surrounded by ecological important areas may substantially improve habitat connectivity which can be critical for the survival of many species.

The interconnected nature of economic productivity and conservation means that no single strategy or policy can be a perfect solution, although some can be more practical and effective than the others within different periods of time, or acceptable by different stakeholders. These inadequacies demand optimally combining the different strategies to reach both ends. This requires a structural thinking in policymaking to manage the entire system. Based on scientific findings of the FABLE Consortium, there is also a need to **co-produce and tailor more knowledge to local specificities**, to model with more granularity the synergies and trade-offs in different areas and contexts in order to communicate, manage, and implement effective national and sub-national policies to achieve a Sustainable Pathway. Engagement with policymakers and others key stakeholders in various forms of communications will be the key upcoming mission for the FABLE Malaysia team.

Our recommended policy improvements are that, as we advance towards 2050, **policies to accelerate Malaysia's transition to the secondary and tertiary sectors, especially bio-based industries and eco-tourisms that leverage on the vast resources in the country are needed to compensate for the reduction in income from agricultural commodities, palm oil in particular**. However, due to uneven development across the country, Malaysia's 5-year national development plan from 2015 to 2020, still places the development of agriculture commodities as one of its key priorities. Moving forward, the federal and state governments should be bold in transforming its agricultural policies and working closely together, so that private investors have the stability and confidence needed to change their investments and reallocate their capital to more sustainable sectors. From an environmental perspective, the reduction in palm oil exports in the Sustainable Pathway, creates the opportunity to increase forest cover by around 0.9 Mha by 2050, which would contribute significantly to Malaysia's carbon-sink capacity. Hence, wise land use planning is needed to **sustainably reforest our land** so that Malaysia can exemplarily deliver on its commitments to the Paris Climate Agreement.

From the perspective of biodiversity policies, current policies are ineffective because they are formulated without adequate data. For example, **the lack of a clear breakdown of forest areas by ecotype and comparison of the loss of areas in each ecotype**, has resulted in policies which are too general and that overlook niche ecosystems which can have significant biodiversity value. Also, **the absence of systemic spatial mapping data** has led to ineffective habitat connectivity policies which risk failure to achieve the outcomes defined in the 8th NBSAP Target of restoring and protecting terrestrial ecological corridors by 2025. Therefore, the dearth of quality data in the biodiversity policy space needs to be addressed with utmost urgency.

Food security is another policy space which requires significant policy improvement. Sundaram et al. (2019) have noted the **need for a cross-ministry, comprehensive national food policy document** as the current policy infrastructure is fragmented and ineffective. Specifically, the National Agro-Food Policy (2011-2020) focuses on food security while the National Plan of Action of Nutrition III (2016-2025) focuses on nutrition. Policy **implementation and outcome monitoring must also be strengthened**, as many well designed and well-intended policies are failing to deliver on their intended outcomes. For example, since the launch of the National Strategic Plan for Food Waste Management in Malaysia, no progress has been reported since nor has it been included in other policy documents (Yahaya, 2013). Unless the efficacy of policy coordination and policy implementation are improved, Malaysia will continue to fall short of its food security and nutrition aspirations.

The key limitations that we were not able to include are the following: **Mega projects like hydropower dams and road building in Sarawak** (which will include the construction of Pan Borneo Highway in the coming years) are also driving the loss and degradation of forest. **Rapid urbanization in Peninsular Malaysia** is also encroaching into high conservation value areas. While these play important roles in land-use system, they are yet to be included in the model.

Currently, some important dimensions to describe land use evolution such as geo-spatial information, supply-demand dynamics and price elasticity have not yet been considered in the FABLE Calculator. In the particular case of Malaysia, we will strive to include in future iterations details of oil palm crop operations, which is such a key commodity in the country.

Annex 1. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)	
Current Trends Pathway	**Sustainable Pathway**
The population is expected to reach 40.8 million by 2050. Based on UN DESA (2019). (SSP1 scenario)	Same as Current Trends

LAND Constraints on agricultural expansion	
Current Trends Pathway	**Sustainable Pathway**
Deforestation for agriculture is relatively low in Peninsular Malaysia, but logging persists in some states, and urbanization also used up some forested land. In Malaysian Borneo, the state governments have made clear their policies in limiting logging activities and further oil palm expansion. The problem of enforcement lies in the premise of illegal logging which may cause further forest degradation. We may safely assume that the deforestation rate due to agricultural expansion will gradually decrease to zero by 2030 in this scenario, but probably we will not be able to track forest degradation due to logging, which is a much serious issue. (No deforestation beyond 2030) Based on Borneo Post (2015, 2019)	In the most sustainable scenario, not only conversion to cropland, unsustainable logging (including previously untraceable illegal logging) is also completely banned, forcing the uptake of stricter sustainable forest management (SFM) certification. Wood production may be reduced but maintained at a reasonable rate. In this case, we can safely assume that no deforestation will take place. Urbanization will be compromised, but that may affect housing prices and thus the GDP growth. (No expansion) Based on Borneo Post (2015, 2019)
LAND Afforestation or reforestation target (1000 ha)	
Some afforestation is going on, as well as natural regeneration. However, without further conversion of forest, those unforested land will remain the only space for agricultural expansion. In such a situation, natural regeneration may not widely take place. Conservatively, we can assume no new forested area. (NoAfforestation scenario selected) No national targets; All assumptions are those of the authors.	Global economic downturn may positively affect natural regeneration as many lands may be abandoned. Under such circumstances, we may see some increase in forested areas in regions far from urbanization. (BonnChallenge scenario selected) No national targets; All assumptions are those of the authors.

BIODIVERSITY Protected areas (1000 ha or % of total land)	
Current Trends Pathway	**Sustainable Pathway**
We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.	Same as Current Trends

PRODUCTION Crop productivity for the key crops in the country (in t/ha)	
Current Trends Pathway	**Sustainable Pathway**
By 2050, crop productivity reaches: • 26.49 tons per ha for palm oil • 3.39 tons per ha for rice • 1.22 tons per ha for rubber (Same growth as over 2000 - 2010) All assumptions are those of the authors.	By 2050, crop productivity reaches: • 29.35 tons per ha for palm oil • 4.02 tons per ha for rice • 1.42 tons per ha for rubber Based on statistical evidence and literature for major cash crops such as palm oil, we conclude that large yield increases are unlikely; with the most sustainable pathway being that of increased resilience against yield declines. (Higher productivity than 2000 – 2010) Based on Malaysian Palm Oil Board, (2020).
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)	
Malaysia's largest source of meat is chickens, followed by pigs, ducks and cattle. Yields for all four groups have been on a general upward trajectory over the last 20 years, albeit with some years of decreasing yields. (BAU Growth) Based on FAO (2020)	With no major modifications to the livestock rearing process, yields for all four livestock groups should remain at roughly the same levels as 2010. This is evident in the FAO dataset's yields for pigs, ducks and cattle only deviating slightly downwards in 2018. An exception to this is chicken which increased its yield by approximately 18% between 2010 and 2018. (No Growth) Based on FAO (2020)
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)	
By 2050, the average ruminant livestock stocking density is 0.44 TLU/ha per ha. All assumptions are those of the authors.	By 2050, the average ruminant livestock stocking density is 0.22 TLU/ha per ha. All assumptions are those of the authors.
PRODUCTION Post-harvest losses	
No data available.	No data available.

TRADE Share of consumption which is imported for key imported products (%)	
Current Trends Pathway	**Sustainable Pathway**
For 16 largest imports consumed in Malaysia in 2010, namely corn, rice, milk, cassava, wheat, beef, coconut, fish, other fruits, onion, orange, potato, soya bean, other vegetables, soy cake, and raw sugar, the share of consumption which is imported in 2050 is calculated to be the average historical share observed in 2000, 2005 and 2010 (FAO, 2013). As the observations of most of the products displayed mean reversion characteristics in the observation period, the average of the observations was used for the basket of 16 products during the forecast period.	The Sustainable Pathway assumes the structural share of imports to be similar to the Current Trends Pathway, allowing domestic policies to improve productivity and reduce food loses, hence describe achievement of environmental targets, without noise from external factors.

TRADE Evolution of exports for key exported products (1000 tons)

Current Trends Pathway	Sustainable Pathway
For palm oil and palm kernel cake, the 1st and 4th largest exports in Malaysia in 2010, export quantities for 2050 were calculated using a growth rate of 3.1%/yr and 2.8%/yr, respectively, which were linearly regressed from actual annual exports from 1990 to 2010 (FAO, 2013). A linear regression was judged to be suitable to model a linear trend over a 40-year forecast period as seasonal trends are not relevant for such a long forecast period. After trade adjustment, net exports were adjusted to track global net imports within a band of no greater than 10% of net imports. Therefore, annual growth rates drop to 1.8%/yr, and 1.9%/yr, respectively. Plywood and sawn wood, the 2nd and 3rd largest exports in 2010, are to be included in the next iteration of the Scenathon which will include a forest product module.	In the Sustainable Pathway, we assume that global net imports for palm oil and palm kernel cake have declined vis-à-vis the Current Trends Pathway. As a result, total palm oil exports for the forecast period falls by 8.4% and total palm kernel cake exports fall by 9.7%.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 2805 kcal and is: • 1,255 kcal for cereals • 107 kcal for fish • 143 kcal for fruits and vegetables Per capita consumption of beef and poultry is increasing while mutton and pork are decreasing (Sheng, Shamsudin, Mohamed, Abdullah, & Radam, 2010). National health and morbidity surveys do not do time series data but suggests that our diet outcomes are very poor (see NHMS 2003 and 2014 conclusions), falling short of the governments' own targets, recommended nutrient intake (RNI). (SSP2 scenario)	By 2030, the average daily calorie consumption per capita is 2805 kcal and is: • 1,255 kcal for cereals • 107 kcal for fish • 143 kcal for fruits and vegetables National Plan of Action for Nutrition of Malaysia III 2016-2025 (Ministry of Health, 2016) in place but no update on progress publicly available. The plan aims to promote healthy eating and active living; address nutritional deficiencies, obesity and other diet-related NCDs; sustain food systems to promote healthy diets, and; ensure food safety and quality. (SSP1 scenario)

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
Increased share by 10% compared to 2010. No time series data available. Badgie puts the waste generation rate for Kuala Lumpur increasing 3% annually, if this is used as a very rough proxy, it looks like a linear upward trend. KPKT estimates of municipal solid waste in 2005 were 17,000 tons and projects for more than 30,000 tons for 2020 (Kementerian Perumahan Dan Kerajaan Tempatan, 2005). Food waste composition in municipal solid waste among residential households between 30.84% (high income) and 54.04% (low income) in KL (Badgie, Abu Samah, Manaf, & Muda, 2012). Plan in place to handle municipal solid waste situation but not specifically food waste. (Increased share compared to 2010)	Reduced share by 50% compared to 2010. Public awareness on the scale of food loss is growing. The development of a National Strategic Plan for Food Waste Management in Malaysia was under way, but no progress reported since. It cites "Solid waste in Malaysia consists of 50% of food waste (at source), and 70% (as disposed at the landfill sites)". The 10th Malaysia Plan (2011-2015) had aimed to "household recovery of waste from 15% to 25% by 2015" (Yahaya, 2013), but no progress has been reported since. (Reduced share compared to 2010)

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
By 2050, biofuel production accounts for: • 474 kt of palm oil production. No national targets. For liquid biofuels, due to low prices of palm oil, more subsidies are given to the local biodiesel market, creating a buffer for excessive stock. This policy may maintain for the next couple of years but highly uncertain due to expected economic downturn. We assume it will maintain at the current rate, 10% (B10 blending) for the next 5 years. In 2018, total diesel consumption was about 10 billion liters. (OECD_AGLINK) All assumptions made with informal communications with the National Agency of Innovation Malaysia and based on the National Biomass Strategy 2020 (Agensi Inovasi Malaysia, 2013).	By 2050, biofuel production accounts for: • 474 kt of palm oil production. No national targets. Second-generation bioethanol and biogas from oil palm residues may be realized with substantial financial inputs from the government. It can only happen if the economic status is going extremely well. In the most extreme, best-case scenario, the biomass in Malaysia may supply up to millions of liters of second-generation bioethanol from all residues, but this is highly uncertain. Due to this uncertainty, a similar scenario to the Current Trends pathway is used. (OECD_AGLINK) All assumptions made with informal communications with the National Agency of Innovation Malaysia and based on the National Biomass Strategy 2020 (Agensi Inovasi Malaysia, 2013).

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

mm – millimeters

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Mexico

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Mexico. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including from the National Institute of Health (INSP) and the Department of Agriculture and Rural Development (SADER), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Mexico's Nationally Determined Contribution (NDC) (Gobierno de México, 2015), Long-Term Low Emissions and Development Strategy (LT-LEDS) (SEMARNAT 2016) treat the FABLE domains. According to the LT-LEDS, Mexico has committed to reducing its GHG emissions by 50% by 2050 compared to 2013. This does include emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include encouraging agriculture practices that preserve and increase carbon capture in soil and biomass (conservation cultivation and productive reconversion), changing livestock and forestry production (silvo-pasture and agroforestry systems), and strengthening forest monitoring to avoid illegal logging and forest fires (SEMARNAT, 2016). Under its current commitments to the UNFCCC, Mexico mentions biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and LT-LEDS

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2013	665	2030	40% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	Y	N	Water and deforestation, GHG emissions
LT-LEDS (2016)	2013	665	2050	50% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	N/A	N/A	N/A	Water and deforestation, GHG emissions

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source: Gobierno de Mexico (2015) for the NDC and SEMARNAT (2016) for the LT-LEDS

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the latest National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020), which are related to at least nine of the FABLE Targets related to agriculture and climate change. In comparison with FABLE Targets, Mexico's NBSAP targets have a more ambitious timetable. While they share the same principles, the NBSAPs intend to broaden the understanding and appreciation of biodiversity within and across sectors, and at all government levels, to ensure the continued provision of ecosystem services necessary for the well-being of the Mexican people (CONABIO, 2016).

Table 2 | Overview of the NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(2.2) **Strategies are in place to integrate biodiversity in the following sectors: agriculture, forestry, fisheries, and tourism.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(4.2) **By 2030 Mexico counts with watersheds and aquifers in equilibrium, with an integrated and sustainable management of water.**	**WATER:** Blue water use for irrigation $<2453\ km^3yr^{-1}$
(5.1) **By 2020, the rate loss of all habitats will maintain a decreasing trend and degradation-fragmentation will significantly be reduced.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(5.2) **By 2030 the decreasing trend in habitat loss and degradation will be close to zero in protected habitats.**	**BIODIVERSITY:** At least 30% of global terrestrial areas protected by 2030
(7.2) **By 2030, the efficient and sustainable use of water will spread significantly on the agricultural area.**	**WATER:** Blue water use for irrigation $<2453\ km^3yr^{-1}$
(7.6) **By 2020, the forest ecosystems that are susceptible to exploitation will be used in a sustainable way and the integrated management of the landscape will be promoted while maintaining their connectivity, as well as their environmental services and biodiversity.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(7.7) **By 2020, forest plantation areas with native species will increase in degraded sites and without incentivizing the loss of natural habitat.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(11.1) **By 2020, at least 17 percent on land areas [...] will be conserved and managed efficiently and equitably through protected natural areas and other conservation instruments (biological corridors, Environmental Conservation Units, community conservation areas, areas voluntarily designated for conservation), while promoting their connectivity, landscape integrity and the continuity of environmental services provided.**	**BIODIVERSITY:** At least 30% of global terrestrial areas protected by 2030
(15.1) **By 2020, the ecosystem's resilience will be maintained and increased, through the conservation of biodiversity, prevention and reduction of threats and impacts that deteriorate and fragment them.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(15.2) **By 2030, at least 15 percent of degraded ecosystems will be restored, contributing to climate change mitigation, adaptation, resilience, and the fight against desertification.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Mexico.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by low population growth (from 128 million in 2020 to 148 million in 2050) (CONAPO, 2018), significant constraints on agricultural expansion, a low afforestation target, a 18% increase in the extent of protected areas, the same productivity growth as over 2000 – 2010 for livestock (SIAP, 2020) and an evolution in diets similar to the trends between 2000 - 2010 (high in cereals and sugar, increased intake in oils and fats, roots, nuts and red meat) combined with low physical activity, increased exports and imports compared to 2010 (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to halting agricultural expansion and a reconversion of cropland towards cultivation of high value exports (SAGARPA, 2017). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for maize, rice, wheat, and soybeans (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to improved diets that rely less on cereals and more on high intake of fruits, vegetables, and pulses as well as animal protein in healthy quantities, a high afforestation target, 30% of the total land covered by protected areas, and no expansion of agricultural area along with high productivity levels for crops and (a relative increase of 48% for) livestock (see Annex 2). This corresponds to a future based mostly on the implementation of current and ambitious public policies, and national and international commitments in areas of biodiversity use and management, food production and land use. Mexico has a strong and ambitious General Law on Climate Change and a multitude of public policies specifically designed to mitigate and reduce the negative effects generated on the environment by its food and land use systems. It has also signed international agreements to protect its biodiversity and reduce its GHG emissions. In the Sustainable Pathway we have incorporated some of the existing public policies and international commitments to assess their impact on our model. With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

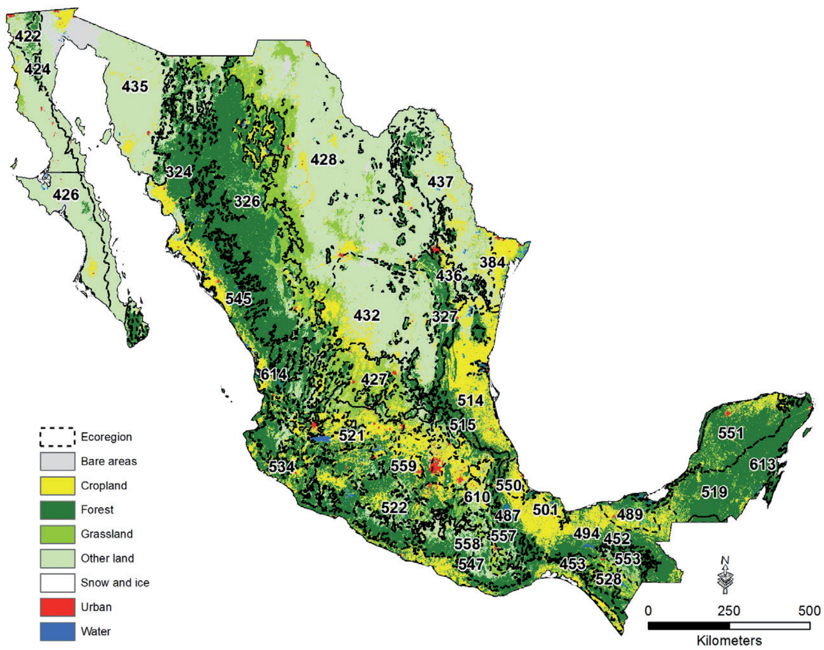
Land and Biodiversity

Current State

In 2010, Mexico was covered by 13% cropland, 41% pasture areas (mainly including induced pastures and semiarid scrubland), 34% forest, 1% urban, and 12% other natural land. Most of agricultural areas are located in the center of the country, the Gulf of Mexico coasts, and the central and southern part of the Pacific coast (Map 1). Temperate forests can be found along the mountain ranges that run along the country from the northeast to the southeast and from the northwest to the southwest, as well as the transversal mountain ranges in the south. Tropical vegetation is distributed along the coasts either in the form of tropical dry forests or tropical humid forest. The arid- to semiarid-lands climate zones are located in the north and represent more than 40% of the country. Other natural land is distributed across the country. The main threat to biodiversity is severe and non-regulated land-use change due to public policies that promote and incentivize agriculture expansion for the production of export crops (berries, avocados, soy and sugar cane), agricultural incentives for smallholders to alleviate poverty, and free-range cattle that roam across natural areas without restriction. Collateral effects of land-use change for agricultural practices include pollution and degradation of agricultural lands and surrounding areas.

We estimate that land where natural processes predominate[2] accounted for 28% of Mexico's terrestrial land area in 2010. In relative terms, the 453-Chimalapas montane forests holds the greatest share of land where natural processes predominate, followed by 487-Oaxacan montane forests, and 424-California montane chaparral and woodlands (Annex 4). Across the country, while 28 Mha (14%) of land is under formal protection, falling short of the

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



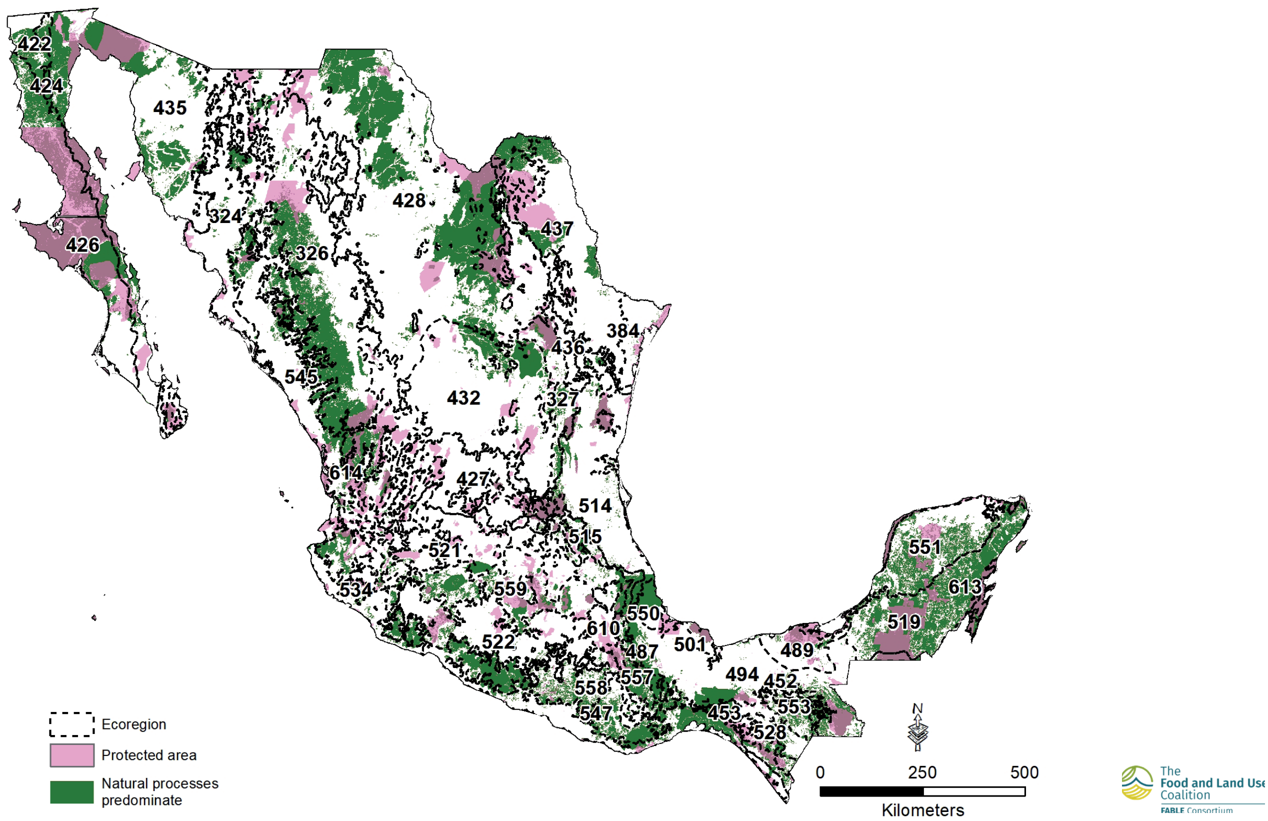
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017) Notes. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

30% zero-draft CBD post-2020 target, only 26% of land where natural processes predominate, including biodiversity hot-spots, is formally protected. This indicates that only areas with abrupt topography and in Mexico's arid north (both important due to high levels of endemism) are likely to continue to experience low levels of transformation, although water availability in specific dryland spots has been used for agriculture (e.g. cereals, tomatoes, and alfalfa) causing their disappearance and the exhaustion of aquifers. On the other hand, tropical humid, dry, and temperate forest are at risk without enough actions to better protect them.

Approximately 41% of Mexico's cropland was in landscapes with at least 10% natural vegetation in 2020 (Map 2). These relatively biodiversity-friendly croplands are most widespread in 511-Yucatán dry forests followed by 519-Yucatán moist forests and 547-Southern Pacific dry forests. The regional differences in extent of biodiversity-friendly cropland can be explained by regional long-term production practices that promote the regeneration of the natural vegetation. The secondary vegetation in the Yucatan Peninsula is a result of these practices.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

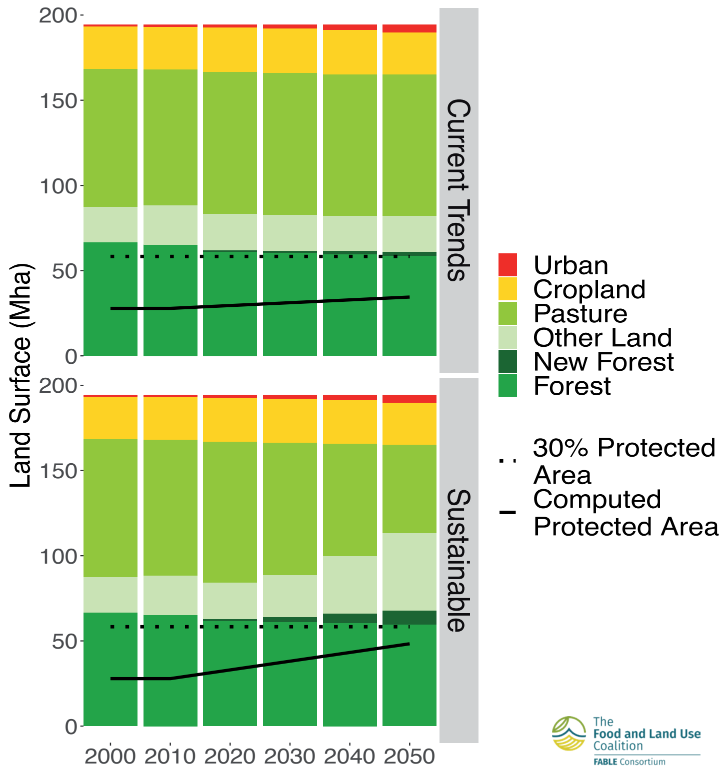
Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including constraints on the expansion of agricultural land beyond its current area by 2015, 2.3 Mha reforested by 2050, and protected areas increase from 14 % of total land in 2010 to 18% in 2050 (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in pasture and cropland area and a decrease in forest area. This trend evolves over the period 2030-2050: forest and new forest area increases, pasture and cropland decreases (Figure 1). Initial pasture expansion is mainly driven by the increase in internal demand for beef due to its increasing role in the dietary mix, while livestock productivity per head and ruminant density per hectare of pasture remains stable over the period 2010-2050. Between 2030-2050, the decrease in cropland and pasture area is explained by the constraints in the expansion of agricultural land and the slow but steady increase of livestock productivity, increase in milk and beef imports, as well as a small rise in the population. This results in a stabilization of land where natural processes predominate at 27% by 2030, which remains the same by 2050 compared to 2010.

In the Sustainable Pathway, assumptions on agricultural land expansion, reforestation, and protected areas have been changed to reflect public policies aiming to improve crop productivity instead of increasing agricultural area, changes in livestock production systems to include silvo-pastoral systems with higher livestock productivity and as

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

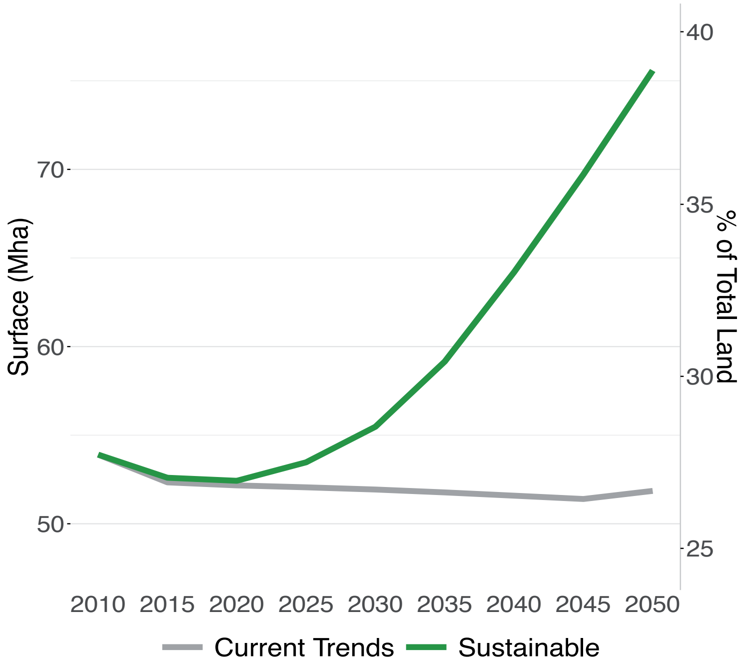


Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

well as international commitments for reforestation (Guevara Sanginés, Lara Pulido, Torres Rojo, & Betancourt Lopez, 2020; CIMMYT & SADER, 2018; SIAP, 2020). The main assumptions include constraints on the expansion of agricultural land beyond its 2016 area, 8.4 Mha reforested by 2050, and protected areas increase from 14 % of total land in 2010 to 30 % in 2050 (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Mexico in the Sustainable Pathway: (i) a slight reduction in deforestation, (ii) the recovery of natural land in the form of other lands (all other types of vegetation in Mexico that are not forest types), (iii) a reduction in pasture, and (iv) an increase of reforested land. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by a change in diets in which the consumption of fruit, vegetables, and pulses increases combined with a reduction in cereals and an implementation of strategies to increase crop and livestock productivity. This leads to an increase in the area where natural processes predominate: the area stops declining by 2025 and increases to 40% between 2010 and 2050 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate

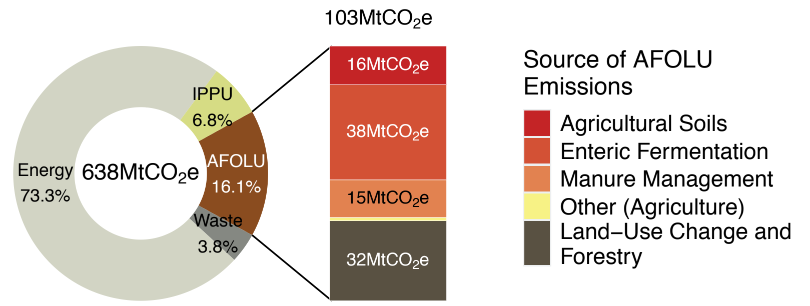


GHG emissions from AFOLU

Current State

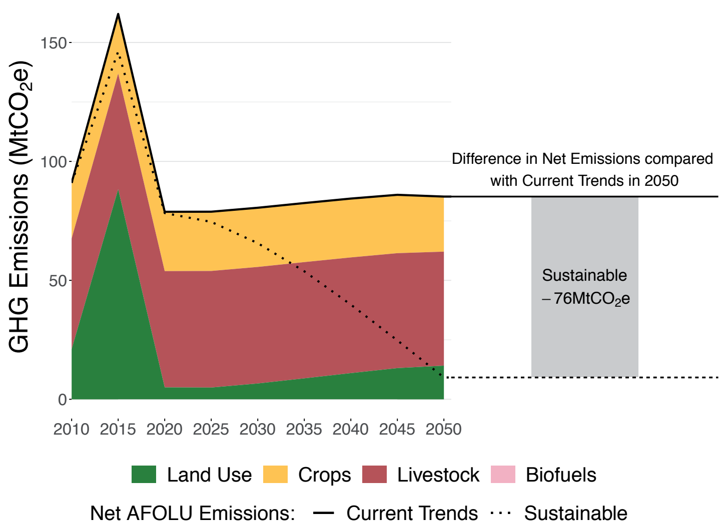
GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 11.6% of total emissions in 2013 (Figure 3). Enteric fermentation and manure management are the main sources of AFOLU emissions, followed by agricultural soils and field burning of agricultural residues. This can be explained by an increase in beef consumption over the last 10 years due to dietary changes (Ibarrola-Rivas & Granados-Ramírez, 2017; Rivera, Barquera, González-Cossío, Olaiz, & Sepúlveda, 2004; Tello, Garcillán, & Ezcurra, 2020), consequently increasing the amount of cattle responsible for enteric fermentation, producing methane. Methane production is a serious problem linked to inefficiencies in bovine diets associated with traditional livestock production systems in temperate and tropical regions (Morante López et al., 2016). Additional important factors are the slash-and-burn cultivation practices used in the southeastern region of the country, the burning of grassland to induce revegetation and the increase in dry matter production for livestock breeding, and of course, the traditional practice of burning rather than harvesting residues (SEMARNAT, 2010). In the other extreme, high intensity agricultural practices involve the application of large quantities of fertilizers and pesticides for prolonged periods of

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2013



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



time, which are often applied incorrectly thus producing important volumes of GHG (Flores Lopez et al., 2012).

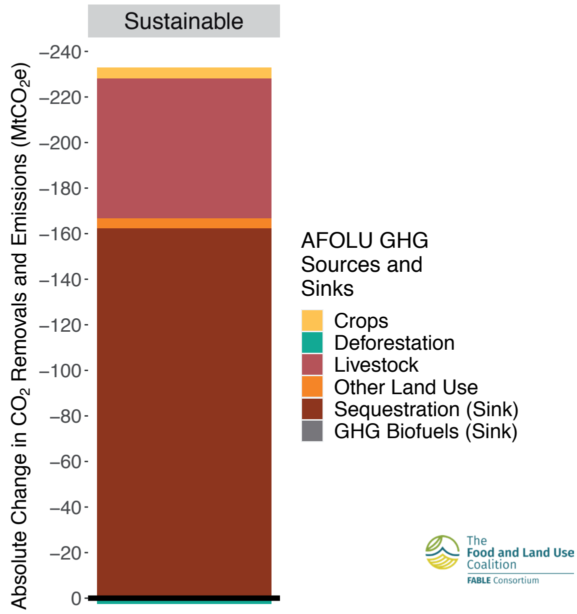
Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU increase to 81 Mt CO2e/yr in 2030, before reaching 86 Mt CO_2e/yr in 2045 and dropping to 85.2 Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock production is the largest source of emissions (48 Mt CO_2e/yr) while new forest act as a sink (-10.5 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for deforestation (164%) while a slight reduction is computed for crop production (-7.1%).

In comparison, the Sustainable Pathway leads to a reduction in AFOLU GHG emissions by 89% by 2050 compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from land use change and livestock production (Figure 5). Change in diets, adoption of strategies to increase productivity in crops and livestock are the most important drivers of this reduction.

Compared to Mexico's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute to as much as 23% of its total GHG emissions reduction objective by 2050. Such reductions could be enhanced through the implementation of policy measures nationwide that would increase agricultural productivity. This can be done by improving the genetic base and updating agricultural practices for the production of corn and other grains. The MASAGRO program led by CIMMYT has been shown to be efficient in reaching this goal, by introducing a strong capacity building program based on productivity gains and the adoption of genetically improved seeds and cultural practices adapted to each municipality (CIMMYT and SADER 2018). For cattle ranching systems, increases in productivity could be achieved through the adoption of silvopastoral practices, which improve the menu of feeding components of traditional cattle diets, increasing weight gains and the herd carrying capacity per unit of area (Alejandro Guevara Sanginés et al. 2020).

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Furthermore, carbon sequestration can be enhanced by implementing programs that promote vegetation restoration and reforestation programs linked to agro-silvicultural practices such as the "Sembrando Vida Program" (DOF - Diario Oficial de la Federación 2020), the National Restoration program and a multitude of private and civil society initiatives (e.g. Reforestamos Mexico, Reforestación Extrema, among others) which add up to the reforestation commitments of the country (DC 2014). In addition, initiatives aimed to reduce pressure on land use change such as: a) the restoration of traditional systems of cattle ranching through the introduction of silvopastoral systems, b) the introduction of high productivity agrosilvicultural systems with the use of high value crops in the agriculture-forest interface, and c) support to different demand-driven mechanisms to increase demand for products with a deforestation-free supply chain, contributing to the recovery of low agricultural productivity areas into natural vegetation lands. These measures could be particularly important when considering options for NDC enhancement.

Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

10% of children under 5 years were stunted and 1.9% were wasted in 2016 (Cuevas-Nasu et al., 2018).

The share of stunted children has decreased from 13.6% in 2012; while the share of wasted children has increased from 1.6% in 2012 (Cuevas-Nasu et al. 2018).

Micronutrient Deficiency

12.6% of women, 26.9% of preschoolers and 12.5% of school children suffer from anemia in 2016, which can lead to maternal death (Cruz-Góngora, Martínez-Tapia, Cuevas-Nasu, Flores-Aldana, & Shamah-Levy, 2017).

54.8% of women had a dietary intake less than the requirement of vitamin A in 2012 (Pedroza-Tobías et al., 2016). By biochemical indicator, 15.7% of preschool children (12 to 59 months) were deficient in vitamin A in 2012 (Villalpando, De la Cruz, Shamah-Levy, Rebollar, & Contreras-Manzano, 2015), which can notably lead to blindness and child mortality.

Overweight/ Obesity

In 2016, 41.7% of men and 37% of women were overweight; 32.4% of men and 37.5% of women were obese (Instituto Nacional de Salud Pública & Secretaría de Salud, 2020).

In preschool children, 5.8% of girls and 6.5% of boys were overweight or obese in 2016. In scholar children (5-11 years old) the prevalence of overweight and obesity in girls was 20.6% and 12.2% respectively, while in boys, it was 15.4% and 18.3% in 2016 (Hernández-Cordero et al., 2017).

For adolescents, the prevalence of overweight was 26.4% in girls and 18.5% in boys; and obesity 12.8% in girls and 15% in boys in 2016 (Hernández-Cordero et al. 2017). These shares were similar between the age groups, except in female adolescents and adults, whose prevalence increased compared to 2012 (Instituto Nacional de Salud Pública & Secretaría de Salud, 2020; Shamah-Levy et al., 2018).

Disease Burden due to Dietary Risks

189 to <249 deaths per year are attributable to dietary risks.

35 deaths and 1,605 DALYS due to type 2 diabetes per 100,000 population (Afshin et al., 2019).

In 2012, 9.4% (with previous diagnosis) of the population suffers from diabetes (Rojas-Martínez et al., 2018).

Table 3 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

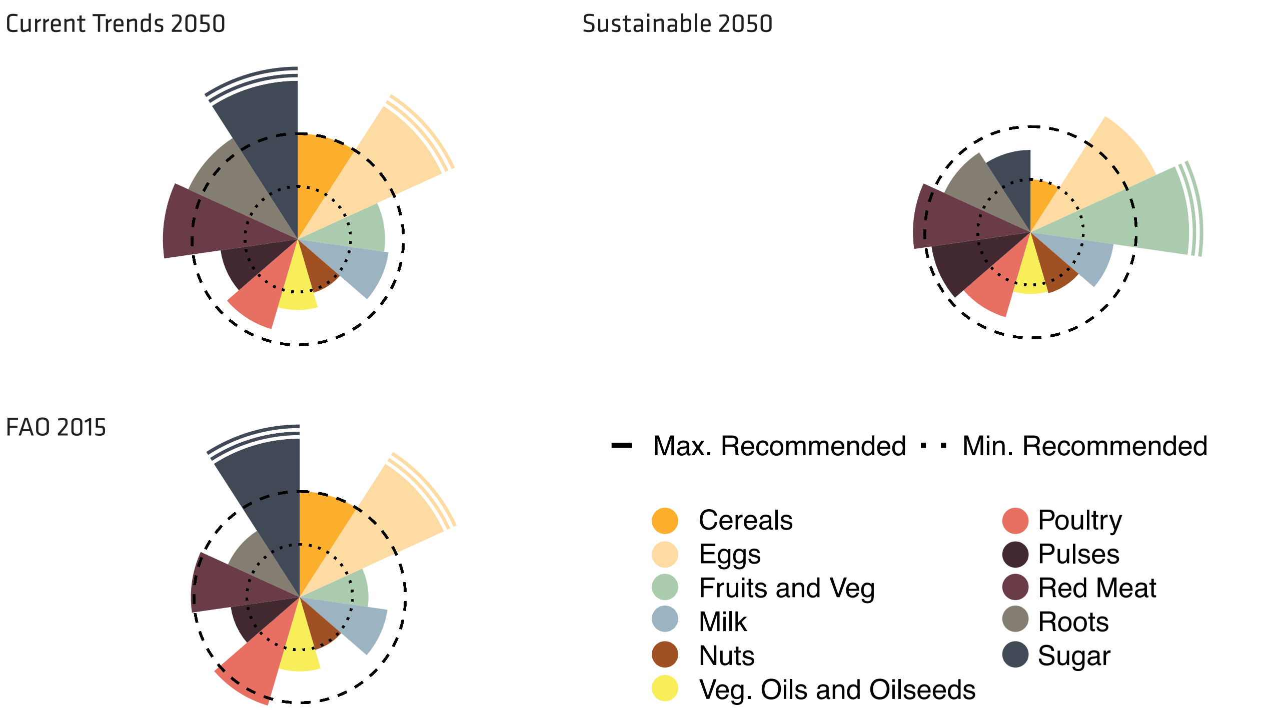
	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,760 (2,052)	2,607 (2,086)	2,613 (2,086)	2,520 (2,090)	2,378 (2,090)
Fats (g) (recommended range	85 (61-92)	86 (58-87)	83 (58-87)	93 (56-84)	78 (53-79)
Proteins (g) (recommended range	81 (69-241)	78 (65-228)	83 (65-228)	80 (63-221)	89 (59-208)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 25% higher in 2030 and 21% higher in 2050 (Table 3). The current average intake is mostly satisfied by eggs, red meat, roots and sugars, with cereals representing 60% of the total calorie intake. We assume that the consumption of roots, dairy and red meat, will increase by 173%, 25%, and 42%, respectively, between 2020 and 2050. The consumption of nuts, fruits and vegetables, and eggs will also increase while the consumption of cereals, poultry, and sugar will slightly decrease. Compared to the EAT-LANCET recommendations, cereals, roots, sugar, red meat and eggs are over-consumed while nuts and pulses are close to the minimum recommended levels (Figure 6). Moreover, fat and protein intake does not follow the same trend, while fat intake is on the upper boundary of the DRI, protein intake falls on the lower boundary in 2030. In 2050, fat intake follows the same trend and exceeds the DRI while protein intake remains on the lower boundary of the recommended dietary intake. This can be explained by an increase in consumption of oil and fat, milk products, and eggs (Figure 6).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings) i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar, eggs, and fruits and vegetables indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Under the Sustainable Pathway, we assume that diets will transition towards a healthier consumption of fats and oils, with a lower reliance on cereals, and with a substantial increase in the intake of fruits and vegetables, pulses, and nuts. The ratio of the computed average intake over the MDER increases to 25% in 2030 and 14% in 2050. Compared to the EAT-LANCET recommendations, the consumption of eggs and red meat remains outside of the recommended range with the consumption of sugar and roots within the recommended range in 2050 (Figure 6). Moreover, the fat intake per capita is still on the upper boundary of the dietary reference intake (DRI) but the protein intake increases in 2030, showing some improvement compared to the Current Trends Pathway.

To promote a necessary shift in diets it is necessary to implement measures that encourage consumers to make healthier food choices. Placing nutrition labels in front of the food packages (Jáuregui et al. 2020), including a purchase tax to reduce sales of sugar-sweetened beverages and increase consumption of untaxed beverages (Colchero, Molina, and Guerrero-López 2017) are some of the general strategies that have been proposed. However, the most important policies need to address the obesity epidemic for school-age children, such as the development of dedicated school curricula where one of the components is the access and availability of food and beverages that facilitate a healthy diet. This policy already was created in 2010 but it has not been fully implemented. It includes the development of general guidelines for the sale and distribution of food and beverages in elementary schools. These guidelines have the objective of facilitating an adequate diet for children in schools and have a structured and unified regulation among states (Secretaría de Salud 2010; Secretaría de Salud and Secretaría de Educación 2014).

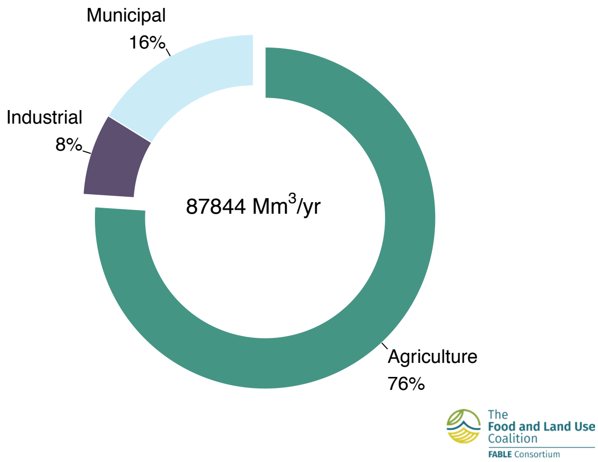
Water

Current State

Mexico is characterized by its diverse climatic conditions, high climate and rainfall variability. The climate ranges from dry regions with mean temperatures above 32°C and precipitation that varies between 60 to 400mm per year, to tropical regions with mean temperatures above 20°C and 800 to 4500mm of precipitation. Between these two extremes are temperate regions with mean temperatures below 10°C, 700 to 1,000mm of precipitation, and that are 1,600 meters above sea level. Precipitation mostly occurs over the period June – October with a limited region of winter rain in the northwestern part of the country.

The agricultural sector represented 76% of total water withdrawals in 2017 (Figure 7; FAO 2020). Moreover in 2016, 32% of agricultural land was equipped for irrigation, representing 33% of estimated-irrigation potential. The three most important irrigated crops, maize, wheat, and sorghum, account for 28%, 12%, and 12% of total harvested irrigated area. Mexico exported 3.1% of corn, 0.81% of wheat, and 0.02% of sorghum in 2016.

Figure 7 | Water withdrawals by sector in 2017

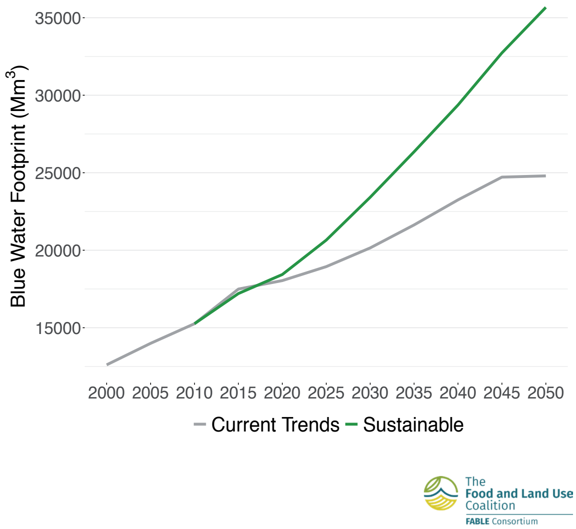


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000-2015 (12,605 Mm^3/yr and 17,494 Mm^3/yr), before reaching 20,149 Mm^3/yr and 24,796 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with wheat, rice, and corn accounting for 41%, 32%, and 12% of computed blue water use for agriculture by 2050[3]. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture reaches 23,415 Mm^3/yr in 2030 and 35,669 Mm^3/yr in 2050. This increase in demand for blue water is explained mainly by an increase in production of fruits and vegetables due to dietary shifts and increased exports (see Annex 2) leading to a 1.8% increase in water use for irrigation by 2050 despite increases in imports for milk and beef that would reduce water use dedicated to feed production.

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



3 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

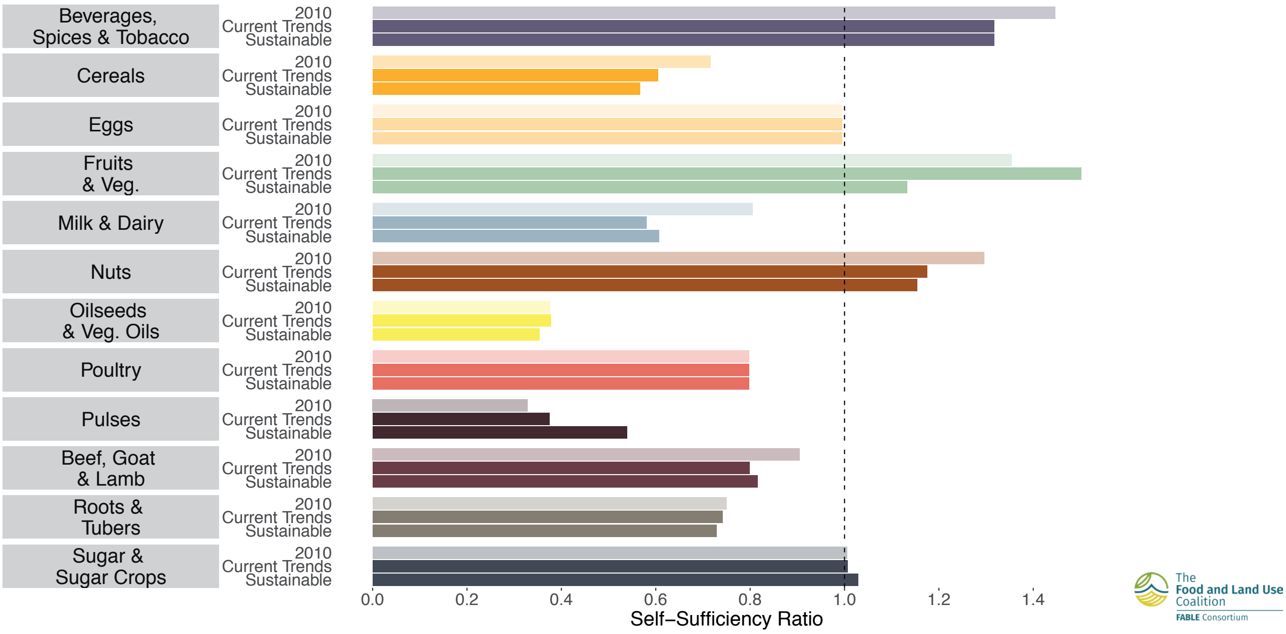
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Mexico's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Currently, the self-sufficiency for some basic products, such as pulses and industrial crops, is at high risk. These crops began losing importance with the introduction of programs to promote the cropping of corn and other basic products (Riedemann 2007). However, the current production of cereals does not guarantee self-sufficiency for products such as wheat, yellow corn, and sorghum, the demand for which has increased markedly due to demand in balanced food products in the poultry, pig, and cattle meat industries (Martínez Damián, Téllez Delgado, and Mora Flores 2018; Nuñez Melgoza and Sempere Campello 2016). Dairy products and most meats are also not trending towards self-sufficiency. High costs of labor, poor technology, and inefficient diets for the production of milk generate an inefficient milk sector that is unable to compete at the international level (Rebollar et al. 2016). Meanwhile, the poultry and pig industries are constrained by the domestic market structure of inputs, despite showing high growth (Martinez-Gomez 2013).

Under the Current Trends Pathway, we project that Mexico would be self-sufficient in eggs, sugar and sugar crops, nuts, fruits and vegetables, and spices, beverages and tobacco in 2050, with self-sufficiency by product group remaining stable for the majority of products from 2010 – 2050 (Figure 9). The product groups on which the country depends the most on imports are milk and dairy, pulses, oil and vegetable seeds, and cereals, a dependency that will remain stable until 2050. Under the Sustainable Pathway, Mexico's self-sufficiency does not change compared to the Current Trend Pathways, it is still self-sufficient in the same product groups as in 2010 and a trend that does not change by 2050. Imports of beef, milk, and corn in 2050 to reduce Mexico's environmental costs does not promote self-sufficiency for those important product groups (Martinez-Melendez and Bennett 2016).

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

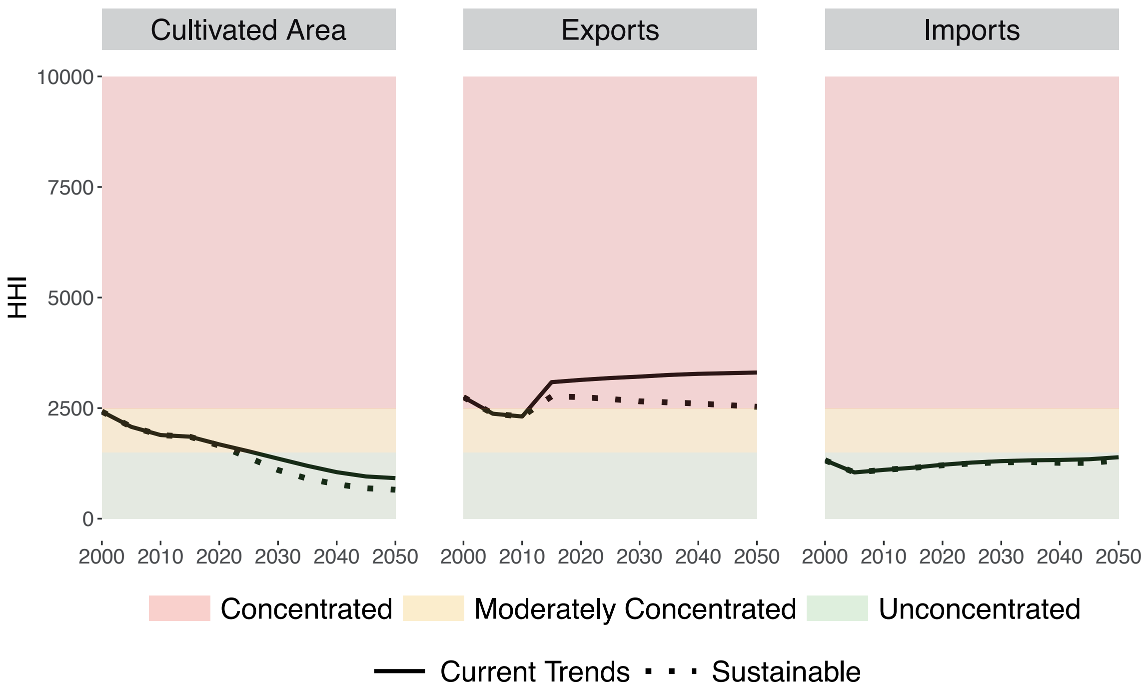
We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Despite a trend of increasing diversification of crops driven by the commercial openness with the US and Canadian markets, the primary sector is still concentrated in very few crops. Cereals, mainly corn, cover more than 70% of the cropping area in the country. However, there is clear scope for greater diversification, which will improve the use of productive land and irrigation water, increase the returns to and wellbeing of producers, and increase the availability of more products.

Current exports are concentrated in very few products (avocado, tequila, fruits, berries, and vegetables) and this concentration remains even under the Sustainable Pathway. This concentration of products is related to market opportunities, investment and capacities needed to maintain supply chain with high standards. Thus, such a trend will remain as long as the programs aimed at promoting new markets do not take off.

Under the Current Trends Pathway, we project high concentration of crop exports, relatively low concentration of imports and a trend towards decreased concentration in crops planted in 2050, trends which are consistent over the period 2010 – 2050. This indicates high levels of diversity across the national production system and imports, but low diversity among exports. Under the Sustainable Pathway, the evolution of the diversification is similar to the Current Trends Pathway with a lower concentration of exports (albeit still high) and even lower concentration of crops planted in 2050, indicating high levels of diversity across the national production system (Figure 10).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

Mexico needs to promote highly productive and sustainable food systems that will increase its self-sufficiency in key products groups (animal protein, pulses, and cereals). Mexico also needs to enact policies to ensure that pressure for land conversion is reduced and that the Mexican population has access to the food it needs. The FABLE project provides an integrated pathway for sustainable land use that can inform Mexico's long-term strategy and the land-use component of the country's NDC. Results suggest that Mexico can adopt a feasible land-use pathway that ensures adequate nutrition for the population, sets a limit to further agricultural expansion, and expands natural habitats. The results also suggest that, over the coming decades, food security is possible without sacrificing Mexico's natural capital.

The results highlight that the key national trade-offs in food and land-use systems involve the promotion of national self-sufficiency through a reduction in imports, at the expense of pastureland. Food production in Mexico has enormous potential for sustainability. It has policies that, if correctly and fully applied, would promote production systems that are highly productive and are also environmentally sustainable in terms of improved water use and GHG reduction. Nevertheless, a large proportion of food would have to be imported. On a 2050 horizon, Mexico is unlikely to be self-sufficient in important food groups (meat from cattle and poultry, milk and dairy, cereals and pulses). Even if the country transitions towards a healthier diet, much of the required protein intake will need to be imported.

The results also highlight the important role that diet plays in reducing land-use change and GHG emissions. A change towards a healthier diet implies a reduction in the intake of cereals and sugar but also an increase in fruits, vegetables, and nuts, and a healthy consumption of animal protein, which includes a higher intake of red meat and dairy products (Villalpando et al., 2015). These changes would affect what is produced in Mexico and what needs to be imported. Without importing beef, milk, and corn for animal feed, the reduction in pasture would not be possible, even with better practices and more productive livestock systems.

An important limitation of this analysis that can be improved in future work relates to the scenario assumptions. In 2019, the Mexican government published its National Development Plan for 2019-2024, with the goal of improving the well-being of Mexicans through sustainable development. While the 2020 FABLE Report was being prepared, we did not have complete information on the programs and operating rules that key federal agencies were considering (e.g., Sustainable Forest Development programs from CONAFOR), or updates on Mexico's international commitments (e.g., INECC will submit Mexico's second NDC in late 2020). Moreover, the federal government has recently created an intersectoral group called "Health, Agriculture, Environment and Competitiveness" (GISAMAC in Spanish). GISAMAC aims to support new forms of agricultural and forestry production to reduce the negative effects on human health and wildlife (SEMARNAT 2020). Under the coordination of the Ministry of Environment, and in collaboration with 18 working groups from more than 10 government agencies and research institutes, GISAMAC focuses on harmonization of public policies to promote sufficient and sustainable production of healthy foods, prioritizing production from family farm producers and medium-sized producers as well as the protection and restoration of ecosystem services.

During the coming months, the Mexican FABLE team will continue to reach out to key Mexican government stakeholders to promote integrated modeling frameworks. Together with other members of the Mexican academic community, this integrated modeling can help ensure policy coherence between the land sector of the country's NDC, the NBSAP, and strategic plans for agricultural self-sufficiency, each authored by different government agencies. Importantly, the results of this exercise highlight the transformative impact that diets have on land-use systems. As such, diet transformation should be included in all climate mitigation plans. In addition, the FABLE team plans to extend the FABLE Calculator with new scenarios to model policies that Mexico might adopt in the coming years. Finally, the team has begun engaging state-level governments to inform their long-term planning to meet the SDGs, and plans to adapt the FABLE Calculator so that Mexican states can model their own sustainable land use pathways at the state level.

The COVID-19 crisis has generated new challenges for Mexico's food systems. In rural areas where health care systems are scarce or nonexistent, local populations have implemented strict controls on accessing their localities as a means of preventing the spread of COVID-19 (Jimenez-Ferrer 2020). These controls have disrupted supply chains for basic foods and commodities, resulting in an increase in prices of crucial goods (e.g., meat, eggs, sugar, medicines, gasoline, etc.), adversely affecting already fragile local economies.

Moreover, reduced mobility to larger cities and the return of the migrant population from the US may lead to an increase in the extent of agricultural lands (e.g. for the production of beans and corn) or forest products. At the same time, the shortage in beef supply in the US is resulting in an increase in Mexico's beef exports to the US (Alire and Huffstutter 2020), potentially increasing the pressure for land conversion to cultivated grasslands but taking advantage of the Mexico's small scale operations where the disease is easier to keep at bay.

Finally, the COVID-19 crisis is decreasing demand for forests products and services. Out of the almost 55 million hectares of tropical and temperate forests in Mexico, only 5.5 million hectares are managed with approved plans for timber extraction. With the current sanitary crisis, the demand for products and services in Mexico's forest sector is drastically decreasing (50-70% reduction) (Mongabay Latam, 2020). National associations of community forestry already estimate a 60% loss in the 160,000 jobs generated by the industry, putting at risk more than three decades of collective work among local communities, foresters, and civil society organizations that consolidated sound management practices and forest conservation, while potentially increasing timber imports and opening the way for the expansion of the agricultural frontier (Mongabay Latam, 2020).

Annex 1. List of changes made to the model to adapt it to the national context

- Crop productivity for four most important crops (maize, beans, wheat, and sorghum) were adapted to reflect Mexican trends under two pathways: Current Trends where the productivity followed the same increase trend as 2006 – 2016 and in the Sustainable Pathway we followed the MASAGRO (CIMMYT & SADER, 2018) program's expected productivity in maize, beans, wheats and sorghum (SAGARPA, 2017).
- Livestock productivity, two scenarios were generated: for the Current Trends Pathway, where livestock productivity followed the same trend of improvement as the period 2000 – 2010 and the Sustainable Pathway, where high-productivity livestock systems based on modern silvopastoral systems were calculated for cattle (Guevara Sanginés et al., 2020; SIAP, 2020)
- Reforestation, scenario for the Current Trends Pathway contemplates the reforestation that occurred from 2010 to 2020 and the intention of reforestation of two programs "Sembrando Vida" and "Programa de restauración forestal". For the Sustainable Pathway, the reforestation occurred from 2010 to 2020 and the BonnChallenge (2019; DOF, 2020; SEMARNAT, 2020)
- Diets, two scenarios were generated, a current diet that mimics the average diet in Mexico and a healthy diet that follows national and international recommendations for sustainability and health (Barquera, Campos, & Rivera, 2013; Behrens et al., 2017; Cruz-Góngora et al., 2017; Fernández-Gaxiola et al., 2015; Willett et al., 2019)
- Protected areas, for the Current Trends Pathway a goal of 17% of total terrestrial area was included, for the Sustainable Pathway the goal of 30% was set.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
The population is expected to reach 146 million by 2050 (name of scenario selected). (CONAPO 2018) (UN_Low scenario selected)	Same as Current Trends

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable pathway
We assume no expansion of agricultural land beyond 2016 agricultural area levels. This is a national policy since 2017 and it is being included as is by the new federal Government. (SAGARPA 2017) *(For Scenario: No productive land expansion beyond 2010 value)*	Same as Current Trends

LAND Afforestation or reforestation target (Mha)

We assume total afforested/reforested area to reach 2.2 Mha by 2020/2030/2050. (DOF - Diario Oficial de la Federación 2020; SEMARNAT 2020) The reforestation efforts from 2010 to 2020 were included, a 30 % of the area intended for the Federal program Sembrando Vida (2019-2024) and finally 30 % of the area for the program “Restauración Forestal”. (ReforestationMexBAU scenario selected)	We assume total afforested/reforested area to reach 8.4 Mha by 2050. (DC 2014; SEMARNAT 2020) *Mexico has signed the BonnChallenge which we used to add to the efforts of reforestation from 2010 to 2018.* (BonnChallenge scenario selected)

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
Protected areas increase by 2050 they represent 17.8% of total land. Mexico has signed the Convention on Biological Diversity and agree to include in Protected areas 17% of its territory. (CONABIO 2016)	Protected areas increase: by 2050 they represent 25% of total land. Use of several conservation instruments to reach 30% of total land area under protection (CONABIO 2016)

PRODUCTION Crop productivity for the key crops in the country (in t/ha)	
Current Trends Pathway	**Sustainable Pathway**
By 2050, crop productivity reaches: • 6.2 tons per ha for corn • 1.5 tons per ha for beans • 5.9 tons per ha for wheat Crop productivity for 4 most important crops (maize, beans, wheat and sorghum) were adapted to reflect Mexican of crop productivity following the same increase trend than 2006 – 2016. (SIAP 2017)	By 2050, crop productivity reaches: • 10 tons per ha for corn • 2.2 tons per ha for beans • 6.3 tons per ha for wheat Based on (Masagro, Siap). Crop productivity increase if the MASAGRO program was implemented for the principal crop (Maize). For the rest other two crops we used the projections generated by the "Planeación Nacional Agrícola" for a sustainable increment on crop productivity (CIMMYT and SADER 2018; SAGARPA 2017).
PRODUCTION Livestock productivity for the key livestock products in the country (in kg/head of animal unit)	
By 2050, livestock productivity reaches: • 80.7 kg per head for cattle • 86 kg per head for pork Following the trend of increase productivity from 2000 – 2010. (SIAP 2020)	By 2050, livestock productivity reaches: • 105.5 kg per head for cattle • 126.4 kg per head for pork Mexico has programs to promote silvopastoral systems for cattle. (Alejandro Guevara Sanginés et al. 2020)
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)	
By 2050, the average ruminant livestock stocking density is 12 animals/ha per ha. National pasture stocking rate without implementing any program to increase productivity in a sustainable way. (COTECOCA - SEMARNAT 2014)	By 2050, the average ruminant livestock stocking density is 24 animals/ha per ha. Silvopastoral systems have the capacity to double the density of animals per hectare. (Alejandro Guevara Sanginés et al. 2020; SEMARNAT 2010)
PRODUCTION Post-harvest losses	
By 2050, the share of production and imports lost during storage and transportation is 10%. However, Mexico does not have data on food loss at national or regional level. (Gustavsson, Cederberg, and Sonesson 2011).	By 2050, the share of production and imports lost during storage and transportation is 5%. Mexico does not have data on food loss at national or regional level. (Gustavsson et al. 2011)

TRADE Share of consumption which is imported for key imported products (%)	
Current Trends Pathway	**Sustainable Pathway**
By 2050, the share of total consumption which is imported is: • 54% for corn for animal feed • 40% by 2050 for milk • 18% by 2050 for beef Products with a high agricultural and water footprint were selected to be imported as other countries are more environmentally efficient in their production.	Same as Current Trends
TRADE Evolution of exports for key exported products (1000 tons)	
By 2050, the volume of exports is: • 12,600 mil tons by 2050 for veggies • 5,300 mil tons by 2050 for tomatoes • 3,600 mil tons by 2050 for fruits The selected crops are the same that Mexico mainly export taking advantage of its environment conditions that allows it to grow these crops most of the year (SAGARPA 2017).	By 2050, the volume of exports is: • 7,200 tons by 2050 for veggies • 3,600 mil tons by 2050 for fruits • 3,200 mil tons by 2050 for tomatoes According to Mexico's agricultural planning, the country has the capacity to reconvert part of its crops land towards high value crop exports taking advantage of its environmental conditions. (Martinez-Melendez and Bennett 2016; SAGARPA 2017).

Mexico

FOOD Average dietary composition (daily kcal per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 2683 kcal and is: • 1012 kcal for cereals • 323 kcal for Oils and fats • 352 kcal for sugar Current diet that mimics the average diet in Mexico.	By 2030, the average daily calorie consumption per capita is 2633 kcal and is: • 992 kcal for cereals • 276 kcal for sugar • 262 kcal for fruits and vegetables Healthy diet that follows national and international recommendations for sustainability.

FOOD Share of food consumption which is wasted at household level (%).

Current Trends Pathway	Sustainable Pathway
Mexico does not have data. We used FAO data for Latin American Countries. By 2030, the share of final household consumption which is wasted at the household level is: • Cereals 9% • Fish 3% • Fruit and Veg 8% • Milk 4% • Fats and oils 2% • Pulses 2% • Red meat 5% • Roots 4% • Poultry 6% (Gustavsson et al. 2011)	Same as Current Trends

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
Mexico does not participate on biofuels production.	Mexico does not participate on biofuels production.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m^2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model Ha HadGEM2-E without CO_2 fertilization effect	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m^2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model Ha HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
426	Baja California desert	7733.195	61	64.5	71.8	28.2	173.87	53.4
521	Bajío dry forests	3757.509	7.5	5.1	2.4	97.6	1963.573	31.6
522	Balsas dry forests	6258.079	10.9	8.3	41.2	58.8	1451.669	45.7
564	Belizian pine savannas	0.006	0	0	0	0	0.006	100
422	California coastal sage and chaparral	1177.622	4.6	52.7	8.5	91.5	21.82	67.7
424	California montane chaparral and woodlands	400.951	16.9	79.2	21.4	78.6	0.322	100
527	Central American dry forests	324.717	14.5	7.7	28.5	71.5	214.245	37
451	Central American montane forests	0.174	90.2	66.1	78.3	21.7	0	0
553	Central American pine-oak forests	1601.563	16.1	36.6	14.4	85.6	31.913	93.5
427	Central Mexican matorral	5948.704	5.4	1.6	60.2	39.8	1963.556	41.4
528	Chiapas Depression dry forests	1315.68	2.8	13.4	7.5	92.5	132.72	78.8
452	Chiapas montane forests	559.097	4.4	43.5	9.3	90.7	5.926	99.7
428	Chihuahuan desert	30439.285	8.4	27.6	10.5	89.5	1581.504	43.1
453	Chimalapas montane forests	208.83	13.6	82.3	10.1	89.9	1.325	94
431	Gulf of California xeric scrub	2311.985	48.9	52.5	66.3	33.7	4.786	78.9
533	Islas Revillagigedo dry forests	13.81	100	70.7	100.7	0	0	0
534	Jalisco dry forests	2545.171	9	7.7	26	74	670.455	43.9
432	Meseta Central matorral	12554.552	5.3	10.9	8.6	91.4	1540.564	45.7
613	Mesoamerican Gulf-Caribbean mangroves	1543.517	63.6	44.1	84.3	15.7	206.024	52.9
614	Northern Mesoamerican Pacific mangroves	665.328	55	16.8	90.3	9.7	109.172	46.5

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
487	Oaxacan montane forests	761.754	2	80.1	2.5	97.5	17.129	88.2
489	Pantanos de Centla	1712.738	28.4	20.5	74.1	25.9	484.896	52
494	Petén-Veracruz moist forests	8434.754	11.3	25.1	29.9	70.1	3009.942	39.6
607	San Lucan xeric scrub	364.328	17.2	2.7	62.3	37.7	10.166	81.1
544	Sierra de la Laguna dry forests	397.285	23	5	87.9	12.1	3.351	94.9
556	Sierra de la Laguna pine-oak forests	106.598	86.8	60	94.9	5.1	1.591	100
501	Sierra de los Tuxtlas	386.727	39.3	39.6	97.4	2.6	161.262	58.1
502	Sierra Madre de Chiapas moist forests	543.602	33.4	55.3	49.5	50.5	41.275	65.2
557	Sierra Madre de Oaxaca pine-oak forests	1437.723	6.5	62.8	8.7	91.3	29.224	90.6
558	Sierra Madre del Sur pine-oak forests	6131.229	2.9	51.4	2.7	97.3	155.151	87.8
326	Sierra Madre Occidental pine-oak forests	21590.017	13.1	29.8	12.2	87.8	529.237	59.8
327	Sierra Madre Oriental pine-oak forests	6175.926	32.9	38.5	48	52	144.676	68
545	Sinaloan dry forests	7762.602	11.1	17.9	19.2	80.8	1589.752	33
435	Sonoran Desert	10621.743	13.5	36.6	27.8	72.2	561.571	43.1
324	Sonoran-Sinaloan subtropical dry forest	5074.817	5.1	6.9	2.3	97.7	980.109	21.6
617	Southern Mesoamerican Pacific mangroves	141.411	63.1	52.2	57.2	42.8	20.576	67.3
547	Southern Pacific dry forests	4180.064	4.2	31.1	8.1	91.9	944.039	66.5
436	Tamaulipan matorral	1630.757	6.2	3.7	43.7	56.3	341.593	46.6
437	Tamaulipan mezquital	7188.567	9.6	14.1	12.2	87.8	1021.987	62
610	Tehuacán Valley matorral	991.45	16.3	4.6	4.9	95.1	434.702	32

Mexico

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
559	Trans-Mexican Volcanic Belt pine-oak forests	9250.213	17.8	25.1	25.1	74.9	2408.496	38.5
550	Veracruz dry forests	663.957	4.7	50.7	0.2	99.8	382.475	40.9
514	Veracruz moist forests	6900.271	7.6	12.6	41.3	58.7	3837.916	27.9
515	Veracruz montane forests	496.771	6.2	28.2	5.9	94.1	17.735	98.4
384	Western Gulf coastal grasslands	1523.11	18.2	5.5	79.3	20.7	935.359	18.4
551	Yucatán dry forests	4981.967	9.6	41.8	13.5	86.5	451.731	74.7
519	Yucatán moist forests	6949.908	23.5	71.7	31.1	68.9	298.449	74.5

Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Nature Map

In 2005, following the Millennium Ecosystem Assessment, Mexico launched a national effort to assess the state of knowledge, the status of the components, and the function of biodiversity, and approaches to its conservation and management. The Mexican National Commission on Biodiversity (CONABIO) was in charge of this effort with the purpose of guiding policy related to the use, conservation and management of Mexico's biodiversity. During the same period, the Mexican National Forestry Commission (CONAFOR) generated a map of aboveground carbon storage created in Mexico. The data for this map was generated from empirical modeling on forest inventory and remote sensing data collected from 2004 to 2007. These efforts have created a wealth of spatially explicit data that has been used to identify priority areas for conservation and restauration.

In this preliminary study, we tested a spatial optimization tool that would identify areas that should be managed for conservation meanwhile generating the greatest synergies between biodiversity and ecosystem services. This effort is necessary because despite substantial achievements and almost 17% of Mexico's terrestrial area under protection, the pace of ecosystem degradation and biodiversity loss in Mexico is unacceptable.

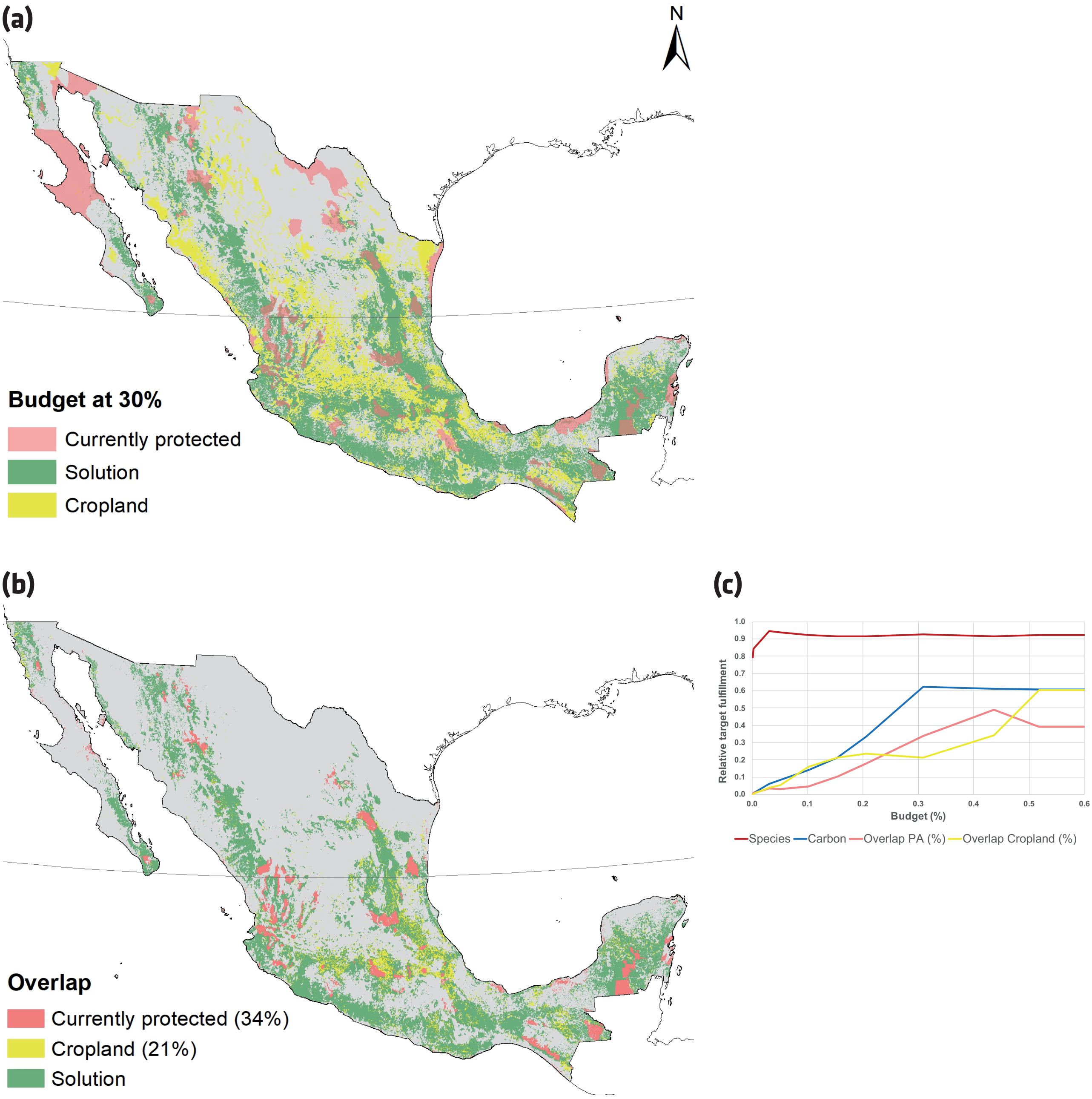
For this preliminary study, we considered all known terrestrial vertebrate species with a conservation status included in one of the following lists: the Mexican list of wild species or species populations at risk (NOM 059), the International Union for Conservation of Nature (IUCN) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). For the ecosystem services in terms of carbon storage we used the spatially explicit map of aboveground carbon storage created by CONAFOR. CONABIO's database provided with 322 species distribution range spread across 24 ecoregions. We divided the entire country in planning units of 4km2 and stablished a conservation target of 40% of the species distribution range independently of their conservation status and 60% of aboveground biomass carbon. We generally followed Nature Map methodology to chart the variables against protection budgets (from 0 to 100% of terrestrial country area) to reach the desired conservation targets.

An initial solution for the optimization problem is shown in figures 11a and 11c. The map shows the optimal amount of area to preserve up to 92% of the selected species and 62% of all aboveground carbon biomass with a budget of 30% of Mexico's terrestrial area. Given that carbon biomass is unevenly distributed in Mexico, mainly located along the Sierras crisscrossing the country and in the southeast humid tropical region, the synergies between carbon and biodiversity benefit areas with high carbon biomass, rich in endemism, and water provision (mountains). The results show the potential to achieve protection for the most vulnerable species in Mexico while protecting ecosystem services that are of outmost importance for a country that has two thirds of its territory in arid and semiarid ecosystems.

Figures 11b-c show in red and yellow the overlap of the solution with current protected areas and cropland. The overlap with cropland would mean that 21% of the agricultural area would be impacted if the proposed solution were implemented. Considering the most current data on crop production and its spatial distribution the economic loss would correspond to 35% of the value of the total crop production for 2016/2017.

The solution given with a 30% budget should be improved because despite having a high percentage of species represented in this initial solution, only 16% of them have at least 40% of their distribution range represented. Furthermore, crop loss of 35% would negatively impact Mexico's food security strategy for the short and medium term. Future optimizations should be carried out with all the available species to increase the number of species and its distribution range while keeping important food production areas with minimal impact. Integrating agrobiodiversity and agricultural areas at the same time as biodiversity and ecosystem services might help to achieve what seems to be contrasting objectives: food security and conservation of natural resources. Mexico already has ample legal tools that make possible the integration of food production and environmental conservation in the same area.

Figure 11 | Prioritization analysis. (a) Map of the solution for a 30% terrestrial area budget. (b) Map of overlapping features, current protected areas and cropland. (c) Calculation of the relative target fulfillment for different sets of features, as a function of the allowed budget: (a) biodiversity (mammals, herps, birds, and amphibian's species with conservation status), aboveground carbon biomass and overlap with current protected areas and cropland.



Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tons

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – tonne

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Norway

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Norway. It presents two pathways for food and land-use systems for the period 2020–2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Norway's NDC treats the FABLE domains. According to the NDC, Norway has committed to reducing its GHG emissions by 50% by 2030 compared to 1990. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). The NDC does not detail the specific measures for emissions cuts in the AFOLU sectors. These measures are instead followed up in separate sector "climate plans", for example for agriculture the *landbrukets klimaplan* (Norges Bondelag, 2020c). Envisaged mitigation measures from agriculture and land-use change include, but are not limited to, the phasing out of fossil fuels and increasing biofuel usage, improved feed quality and feed additives for livestock, breeding programs, improved drainage, improved fertilizing practices, and carbon capture through the use of biochar and capture crops. The agricultural sector climate plan aims to reduce emissions by 5 Mt CO2e over the period 2021–2030 without reducing food waste and meat consumption (Government of Norway, 2020b; Norges Bondelag, 2020c). The forestry sector plans for active forestry, where forest products can replace fossil fuel use and other products. The sector aligns its activities with the EU guidelines through the LULUCF regulations. The resulting source/sink effects depend significantly on which reference pathway is used, and how the balance between carbon emissions and uptake is calculated. The current strategy envisages an increase of soil carbon uptake in forests and has a strong focus on increased use of residual materials (AHO et al., 2016; Treindustrien, 2016). Under its current commitments to the UNFCCC, Norway does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2017)	1990	52	2030	50% reduction	energy, industrial processes and product use, agriculture, land-use change and forestry, and waste	Y	N	N	N

Note. "Total GHG Mitigation" and "Mitigation Measures related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source. Norway (2016)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. Comparing the FABLE and NBSAP targets in terms of deforestation and biodiversity, it appears that while the FABLE Targets include a target for zero net deforestation, this is not part of the NBSAP targets. For biodiversity, FABLE Targets include a specific amount of global terrestrial area protected by a certain year, which is not included in the NBSAP targets. Norway shows strategies to safeguarding plant and genetic diversity, for example aiming to improve landscape diversity and management of semi-natural habitats within existing protected landscapes in order to maintain their conservation value. It is also taking action to identify 70,000 areas as key biotopes, corresponding to almost 1% of the total area of productive forest. In-situ conservation programs by the Norwegian Genetic Resource Centre have identified flora species and crop wild relatives to be safe guarded. However, it lacks strong policies for example conserving (agro-) biodiversity ex-situ.

Table 2 | Overview of the latest NBSAP Targets in relation to FABLE Targets

NBSAP Target	FABLE Target
(4.2) **All forestry areas will be sustainably managed by 2020.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(4.1) **By 2020, the diversity of habitat types in forests will be maintained or restored; this will include safeguarding genetic diversity and important ecological functions and services.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards **BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(4.5) **Management of all harvested stocks of forest animals and plants will be ecosystem-based, and they will be harvested sustainably by 2020.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(2.1, 3.1, 4.1, 5.1, 6.5) **By 2020, the diversity of habitat types in freshwater, forest, wetlands, mountain and in cultural landscapes will be maintained or restored**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(6.5) **By 2020, the diversity of habitat types in cultural landscapes will be maintained or restored; this will include safeguarding genetic diversity and important ecological functions and services.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(2.3, 4.3, 5.2, 6.6) **A representative selection of wetlands, forest habitat, mountain habitat and habitat types in the cultural landscape will be protected for future generations, and the conservation value of protected areas will be maintained or restored.**	**BIODIVERSITY:** At least 30% of global terrestrial area protected by 2030

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Norway.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth based on SSP2 (from 5 million inhabitants in 2020 to 7 million in 2050) accompanied by a slow urban expansion, no expansion of agricultural areas, no afforestation target, no change in the extent of protected areas, no productivity increases in the agricultural sector, a decrease in food waste, an evolution of diets towards national dietary recommendations with more vegetables, grains and fruits, more fish, and reductions in especially red meat consumption (Annex 2). This corresponds to a future based on current Norwegian policy and historical trends. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for wheat (see Annex 2).

Our Sustainable Pathway represents a future in which efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to a similar population growth with a slow urban expansion but under different conditions, based on SSP1. As in the Current Trends Pathway, there is no expansion of agricultural areas, no afforestation target, no change in the extent of protected areas and no productivity increases in the agricultural sector. However, this pathway includes a stronger decrease in food waste and an evolution towards a more sustainable diet with more vegetables, grains and fruits, more fish, and higher reductions in red meat compared to the Current Trends Pathway (see Annex 2). This corresponds to a future where measures in Norway trigger a change towards a more sustainable diet and a strong reduction in food waste, while land use would remain under constraints similar to the present state. With the other FABLE country teams, this Sustainable Pathway is embedded in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

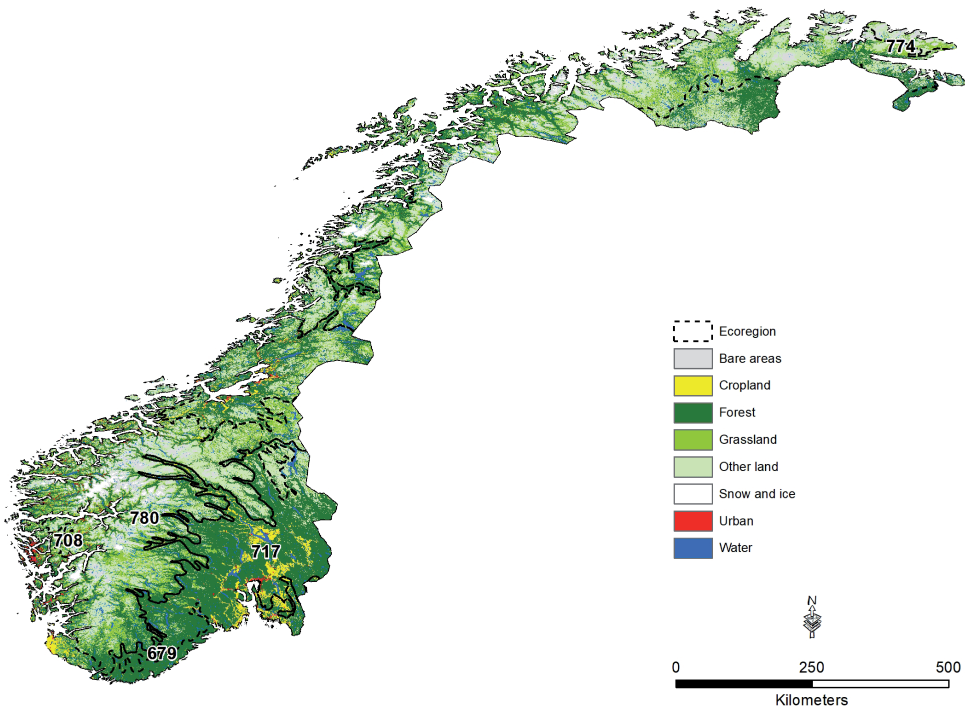
Land and Biodiversity

Current State

In 2010, Norway was covered by 2.5% cropland, 0.5% cultivated grassland, 25.5% forest, 0.6% urban and 71% other natural land. Most of the agricultural area is located in the south while forest and other natural land can be found almost everywhere in the country (Map 1). In Norway, biodiversity hot spots are located in the most populated areas (Miljødirektoratet, 2020) as urban expansion puts endangered species under pressure. Furthermore, in Norway, 90% of threatened species are assumed to be adversely affected by future climate change.

We estimate that land where natural processes predominate[2] accounted for 67% of Norway's terrestrial land area in 2020 (Map 2). The category 780-Scandinavian Montane Birch forest and grasslands holds the greatest share of land where natural processes predominate, followed by 717-Scandinavian and Russian Taiga and 708-Scandinavian coastal conifer forests (Table 3). In the model, across the country, while 5.4 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 20% of land where natural processes predominate is formally protected. Recent findings (Miljødirektoratet, 2020) show that while Norway is coming closer to the goal of protecting a representative share of Norwegian nature, a considerable number of threatened species are located outside protected areas. This indicates that protection alone is not enough: a sustainable use and management of nature outside conservation areas is also crucial to stop the loss of natural diversity.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

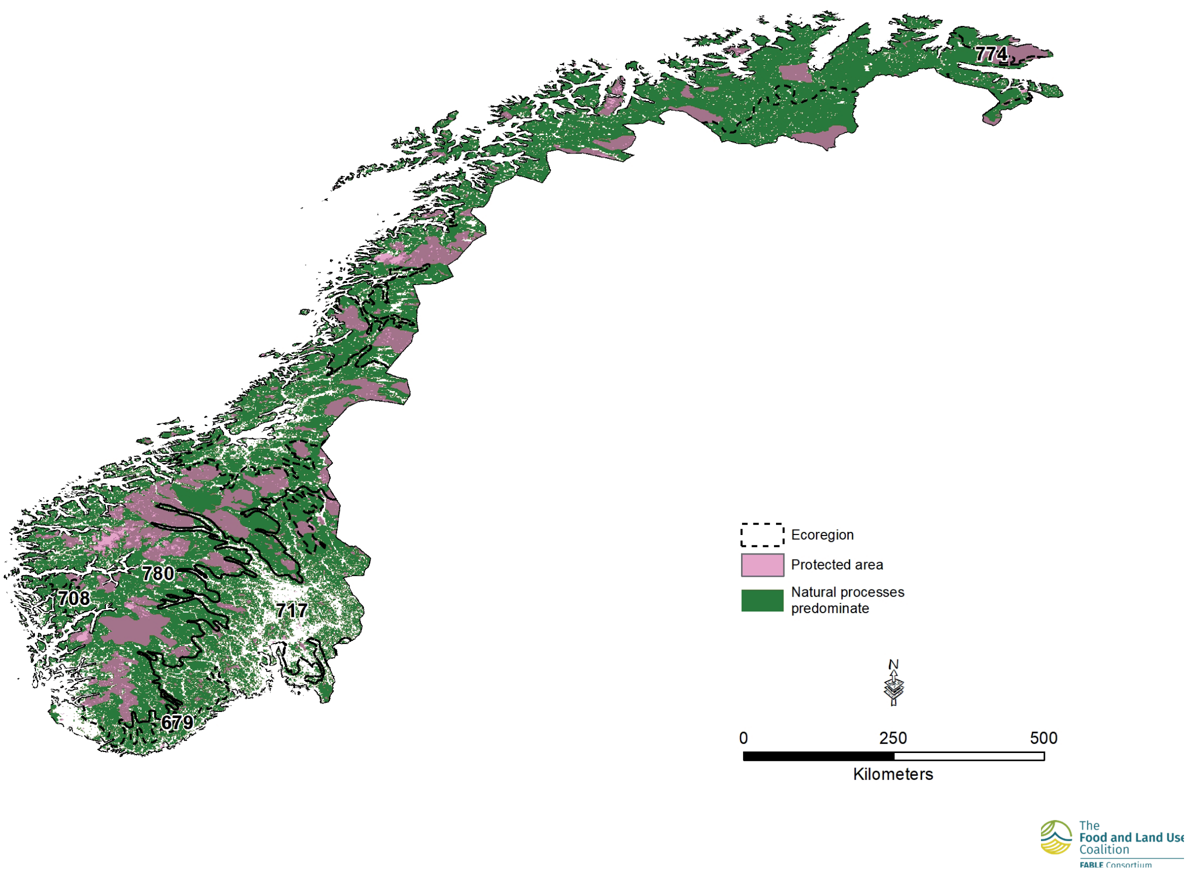


Note. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 60% of Norway's cropland is in landscapes with at least 10% natural vegetation in 2020. These relatively biodiversity-friendly croplands are most widespread in ecoregion categories 774-Kola Peninsula tundra, followed by 780-Scandinavian Montane Birch forest and grasslands and 708-Scandinavian coastal conifer forests. The regional differences in the extent of biodiversity-friendly cropland can be explained by the landscape in Norway. Due to Norway's very complex topography, with high mountains, agriculture is possible in only a few locations (see Map 1).

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
679	Sarmatic mixed forests	896.9	3.1	52.9	3.9	96.1	106.6	48
708	Scandinavian coastal conifer forests	1709.8	5.4	56	7.5	92.5	122.9	53.4
717	Scandinavian and Russian taiga	9721.5	8.8	72.5	11.4	88.6	655.4	53.1
774	Kola peninsula tundra	365.6	38.6	92	41	59	0.398	96.2
780	Scandinavian Montane Birch forest and grasslands	18274.5	23.3	86.7	24.7	75.3	208.7	90.7

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

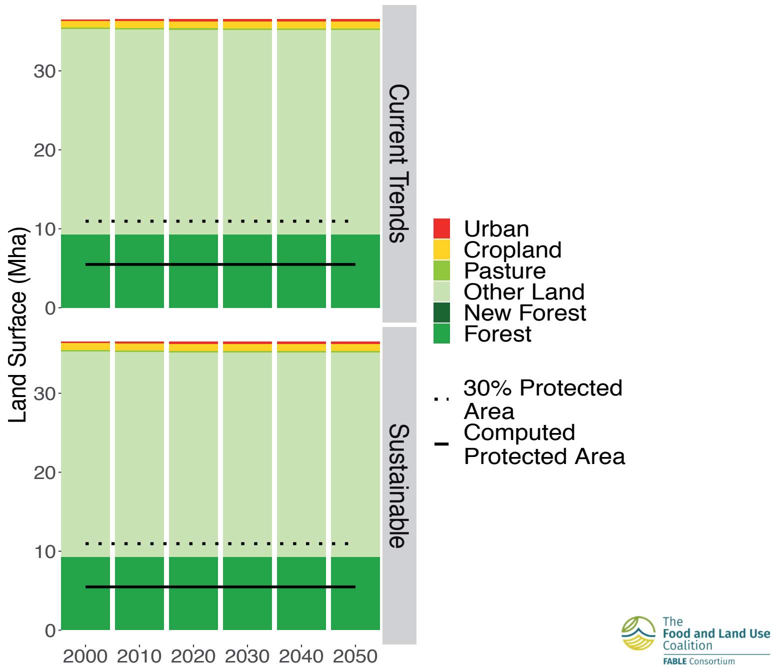
3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including slow urban expansion, no constraints on land conversion beyond protected areas, no expansion of agricultural land beyond its current area and no planned afforestation or reforestation. Protected areas remain at 5.4 Mha, representing 15% of total land cover (see Annex 2).

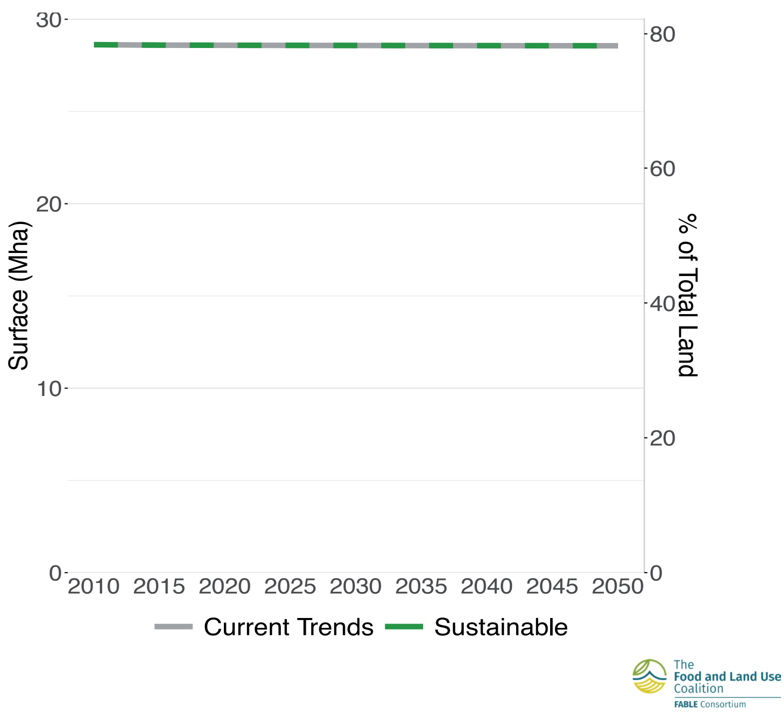
By 2030, the model suggests that the main changes in land cover in the Current Trends Pathway will result from a small increase in urban areas and a resulting decrease of other land area. This trend continues over the period 2030–2050 (Figure 1). In the Sustainable Pathway, assumptions are very similar to the Current Trends Pathway with similar changes in land distribution (see Annex 2). The main reason for the similarity between the pathways is that it is unlikely that land use will change significantly in Norway in the coming decades. Agricultural land could expand into new areas, but this is mostly constrained to peat soils, which is prevented by specific policies. These small changes in land cover are also related to a moderate increase in urban areas due to the slow increase in population and the increase in the density of populated areas. Finally, there has been a large growth in forest areas since the 1940s so there is not a lot of room left for afforestation. On the other hand, there are currently no clear drivers for deforestation as land would not be suitable for agriculture and urban expansion is moderate.

Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Source: Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) from 2020 for protected areas for years 2000, 2005 and 2010.

Figure 2 | Evolution of the area where natural processes predominate

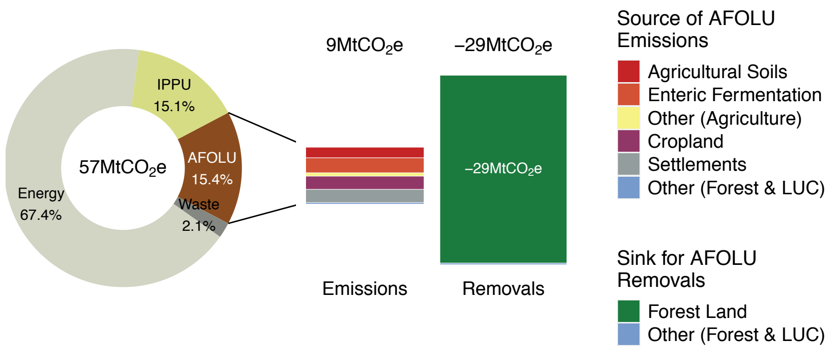


GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 15.4% of total emissions in 2017 (Figure 3). Enteric fermentation is the principle source of AFOLU emissions followed by settlements, cropland, agricultural soils and other (agriculture). This can be explained by the fact that Norway is self-sufficient in meat from ruminant livestock (Helsedirektoratet, 2020) and that the total forest area has not changed very much in recent decades (UNFCCC, 2020b).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2017

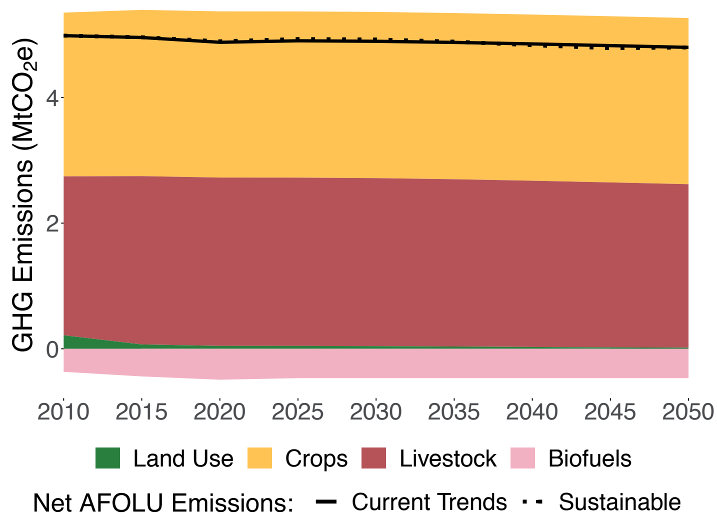


Source. Adapted from GHG National Inventory (UNFCCC, 2020a)
Note. IPPU = Industrial Processes and Product Use

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU remain stable over the period 2020 to 2050, at around 4.9 Mt CO_2e/yr and 4.8 Mt CO_2e/yr (Figure 4). In 2050, agriculture and livestock are the largest sources of emissions. The Sustainable Pathway leads to similar AFOLU GHG emissions (Figure 4). The potential slight emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from livestock (Figure 5). Dietary change that leads to declining meat consumption is the most important driver of this reduction. In this context, the contribution of AFOLU to total GHG emissions is limited. It is important to note

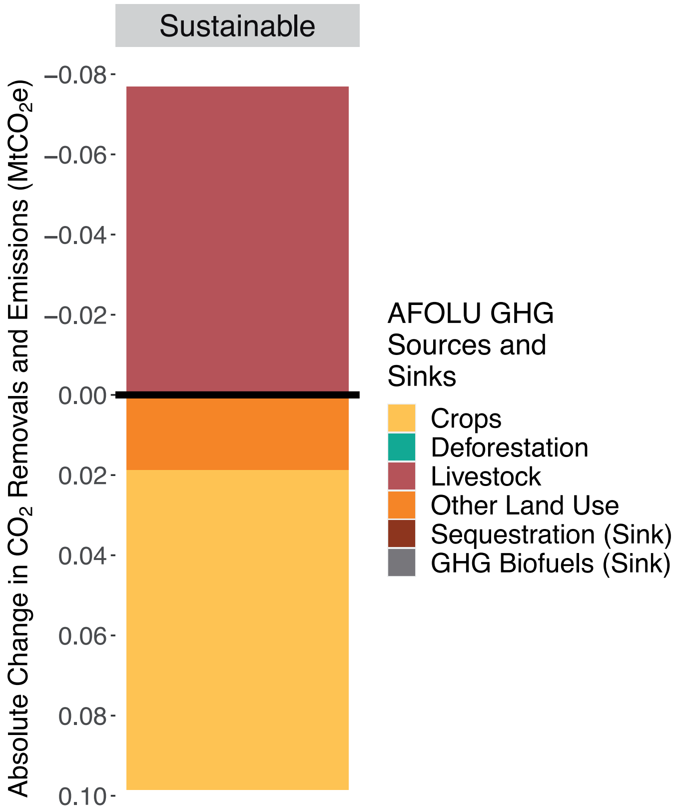
Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



that Figure 3 is based on data from the UNFCCC's national GHG inventory while Figures 4 and 5 are based on FABLE Calculator projections. Currently, the cultivation of organic soils is not accounted for in our projections for Norway's land-use and food systems pathways.

In Norway, reductions in GHG emissions from AFOLU could be achieved through a number of different policy measures. Farmer unions have made a new plan for decreasing emissions based on several measures such as a change in feed supplements to reduce methane emissions, a move from fossil fuels to biofuels or smarter- and reduced-use of fertilization (Norges Bondelag, 2020c). In the meantime, the forestry sector is planning to use active forestry where forest waste products can replace fossil fuel use; the current strategy envisages an increase in soil carbon uptake in forests and an increased use of residual materials. All these measures could contribute to decreasing GHG emissions from AFOLU. These measures were not included in our Sustainable Pathway for a number of reasons. Some of these options are quite speculative, in particular those for which certain technologies are not yet available for commercial application. Therefore, we consider them as part of a Sustainable High Ambition Pathway, which we did not develop, and not suitable for a Sustainable Pathway. Some measures have not been implemented for technical reasons as the FABLE Calculator needs more development on the forestry sector. Finally, some issues such as biofuels were left untouched due to time constraints.

Figure 5 | Cumulated GHG emissions reduction computed over 2020–2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

Child poverty has recently become a growing concern in Norway over the last 20 years as 100,000 children grow up in low income families, which is often a factor leading to undernutrition (Bufdir, 2020). Undernutrition is also a considerable problem among the elderly (Devik, 2019).

Micronutrient Deficiency

22.4% of women and 21% of children under 5 suffered from anemia in 2017, which can lead to maternal death (IHME, 2020).

5% of the population are deficient in vitamin A, which can notably lead to blindness and child mortality. 1.2% are deficient in iodine, which can lead to developmental abnormalities (IHME, 2020).

Lack of vitamin D is an issue in Norway, particularly among non-western immigrants (Nasjonalt Råd for Ernæring, 2018).

Overweight/ Obesity

Around 25% of middle-aged men and 20% women were classified as obese with body mass index of 30 kg/m^2 in Norway in 2017. Moreover 60% of adults were overweight in 2017. These rates have increased since 2000 (NIPH, 2017).

Between 15 and 20% of children were overweight or obese in 2017. This proportion has stabilized in the last decade (NIPH, 2017).

Disease Burden due to Dietary Risks

0.13% of deaths are attributable to nutritional deficiencies, which represents 1.0 deaths per year (per 100,000 people) in 2017 (IHME, 2020).

17% of the population suffers from diabetes and 10% from cardiovascular diseases, which can be attributable to dietary risks (IHME, 2020).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,916 (2,088)	2,667 (2,093)	2,794 (2,093)	2,358 (2,089)	2,471 (2,089)
Fats (g) (recommended range	154 (65-97)	125 (59-89)	130 (61-91)	113 (54-81)	116 (54-81)
Proteins (g) (recommended range	115 (73-255)	85 (67-233)	88 (69-240)	80 (60-211)	85 (61-212)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

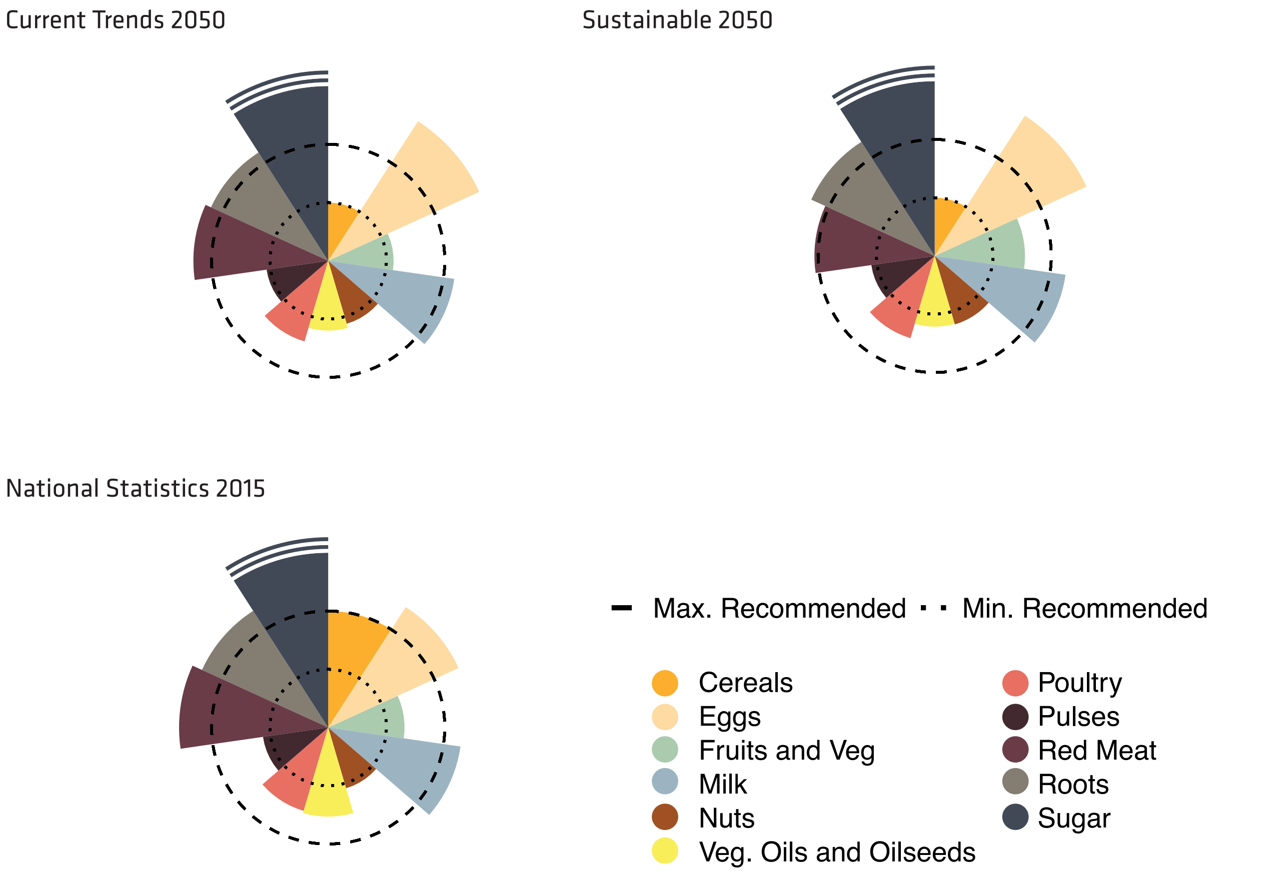
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 27% higher in 2030 and 13% higher in 2050 (Table 4). The current average intake is satisfied by eggs, fish, milk, red meat, root vegetables, sugar, animal fat and animal products. Animal products and animal fat represent 33% of the total calorie intake. This pathway results in an increase in the consumption of eggs and nuts between 2020 and 2050 while the consumption of cereals, fish, fruit and vegetables, red meat, sugar is assumed to decrease. Looking at the EAT-Lancet recommendations (Willett et al., 2019), red meat, fish, eggs, roots, sugar, and animal fat are over-consumed in 2050 while cereals, fruits and vegetables, nuts, oilseed and vegetable oils, and pulses are in the lower, but within the recommended range (Figure 6). Moreover, fat intake per capita exceed the dietary reference intake (DRI) in 2030 and 2050 but decreases between 2030 and 2050 while the protein intake remains stable. This can be explained by a decline in the consumption of pork and red meat (Table 4).

Under the Sustainable Pathway, we assume that diets will transition towards a more sustainable diet with the consumption of fruits and vegetables reaching the average EAT-*Lancet* recommendation in 2050 and where less red meat is consumed. The ratio of the computed average intake over the MDER decreases to 33% in 2030 and 18% in 2050 under the Sustainable Pathway. This pathway results in an increase in the consumption of eggs, nuts, fish, fruits and vegetables between 2020 and 2050 while the consumption of cereals and red meat is assumed to decrease. Compared to the EAT-Lancet recommendations, the consumption of fish, eggs, roots, sugar and animal fat remains outside of the recommended range (Figure 6). Moreover, the fat intake per capita still exceeds the dietary reference intake (DRI) in 2030 and 2050 while the protein intake remains stable, showing almost no improvement compared to the Current Trends Pathway.

To go towards more sustainable diets in Norway, several measures could be introduced such as using food taxes and subsidies (Abadie, Galarraga, Milford, & Gustavsen, 2016). There is also the option of acting indirectly on consumer preferences and consumption habits (Milford, Le Mouël, Bodirsky, & Rolinski, 2019), for instance through information, education policy, and increased availability of ready-made plant-based products. The latter could be of key importance for mitigating an increase in meat consumption and promote consumption of low-fat and low-emission products.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



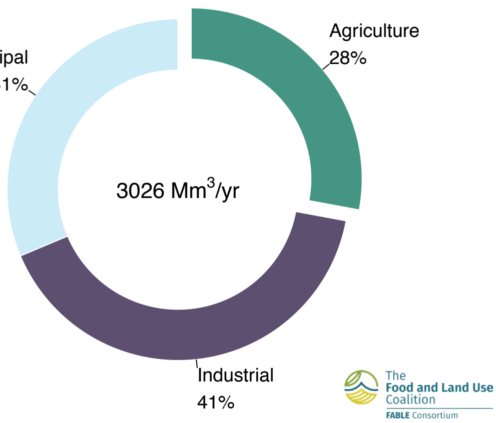
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore the different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar indicate that the average kilocalorie consumption of this food category is significantly higher than the maximum recommended.

Water

Current State

Norway is characterized by a marine climate in the west with, by comparison with eastern Norway, cool summers, mild winters and high precipitation rates (2250 mm average annual precipitation). In contrast, Eastern Norway is sheltered by mountains and has an inland climate with warmer summers, cooler winters and generally less precipitation (760 mm average annual precipitation). Because of temperature variations through the year and across the country, precipitation in Norway falls both as rain and snow. In terms of agriculture, the sector represented 28% of total water withdrawals in 2006 (FAO, 2016; Figure 7). Agricultural water withdrawal is defined as the annual quantity of self-supplied water withdrawn for irrigation, livestock, and aquaculture purposes. In 2008, the total irrigated area was about 130 kha, which represents 14% of Norway's agricultural area. Most of these irrigated areas are found in eastern Norway. Data are lacking on the individual crops that are irrigated but the most important irrigated crops seem to be vegetable crops, potatoes, and cereals (Riley & Berentsen, 2009).

Figure 7 | Water withdrawals by sector in 2006–2007

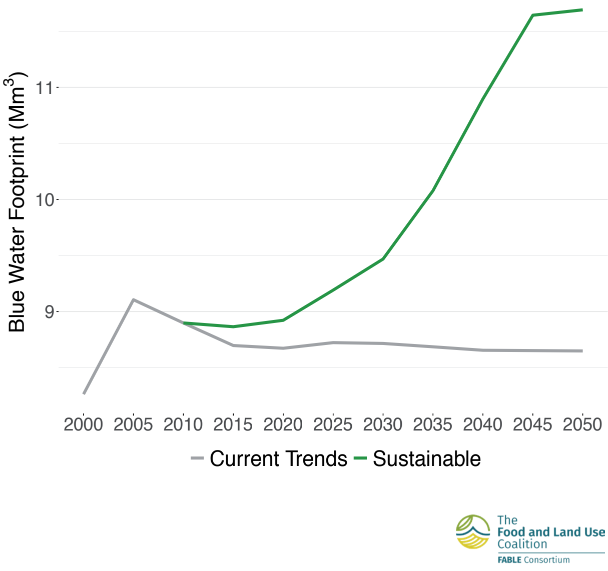


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000–2015, from 8.3 Mm^3/yr to 9.1 Mm^3/yr, before reaching 9.6 Mm3/yr and 10.4 Mm^3/yr in 2030 and 2050 (Figure 8), with potato and vegetables accounting for 62% and 32%, respectively, of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture reaches 10.4 Mm^3/yr in 2030 and 14 Mm^3/yr in 2050. These increases in water use for both the Current Trends and Sustainable Pathways are explained by a potential increasing need in irrigation due to climate change (i.e. potential droughts).

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account

Resilience of the Food and Land-Use System

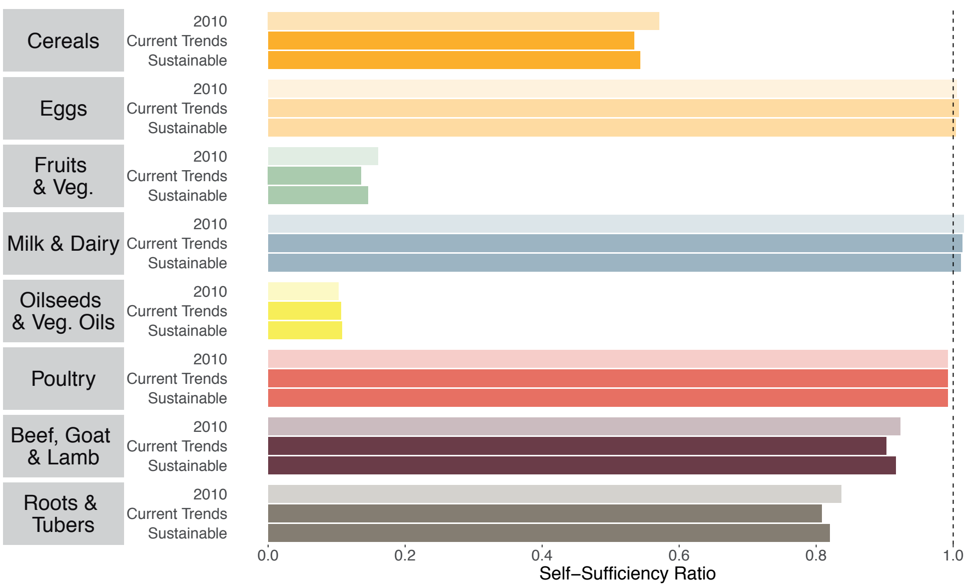
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Norway's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Norway is largely self-sufficient (80-100%) when it comes to animal products such as meat, cheese, eggs, and fish, being a net exporter of seafood. For vegetable and grain products, Norway is only partly self-sufficient (10-60%), with production depending, among other variables, on annual climate variations (www.regjeringen.no). Norway is largely dependent (80-95%) on imports of sugar, oils, and other fats. Overall Norway has less favorable conditions for agriculture than many other countries as the growing season is short, there is a cool climate, and farmlands only take up a small portion of the land.

Under the Current Trends and Sustainable Pathways, we project that Norway would be largely self-sufficient in eggs, dairy, poultry, beef and lamb, and roots and tubers in 2050, with self-sufficiency by product group remaining stable for the majority of the products from 2010 – 2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are fruits and vegetables and oilseeds and vegetable oils. This dependency remains stable until 2050. The self-sufficiency measures for animal products presented here do not account for the fact that a significant amount of animal feed is imported.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Diversity

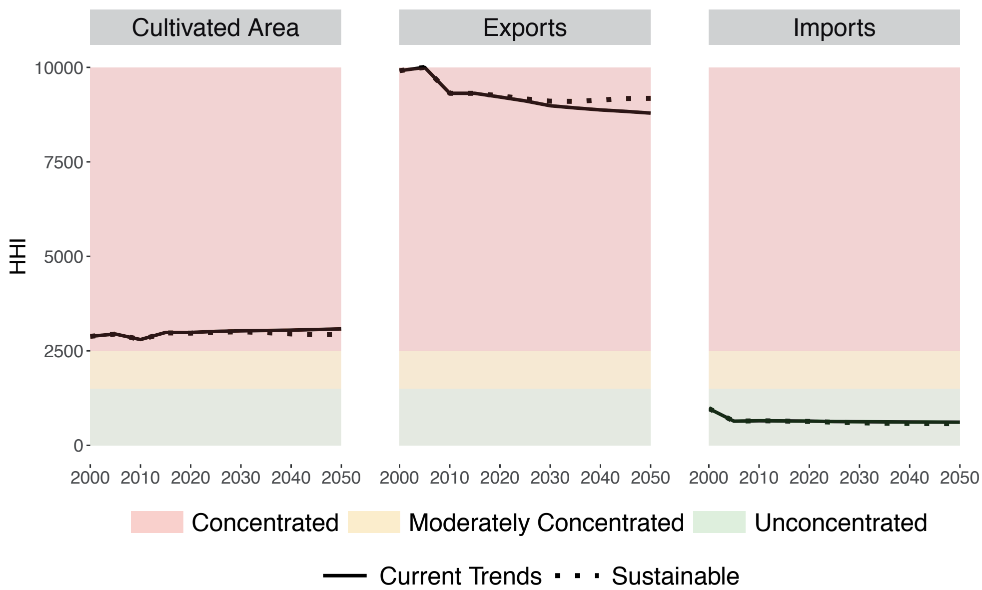
The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

The HHI for crop exports is very high, indicating a very concentrated export market for crops, but as Norway's level of crop exports is very low, this has little significance. Norway exports fish and fish products and imports cereals, roots, pulses, dairy and eggs. Meanwhile, the HHI for crop imports is very high, reflecting a highly diverse sourcing of imported crops and crop products. Crop production is dominated by cereals, leading to a high HHI for planted area. Under the Current Trends and Sustainable Pathways, the HHI index remain stable over the period 2010–2050 for both exports and imports (Figure 10). This means that exports are not more diversified in the future while imports remain highly diverse.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI).



Discussion and Recommendations

In this work, two pathways related to potential changes in food and land-use are compared for Norway: Current Trends and Sustainable Pathways. The Current Trends Pathway follows today's policies, and our Sustainable Pathway represents a future in which efforts are made to adopt sustainable policies and practices that correspond to an intermediate boundary of intentionally feasible action. A justification for the choices made in each pathway can be found in Annex 2. As a result, the pathways are rather similar, and assume a similar population growth, no agricultural expansion but an increase in water usage for irrigation, no afforestation target, no change in the extent of protected areas, and no productivity increases in the agricultural sector. Both pathways also assume a decrease in food waste and an evolution towards a more sustainable diet however these changes are stronger in the Sustainable Pathway (see Annex 2). Another difference between the two pathways is the choice in RCP scenario for including the impact of climate change on crop yields: RCP6.0 for the Current Trends Pathway and RCP2.6 for the Sustainable Pathway. This corresponds to the Sustainable Pathway, in a future where measures in Norway would trigger a change towards a more sustainable diet and a strong reduction in food waste, while land-use would have similar constraints as the present. Without a "Sustainable High Ambition" pathway, our results do not show significant reductions in environmental impacts by 2050.

One key reason for the similarity between the pathways is that there is a low likelihood that land use will change significantly in Norway. Agricultural land could expand into new areas, but largely this is constrained to areas on peat soils, and there are specific policies accepted and being detailed to prevent this. As a result, we do not see significant potential for expansion of agriculture. However, our results do show some changes of land use within agriculture. While irrigation is not widely installed in Norway, in the context of climate change, with expectation of longer and deeper periods of drought, irrigation could see considerable expansion.

Potential trade-offs in the food and land-use system are related to the current main focus on livestock production and linked to pastures and feed production. A scenario of reduced meat consumption will reinforce the ongoing shrubification process especially in outfield pasture areas. This will decrease the total area of such cultural landscapes and reduce the biodiversity linked to these areas, especially in the northern and rural areas of Norway that depend on livestock. Consequently, it may also reinforce the process of farms going out of business, which is contrary to policy targets to keep rural areas populated. On the other hand, a concentrated effort to use agricultural land optimally, with grazing in areas with no other options and food production in areas with high quality agricultural land (a process called re-canalization) will reduce these trade-offs, free up land for food production, and is projected to increase self-sufficiency (Vangelsten, 2017) and substantially increase the potential area for potato and vegetable production (6-7 times; Mittenzwei, Milford, & Grønlund, 2017).

Our results show that changes in land use, agriculture, and food consumption can contribute to achieving national climate targets and policies, but by itself certainly cannot achieve the climate goals Norway has set. To achieve ambitious climate goals such as a low-emission society by 2050 (Govt of Norway, 2020), including all sectors becomes necessary, including agriculture. The changes in diet we propose are also not sufficient to meet the EAT-*Lancet* recommendations in terms of emission reductions but are more closely linked to national dietary recommendations, which mainly emphasize the public's nutritional health.
Our results may also influence national biodiversity policies. In Norway, around 90% of threatened species are negatively affected by land use change. While hotspots are mainly found near rural areas (Miljødirektoratet, 2020), shrubification of pasture areas due to discontinued or reduced grazing is assessed to negatively affect around 685 species (Henriksen & Hilmo, 2015). This highlights that biodiversity

management is not only about protection of areas, but also of management and intervention in existing habitats. Changes in diet supporting a reduction in grazing livestock may reinforce this declining trend in pasture areas. Furthermore, as described earlier, changes in livestock may also affect policy targets to maintain the population in rural areas (district policy) if no alternative production or livelihoods are developed for these areas.

We stress careful consideration of the following selected limitations of the model and pathways in the interpretation of the results. The FABLE Calculator stills need to be improved and have more features to better represent Norway as, for example, through better inclusion of forests, which is very important for Nordic countries. Moreover, we have noticed several errors in the FAO datasets used in the FABLE Calculator, many of which we managed to fix (see Annex 1), but several likely remain. Examples include a high calculated crop export index for Norway (in reality, Norway does not export many crops at all, so this error has little impact due to its low absolute level) and many other mismatches in data such as: 1) a high calculation for fish consumption (based on a high production of fish); 2) productivity and growth rate mismatches in meat and eggs due to errors in number of hens and chickens; 3) crop growth rates estimated from few data points but with highly fluctuating yields in particular crops; etc. The pathways also have their own limitations since the RCP choice influences the model and choices of definition also play a role. For example, sustainable livestock productivity was interpreted as sustainable when not increasing, because this would rely on less sustainable practices such as more imports of concentrated feed from developing countries. Finally, some issues such as biofuels were left untouched due to time constraints.

This latter point is an example of some of the next steps and remaining work to be done. Some issues remain in the FABLE Calculator, and some of the historical data should still be replaced by more accurate data from national registries (see Annex 1). Also, a forest module should be added to reflect this sectors impact on land, the climate, and the environment. Finally, the results of a recent food system transformation dialogue that took place in January 2020 should be incorporated in the pathways and interpretation of results.

Annex 1. List of changes made to the FABLE Calculator to adapt it to the Norwegian context

- Modification of the scenario for diets to include the scenarios based on Mittenzwei et al. (2019): RefPathway and MG2020.
- Modification of the scenario on water efficiency to include a higher use of water for irrigation instead of a more efficient use of water as Norway does not yet use irrigation on a large scale.
- Several changes have been made in the FABLE Calculator to include more accurate historical data, using available national datasets:
    - Correction of land areas: as urban expansion was too high, we corrected this to a lower rate related to population growth.
    - Correction in feed for animals: inclusion of oats and rapeseed as a feed for animals.
    - Correction of the protein intake: fish was not included correctly in the calculator. The consumption of fish was too high as it was based on the high production of fish.
    - Correction of the productivity and growth rate: mismatches in meat and eggs due to errors in number of hens and chickens.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)	
Current Trends Pathway	**Sustainable Pathway**
The population is expected to reach 7 million by 2050 (SSP2). Based on (KC & Lutz, 2017). (SSP2 scenario selected)	The population is expected to reach 7 million by 2050 (SSP1). Based on (KC & Lutz, 2017). (SSP1 scenario selected)

LAND Constraints on agricultural expansion	
Current Trends Pathway	**Sustainable Pathway**
We assume no expansion of agricultural land beyond 2010 agricultural area levels. Agricultural land could expand into new areas, but largely this is constrained to areas on peat soils, and there are specific policies accepted and being detailed to prevent this.	Same as Current Trends
LAND Afforestation or reforestation target (1000 ha)	
We do not expect afforestation/reforestation. The total forest area has not changed very much since 1990 (UNFCCC, 2020b) and we expect this trend to continue. Since 1990, 1,648 km2 has been deforested in Norway but there is also natural regrowth with forest in the mountains and some afforestation.	Same as Current Trends

BIODIVERSITY Protected areas (1000 ha or % of total land)	
Current Trends Pathway	**Sustainable Pathway**
Protected areas remain stable: by 2050 they represent 15% of the total land area. Recent findings (Miljødirektoratet, 2020) show that while Norway is getting closer to the goal of protecting a representative share of Norwegian nature, a considerable number of threatened species are located outside protected areas.	Same as Current Trends

PRODUCTION Crop productivity for the key crops in the country (in t/ha)	
Current Trends Pathway	**Sustainable Pathway**
Apart from changes driven by the climate change scenario, no changes were made to crop productivity in Norway in the FABLE Calculator. Because the climate change scenarios did not include yields for the top-three crops in Norway (barley, oats, and potatoes), the yields of these three are therefore the same in 2050 as in 2010.	Same as Current Trends
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)	
By 2050, livestock productivity reaches: • 3600 kg per head for chicken.	By 2050, livestock productivity reaches: • 3400 kg per head for chicken.
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)	
By 2050, the average ruminant livestock stocking density is 5.82 TLU/ha.	Same as Current Trends
PRODUCTION Post-harvest losses	
By 2050, the share of production and imports lost during storage and transportation remains stable. This is based on the assumption behind this scenario, keeping similar practices as today.	By 2050, the share of production and imports lost during storage and transportation is reduced by 50%. Based on (Government of Norway, 2017).

TRADE Share of consumption which is imported for key imported products (%)	
Current Trends Pathway	**Sustainable Pathway**
By 2050, the share of total consumption which is imported remains stable compared to 2010. Overall Norway has less favorable conditions for agriculture than many other countries as the growing season is short, there is a cool climate and farmlands only represent a small portion of the land. So, we expect imports to remain stable in the future.	Same as Current Trends
TRADE Evolution of exports for key exported products (tons)	
By 2050, the volume of exports is: • 26,420 tonnes by 2050 for milk • 910 tonnes by 2050 for eggs • 880 tonnes by 2050 for pork	By 2050, the volume of exports is: • 23,620 tonnes by 2050 for milk • 450 tonnes by 2050 for eggs • 600 tonnes by 2050 for pork

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 2,667 kcal and is: • 646 kcal for cereals • 359 kcal for milk • 327 kcal for plant oils Based on the “referanse bane” of Mittenzwei, Walland, Milford, & Grønlund (2020).	By 2030, the average daily calorie consumption per capita is 2,794 kcal and is: • 678 kcal for cereals • 335 kcal for milk • 349 kcal for plant oils Based on the “2/3 kjøtt, kostråd” diet of Mittenzwei et al., (2020).

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Pathway
By 2030, the food loss is reduced by 20%. This is based on the fact that the issue of food loss has gained importance in Norway but is addressed to a smaller extent compared to the sustainable pathway.	By 2030, the food loss is reduced by 50%. Based on the dietary change towards national dietary recommendations, linked to health (Helsedirektoratet, 2016) and linked to the agricultural sector (Government of Norway, 2019)

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
By 2050, biofuel production from rapeoil increases by 8% compared to 2010.	Same as Current Trends

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

mm – millimeters

Mm^3 – million cubic meters

Mt – million tonnes

t – tonnes

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Russian Federation

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Russia. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. These pathways were prepared within RANEPA's state assignment research program using assumptions based on official documents from the Russian Government on pathways until 2030 and 2050 and in consultation with stakeholders and experts at the Russian Ministry of Agriculture, the Soil Department of Lomonosov Moscow State University, and the Institute of Global Climate and Ecology (IGCE, Moscow, Russia). They were modeled with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019).

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Russia's draft Long-Term Low Emissions and Development Strategy (Government of Russia, 2020d) treats the FABLE domains. According to the LT-LEDS base scenario, Russia is projected to increase its GHG emissions by 31.6% (in all sectors of the economy) by 2030 compared to 2017. The projected 2,077 Mt CO_2e of emissions in 2030, including forestry and other land use (FOLU) sequestration, are 33% lower than Russia's emissions in the 1990s. The LT-LEDS base scenario's projected changes in the FOLU sector are not particularly ambitious and lead to a decrease in sequestration from the current levels of -577.8 Mt CO_2e to -246 Mt CO_2e in 2030. Meanwhile, emissions from agriculture are projected to increase from 128 Mt CO_2e to 144 Mt CO_2e in 2030. Nevertheless, the draft LT-LEDS also provides theoretical assumptions of measures that could lead to a potential reduction of almost 263% in agricultural emissions, which could turn the sector into a net carbon sink reserve [p. 48, table 6 of Government of Russia, 2020d]. Envisaged mitigation measures from agriculture include the optimal use of organic (manure) fertilizers, measures to tackle soil erosion, and decreasing carbon loss on cropland and increasing carbon-sink capacity on pastures. The maximum theoretical ambition in the FOLU sector is to improve the carbon sequestration capacity from -577.8 Mt CO_2e to -723 Mt CO_2e in 2030 (page 48, table 6 of Government of Russia, 2020d). Measures to increase the sequestration ambition in the Russian FOLU sector include measures against forest fires, optimization of wood cutting technologies, replacing conifers with broadleaf and mixed forest trees, economic stimulation for life-long timber-product production, and land rehabilitation projects. Under its current commitments to the UNFCCC, Russia does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current LT-LEDS.

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
LT-LEDS (2016)	2017	1,577.8	2030	2,077	Energy, industry, agriculture, LULUCF, waste	Y	N	N	Water, forests

Source: Government of Russia, 2020d

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2015, as listed on the CBD website (CBD, 2020) which are related to at least one of the FABLE Targets. According to this document Russia accepts that “by 2020, no less than 50% of exploited and protected forest are sustainably managed which ensure the conservation of biodiversity,” which is close to the FABLE Targets on maintaining enough land for biodiversity protection. Currently, Russia does not have biodiversity policies in place beyond 2020.

Table 2 | Overview of the NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
By the year 2020 the rate of natural habitat loss, including those of forests and grass ecosystems, are cut by at least half and completely halted where it is necessary. The degradation and fragmentation of habitats is also significantly decreased.	**DEFORESTATION:** Zero net deforestation from 2030 onwards **BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
Sub-target: By 2020, no less than 50% of exploited and protected forest are sustainably managed which ensure the conservation of biodiversity.	**DEFORESTATION:** Zero net deforestation from 2030 onwards
By 2020, the recovery of forests and their stable accumulation of carbon has been ensured on 15% of all degraded agricultural lands. Owing to increased efforts for conservation of existing forests, their carbon losses have been decreased by 17%.	**DEFORESTATION:** Zero net deforestation from 2030 onwards **GHG EMISSIONS:** Zero or negative global GHG emissions from LULUCF by 2050
Sub-target: By 2020 no less than 20% of all agricultural lands are managed and used in accordance to biodiversity conservation goals.	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
By 2020, the total area of terrestrial [...] territories with regulated resource use policies and which play a key role in the provision of ecosystem services is increased to the point where it composes 17% of all terrestrial territories	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in the Russian Federation.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by a sharp decline in population (from 146 million in 2015 to 135 million in 2050), no constraints on agricultural land expansion, no afforestation target, no change in the extent of protected areas, low productivity increases in the agricultural sector, no change in diets, no forest land expansion, and no biofuel policy (see Annex 1). This corresponds to a future based on current policy and historical trends that, in line with the aims of current policy makers in Russia, would see an increase in agricultural area (Government of Russia, 2015, 2020a), an increase in agricultural exports (Government of Russia, 2020b, 2020c), and low-ambition forestry policy (Government of Russia, 2020d), which is expected to show an unfortunate decrease in carbon sequestration from the current level of -577 Mt CO_2 (IGCE, 2020) to -246 Mt CO_2 in 2050 (Government of Russia, 2020d). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for wheat, barley, rice sunflower and soy (see Annex 1).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to a more moderate decline in population (from 146 million in 2015 to 144.5 million in 2050), no increase in cropland area as a result of the implementation of a possible high-yield policy, and moderate growth of livestock productivity. This corresponds to a future with significant potential to close the yield gap for several key crops that currently have low yields in Russia (Schierhorn et al., 2014) and opportunities to reduce GHG emissions from land use (Romanovskaya et al., 2019). However, due to gaps in the literature and in policy action, the costs of possible policy measures to achieve high yields, high carbon sequestration, and sustainable land-use change remain uncertain. With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

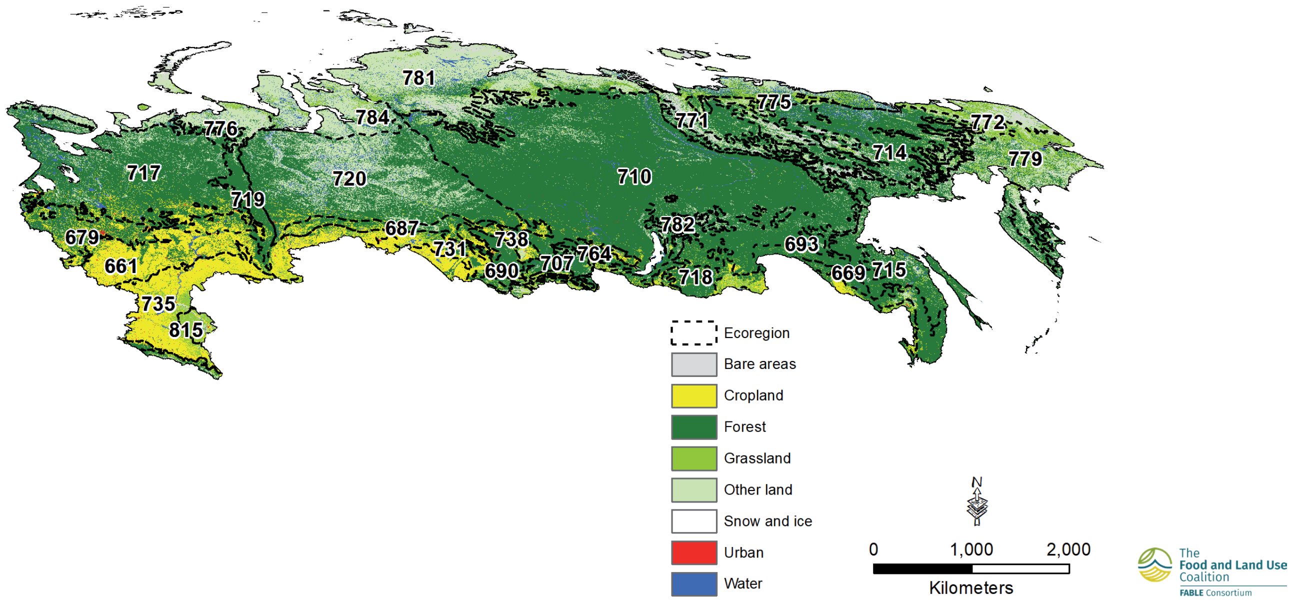
In 2010, Russia was covered by 3% cropland, 7% grassland, 54% forest, and 36% other natural land. Most of the agricultural area is located in the southwest, the Volga river basin, the Southern Ural and Southern Siberia while forest and other natural land can be mostly found in the northwest and Far East, as well as North, Central and Eastern Siberia (Map 1). Most of the territory is favorable for biodiversity due to its remoteness and low-population density, which is especially the case in areas where natural processes predominate (mostly territories with forest and other natural land). However, this poses an additional challenge to properly collect data and conduct year-to-year observations to monitor the accounting for species.

We estimate that land where natural processes predominate[2] accounted for 83% of Russia's terrestrial land area. The 710-East Siberian Taiga holds the greatest share of land where natural processes predominate, followed by 720-West Siberian Taiga and joint territory of 717-Scandinavian and Russian Taiga (Annex 3). Across the country, while only 9% (150 Mha) of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 11% of land where natural processes predominate is formally protected. This indicates that more research is needed to understand how remote areas contribute to biodiversity protection, and how climate change might impact species migration in or near areas with higher population density.

In 2010 approximately 28% of Russia's cropland was in landscapes with at least 10% natural vegetation (Jacobson et al., 2019). These relatively biodiversity-friendly croplands are most widespread in 735-Pontic steppe, followed by 661-East European Forest steppe, and 679-Sarmatic Mixed forests. The regional differences in the extent of biodiversity-friendly cropland can be explained by differences in data aggregation and official misclassification of large abandoned territories as cropland (Russian Registry Agency, 2020)[3].

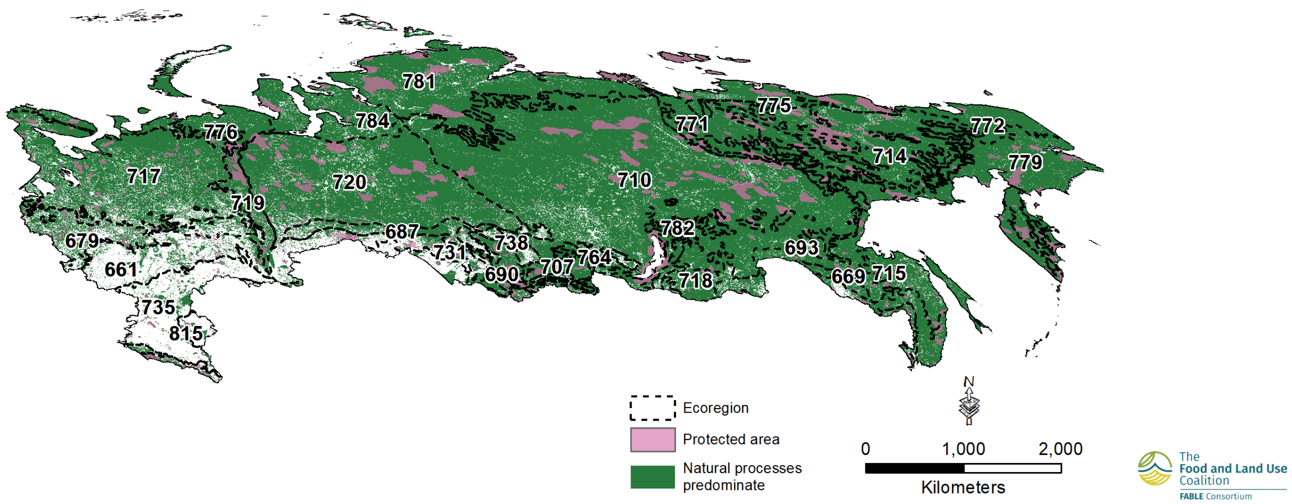
2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".
3 According to Jacobson et al., 170 Mha is used for cropland, while, in fact, Russia cultivates around 93 Mha of cropland annually (approximately 80 Mha of sown area and 13 Mha of fallow land in 2017-2019) and uses 40 Mha for pastures and hayland (Statistical Agency of Russia, 2020). This together equals 133 Mha of agricultural land. It is possible that the methodology employed by Jacobson et al. included abandoned land (37 Mha). We obtained this result by comparing the ploughed land in 1990 (130 Mha), and the current cropland (93 Mha). By combining the data from Russian sources, we obtained 170 Mha, which includes annual cultivated cropland, pasture and hayland, and abandoned land. This result is precisely the estimate Jacobson et al. provided for cropland in Russia.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)
Notes: Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 2.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



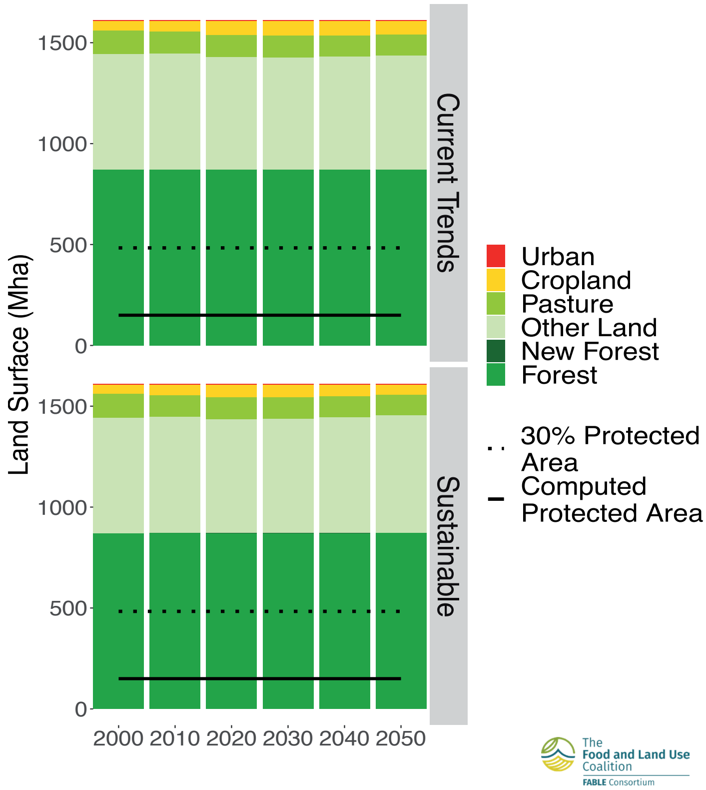
Notes: Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including the planned increase in the use of former abandoned land as cropland or pastures by 2030, as stipulated in the Russian Plan for Efficient Agricultural Land Use (Government of Russia, 2020a), no planned afforestation by 2030, and maintaining protected areas at 150 Mha, the equivalent of 9% of total land cover (Annex 1). The main difference between our assumptions and estimates on cropland use, compared with the Russian Plan for Efficient Agricultural Land Use (Government of Russia, 2020a) is that our model projects a 3 Mha increase by 2030, while the Plan proposes a 12 Mha increase. It is important to specify that this plan does not reveal the type of land that will be increased (cropland or pastures, or both) or their proportions. The Plan also does not contain any justification behind Russia's need to increase the agricultural land by 12 Mha, thus possibly reducing fallow land (currently approximately 13 Mha). Our estimates instead are based on the necessity to increase crop production (especially wheat, barley, and oil crops) for the development of Russia's agricultural exports.

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from a 3 Mha increase in cropland area and a 2.6 Mha decrease in pasture area. This trend evolves over the period 2030-2050: cropland area decreases by 3.7 Mha while pasture decreases by 6.1 Mha as a result of declines in cattle and sheep herds. Other types of land (forests and other natural land) cover more than 83% of Russia's land surface, and our projections indicate it is likely to stay constant over time (Figure 1). The expansion of the planted area for wheat, sunflower, and barley explains 86% of total cropland expansion between 2010

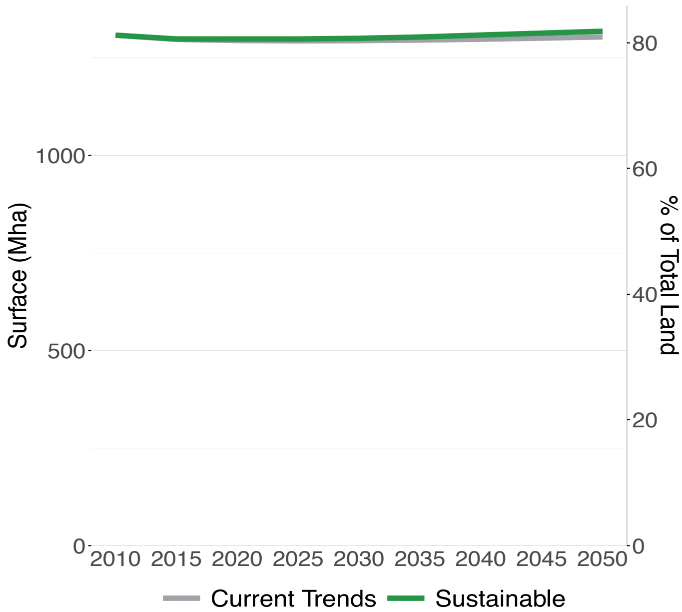
Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Source. Authors' computation based on FAOSTAT land cover map (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC, & IUCN, 2020) from 2000 for protected areas for years 2000, 2005 and 2010.

and 2030. For wheat, most expansion is explained by growing external demand for staple crops. For sunflower, the expansion is explained by the government policy to promote sunflower oil exports (as of July 1st 2020, Russia implemented a 20% export tariff on sunflower seeds to increase the domestic supply of sunflower for vegetable oil processing). Finally, for barley, the expansion is driven by the growth of domestic demand and exports. Pasture decline is mainly driven by decreasing herds and higher resource-use efficiency, which could contribute to the abandoning of pastures and their possible transformation in future carbon sinks. Livestock productivity per head and ruminant density per hectare of pasture remains constant over the period 2020-2030. Since Russian cropland and pastures comprise barely 15% of total land area, the changes in their use will not affect most of the land where natural processes predominate.

Figure 2 | Evolution of the area where natural processes predominate



In the Sustainable Pathway, assumptions on agricultural land expansion have been changed to reflect possible yield increases of major crops (Government of Russia, 2015; Schierhorn et al., 2014). These include a decrease of cropland area by 10 Mha and decline of pastures by 9 Mha over the period 2030-2050, which only influence the expansion of other land. Protected areas stay constant, but we assume an increase of new forest area by 2 Mha in 2050 as a very conservative but feasible objective (see Annex 1).

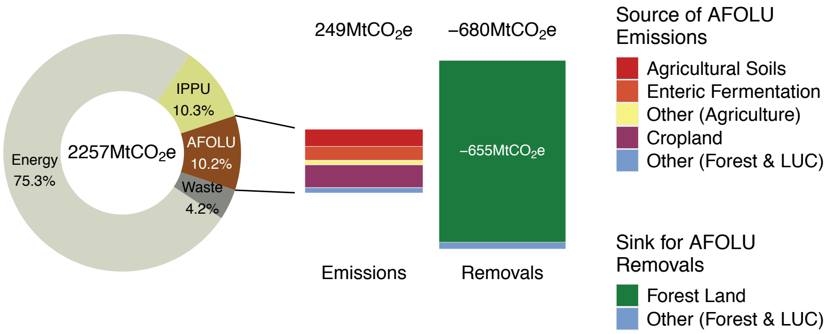
Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Russia in the Sustainable Pathway: the agricultural area (cropland and pastures) will decrease by 22 Mha, compared to the 5.4 Mha decrease in the Current Trends Pathway in 2050 (Figure 2). This will lead to an increase in the area where natural processes predominate and biodiversity protection. In addition, these changes compared to the Current Trends Pathway are explained by possible advances in technology and industry which will contribute to more rational land use (partly described in Romanovskaya et al, 2019 and Government of Russia, 2020d – p. 48, table 6).

GHG emissions from AFOLU

Current State

Greenhouse gas emissions inventory (UNFCCC, 2020) is the principle source of data for Forestry and Other Land Use (FOLU) emissions, comprising forests, agricultural land, wetlands, urban area, and other land territories, where most sequestration is accounted in forests (655 Mt CO_2e/yr), followed by 24 Mt CO_2e/yr in grassland in 2017 (Figure 3). The other land use types of FOLU are sources of net-emissions. This can be explained by the fact that almost 53% of Russia is comprised of forests with high potential for carbon sequestration. Using the method of accounting from the National Inventory Report (IGCE, 2020), direct GHG emissions from FOLU accounted for 577 Mt CO_2e/yr of removals compared to 2,155 Mt CO_2e/yr emissions from all sectors of the Russian economy in 2017.

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2017

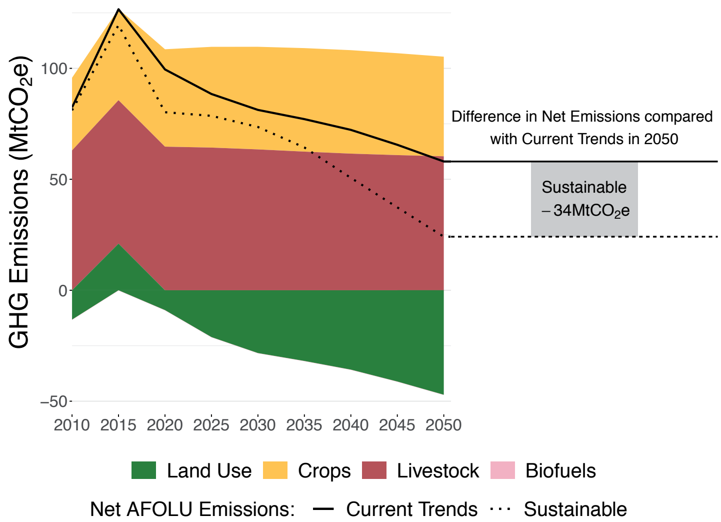


Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 81 Mt CO_2e/yr in 2030, before reaching 58 Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock is the largest source of emissions (60 Mt CO_2e/yr), followed by crop cultivation (45 Mt CO_2e/yr) while land-use change (LUC) acts as a sink (-47 Mt CO_2e/yr). Over the period 2020-2050, a decrease in GHG emissions is caused by a decline in

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

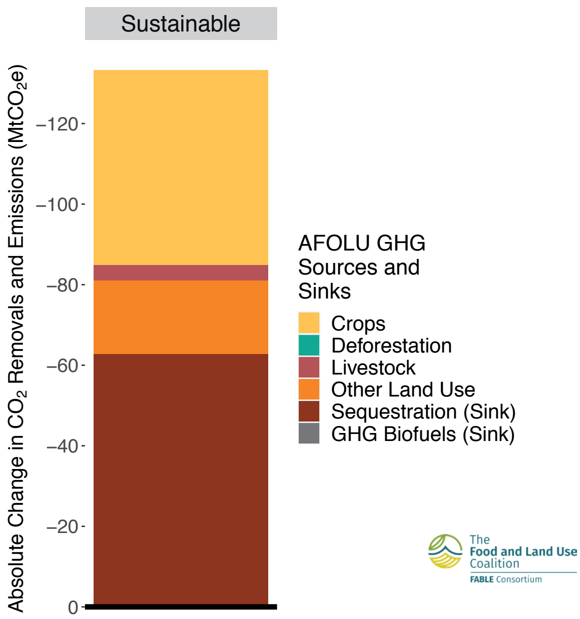


crop and pasture areas that are transformed into other land categories with natural vegetation regrowth, which serves as additional carbon sink.

In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by 25% in 2020-2050 period (Figure 4) – from 58 Mt CO_2e/yr to 24 Mt CO_2e/yr in 2050 compared to the Current Trends Pathway. The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from livestock and crops (Figure 5). Higher yield and livestock productivity are the most important drivers of this reduction. Currently, due to low productivity levels in Russia, productivity increases are technically feasible (Schierhorn et al., 2014, and Romanovskaya et al., 2014) and could be achieved by applying resource-saving techniques, and better agronomic technologies (Government of Russia, 2020d). Under the Sustainable Pathway, the GHG emissions from agricultural activities further decrease due to the abandoning of agricultural areas that become other types of land, forming an additional carbon sink. This trend is very similar to the Current Trends Pathway, but with larger volumes of land sparing and thus larger carbon sequestration by 2050 (-69 Mt CO_2e/yr in the Sustainable Pathway, compared to -47 Mt CO_2e/yr in the Current Trends Pathway).

To interpret these findings, it is important to note that the underlying data in the FABLE Calculator and the Russian National GHG Inventories (IGCE, 2020) account for GHG emissions differently. For example, the Inventories classify agricultural emissions as part of economy-wide emissions, while the FABLE Calculator, following the IPCC methodology, classifies them within Agriculture, Forestry and Other Land Use. The official Inventories account for annual removals in the forestry sector when forest area does not change, while the FABLE Calculator takes into account only the emissions or removals caused by approved land used change, such as a decrease in cropland area in favor of other land area, which causes emission removals as a result of natural vegetation regrowth. These differences in accounting explain the moderate amount of historical and future emissions sequestration in the Russian land sector and will need to be addressed in future analyses.

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Compared to Russia's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute to capturing only a small share of total GHG emissions in Russia (2.3% - 3.3%, or sequestrating respectively 47 Mt CO_2e/yr and 69 Mt CO_2e/yr) across both pathways compared to 2,077 Mt CO_2e of economy-wide emissions projected in the draft LT-LEDS. It is important to note, that other research shows that potential reductions could be much larger - 9% in the agricultural sector (mostly due to resisting soil erosion on cultivated land), and almost 30% in LUC sector (mostly due to forest management) (Romanovskaya et al., 2019).

Food Security

Current State

The “Triple Burden” of Malnutrition

Undernutrition

2.5% of the population undernourished in 2017. This share has decreased two-fold since 2000 (World Bank, 2020).

Micronutrient Deficiency

23.3% of women of reproductive age and 25.7% of children under 5 suffered from anemia in 2016, which can lead to maternal death (World Bank, 2020).

57.5% of adults are deficient in vitamin D; 12.6% in vitamin B; 12.6-34.5% in vitamin A; 5.3-10.8% in vitamin E; and 67.3% in carotene.

Multivitamin insufficiency (the lack of three or more vitamins) was found in 22-38% of adults (Kodentsova et al. 2017).

Overweight/ Obesity

21.3% of children (5-19 years) were overweight in 2016 (World Health Organization, 2020). The growth of obesity rate in the general adult population in Russia was 0.4% per year in the period 2000-2012. Men experienced higher growth rates in obesity from 2005-2012 (0.61% per year) compared with the period 2000-2005 (0.44% per year) (Martinchik et al., 2015).

Disease Burden due to Dietary Risks

63.3 deaths per year (per 100,000 people) were attributable to dietary risks in 2017 (Ministry of Health of Russia, 2020). This increased by 28% from 2012.

3.2% of the population suffers from diabetes, which can be attributable to dietary risks (Ministry of Health of Russia, 2020).

Table 3 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	3,107 (2,057)	3,094 (2,073)	3,052 (2,073)	3,094 (2,079)	3,094 (2,079)
Fats (g) (recommended range)	89 (69-103)	89 (69-103)	89 (68-102	89 (69-103)	89 (69-103)
Proteins (g) (recommended range)	98 (78-272)	98 (77-270)	97 (76-267)	98 (77-270)	98 (77-270)

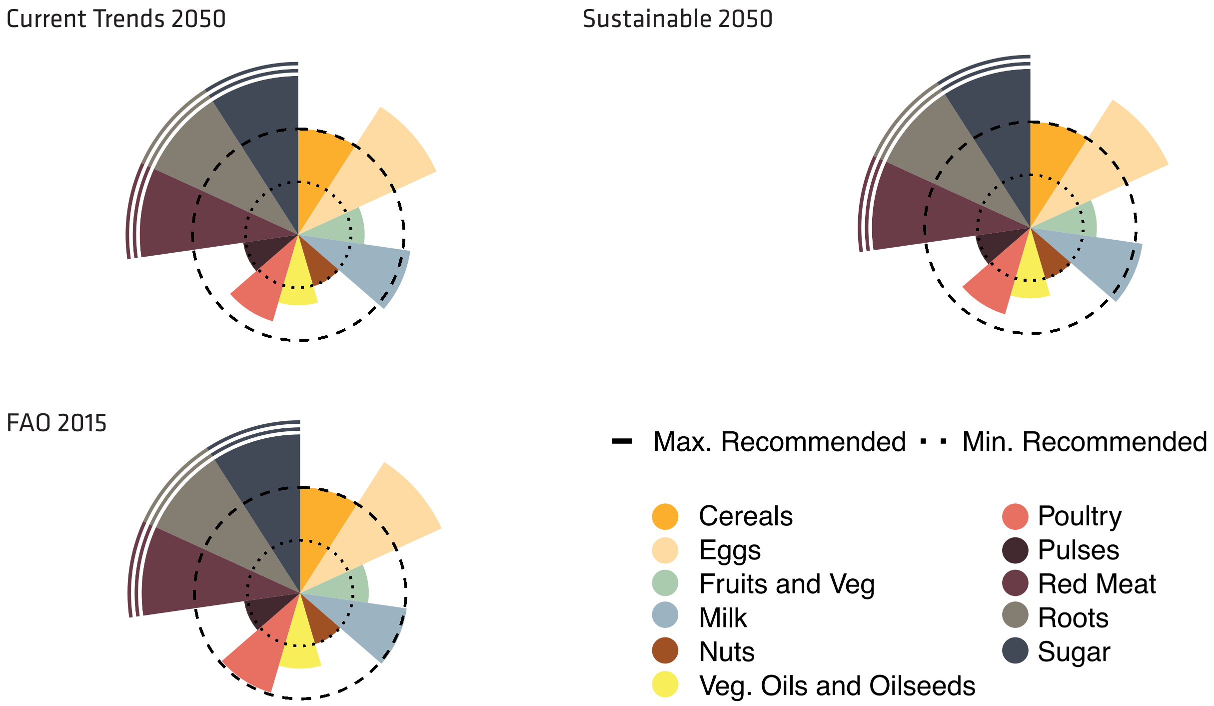
Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 49.2% higher in 2030 and 48.8% higher in 2050 (Table 3). The current average intake is mostly satisfied by cereals (38% of calorie intake), while animal products represent 22% of the total calorie intake. We assume that the consumption of animal products will be stable between 2020 and 2050. The consumption level of all other products remains the same in the projection period because Russia does not have a national policy to increase the consumption of specific food products.

We assume no changes in diets between the Current Trends and Sustainable pathways due to the absence of a national nutrition pathway. However, according to the EAT-Lancet recommendations (Willett et al., 2019), Russia should shift its consumption towards a higher intake of fruits and vegetables, and a lower intake of cereals and sugar, to achieve healthy diets. This is close to what researchers recommend when comparing the recent food production trends and food consumption patterns, indicating that appropriate, evidence-informed food and nutrition policies might help address Russia's burden of non-communicable diseases (NCD) on a population level (Lunze et al., 2015).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore the different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and roots indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

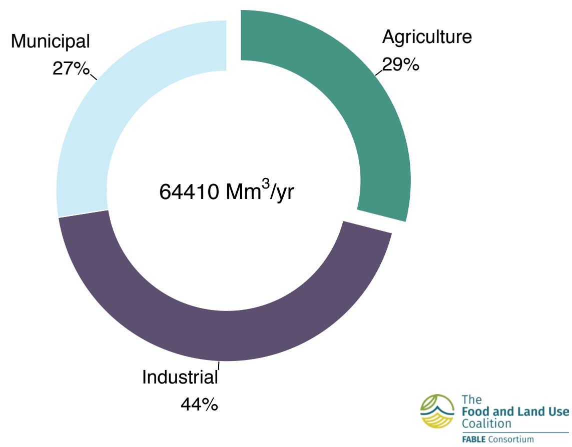
Current State

Russia is characterized by diverse climatic regions due to its large territory. In agricultural areas (see Land and Biodiversity section) annual precipitation mostly occurs during autumn and winter, while other regions it also occurs in the spring. Summers are usually dry. The agricultural sector represented 29% of total water withdrawals in 2015 (Figure 7; FAO). Moreover in 2016, 2.5% of agricultural land was equipped for irrigation, representing 50% of estimated-irrigation potential (Statistical Agency of Russia, 2020). A significant portion of irrigated land is dedicated to rice production, around 20% of which is exported (Rosstat, 2020).

Pathways and Results

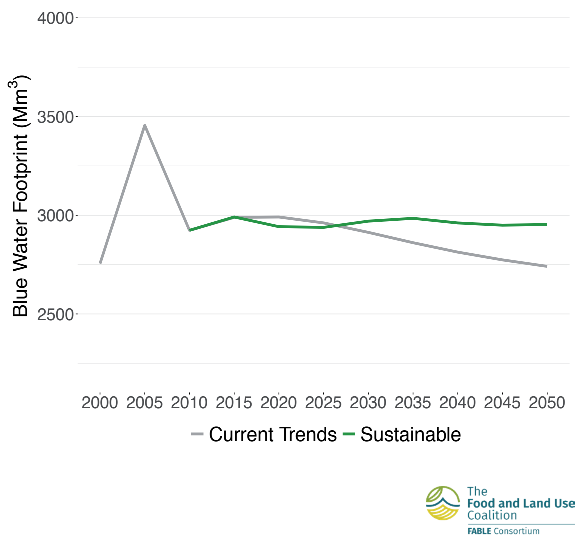
Under the Current Trends Pathway, annual blue water use is projected to increase between 2000-2015 (2,755 Mm^3/yr and 2989 Mm^3/yr), before decreasing to 2,913 Mm^3/yr and 2,741 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with vegetables accounting for 60% of the water intake in 2050[4]. Under the Sustainable Pathway, Russia is projected to use 7% more blue water. This increase is mainly due to an increase in rice and vegetables yields.

Figure 7 | Water withdrawals by sector in 2016



Source. Adapted from AQUASTAT Database (FAO, 2017)

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Russia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

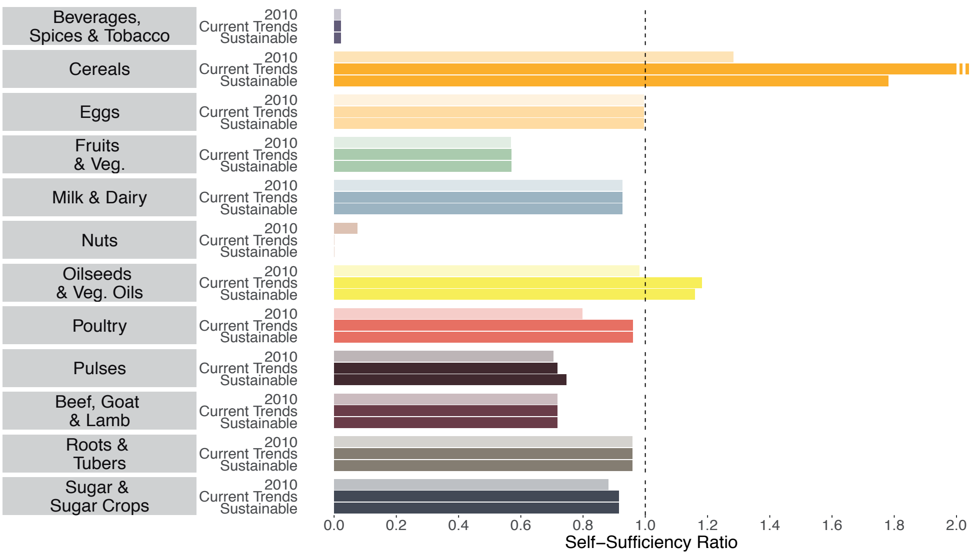
Self-Sufficiency

Russia is self-sufficient in cereals, oilseed, and potato, and in recent years succeeded in increasing the internal production of meat and sugar. However, Russia still relies on imports of specific fruits and vegetables, and milk products (Statistical Agency of Russia, 2020).

Under the Current Trends and Sustainable Pathways, we project that Russia would remain self-sufficient in cereals, eggs, and oilseeds and vegetable oils. However, it is important to note that we have not been able to capture several recent trends which have seen Russia become self-sufficient, and every begin exporting, poultry and pork meat. In addition, Russia has large sugar beet production and recently became a net exporter of sugar in 2020. However, it will still have to rely on imports of beef, nuts, fruits, dairy products, roots and tubers and some vegetables (tomatoes and cucumbers).

In the mid-term (3-5 years), Russia needs to expand its capacity to increase exports of sugar, oilseeds, pork, and poultry, which are currently over-produced, thus keeping prices low. The priority for Russia is to find the markets to sell these products.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for cereals, oilseeds and vegetable oils, indicate a high level of self-sufficiency in these categories.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

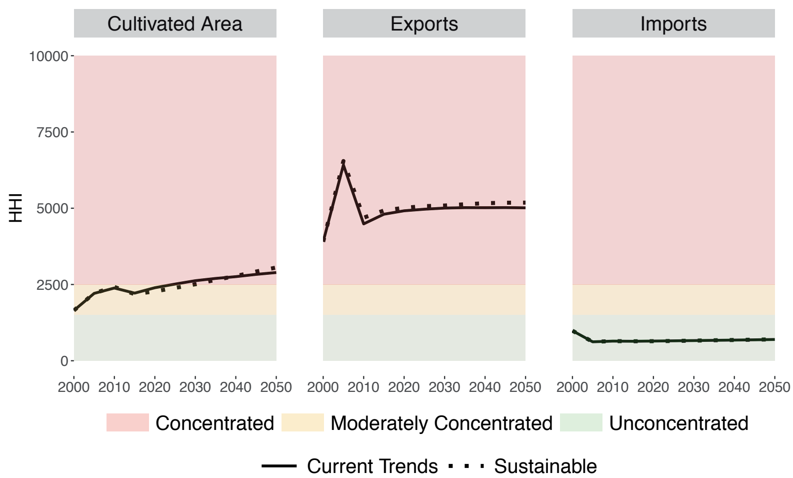
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

According to historical data, Russia's exports are highly concentrated (HHI of 4,000 in 2010) due to the prevalence of cereals and oilseed in Russian agricultural foreign trade. Imports have a low concentration index due to the diversity in the range of products that Russia imports. The crop area shows the most interesting dynamics shifting from low concentration in 2000 to high concentration in 2020 and beyond. This high concentration could be explained by the fact that Russian agricultural producers have historical experience with and good equipment to grow cereals (mostly wheat and barley) as well as sunflower. Therefore, shifting to other crops has been more difficult for them, due to lower technological knowledge and the absence of policy incentives. The high concentration in crops could also be explained by the devaluation of the ruble in 2014, which significant favored Russian agricultural exports.

Under the both the Current Trends and Sustainable Pathways, we project that the high concentration of crop exports and low concentration if crop imports will remain constant. As for the diversification of cropland area, the HHI moderately increases in the Sustainable Pathway, which indicates that the share of wheat and oilseeds will be moderately higher than in the Current Trends Pathway.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

Our estimates show that Russia has great capacity for continued agricultural growth with fewer land resources. In both pathways, Russia enjoys an increase in production, a rise in exports, and a minor decrease in agricultural land use (although the growth rates of this decline differ across pathways), which leads to a decrease in GHG emissions from agricultural and land use. This is in line with national agricultural-development trends over the last decade, and thus serves as a good platform for further achievements. Previous work has demonstrated that Russia can further boost yield growth, especially for cereals like wheat (Schierhorn et al., 2014), and reduce GHG emissions in the agricultural and land-use sector (Romanovskaya et al., 2019). However, this capacity is not reflected in current policy documents, including the Agricultural strategy and draft LT-LEDS (Government of Russia, 2020d). Consequently, our projections for agricultural land use and GHG emissions (including those in the Sustainable pathway) were rather moderate, and not ambitious. According to the draft LT-LEDS, Russia has great capacity to increase its ambition in terms of FOLU carbon sequestration through the application of resource saving technologies and policy measures. These policies include measures against forest fires, optimization of wood cutting technologies, replacing conifers with broadleaf and mixed forest trees, economic incentives for long-life-timber production, and land rehabilitation projects (LT-LEDS). The agricultural sector can also contribute through the application of carbon saving measures, including through optimizing the use of manure as fertilizer, tackling soil erosion issues, decreasing carbon loss on cropland, and increasing carbon sink capacity of pastures. Unfortunately, the draft LT-LEDS considers these measures to be theoretical and they are not set out as concrete steps for policy action.

In terms of biodiversity policy, it is mostly disconnected with agricultural and food production development because these policy scopes tend to address different geographical areas. Most agriculture is practiced in the southwest and south (near the Black Sea) and in Southern Siberia, while most of the territories in the north, Siberia, and Far East are uninhabited and uncultivated, thus serving as a biodiversity-friendly zone. In terms of biodiversity conservation, Russia serves as a good natural protective territory because of its numerous remote areas with no human interference, which creates untouched natural conditions for species that live in Russian forests, shrublands, tundra, and steppes. Forest fires represent the greatest threat for biodiversity in the forests of the Far East (Wu et al., 2018; Shvidenko et al., 2011) and Russia still needs to improve its control and prevention policies against fires that threaten forests, wild animals, and civilians. Moreover, it still has to increase its capacity and allocate resources to properly document the number of wild animals and to trace their possible migration due to global warming, which is crucial for Russia's northern territories.

Russia has extensive agricultural land which is productive but currently abandoned. This land could be used to produce food to satisfy domestic demand, or for exports to meet external demand, and thus contribute towards global food security. Current Russian development programs aim to use at least 12 Mha of this type of land for the purposes explained in previous sections (Government of Russia, 2020a). However, these government programs do not specify whether this land rehabilitation – from abandoned to cultivated – will be economically efficient, and which environmental drawbacks it will entail. Previous research has shown that only 5 Mha of abandoned land in Russia could be used efficiently with low or minimal ecological discrepancies (Meyfroidt et al, 2016). Official data reveals that Russia has already increased its cropland by 6 Mha during the period 2010-2019 (Rosstat, 2020). Part of this land had a natural vegetation cover similar to pastures and produces high GHG emissions during the first year of ploughing (IGCE, 2020). According to National GHG Inventories, in 2011 the cultivation of 0.8 t/ha caused 34 TCO_2 per hectare in GHG emissions, compared to only 0.6 TCO_2 per hectare on annually cultivated cropland.

In our pathways, we attempted to distinguish between different approaches to cropland expansion. Our estimates in the Current Trends Pathways show that Russia can increase its crop area by only 3 Mha by 2030, which increases crop production – driven by domestic and external demand. In the Sustainable Pathway we assume that Russia can increase its production partly by closing the yield gap. We suggest that Russia will not change the crop area until 2030 but will sufficiently decrease its cropland area by 10 Mha between 2030 and 2050, turning it into an additional carbon sink achieved through productivity gains. Thus, if policies are applied to save land and increase crop productivity, Russia could achieve the necessary growth in production and contribute to carbon sequestration called for under the Paris Agreement.

The main limitations of our approach are related to our estimates for GHG emissions, the problems to define the adequate growth rate of forests area, estimates in meat production during the historical period, and differences with Russia's official statistics for nutrient content.

For the GHG emission estimates, out analysis includes land-use types (forests, pasture, cropland etc.) that are similar to Russia's National GHG Inventories (IGCE, 2020). However, the FABLE Calculator does not allow us to estimate full GHG removals in areas where natural vegetation cover does not change for long periods, such as forests, which is a net sequester of almost 600 Mt CO_2, and pastures, 80 Mha which are classified as a source of net-emissions (IGCE, 2020). In the FABLE Calculator, we only estimate emissions from agricultural activities whose estimates are similar to IGCE results and GHG emissions and removals from land use change, such as conversion of cropland to other land in cases where yields increase. Therefore, our total AFOLU emissions are significantly different from estimates of total AFOLU emissions in Russia's National GHG Inventories. Nevertheless, in terms of dynamics of fluxes, the FABLE Calculator captures emissions from land use change that are close to those of the Inventories. For example, both the estimates in the Russian National GHG Inventories and the FABLE Calculator agree that when cropland is abandoned to be used as other land, it becomes a net sequester of carbon.

Regarding forests, we did not allow the FABLE Calculator to extend Russia's forest area. There are two main reasons behind this decision. First, we do not have an appropriate source or action plan in the current Russian forest sector that looks at long-term developments. Second, when we calculated the forest land expansion in the FABLE Calculator, results led to a large increase in carbon sequestration that does not correspond to current draft LT-LEDS. Nevertheless, we applied the possible new forest growth concept, but only for the Sustainable Pathway. This is necessary to demonstrate that Russia still has a large potential to increase its carbon sinks.

Additionally, several sectors are not yet properly captured in our model. Specifically, it does not yet capture the rapid growth of Russia's pork and poultry sectors which occurred in the last 15 years (2000-2015). The FABLE Calculator estimated 2.7 Mt for poultry meat production in 2015, when in reality it reached 4.5 Mt (Rosstat, 2020). Similarly, pork meat production was estimated to be 2.5 Mt in 2015, when in reality it reached 3 Mt. Finally, the proper estimates of the nutrient content of consumed food in the historical period needs to be further refined. For our 2010 estimates, the kcal food consumption is 17% higher, specifically 28% higher for proteins and 15% lower for fats compared with official data for the respective year (Rosstat, 2020).

Out next steps will be to focus on improving the FABLE Calculator to address these discrepancies and by including additional land-use variables. For example, the FABLE Calculator currently only includes one type of pasture (120Mha), while in Russia there are used pastures (around 40 Mha), which serve as a net-emitter of GHG, and almost 80 Mha of unused pastures which likely serve as a net carbon sink, even though this dynamic is not currently revealed in the National GHG Inventories. We will also improve the estimates for pork and poultry production to approach the current levels and apply it to current national plans for Russia to become a net exporter of pork and poultry.

Annex 1. Underlying assumptions and justification for each pathway

Please note that this represents the value by 2050, or change in 2050 compared to 2010, or trend over 2010-2050.

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
The population is expected to decrease from 146 million to 135 million in 2050. This is a rather conservative scenario based on current decrease of Russian population (UN_medium scenario selected).	The population is expected to decrease from 146 million in 2020 to 144.5 in 2050. This assumption is based on current government programs to financially support families that give birth to two or more children. Although we have not seen specific plans and projections for the future population growth numbers. (UN_instant replacement scenario selected)

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
Based on the government's current strategy for Russian rural development 2030 (Government of Russia, 2015), and the Project State Program for Russian Agricultural Land Rehabilitation and Melioration 2030 (Government of Russia, 2020a). (FreeExpansion scenario selected)	We assume no agricultural land expansion beyond 2010 agricultural area levels. In recent years Russia faced over-production of major crops like grains and sugar beet, which led to sharp decreases in prices (in 2008, 2017, and 2019). Currently there is no measure in place to support prices and the supply management in terms of its limitation of cultivated crop area. We assume this scenario if price supports or supply support mechanisms are implemented. (NoExpansion scenario selected)

LAND Afforestation or reforestation target (Mha)

Current Trends Pathway	Sustainable Pathway
We do not expect afforestation because the Russian draft LT-LEDS does not mention any possible increase of the forest area.	We assume total afforested area to reach 2 Mha by 2050 (BonnChallenge scenario selected). Even though Russia is not a signatory member of the Bonn agreement, Russia has enough land to increase forest area by 2 Mha to 2050. Also, according to current statistics, Russia manages to keep forest restoration of average 0.8 Mha every year (Statistical Agency of Russia, 2020).

BIODIVERSITY Protected areas (% of total land)

Current Trends Pathway	Sustainable Pathway
Protected areas remain stable based on historical trends: by 2050 they represent 9% of total land. Due to the absence of biodiversity policy in Russia and based on our estimates with Russian FABLE Calculator	Same as Current Trends

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Pathway
By 2050, crop productivity reaches: • 2.5 tons per ha for wheat. • 1.3 tons per ha for sunflower. • 4.2 tons per ha for barley. Based on current productivity levels on our estimates with Russian FABLE Calculator.	By 2050, crop productivity reaches: • 3.0 tons per ha for wheat. • 1.8 tons per ha for sunflower. • 5.5 tons per ha for barley. We assume that Russia will continue to improve cropland productivity based on historical crop yield trends. There are, however, currently no sources, either official or in the literature, to prove this. Based on our estimates with Russian FABLE Calculator.

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway
By 2050, the share of total consumption which is imported is: • 85 % by 2050 for apples. • 31 % by 2050 for beef. • 40 % by 2050 for tomato. Based on current trends and on our estimates with Russian FABLE Calculator.	Same as Current Trends

TRADE Evolution of exports for key exported products (million tons)

Current Trends Pathway	Sustainable Pathway
By 2050, the volume of exports is: • 51.6 million tons by 2050 for wheat. • 3.8million tons by 2050 for sunflower oil. • 6.6 million tons by 2050 for barley. Based on current trends and on our estimates with Russian FABLE Calculator.	By 2050, the volume of exports is: • 41.9 million tons by 2050 for wheat. • 3.8 million tons by 2050 for sunflower oil. • 5.0 million tons by 2050 for barley. Based on our estimates with Russian FABLE Calculator.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Pathway
By 2030, the average daily calorie consumption per capita is 3094 kcal and is: • 1161 kcal for cereals. • 145 kcal for fruits and vegetables. • 682 kcal for animal products (kcal sum of meat, milk, eggs, animal fat). Due to the absence of National Nutrition policy and based on our estimates with Russian FABLE Calculator.	Same as Current Trends.

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
"No change" scenario was chosen because Russia does not have a specific biofuel policy, and Russian food and production balance sheets do not identify separately the biofuel use of produced crops. This impedes estimating the capacity for biofuels.	Same as Current Trends

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m^2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m^2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 2. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 3. Overview of biodiversity indicators for the current state at the ecoregion level[5]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
650	Caucasus mixed forests	5751	32	59	52	49	661	50
654	Central European mixed forests	3414	5	39	12	88	1 886	28
658	Crimean Submediterranean forest complex	2216	8	57	13	87	656	29
661	East European forest steppe	57962	5	25	18	82	41917	15
666	Hokkaido deciduous forests	1094	24	92	26	74	46	67
669	Manchurian mixed forests	9554	14	93	14	86	295	61
679	Sarmatic mixed forests	47255	9	58	15	86	13652	44
685	Ussuri broadleaf and mixed forests	19721	9	94	9	91	267	71
687	Western Siberian hemiboreal forests	22393	7	72	9	91	5 329	52
690	Altai montane forest and forest steppe	2539	9	95	9	91	143	75
693	Da Hinggan-Dzhagdy Mountains conifer forests	9741	8	94	8	92	6	93
707	Sayan montane conifer forests	31960	16	93	16	84	1 026	76
710	East Siberian taiga	390852	7	94	8	93	1 953	62
712	Kamchatka taiga	1526	18	98	18	82	1	98
713	Kamchatka-Kurile meadows and sparse forests	13986	19	98	19	81	108	82
714	Northeast Siberian taiga	112601	11	97	11	89	151	93
715	Okhotsk-Manchurian taiga	39961	8	93	9	91	133	96
716	Sakhalin Island taiga	6478	5	93	6	95	94	58
717	Scandinavian and Russian taiga	147537	6	82	7	93	7068	61

5 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km^2(%)
718	Trans-Baikal conifer forests	16281	10	86	9	91	983	58
719	Urals montane forest and taiga	17500	21	89	23	77	381	72
720	West Siberian taiga	167412	9	91	9	91	2191	65
726	Daurian forest steppe	11211	2	75	2	98	1506	70
731	Kazakh forest steppe	37431	12	39	23	78	21450	30
732	Kazakh steppe	14156	4	26	12	88	10631	18
734	Mongolian-Manchurian grassland	267	77	97	79	21	3	96
735	Pontic steppe	64489	5	14	26	74	47495	17
736	Sayan Intermontane steppe	3374	9	82	11	89	352	51
737	Selenge-Orkhon forest steppe	2580	3	76	4	96	291	68
738	South Siberian forest steppe	16223	6	51	10	90	6633	40
741	Amur meadow steppe	7059	15	67	20	80	1972	35
746	Suiphun-Khanka meadows and forest meadows	1558	6	67	5	95	553	46
749	Altai alpine meadow and tundra	2748	33	90	35	65	55	96
764	Sayan alpine meadows and tundra	5917	8	94	9	92	174	94
771	Cherskii-Kolyma mountain tundra	55777	13	99	13	87	51	99
772	Chukchi Peninsula tundra	29324	8	98	8	92	12	98
773	Kamchatka tundra	11840	21	99	21	79	29	85
774	Kola Peninsula tundra	5227	6	91	6	94	2	97
775	Northeast Siberian coastal tundra	21945	23	95	24	76	44	96
776	Northwest Russian-Novaya Zemlya tundra	27147	7	95	7	93	2	86

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
777	Novosibirsk Islands Arctic desert	3480	100	99	100	0	0	N/A
778	Russian Arctic desert	8729	16	42	9	91	0	N/A
779	Russian Bering tundra	47142	9	97	9	91	237	99
781	Taimyr-Central Siberian tundra	94600	14	95	14	86	45	99
782	Trans-Baikal Bald Mountain tundra	21807	8	99	8	92	21	94
783	Wrangel Island Arctic desert	722	100	100	100	0	0	N/A
784	Yamal-Gydan tundra	40500	8	91	7	93	2	100
815	Caspian lowland desert	8615	18	28	60	40	700	68
826	Great Lakes Basin desert steppe	2200	15	82	15	86	131	94

Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – ton

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Rwanda

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Rwanda. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including from Ministry of Agriculture and Animal Resources, Rwanda Agriculture Board, National Agricultural Export Development Board, Rwanda Environment Management Authority, Forestry Authority, Land authority, Water authority, University of Rwanda, Mining authority, National Institute of Statistics of Rwanda (NISR), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019).

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Rwanda's Nationally Determined Contribution (NDC) and Urban Low Emissions and Development Strategy (Urban-LEDS) treat the FABLE domains. In the AFOLU sector, Rwanda's NDC targets to reduce GHG emissions from agriculture, despite the potential for increased productivity. Agricultural output is expected to be limited due to land availability, thereby limiting the emissions growth from this sector, without an emissions target from forestry or land use change. Envisaged mitigation measures from agriculture and land-use change include mainstreaming agroecology techniques using spatial plant stacking as in agroforestry; promoting kitchen gardens, nutrient recycling, and water conservation to maximize sustainable food production; utilizing resource

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially explicit planning in current NDC and Urban-LEDS

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2020)	2015	5.33 (2.94 for agriculture)	2030	Three scenarios: 1. BAU projects 12.1 (5.1) 2. A 16% unconditional from BAU = 10.2 3. A 38% combined unconditional and condition reduction from BAU =7.5	Energy, Transport, Industry, Waste and Forestry	Only agriculture	Y	N	food security, water, deforestation
Urban-LEDS (2019)	2015	0.5	2030	18.8	Energy, Transport, Industry, Wastes, Agriculture, and Animal Husbandry	Y	Y	N	food security, water, deforestation

Note. "Total GHG Mitigation" and "Mitigation Measures related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019).
Sources. Compiled from Updated Nationally Determined Contribution (INDC) (Republic of Rwanda, 2020)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

recovery and reuse through organic waste composting and wastewater irrigation; using fertilizer enriched compost; mainstreaming sustainable pest management techniques to control plant parasites and pathogens; soil conservation and land husbandry; irrigation and water management; adding value to agricultural products through processing to meet its own market demand for food stuffs; employing an integrated approach to planning and sustainable land use management and improving spatial data by harnessing ICT and GIS (Geographic Information System) technology. Under its current commitments to the UNFCCC, Rwanda mentions biodiversity conservation.

Table 2 provides an overview of the targets listed in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. In comparison with FABLE Targets, there is a linkage between both targets in terms of area covered by forests and zero net deforestation from 2030 onwards. Compared to the FABLE target of having at least 30% of global terrestrial area protected by 2030, our assumption is below the Government of Rwanda's target to increase the percentage of land designated for biodiversity conservation from 10.13% in 2017 to 10.3% in 2020 of its total land.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE Targets

NBSAP Target	FABLE Target
(5) **By 2020, at least 50% of natural ecosystems are safeguarded, their degradation and fragmentation significantly reduced.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(9) **By 2020, at least 10.3% of land area is protected to maintain biological diversity.**	**BIODIVERSITY:** At least 30% of global terrestrial area protected by 2030
(14) **By 2020, 30% of the country is covered by forests hence increasing carbon stocks and contributing to climate change mitigation and adaptation.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Rwanda.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth from (8 million in 2000 to 22 million in 2050), no constraints on agricultural expansion, no-afforestation target, 9% change in the extent of protected areas, medium productivity increases in the agricultural sector, an evolution towards national healthy diets, and high livestock productivity (see Annex 1). This corresponds to a future based on current policy and historical trends that would also see considerable progress in measures and national strategies that support agriculture through subsidies; livestock and livelihoods through the One Cow per Poor Family Program, and food security, through the improvement of soil fertility. Moreover, capacity building of government personnel will have a significant impact in supporting these pathways. Furthermore, the government's adoption of agroforestry practices is complementing the afforestation/reforestation efforts as reported by Ministry of Lands and Forestry (2018). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, wheat, rice, and soybean (see Annex 1).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to no deforestation beyond 2030, stronger measures for protected areas, higher livestock productivity along with a high-fat diet, higher criteria for agricultural expansion formalized in government master plans for proper land use allocation, lower population growth, and no-afforestation target for both models (see Annex 1). This corresponds to a future based on the improvement of policies already in place and the integration of new ambitious policies that would also lead to considerable progress in the management of environment and natural resources. These policies include the adoption of irrigation systems to cope with climate change impacts, the banning of plastic bags, the promotion of tree planting, the establishment of green funds, the inclusion of environmental considerations into policy making ("green politics") and landscape restoration; which would help Rwanda become a low-carbon economy and climate-resilient by 2050 (World Economic Forum, 2016). With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

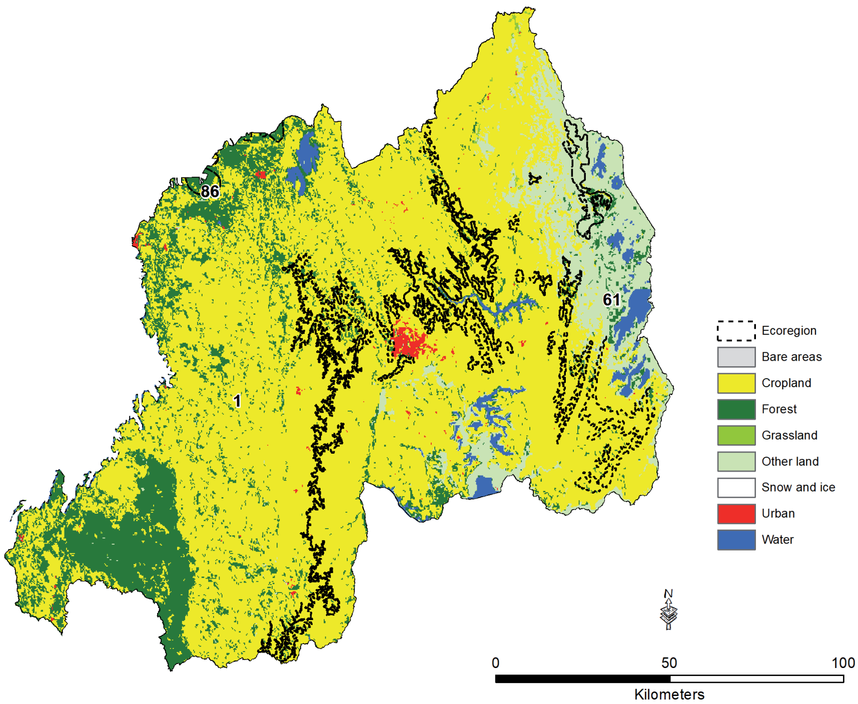
Land and Biodiversity

Current State

In 2010, Rwanda was covered by 58% cropland, 17% grassland, 14% forest, 1% urban and 10% other natural land. Most of the agricultural area is located in the Northern part of Rwanda while forest and other natural land can be mostly found in the Southern part (Map 1). We know that biodiversity is life as it is part of us as human beings, it is our air, our food and our water. Despite the government's conservation efforts, Rwanda's biodiversity remains under pressure due to natural habitat degradation, climate change, pollution, mining, poaching, and invasive alien species. Moreover, we still observe gaps as biodiversity is not integrated into national development policies and programs.

We estimate that land where natural processes predominate[2] accounted for 14% of Rwanda's terrestrial land area in 2010 (Map 2). The *86-Rwenzori-Virunga montane moorlands* hold the greatest share of land where natural processes predominate, followed by *61-Victoria Basin forest-savanna* and *1-Albertine Rift montane forests* (Table 3). Across the country, while 0.23 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 64% of land where natural processes predominate is formally protected. This indicates that *61-Victoria Basin forest-savann*a and *1-Albertine Rift montane forests* are likely to remain important into the future due to their roles in the ecological, economic, social and cultural sphere. Moreover, these ecoregions fulfill a central role in the conservation of species and biodiversity habitats for educational, tourism and research purposes.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions



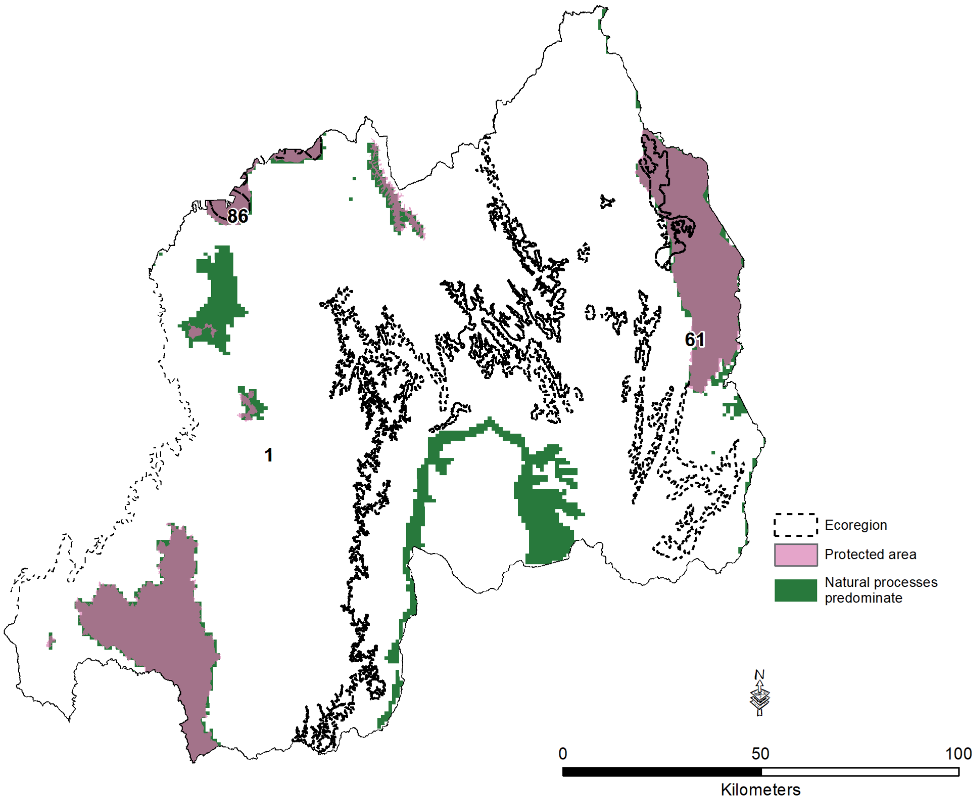
Note. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)
Sources. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 2.

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

However, *86-Rwenzori-Virunga montane moorlands* and wetlands areas may be at risk without actions to better protect them.

Approximately 28% of Rwanda's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in *86-Rwenzori-Virunga montane moorlands,* followed by *1-Albertine Rift montane forests* and 61-*Victoria Basin forest-savanna.* The regional differences in extent of biodiversity-friendly cropland can be explained by regional production practices.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
1	Albertine Rift montane forests	1345.107	9.7	12.7	74.6	25.4	989.358	32.5
61	Victoria Basin forest-savanna	1087.637	8.3	15.6	52.3	47.7	757.079	22.2
86	Rwenzori-Virunga montane moorlands	8.564	97.5	99.7	97.7	2.3	1.716	86.4

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

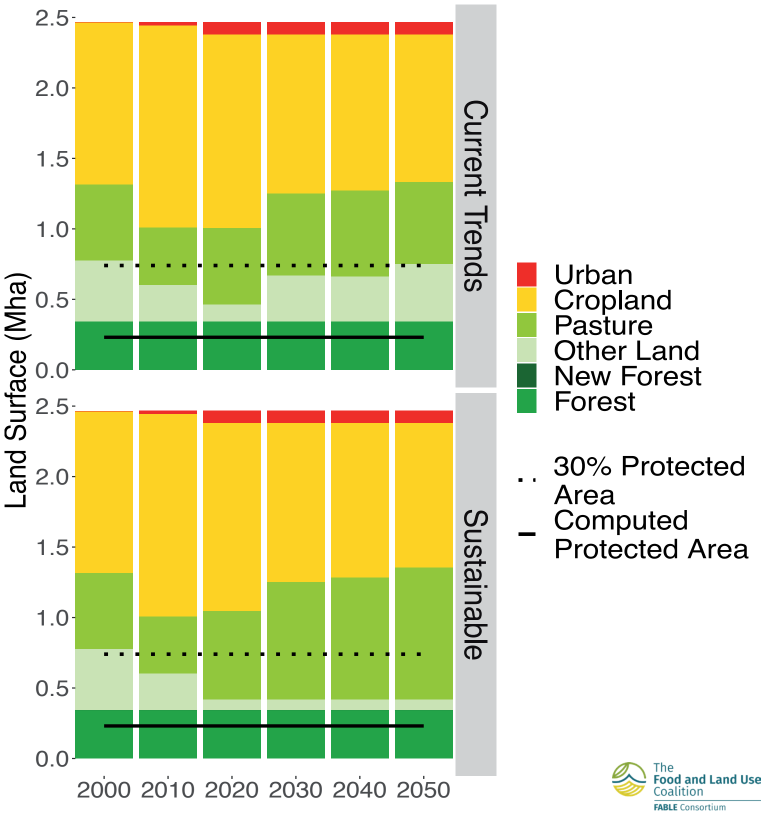
Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, no planned afforestation or reforestation, and protected areas remain at 0.23 Mha, representing 9% of total land cover (see Annex 1).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase of pasture and other land area, as well as a decrease of cropland area. This trend evolves over the period 2030-2050: cropland area further decreases, urban area stabilizes, and pasture area begins to decrease as well.

Pasture expansion is mainly driven by the increase in internal food consumption of cattle (beef, milk) while livestock productivity per head increases and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, pasture change is explained by a strong increase in internal demand for livestock products and high population growth. This results in the expansion of land where natural processes predominate by 60% by 2030 and by 88% by 2050 compared to 2010, respectively.

In the Sustainable Pathway, assumptions on agricultural land expansion have been changed to reflect the National Land Use Development Master Plan which designates areas in Rwanda that are most suitable for agricultural development. The Master Plan also seeks to improve the land use sustainability of the country and to enhance the quality of the

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

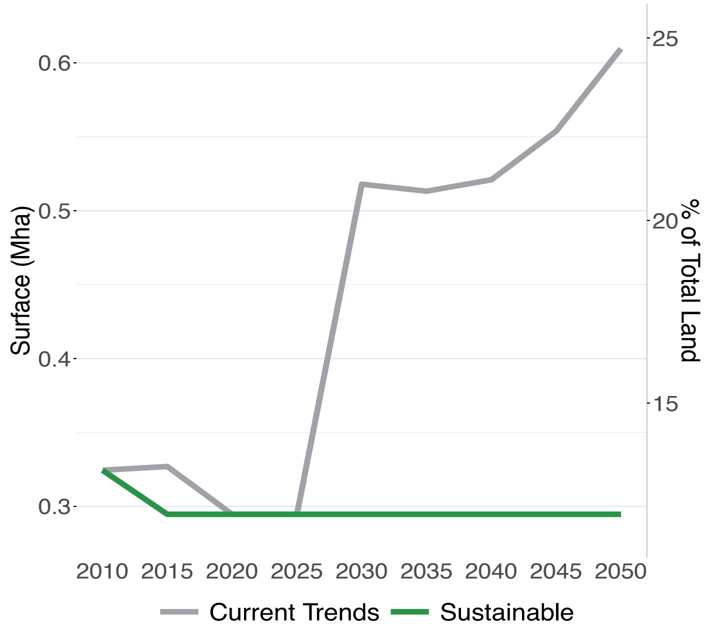


Source: Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

built environment (Ministry of Natural Resources, 2017). Moreover, the adoption of professional agriculture would increase the yield on small plots and compensate for the land expansion. The main assumptions also include the prevention of deforestation by 2030 (see Annex 1).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Rwanda in the Sustainable Pathway: there is a decrease in cropland and other land from 2010 and 2030 and an increase in pasture from 2030 to 2050. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by an increase in exports of tea and coffee, an increase in demand for various feed products and an increase in food consumption of milk, coupled with a decrease in production of potatoes, cassava and beans between 2010 and 2030. This leads to a stabilization in the area where natural processes predominate: the area stops declining by 2015 and remains the same by 9% between 2015 and 2050 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate



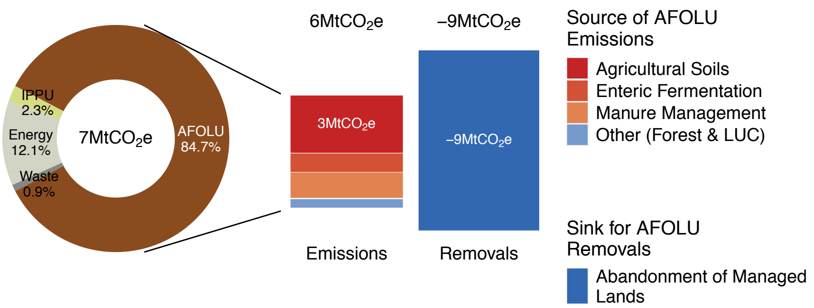
GHG emissions from AFOLU

Current State

The Agriculture, Forestry, and Other Land Use (AFOLU) sector is a critical component of the Malaysian plan to address climate change largely due to the extent of carbon sinks in the region such as forests and peatlands. The effort to balance economic concerns, food security, and the preservation of the country's vast carbon sinks remains a point of debate to this day. In particular, peatlands pose a unique challenge due to the lack of national data available.

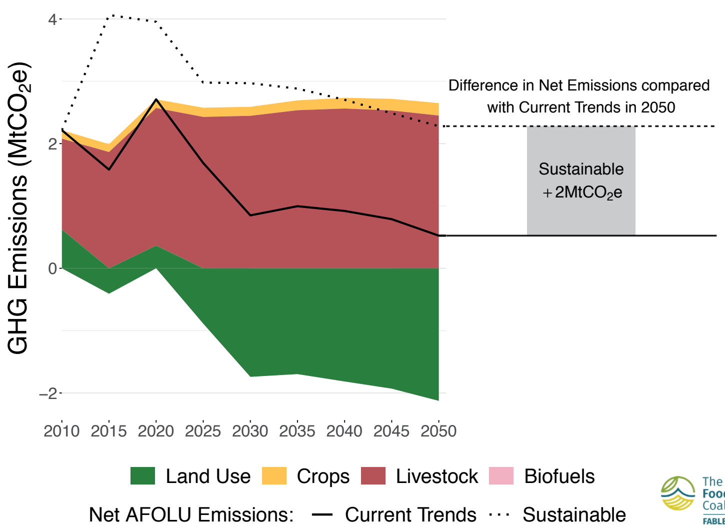
Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 84.7% of total emissions in 2010 (Figure 3). Agricultural soils are the principle source of AFOLU emissions, followed by manure management, enteric fermentation, and other (agriculture). This can be explained by the fact that Rwandan soil is inherently acidic, and steep slopes expose the soil to erosion, fertility loss and landslides. Additionally, the Crop Intensification Programme (CIP), launched by the government of Rwanda in 2007, focuses on the consolidation of land use to increase the productivity of high potential staple food crops, and ultimately ensure the country's food security and self-sufficiency. CIP also promotes the increased use of fertilizers which could be a reason for the rise in agricultural emissions (Nilsson, 2018). Another reason can be linked to the One Cow per Poor Family

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2005



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway



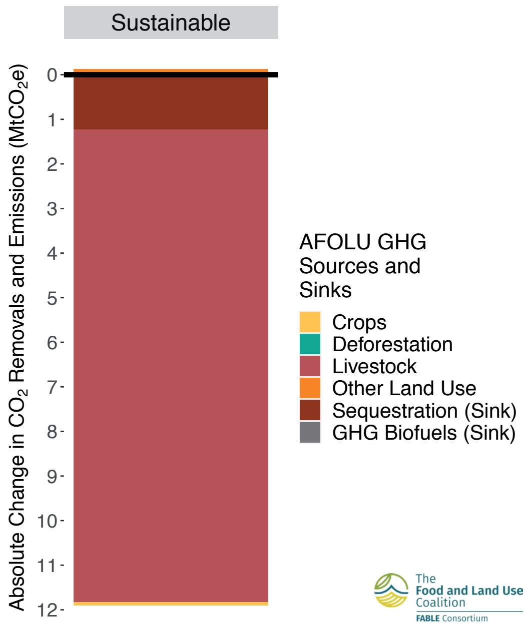
program which aims to reduce the rate of child malnutrition and increase household incomes for poor families in Rwanda (Rwanda Governance Board, 2018). However, the program has also led to high quantities of manure produced that are not appropriately managed to minimize Nitrogen losses and environmental pollution.

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 0.8Mt CO_2e/yr in 2030, before declining to 0.5Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock is the largest source of emissions (2.5Mt CO_2e/yr) while sequestration acts as a sink which almost offsets emissions (-2.1 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for N20 emissions from crop production (63%) while a reduction is computed for methane emissions from crop production (52%).

In comparison, the Sustainable Pathway leads to an increase of AFOLU GHG emissions compared to the Current Trends Pathway reaching 3 Mt CO2e in 2030 and 2.3 Mt CO_2e in 2050 (Figure 4). The emissions increase under the Sustainable Pathway is dominated by an increase in GHG emissions in the livestock sector. The change assumed in diets i.e. an increase in the total average calorie intake per capita including an increase of the consumption of livestock products have induced an increase in emissions from domestic cattle production.

Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Rwanda's commitments under the UNFCCC (Table 1) forecast a doubling of total GHG emissions over the 2015-2030 period under BAU projections (from 5.33 Mt CO_2e/yr to 12.1 Mt CO_2e/yr). For the AFOLU sector, the NDC does not include emissions from forestry or land-use change, only emissions from agriculture which amount up to 2.94 Mt CO_2e for the baseline year 2015 and add up to 5.1 Mt CO_2e in 2030 under a BAU Scenario. The NDC also projects two different pathways, one with a 16% and a second one with a 38% reduction in total emissions from the BAU scenario by 2030; which would lead to a total emissions projection of 10.2 Mt CO_2e and 7.5 Mt CO_2e, respectively. Each sector was estimated to have different mitigation potentials. In the pathway with 38% reduction in total emissions, the agriculture sector's mitigation potential accounted for 44% in emission reductions.

In comparison, it seems that we underestimate the GHG emissions from agriculture in the Current Trends Pathway. For the 2030 projection, the agriculture BAU scenario in the NDC (5.1 Mt CO_2e) doubles the results of the FABLE Calculator (2.1 Mt CO_2e) under the Current Trends Pathway but are slightly higher than our results in the Sustainable Pathway, where emissions from agriculture increase to 4.5 Mt CO_2e.

Moreover, we need to compare our assumptions in the evolution of the livestock herd and productivity with the assumptions used for the NDC. In the NDC, most of the mitigation potential of the agriculture sector is estimated to come from soil conservation through terracing (20%) and rotation (24%), and compost production (28%) (Republic of Rwanda, 2020). Unfortunately, these measures are not yet represented in our FABLE Calculator.

Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition	Micronutrient Deficiency	Overweight/ Obesity
45.2% of the population undernourished in 2007. This share has decreased since 2014 (FAO, 2016).	17% of women and 37% of children suffer from anemia in 2015, which can lead to maternal death (Compact2025, 2016; NISR, Ministry of Health, & ICF International, 2015).	16% of women, and 11% of adults and 7% of children were obese in 2010. These shares have increased since 2016 (UNICEF, 2019).
36.7 % of children under 5 stunted and 1.7% wasted in 2015 (Hjelm, 2016).	7% of women/the population are deficient in vitamin A (Rwanda National Nutrition Policy, 2007), which can notably lead to blindness (Rwanda National Nutrition Policy, 2007) and child mortality, and 26% are deficient in iodine, which can lead to developmental abnormalities (Rwanda National Nutrition Policy, 2007).	17% of women, and 20% of adults and 11% of children, were overweight in 2016. These shares have decreased since 2019 (UNICEF, 2019).

Disease Burden due to Dietary Risks
5.55% of deaths are attributable to dietary risks, or 3,783.19 deaths per year (per 100,000 people) (World Health Organization, 2017).
Dietary risks also lead to/cause 5 disability-adjusted life years (DALYs), or years of healthy life lost due to an inadequate diet (Institute for Health Metrics and Evaluation, 2010).
2.8% of the population suffers from diabetes and 14% from cardiovascular diseases, which can be due to/caused by dietary risks (Kabeza et al., 2019 and WHO, 2018).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,082 (1,950)	2,142 (2,021)	2,428 (2021)	2,247 (2057)	2,804 (2,057)
Fats (g) (recommended range	24 (46-69)	48 (48-71)	71 (54-81)	72 (50-75)	117 (62-93)
Proteins (g) (recommended range	55 (52-182)	60 (54-187)	66 (61-21)	66 (56-197)	78 (70-245)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 6% higher in 2030 and 9% higher in 2050 (Table 4). The current average intake is mostly satisfied by roots (30%), cereals (22%), fruits and vegetables (17%), and pulses (17%). We assume that the consumption of animal products namely poultry and eggs will increase by 277% and 218%, respectively, between 2020 and 2050. The consumption of cereals and sugar will also increase while roots and red meats consumption will decrease by 58% and 33%, respectively.

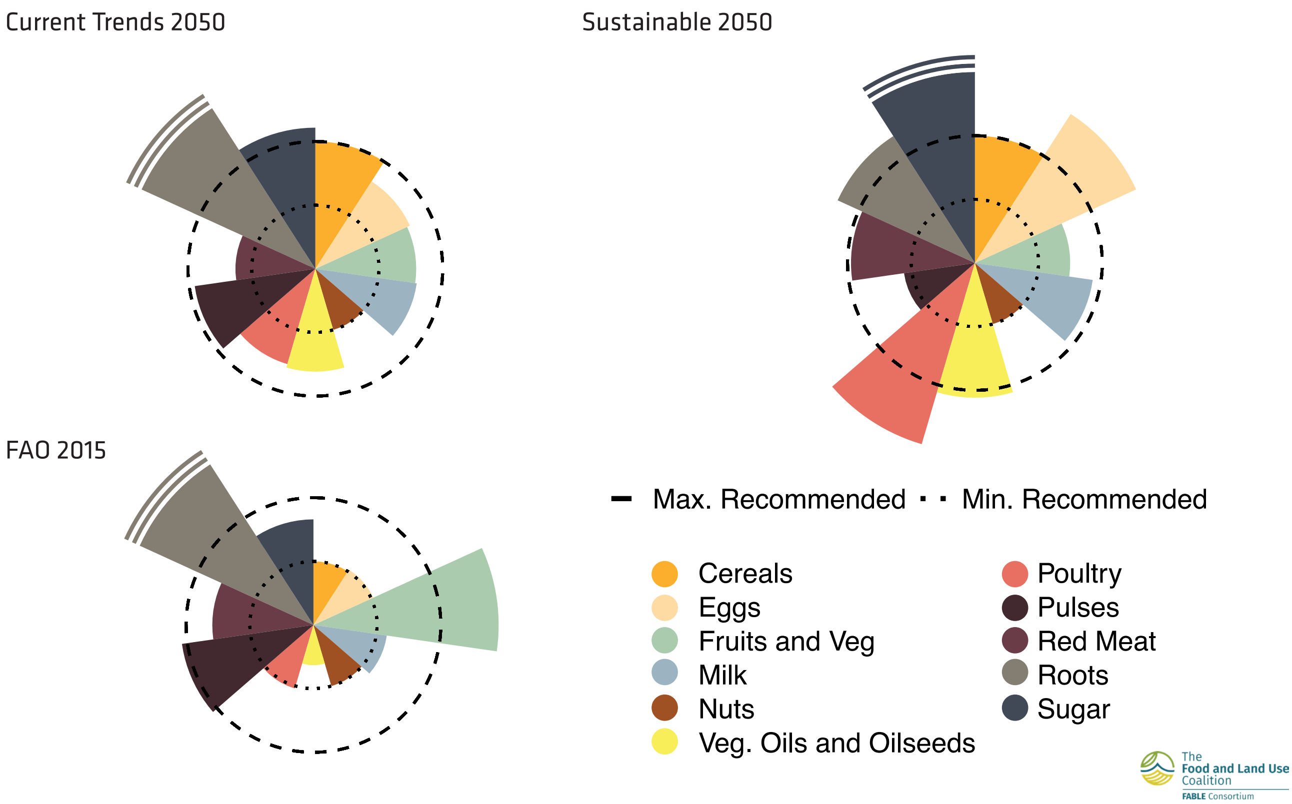
Compared to the EAT-*Lancet* recommendations (Willett et al., 2019), roots and cereals are over-consumed while nuts and red meats under-consumed in 2050 (Figure 6). Moreover, protein intake per capita is within range of the dietary reference intake (DRI) for all years, while in 2010 fat intake per capita (24 g fat per capita per day) is inferior to the range of the DRI (46-69 grams) but comes within range by 2030 and 2050. This can be explained by the increase in the consumption of poultry (277%) and eggs (218%) between 2020 and 2050 (Figure 6).

Under the Sustainable Pathway, we assume that diets will transition towards a diet higher in meat, milk, sugar, and fat. We assume that roots, pulses and fruits and vegetables oils are over-consumed whereas the remained food categories are inferior to the average recommended except red meats. With these assumptions, the ratio of the computed average intake over the MDER increases to 20% in 2030 and 36% in 2050 under the Sustainable Pathway.

Compared to the EAT-Lancet recommendations, only the consumption of eggs, poultry, roots and sugar remains outside of the recommended range; and the consumption of animal fat, cereals, fish, fruit and vegetables, milk, nuts, oilseeds and vegetable oils, pulses and red meat being now within the recommended range in 2050 (Figure 6). However, fat intake per capita continues to be outside of the recommended range throughout the entire period, while protein intake per capita does fall within recommended range except for 2050, showing little improvement compared to the Current Trends Pathway.

Rwanda intends to mainstream agro-ecology techniques using spatial plant stacking as in agro-forestry, kitchen gardens, nutrient recycling, and water conservation in its current agriculture intensification program and other natural resource-based livelihood programs. The total households involved in agriculture production are expected to be implementing agro-forestry sustainable food production by 2030 (Republic of Rwanda, 2015).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and roots indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

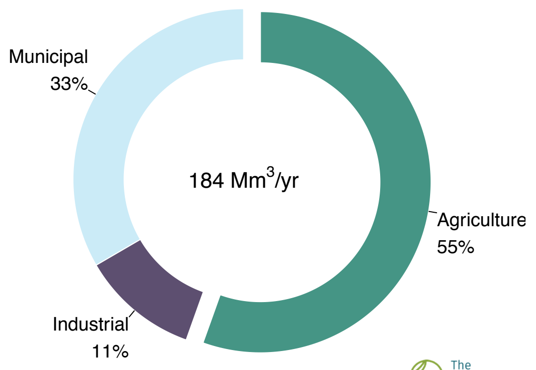
Current State

Rwanda is characterized by high altitude ranging between 915m and 4,486m – it is also known as the *'country of a thousand hills'* – with a tropical temperate climate. The average annual temperature ranges between 16°C and 20°C, with 1,156 mm average annual precipitation that mostly occurs over the period of March-May. The agricultural sector represented 55% of total water withdrawals in 2000 (Figure 7; FAO, 2017). Moreover in 2007, 0.7% of agricultural land was equipped for irrigation, representing 5.8% of the estimated-irrigation potential (FAO, 2017). The most important irrigated crop is rice which accounts for 46% of total harvested irrigated area.

Pathways and Results

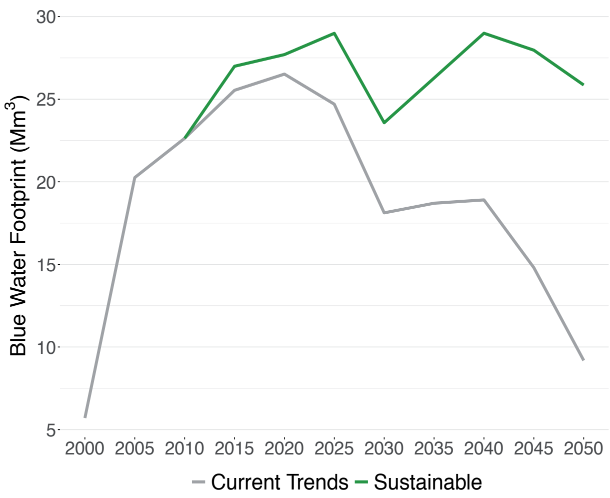
Under the Current Trends Pathway, annual blue water use increases between 2000-2015 (from 5.7 Mm^3/yr to 25.5 Mm^3/yr), before reaching 18 Mm^3/yr and 9.2 Mm3/yr in 2030 and 2050, respectively (Figure 8), with rice, sweet potato, and other vegetables accounting for 59%, 6%, and 34% of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Pathway, blue water footprint in agriculture reaches 23.5 Mm^3 in 2030 and 25.8 Mm^3 in 2050.

Figure 7 | Water withdrawals by sector in 2000-2005



Source. Adapted from AQUASTAT Database (FAO, 2017) with data from 2000 (agriculture water withdrawals) and 2005 (municipal and industrial water data)

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

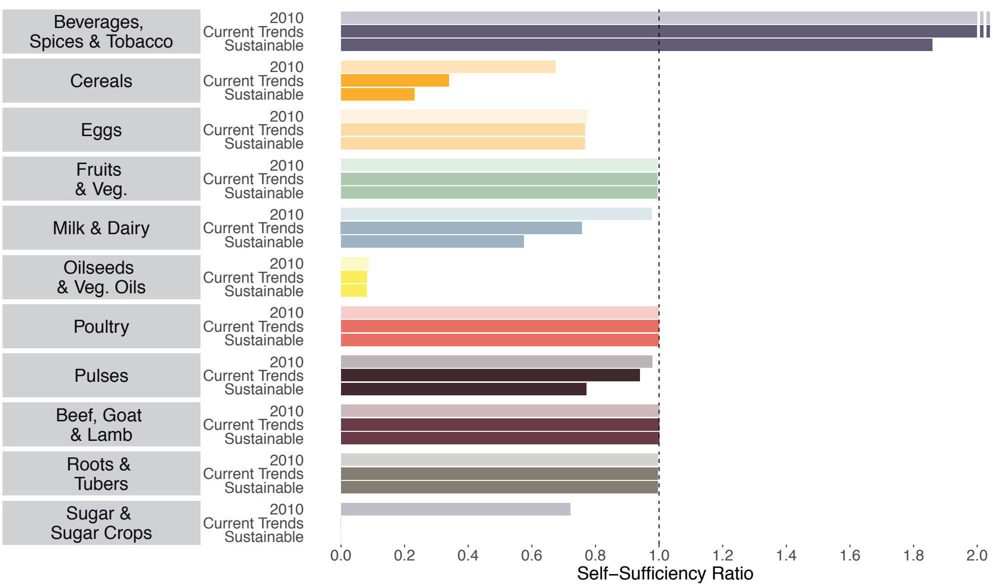
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Rwanda's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

In 2010, Rwanda appeared to be self-sufficient mostly in livestock products including poultry meat, beef, goat lamb, and fruits and vegetables, roots and tubers. It is also self-sufficient in beverages, spices and tabacco, which will be exported; and an importer of other remaining products for both Current Trends and Sustainable Pathways.

Under the Current Trends Pathway, we project that Rwanda would be self-sufficient in beverages, spices and tobacco, poultry meat, beef, goat lamb, fruits and vegetables, and roots and tubers in 2050, with self-sufficiency by product group remaining stable for the majority of products from 2010 – 2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are cereals, eggs, milk and dairy, oilseeds and vegetables, pulses, sugar and sugar crops, and this dependency will increase until 2050. In contrast, under the Sustainable Pathway, Rwanda remains self-sufficient in beverages, spices and tobacco, poultry meat, beef, goat lamb and for fruits and vegetables and roots and tubers, but would not be self-sufficient in cereals, eggs, milk and daily, oilseeds and vegetable oils, pulses, sugar and sugar crops by 2050, representing lower self-sufficiency. This is explained by changes in volume of productivity and change in diets.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for beverages, spices and tobacco, indicate a high level of self-sufficiency in these categories.

Diversity

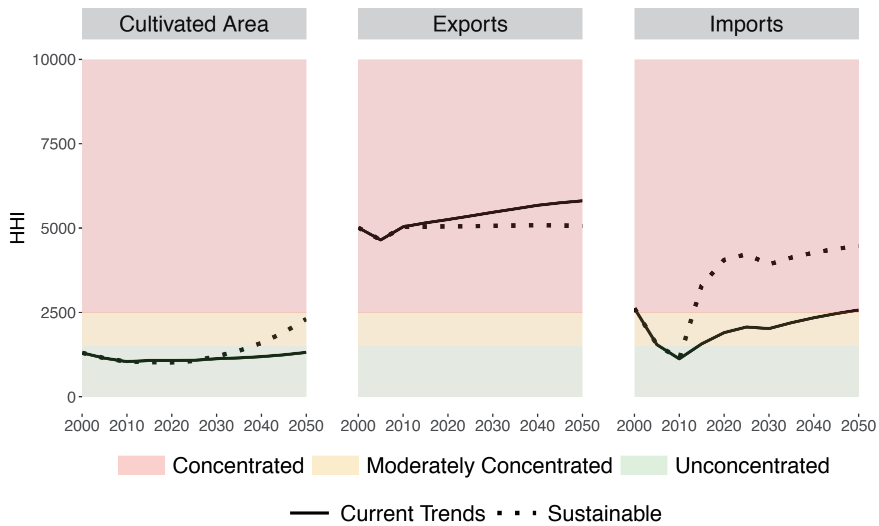
The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

According to the HHI, the planted crop area in 2010 is unconcentrated. While imports are not concentrated, exports are concentrated. Under the Current Trends Pathway, we project high concentration of crop exports and imports and low concentration in the range of crops planted in 2050, trends which increase over the period 2010 - 2050. This indicates low levels of diversity across the national production system and imports and exports. In contrast, under the Sustainable Pathway, we project high concentration of crop exports and imports, and medium concentration in the range of crops planted in 2050, indicating moderate levels of diversity across the national production system and imports and exports (Figure 10). This is explained by changes in the types of crops planted and political economy considerations.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

Rwanda is fighting to become a developed, climate-resilient, low-carbon economy by 2050 (Parker Helen, 2015). Under these Pathways, we assume that moving towards more sustainability should focus first and foremost on increasing the quality of diets for Rwanda's growing population. According to our results, this may lead to an unwanted tradeoff in terms of GHG emissions from AFOLU, which increase by 335% by 2050 between our Current Trends and Sustainable Pathways. This tradeoff may also be explained by the absence of afforestation, such as those suggested by the Bonn Challenge (Rwanda has pledged 2 Mha by 2030). We do not consider afforestation in the FABLE Calculator for Rwanda as afforestation could cause both a decrease in available calories and overall agricultural production due to the reduction of croplands and pasture.

Moreover, we do not change the extent of protected areas in either the Current Trends or Sustainable Pathways due to land shortages and an increasing population that depends on a small area of land. Instead, we recommend stronger measures to ensure the effectiveness of existing protected areas and the integration of biodiversity into national development policies and programs. Finally, we also assume that the consumption of animal products and, in particular, poultry and eggs will increase by 277% and 218%, respectively, between 2020 and 2050 due to the increase in pasture area, though cropland will continue to decrease due to pressure from population growth. While we find that livestock productivity will increase, livestock production will remain the largest source of emissions from AFOLU, making its proper management critical.

Though our assumptions do not respond to the objective of reducing GHG emissions, these tradeoffs and changes show that the adoption of an integrated approach to planning and sustainable land use management should be considered. It is important to note that we were unable to include agroforestry in this analysis due to the limitations of our model, though agroforestry is a common agricultural practice in Rwanda. This may influence our results and will be addressed in future analyses.

Moreover, Rwanda has proposed various actions and goals to support forests to mitigate GHG emissions as part of its NDC. These actions and goals include the deployment of improved forest management for degraded forest resources without converting additional land, as well as the use of mixed-species approaches (agroforestry) that contribute significantly to achieving mitigation objectives and adaptation benefits of ecosystem resilience and biodiversity conservation (Republic of Rwanda, 2015). Furthermore, Rwanda's Green Growth and Climate Resilience Strategy, Clean Development Mechanism (CDM), and Nationally Appropriate Mitigation Actions (NAMAs) are also important policies for achieving important climate goals. In the future, we will seek to better capture these policies in our analysis and will explore with stakeholders how to address them while still balancing the need to ensure food security and better nutrition. One viable pathway is climate-smart agriculture, which aims to achieve the triple win of improving food security and climate change adaptation, while contributing to mitigation, if possible.

Additional policies and programs to improve land use are already being implemented in Rwanda. These include measures to modernize Rwanda's agriculture sector. The Crop Intensification Programme (CIP) is the main policy adopted by the Rwandan government to bring about agricultural modernization. It has led to encouraging results in terms of productivity for staple crops (Cioffo et al., 2016). This program could be interlinked with government efforts to store and manage production to support domestic food security. Additional measures could help Rwanda raise the level of ambition of its objectives for sustainable land-use and food systems: strengthening its adaptive capacity to manage and mitigate the impact of disasters, including insurance and building storage at the national and household level; adopting technologies for the efficient use of irrigation water and fertilizer; promoting organic farming and conservation agriculture; advancing food processing technologies; and promoting farmer education focused on developing adaptive capacities and the rapid uptake of new technologies, as well as family planning.

Such measures may help address some of the several challenges of Rwanda's agricultural sector, which faces increasing environmental degradation that results in declining productivity. This problem will likely be further aggravated by the growing population pressure. Moreover, over the near term, due to COVID-19, the unemployment rate is likely to rise. This will further increase the pressure on land without incorporating farm inputs and lead to a decrease in yields, causing food shortages, and increases in poverty and malnutrition rates. In addition, COVID-19 had a negative impact on certain links along the agricultural value chain. Some products, including livestock products such as meat, milk, and eggs, and horticulture products such as vegetables, fruits, and roses, have suffered from limitations to domestic markets mainly due to the lockdown, and the temporary closure of hotels and restaurants. The goods meant for exports have also faced challenges linked to a decreasing market niche. Thus, the government has deployed additional efforts to ensure that all potential lands are cultivated, and that the production yield improves at the end of the season. For instance, in the Eastern Savanna region, the government has provided farmers with mechanization facilities to increase the cropped land as well as irrigation solutions for the upcoming dry season.

All this may impact the government's goal to reduce Rwanda's poverty rate to 20% by 2020 (Republic of Rwanda, 2017). Analysis of poverty trends by the National Institute of Statistics of Rwanda (2016) has shown that 39.1% of the population still lives in poverty, including 16.3% who live in extreme poverty. This trend will be aggravated due to COVID-19, which will have a large impact on food accessibility, given the low cash flow induced by the high rate of unemployment in the mid-term. Therefore, measures on how land can be used sustainably must be urgently taken into consideration. Otherwise, the processes of land fragmentation and soil degradation will accelerate. To reduce the pressure on the land, the government should design and implement policies to further develop the non-farm economy. Education and capacity building programs that support self-employment and entrepreneurship could help achieve this. Lastly, addressing the weaknesses in the agri-food value chain such as food distribution will also be essential to mitigate the impacts of COVID-19 on food security.

Annex 1. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
The population is expected to reach 22 million by 2050. Based on the projections that the population will more than double from 11 million today to 22 million by 2050, due to their growing rate of 2.8% per year. Based on Republic of Rwanda (2011). (SSP2 scenario selected)	The population is expected to reach 20 million by 2050. The population growth rate is estimated at 2.37% for 2013 and it is estimated to decrease to 1.89% in 2032. Based on National Institute of Statistics of Rwanda, and Rwanda's Ministry of Finance and Economic Planning (2012). (SSP2 scenario selected)

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
We assume that there will be no constraint on the expansion of the agricultural land outside beyond existing protected areas and under the total land boundary. Based on land shortage, about 30% of the households cultivate less than 0.2 ha, accounting for about 5% of total arable land, while about 25% cultivate more than 0.7 ha, accounting for 65% of the national farmland. 15% of rural households farm less than 0.1ha, many of which are female-headed households who cultivate 1.32% of national cultivable land. Based on Michigan State University (2016) and Rwanda's Ministry of Agriculture and Natural Resources (2018).	We assume that deforestation will be halted beyond 2030. Based on readiness proposal prepared by Rwanda to Reduce Emissions from Deforestation and Forest Degradation (REDD+) which goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. Based on Rwanda's Ministry of Natural Resources (2017).

LAND Afforestation or reforestation target (1000 ha)

Current Trends Pathway	Sustainable Pathway
We do not expect afforestation/reforestation. Based on the Ministry's report noting that the role of forest is complemented by Agroforestry. Based on Rwanda's Ministry of Lands and Forestry (2018). (No Afforestation scenario selected)	Same as Current Trends

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
Protected areas remain stable: by 2050 they represent 9% (0.23Mha) of total land. Based on Rwanda's Ministry of Natural Resources (2017).	Same as Current Trends

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Pathway
By 2050, crop productivity reaches: • 2.4 tons per ha for beans. • 10.2 tons per ha for rice. • 6.8 tons per ha for wheat. The above results are in line with the national targets of increasing crop productivity through an intensification program. Based on Rwanda's Ministry of Agriculture and Animal Resources (2012).	By 2050, crop productivity reaches: • 2.4 tons per ha for beans. • 10.7 tons per ha for rice. • 6.0 tons per ha for wheat. The above results are in line with the national targets of increasing crop productivity through an intensification program. Based on Rwanda's Ministry of Agriculture and Animal Resources (2012).

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

Current Trends Pathway	Sustainable Pathway
By 2050, livestock productivity reaches: • 2.4 tons per head for chicken. • 14.2 tons per head for eggs. • 1.9 tons per head for milk. Based on the International Livestock Research Institute (2017), these results are in accordance with national targets for increasing productivity and total production in livestock value chains for cow dairy, red meat-milk, poultry, and pork based on using better genetics, feed, and the adoption of health services, among others.	Same as Current Trends

PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

Current Trends Pathway	Sustainable Pathway
By 2050, the average ruminant livestock stocking density is 2.35 TLU/ha per ha. Based on FABLE (2019), there is no data on national average livestock stocking densities to compare this value with.	Same as Current Trends

PRODUCTION Post-harvest losses

Current Trends Pathway	Sustainable Pathway
By 2050, the share of production and imports lost during storage and transportation is 25% for corn, 10% for plantain and 4% other cereals. The above values are not in line with Rwanda's targets aiming to provide 100% farmers with access to services for post-harvest treatment and storage of food crops, and reduce post-harvest losses to at least 1% by 2030 from 10.4%, 27.4% and 8.3% in 2014 for maize, beans and rice respectively (Republic of Rwanda, 2015).	Same as Current Trends

TRADE Share of consumption which is imported for key imported products (%)	
Current Trends Pathway	**Sustainable Pathway**
By 2050 the share of total consumption which is imported is: • 69% for wheat. • 124% for raw sugar. • 81% for rice. Rwanda's Ministry of Trade and Industry (2010) reported that the country's main commodity imports are animal, vegetable fats and oils, wheat, sugar, maize, rice, and palm oil. Thus, there is an increase in imports for the above-mentioned commodities.	Same as Current Trends.
TRADE Evolution of exports for key exported products (1000 tons)	
By 2050, the volume of exports is: • 33 tons by 2050 for tea • 26 tons by 2050 for coffee Based on Ministry of Agriculture and Animal Husbandry (2008) and the Ministry of Agriculture and Animal Resources (2008), the government prioritizes the progress in the coffee and tea sectors by increasing the quantity and the quality of tea and fully and semi-washed coffee exported. (For Scenario: E3 where exports are multiplied by 1.5 by 2050)	By 2050, the volume of exports is: • 66 tons by 2050 for tea. • 52 tons by 2050 for coffee. Based on the Ministry of Agriculture and Animal Resources (2018), there is expected to be a significant increase in fertilizer application, increase in the land area covered by coffee and tea, the introduction of drought and disease resisting varieties, and an increase of mulched coffee up to 80%. (*For Scenario: E1 where exports are multiplied by 3 by 2050*)

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)	
Current Trends Pathway	**Sustainable Pathway**
By 2030, the average daily calorie consumption per capita is 2,171 kcal and is: • 454.8 kcal for roots • 536.4 kcal for cereals • 286.2 kcal for fruits and vegetables • 251 kcal for oilseeds and vegetables oils • 94 kcal for milk • 17 kcal for red meat Based on FABLE Calculator (2020). (*National Health Diet scenario selected*)	By 2030, the average daily calorie consumption per capita is 2,548 kcal and is: • 379.9 kcal for roots • 605.6 kcal for cereals • 278.02 kcal for fruits and vegetables • 360 kcal for oilseeds and vegetables oils • 135 kcal for milk • 34 kcal for med meat Based on FABLE Calculator (2020). (*For Scenario: Fat Diet scenario selected*)
FOOD Share of food consumption which is wasted at household level (%)	
By 2030, the share of final household consumption which is wasted at the household level is 5%. Based on FABLE (2019), there is very little research on food waste in Rwanda, thus there is no data to compare this value with.	Same as Current Trends

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
There is no data available for Rwanda.	There is no data available for Rwanda.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model. HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 2. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needle leaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tons

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – ton

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – ton per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- ton per TLU, kilogram per TLU, ton per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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South Africa

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in South Africa. It presents two pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. They were derived from policy and other documents and modeled with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019).

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how South Africa's Nationally Determined Contribution (NDC) and Long-Term Low Emissions Development Strategy treat the FABLE domains. According to the NDC, South Africa has committed to plateauing and reducing emissions starting from 2025, before which the country will increase emissions and peak at 614 MT CO_2. Although South Africa's NDC includes emissions reductions from agriculture, forestry, and other land use (AFOLU), and considers the land sector to be a net carbon sink, it also entails uncertainty about how the emission reductions from these sectors will be achieved. The current estimates are that grasslands and savannas hold three quarters of the country's carbon stocks, making them significant contributors to the national greenhouse gas budget (DEA, 2015a). South Africa is working to reduce this uncertainty in the data over time, with a view to arrive at a comprehensive

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2015)	N/A	N/A	2025-2030	398-614 Mt CO_2e	Energy, industrial processes & product use, forestry, agriculture, and other land use	N	Y	N	Food security, water, afforestation
LT-LEDS (2020)	N/A	N/A	2025-2030 (398-614 Mt CO_2e)	2050 (212 - 428 Mt CO_2e)	Forestry, agriculture	Y	Y	N	

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source. South Africa's Department of Environmental Affairs (2015b, 2020)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

accounting approach for land-based emissions and removals. According to the 2015 climate change sector plan, agriculture, forestry and fisheries mitigation options include the development and implementation of policies addressing conversion of land from sink to sources, reducing enteric fermentation, reducing tillage, and reducing fossil fuel dependence in the sector (DAFF, 2015a).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2016 (DEA, 2016a), as listed on the CBD website (CBD, 2020) which are related to at least one of the FABLE Targets. In comparison with FABLE Targets, the NBSAP targets have a social-ecological perspective, ranging from protected area expansion, to expanding the bio economy and public awareness raising.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE Targets

NBSAP Target	FABLE Target
(1.1) **The network of protected areas and conservation areas includes a representative sample of ecosystems and species and is coherent and effectively managed. This protected network has increased to 9% of total land in 2018 (about 109 800km^2).** **Areas protected under Protected Areas Act: By 2028, 10.8 million land-based hectares are protected.** **The South African national protected area strategy (2016) sets a target of 413 163km2 to meet long-term protected area targets. The medium-term goal of this strategy is to add 255 877km^2 for both marine and terrestrial protection to the protected area network by 2036. Of this, 146 814km^2 is required for terrestrial systems (a 133% increase from the current 108 900 km^2 protected area network). The long-term strategy aims to increase protected areas by an additional 413 163km^2 (Balfour, Holness, Jackelman, & Skowno, 2016).**	**BIODIVERSITY:** At least 30% of global terrestrial area protected by 2030

Brief Description of National Pathways

Among possible futures, we present two alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in South Africa.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by low population growth (from 58 million in 2020 to 67 million in 2050), no agricultural expansion, no afforestation target, low productivity increases in the agricultural sector, an evolution towards a high-sugar-content and processed-food diet (including meats and fat), and no change in postharvest losses (see Annex 1). This corresponds to a future based on current policy, risks, and historical trends that would also see considerable progress with regards to biodiversity loss, urbanization, and soil degradation (von Bormann, 2019). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, rice, soyabean, and wheat (see Annex 1).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to lower food loss but will also lead to a similar trajectory in population growth, agricultural expansion, and no afforestation target (see Annex 1). This corresponds to a future based on the adoption and implementation of new ambitious policies that would also see considerable progress with regards to reductions in food losses motivated by economic cost, input losses, and social pressure (Nahman, de Lange, Oelofse, & Godfrey, 2012; von Bormann et al., 2017). Although an unlikely pathway by 2050 for South Africa due to the required reduction in meat, we also include the healthy diet scenario recommended in the EAT-*Lancet* for the Sustainable Pathway. With the other FABLE country teams, we embed this Sustainable Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.
Land and Biodiversity

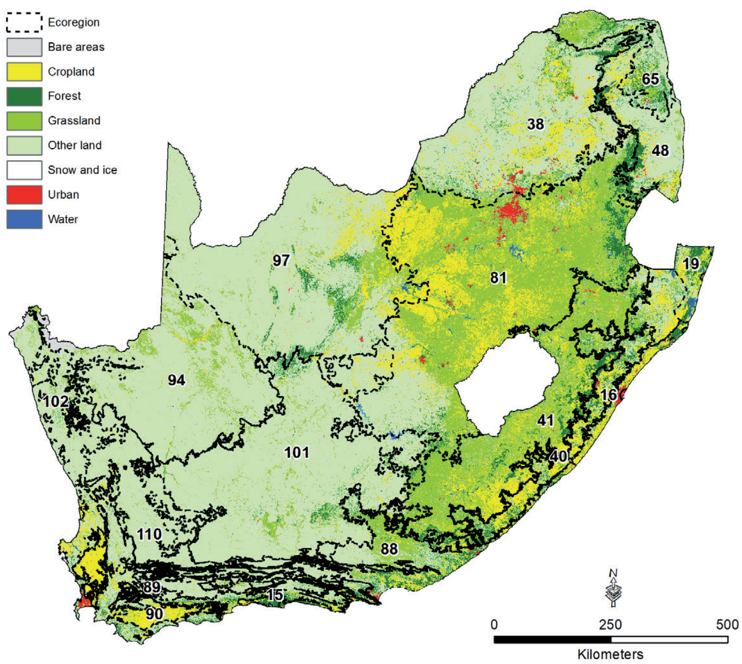
Land and Biodiversity

Current State

In 2010, South Africa was covered by 10% cropland, 69% grassland, 8% forest, 1% urban, and 12% other natural land (Map 1). Agricultural areas overlap with most natural areas and remain a major source of biodiversity loss, with land clearing for croplands being a key driver alongside human settlements, plantation forestry, mining, and infrastructure development (Skowno et al., 2019).

We estimate that land where natural processes predominate[2] accounted for 44% of South Africa's terrestrial land area in 2010 (Map 2). The 81-Highveld grasslands hold the greatest share of land where natural processes predominate, followed by 97-Kalahari xeric savanna and 101-Nama karoo shrublands (Table 3). Across the country, while 10 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 15% of land where natural processes predominate is formally protected. The country's National Biodiversity Assessment report shows that areas of poor ecosystem condition – defined by combining biodiversity information with human pressures such as mining, human settlements, and agriculture – occur across all ecosystems in the country (Skowno et al 2019).

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

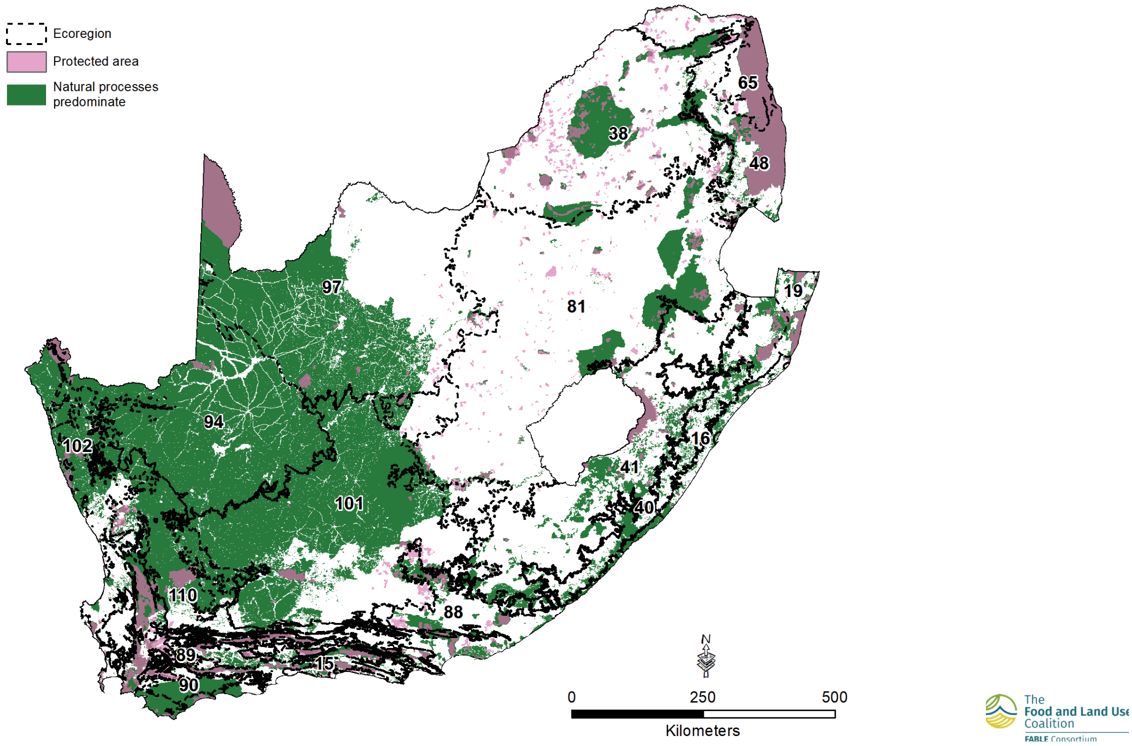


Note. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 2.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 62% of South Africa's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in 81-Highveld grasslands, followed by 41-Drakensberg grasslands and 38-Central bushveld. The regional differences in extent of biodiversity-friendly cropland can be explained by intensive production of key crops and extensive production of livestock.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Note. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
101	Nama Karoo shrublands	16224.2	2.3	62.1	1.8	98.2	238.3	69.3
102	Namaqualand-Richtersveld steppe	3292	6.3	78.3	7.8	92.2	17.9	90.1
110	Succulent Karoo xeric shrublands	5719.1	6.1	63.9	8.3	91.7	89	75
116	Southern Africa mangroves	85.2	13.8	53.2	25	75	7.2	88.7
15	Knysna-Amatole montane forests	205.7	35.6	50.4	62.4	37.6	38.7	45.7
16	Kwazulu Natal-Cape coastal forests	1098.4	3.4	50.4	6.1	93.9	329.4	58.4
19	Maputaland coastal forests and woodlands	908.9	24.5	43	55.5	44.5	120.9	87.4
38	Central bushveld	11698.1	10.3	22.2	21.7	78.3	1187.5	72.7
40	Drakensberg Escarpment savanna and thicket	3508.1	0.6	30.5	1.4	98.6	483.6	81.1
41	Drakensberg grasslands	9416.1	4.7	24.8	16.6	83.4	1446.1	83.9
48	Limpopo lowveld	4927.8	30.2	44.2	64.6	35.4	439	79.8
65	Zambezian mopane woodlands	2649.3	46.5	42.2	94.8	5.2	106.9	90
66	Zambezian-Limpopo mixed woodlands	0.06	100	100	100	0	0.01	100
81	Highveld grasslands	22878.8	3.9	13.1	14.1	85.9	5475.9	56.2
88	Albany thickets	3680.9	12.6	32	25.4	74.6	260.7	77.1
89	Fynbos shrubland	5377.7	31.9	51.5	51.2	48.8	630.3	64.6
90	Renosterveld shrubland	2843.8	3	41.6	4.7	95.3	1140.9	27.8
94	Gariep Karoo	10981.4	1.5	91.7	1.6	98.4	77.3	80.5
97	Kalahari xeric savanna	16859	7.1	54.3	12.1	87.9	1266.2	55.2

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

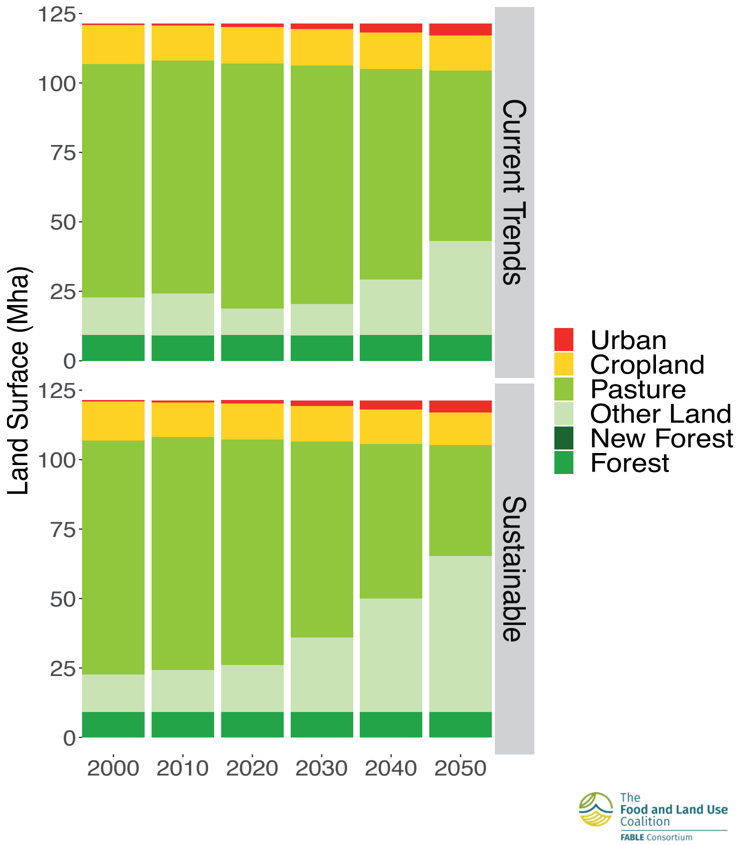
3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including constraints on the expansion of agricultural land beyond its current area, and no planned afforestation (see Annex 1).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in pasture area and cropland, and a decrease in other land areas. This trend evolves over the period 2030-2050: other land areas increases dramatically while cropland and pasture areas decrease, with pastures declining significantly (Figure 1). The expansion of the planted area for sunflower and wheat explain 96% of total cropland expansion between 2010 and 2030. For sunflower, 100% of the expansion in demand is explained by non-food consumption and the expansion in supply is explained by an increase of 193% in production. For wheat, the increase in productivity and production is the main cause for the supply increase, while the rise in demand is driven by food consumption (79%) and feed (17%). Pasture decline is mainly driven by the decrease in cattle, while livestock productivity per head increases and ruminant density per hectare of pasture remains constant over the period 2020-2030. The increase in pasture between 2010 and 2030 is due mainly to an increase in the production of milk for food consumption. Between 2030-2050, a decrease in planted area is explained by a decrease in demand for wheat used as food (151%), while a decrease in pasture land is explained by a decrease in beef consumption from 149 kt to 57.9kt. This results in a reduction of land where natural processes predominate by -1% by 2030 and expansion by 42% in 2050 compared to 2010, respectively.

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

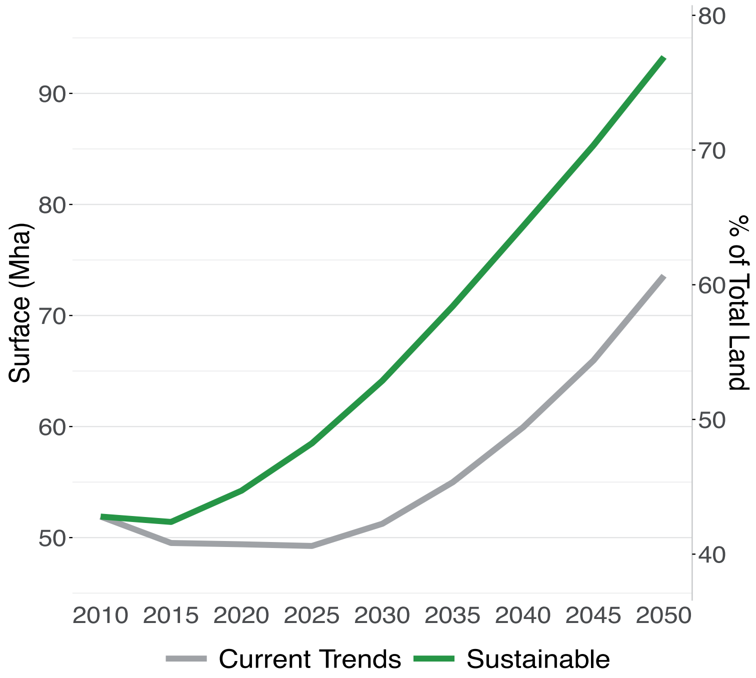


Source: Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000.

In the Sustainable Pathway, the diet assumption is based on a hypothetical extreme, radical change (as far as meat consumption in the region), which may not be feasible given the vast suitability of South Africa for livestock production (see Annex 1).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in South Africa in the Sustainable Pathway: (i) no impact on deforestation, reforestation or afforestation in either pathways, (ii) a larger increase in other land during 2030 – 2050 compared to the decline in 2010 – 2030 in the Current Trends Pathway, (iii) a more dramatic decrease in pastures and a moderate decrease in cropland. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by a reduction in demand for milk and beef and the reduction in the production of these products. This leads to an increase in the area where natural processes predominate: the area stops declining by 2015 and increases by a staggering 80% between 2030 and 2050 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate

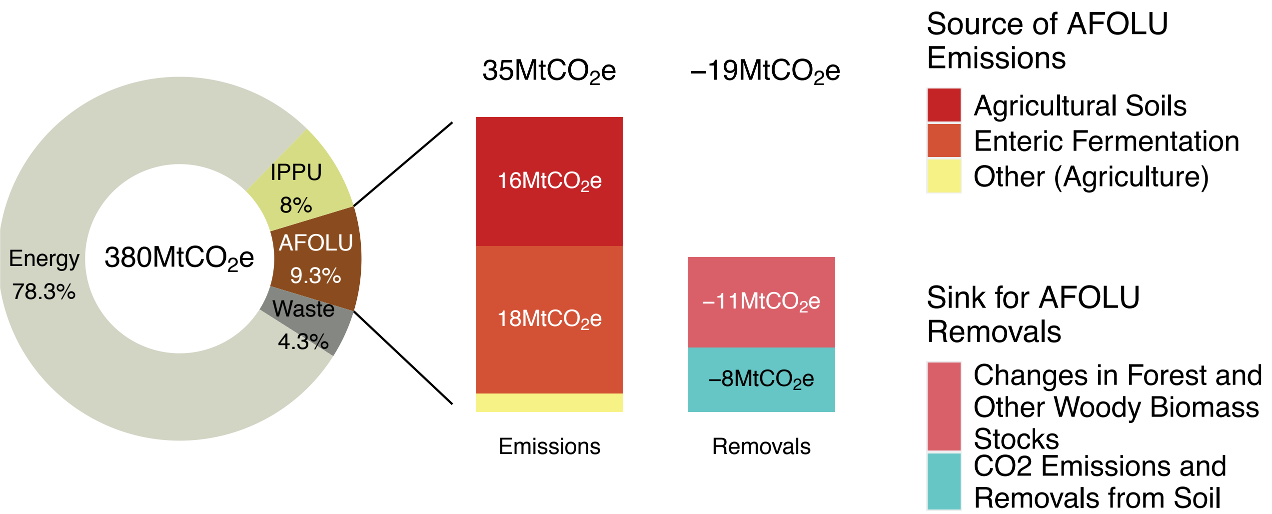


GHG emissions from AFOLU

Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 9.3% of total emissions in 1994 (Figure 3). Enteric fermentation is the principle source of AFOLU emissions, followed by agricultural soils and manure management. This can be explained by the large numbers of herds in South Africa, and the widespread suitability of land for livestock (69%) compared to 11% for crops (DEA, 2016b).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 1994



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease to 14.1 Mt CO_2e/yr in 2030, before dropping significantly to -96.6 Mt CO_2e/yr in 2050 (Figure 4). In 2050, CH_4 emissions from livestock is the largest source of emissions (12.1 Mt CO_2e/yr) while carbon sequestration from vegetation becomes a sink (-129.4 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for N_2O from crops (7%) while a staggering reduction in emissions is computed for carbon sequestration from vegetation (550%).

In comparison, the Sustainable Pathway leads to a reduction of AFOLU GHG emissions by -85% in 2050, compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Pathway is dominated by carbon sequestration from vegetation and livestock (Figure 5). Reduction in milk for food and livestock production are the most important drivers of this reduction.

Reductions in GHG emissions could be achieved in large part through the decrease in milk and meat consumption. These measures could be particularly important when considering that AFOLU baselines are still not clearly defined (DEA, 2016b)), and that these targets can potentially be incorporated into the current process to enhance the NDC.

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

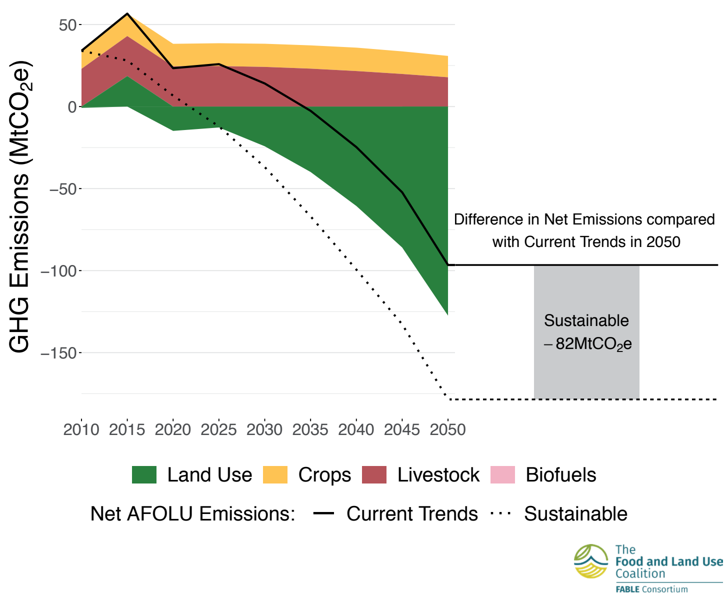
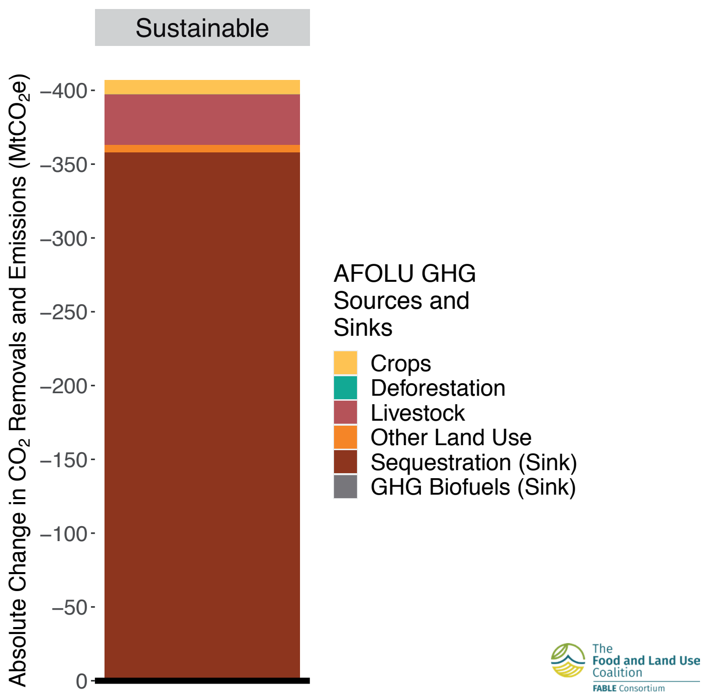


Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

6.1% of the population undernourished in 2015-2017. This share has increased from 4.5% since 2008-2010 (FAO, 2020).

27.4% of children under 5 stunted and 2.5% wasted in 2016 (World Bank, 2016a, 2016b)

Micronutrient Deficiency

25.8% of women and 36.8% of children under 5 suffer from anemia in 2016, which can lead to maternal death (WHO, 2020).

Around 18.9% of pregnant women and 16.9% of children had a poor vitamin A status in 2005 (Ritchie, 2017)

Overweight/ Obesity

28.3% of adults were obese in 2016 (Ritchie, 2017). These shares have increased since 1990 (Ritchie, 2017).

51.9% of adults and 31.8% of children were overweight in 2016 (Global Nutrition Report, 2019). These shares have increased since 2000 (Ritchie, 2017)

Disease Burden due to Dietary Risks

9.4% of deaths are attributable to dietary risks (Institute for Health Metrics and Evaluation, 2020)

12.7% of the adult population suffers from diabetes (World Bank, 2019)

9.4% of premature deaths were attributed to obesity in 2017 (Ritchie, 2017)

Table 4 | Daily average fats, proteins and kilocalorie intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,958 (1,827)	3,009 (1,845)	2,812 (2,073)	3,060 (1,852)	2,665 (2,079)
Fats (g) (recommended range)	79 (66-99)	91 (68-100)	78 (62-94)	106 (68-102)	78 (59-88)
Proteins (g) (recommended range)	81 (74-259)	82 (75-263)	78 (70-246)	87 (76-268)	77 (66-233)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 57% higher in 2030 and 64% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals, oils, and sugar, and animal products represent 16% of the total calorie intake. We assume that the consumption of animal products, and in particular milk, will increase by 77% and pork by 56% between 2020 and 2050. The consumption of nuts (90%), beverages and spices (51%), fruits and vegetables (38%) will also increase while cereals and red meat consumption will decrease. Compared to the EAT-*Lancet* recommendations (Willett et al., 2019), red meat, sugar, poultry, eggs, and roots are over-consumed in 2050 (Figure 6). Moreover, fat and protein intake per capita are in line with the dietary reference intake (DRI) in 2030, although fat exceeds the dietary reference intake (DRI) in 2050. This can be explained by an increase in consumption of milk and pork between 2020 – 2050 (Figure 6).

Under the Sustainable Pathway, we assume that diets will transition towards the EAT-*Lancet* diet (Willett et al., 2019). The ratio of the computed average intake over the MDER decreases to 34% in 2030 and 27% in 2050 under the Sustainable Pathway. Compared to the EAT-*Lancet* recommendations, only the consumption of sugar and red meat remains outside of the recommended range with the consumption of poultry, eggs, and roots being within the range (Figure 6). Moreover, the fat and protein intake per capita are within the recommended ranges in 2030 and 2050, showing some improvement compared to the Current Trends Pathway. This diet was mainly selected for illustrative purposes as it is unlikely to fit the South African context.

Figure 6 | Comparison of the computed daily average kilocalorie intake per capita per food category across pathways in 2050 with the EAT-*Lancet* recommendations

Current Trends 2050

Sustainable 2050

FAO 2015

Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

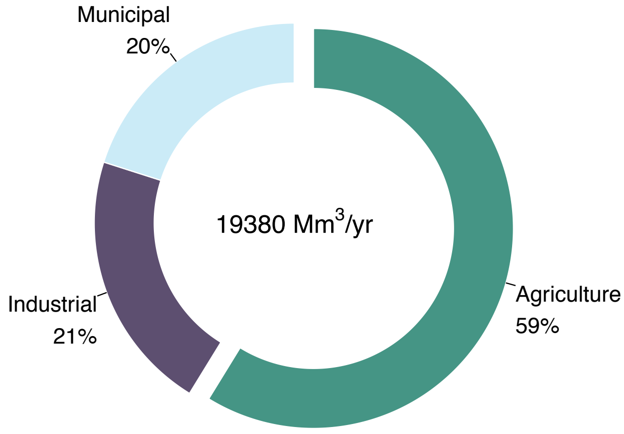
Current State

South Africa is characterized as a water scarce country with 470 mm average annual precipitation. The agricultural sector represented 60% of total water withdrawals in 2017 (Figure 7; FAO, 2017). The three most important irrigated crops, corn, wheat, and sugarcane account for 48%, 18%, and 14% of total harvested irrigated area. South Africa exported 11% of corn in 2015, and 75% of sugar in 2016.

Pathways and Results

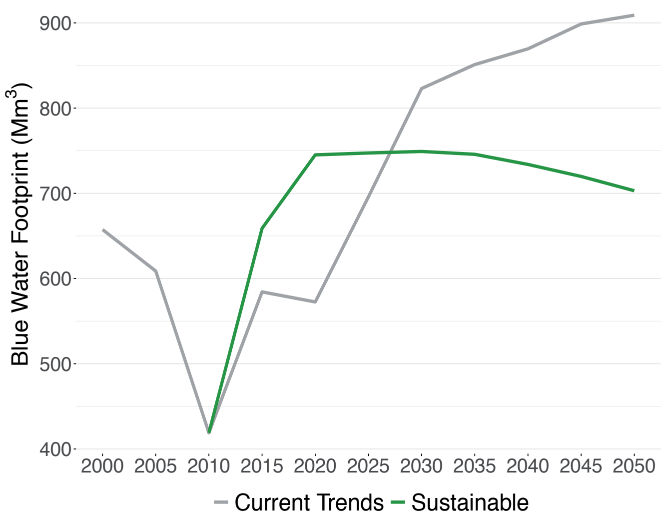
Under the Current Trends Pathway, annual blue water use decreases between 2000-2015 (657 and 584 Mm^3/yr), before increasing to 823 Mm^3/yr in 2030 and 909 Mm^3/yr in 2050, respectively (Figure 8), with wheat, oats, and barley accounting for 78%, 9%, and 7% of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Pathway, the blue water footprint in agriculture decreases and reaches 749 Mm^3/yr in 2030 and 703 Mm^3/yr in 2050, respectively. This is explained by a rise in imports of beans and pulses, an increase in productivity of soybeans, and a decrease in the production of corn and sugarcane.

Figure 7 | Water withdrawals by sector in 2016



Source. Adapted from AQUASTAT Database (FAO, 2017)

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



4 We compute the blue water footprint as the average blue fraction per ton of product times the total production of this product. The blue water fraction per ton comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

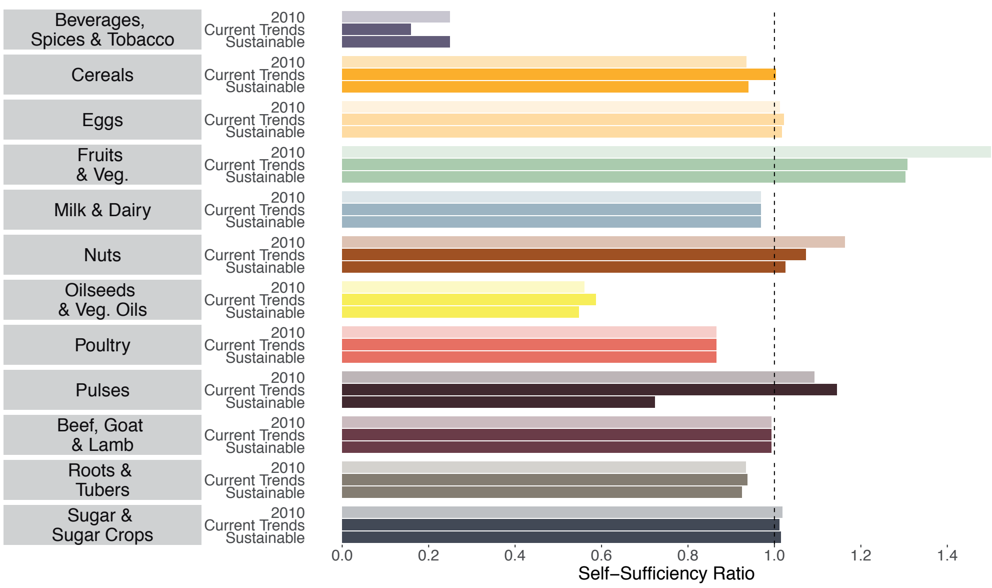
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge South Africa's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

In 2010, South Africa was not self-sufficient in one of its main staple crops: corn. This is significant because a large part of the population depends on this crop for daily use. Interestingly, South Africa is self-sufficient in fruits and vegetables, which are primarily export oriented.

Under the Current Trends Pathway, we project that South Africa would be self-sufficient in fruits and vegetables, pulses, nuts, eggs, sugar, and cereals (cereals only in 2050), with self-sufficiency by product group remaining stable for the majority of products from 2010–2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are beverages, spices and tobacco, and oilseeds and vegetable oils, and this dependency will remain relatively stable until 2050. In contrast, under the Sustainable Pathway, South Africa remains self-sufficient in fruits and vegetables, nuts, sugar, and eggs but would no longer be self-sufficient in pulses and cereals by 2050, representing lower self-sufficiency.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

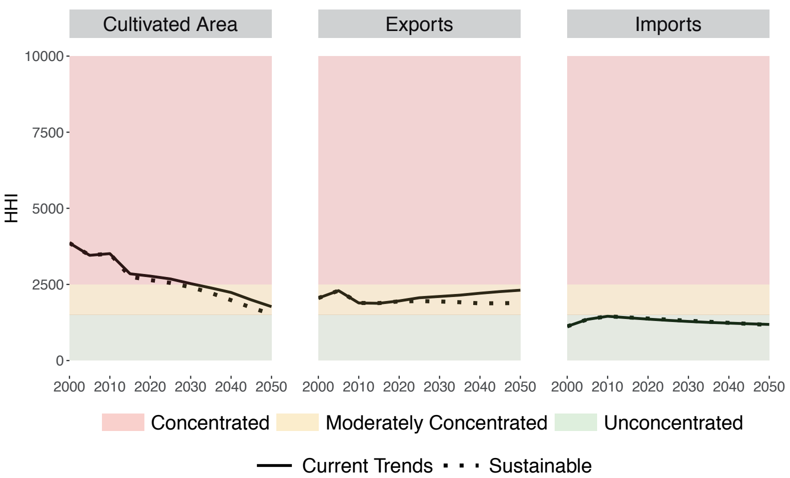
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

According to the HHI, cultivated area for crops was highly concentrated in 2010. During the same period, imports were highly diversified while exports were moderately diversified.

Under the Current Trends Pathway, we project medium concentration of crop exports, low concentration of crop imports, and medium concentration of planted crops in 2050. Exports and imports remain relatively stable, with exports remaining moderately concentrated and imports remaining unconcentrated from 2010 to 2050. This indicates moderate levels of diversity for exports and high levels of diversity for imports. Planted crop area changes from high concentration in 2010 to moderate concentration by 2050. Under the Sustainable Pathway, we project similar concentration of exports with a slight decrease in diversity of exports. Similarly, there is no change in the concentration of imports, while planted crops become more diverse (moderate concentration) in 2050, compared to the Current Trends Pathway (Figure 10). The change in concentration of planted area is explained by the reduction of consumption of milk and beef, substituted by increased consumption of nuts and pulses, and a decrease in the production of main crops (corn and sugarcane).

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

The two pathways described in this chapter represent a comparison between the Current Trends, which illustrates the implementation of a few current policies but not all (e.g. no protected area expansion; and medium Sustainable Pathway, which shows the implementation of several current and aspired policy targets. Both pathways lead to a reduction in land needed for agriculture in 2050, an increase in biodiversity protection, and reductions in emissions from the AFOLU sectors. The changes in biodiversity and GHG emissions are driven by a dietary shift, exemplified in the adoption of the EAT-Lancet recommended diet (Willett et al., 2019). While this recommended diet might not fit with the South African context where much of the land is suitable for livestock production, it is nevertheless an interesting exercise to explore what the implementation of this diet could mean for the country.

The South African protected area strategy aims to increase the terrestrial protected area by an additional 146,814 km^2 by 2036 (the 20-year target period from the publication of the strategy) (Balfour et al., 2016). This is a 133% increase from today's 108,900 km^2, and an increase from 10% of total land in 2018 to 21% by the 2030s. This will require unprecedented efforts in the design and implementation of policies. It is obviously a tall order but not entirely insurmountable. For example, during the period 2010 – 2018, South Africa's terrestrial mainland protected area increased by 11%. To achieve this new target, the protected area network will have to grow by similar rates over the next 15 years.

The FABLE Calculator estimates that by 2035, protected areas could grow by up to 117,860 km^2, which is only 28,954 km^2 short of the target expressed in the protected area expansion strategy. When we account for land where natural processes predominate, an additional 64,677 km^2 becomes available for biodiversity conservation – even though this land is outside of protected areas. This highlights the importance of conservation beyond protected areas. Both the intention to incorporate these areas into formal protection as expressed by the protected area expansion strategy (Balfour et al., 2016) and the fact that biodiversity intactness scores in South Africa are high in rangelands (Biggs, Reyers, & Scholes, 2006), attest to this importance.

South Africa does not have an explicit baseline to start reducing GHG emissions included in the Nationally Determined Contribution (NDC) but it has a target to reduce GHG emissions to between 398 Mt CO_2e and 614 Mt CO_2e over the period 2025 – 2030. Although there is no explicit target for the AFOLU sector expressed in the NDC, the Department of Environmental Affairs started a process to define these targets (Department of Environmental Affairs, 2016; Stevens et al., 2016). The AFOLU emissions baselines defined for agriculture in this document indicate that emissions will continue to increase up to 2050, whereas the FABLE Calculator shows that up until 2030 (for the Current Trends Pathway) emissions from the sector will increase and then decline, with the decline starting earlier in 2020 for the Sustainable Pathway. The reason for this – as far as the model calculations and the baselines defined in the baseline documents are concerned – is that land-based emissions differ significantly between the two.

In the baseline document of the Department of Environmental Affairs, the capacity of land to sequester carbon ranges from 22.9 Mt CO_2e in 2010 to 32.4 Mt CO_2e in 2050 (DEA, 2016b). In contrast, the FABLE Calculator estimates the land to sequester 08 Mt CO_2e in 2010 and a staggering 127 Mt CO_2e in 2050 for the Current Trends Pathway; and up to 200 Mt CO_2e for the Sustainable Pathway. In the Current Trends Pathway, this decline is explained primarily by productivity gains in livestock production, which may be overstated. The productivity growth assumed to stay constant as 2000-2010 levels until 2050 might not be realistic. In addition to productivity gains, the Sustainable Pathway's declines in pastures are further explained by the significant decreases in meat and milk consumption determined by the shift towards the EAT-Lancet recommended diet, which will require a substantial adjustment to the South African diet. The emissions declines are therefore directly explained by the reduction in herd size, reducing enteric fermentation which accounts for 60% of agricultural emissions in South Africa (DEA, 2016b).

Most changes in land use in the Sustainable Pathway were driven by the change in diet, which reduced the amount of beef consumption and other animal products such as milk. Given that this diet might not be feasible for South Africa, the next steps will be to define a diet scenario that is feasible in the South African national context. Changes driven by a diet that respects this context will reflect more feasible (and realistic) changes in reaching emissions and biodiversity targets. Currently, much of the potential biodiversity and emissions gains depend significantly on the chosen diet. Overall, the pathways defined for South Africa did not benefit from a broader stakeholder engagement (due to COVID-19 primarily). Therefore, it would be beneficial for future projections to consult relevant stakeholders to guide the selection of scenarios.

Annex 1. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway
The population is expected to reach 67 million by 2050 (UN DESA, 2019). (SSP2 scenario selected)	

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway
We assume no expansion of agricultural land beyond 2010 agricultural area levels. (No productive land expansion beyond 2010 value) (BFAP 2018)	

LAND Afforestation or reforestation target (1000 ha)

We do not expect afforestation/reforestation
(DEA, 2015a; Driver et al. 2015).

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway
Protected areas remain stable: by 2050 they represent 10 million ha. (Skowno et al 2019, 2019).	Protected areas increase to 13 million ha in 2050. We used the by-default assumption in the FABLE Calculator which is that in the ecoregions where current level of protection is between 5% and 17%, the natural land area under protection increases up to 17% of the ecoregion total natural land area by 2050.

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Pathway
In the calculator, we obtain the following values of crop productivity by 2050: • 11.31 tons per ha for corn. • 2.71 tons per ha for wheat. • 2.22 tons per ha for soybean. According to other sources, by 2050 crop productivity reaches: • 6 tons per ha by 2030 for white maize; 6.5 per ha by 2030 for yellow maize. • 5.5 tons per ha by 2030 for wheat for summer area, and 3 tons per ha by 2030 for winter area. • Soybean is projected to grow by 2.2% per annum based on current trajectories. (Balfour, 2016; BFAP 2018).	In the calculator, we obtain the following values of crop productivity by 2050: • 9.89 tons per ha for corn. • 2.79 tons per ha for wheat. • 2.22 tons per ha for soybean. According to other sources, by 2050 crop productivity reaches: • 6 tons per ha by 2030 for white maize; 6.5 per ha by 2030 for yellow maize. • 5.5 tons per ha by 2030 for wheat for summer area, and 3 tons per ha by 2030 for winter area. • Soybean is projected to grow by 2.2% per annum based on current trajectories. (Balfour, 2016; BFAP 2018).

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

By 2050, livestock productivity reaches:
- 0.2 t/head for cattle.
- 0.1 t/head sheep and goat.
- 2.0 t/head for pig.

(BFAP, 2018).

PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

By 2050, the average ruminant livestock stocking density is 0.15 TLU/ha. (BFAP, 2018).

PRODUCTION Post-harvest losses

By 2050, the share of production and imports lost during storage and transportation is 33% (von Bormann et al 2017; Oelofse & Naham 2013).

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway
By 2050, the share of total consumption which is imported is: • 100% for rice. • 46% for wheat. • 5% for sunflower. (BFAP, 2018).	

TRADE Evolution of exports for key exported products (tonnes)

Current Trends Pathway	Sustainable Pathway
In the calculator, we obtain the following 2050 values of exports: • 2,699 tons for corn. • 457 tons of apples. • 167 tons of groundnut. According to other sources, by 2050 the volume of exports is: • 1286 tons for corn. • 239 tons for apples. • 138 tons for groundnut. (DAFF, 2017).	In the calculator, we obtain the following 2050 values of exports: • 2,699 tons for corn. • 288 tons of lemons. • 1,312 tons of oranges. According to other sources, by 2050 the volume of exports is: • 107 tons by 2050 for corn. • 112 tons by 2050 for lemons. • 61 tons by 2050 for oranges. (DAFF, 2017).

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)	
Current Trends Pathway	**Sustainable Pathway**
In the calculator, by 2030, the average daily calorie consumption per capita is 3,009 kcal and is: • 1,367 kcal from cereals. • 377 kcal from oilseeds and vegetable oils. • 317 kcal from sugar. • 145 kcal from milk. According to other sources, by 2030, the average daily calorie consumption per capita is 3,060 kcal and is: • 438 kcal for cereals. • 269 kcal for fruits and vegetables. • 254 kcal for milk. • 99 kcal for poultry. (Vorster et al., 2013; Venter et al., 2013).	In the calculator, by 2030, the average daily calorie consumption per capita is 2,812 kcal and is: • 1,344 kcal from cereals. • 311 kcal from oilseeds and vegetable oils. • 277 kcal from sugar. • 94 kcal from milk. According to other sources, by 2030, the average daily calorie consumption per capita is 2,665 kcal and is: • 1,344 kcal for cereals. • 277 kcal for sugar. • 94 kcal for milk. • 115 kcal for poultry. (Willett et al., 2019).
FOOD Share of food consumption which is wasted at household level (%)	
Scenario selected: Same share as in 2010. Source: Nahman et al 2012	Scenario selected: Reduced share compared to 2010. Source: No relevant information found for South Africa.

BIOFUELS Targets on biofuel and/or other bioenergy use	
Current Trends Pathway	**Sustainable Pathway**
Scenario selected: Stable biofuel demand as 2010. Source: Pradhan and Mbhowa 2014; Blanchard et al 2011	

CLIMATE CHANGE Crop model and climate change scenario	
Current Trends Pathway	**Sustainable Pathway**
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 2. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland<50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

Gt – gigatons

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tons

m – meter

Mha – million hectares

mm – millimeters

Mm^3 – million cubic meters

Mt – million tons

t – ton

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – ton per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- ton per TLU, kilogram per TLU, ton per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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Sweden

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in Sweden. It presents three pathways for food and land-use systems for the period 2020-2050: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition (referred to as "Current Trends", "Sustainable", and "Sustainable +" in all figures throughout this chapter). These pathways represent the low, medium and higher bounds of realistic pathways to achieve sustainability in food and land-use systems at the national level. They examine the trade-offs between achieving the FABLE targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders, including representatives from farmers' unions, producers, retailers, government agencies, and environmental organizations, and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Sweden's Nationally Determined Contribution (NDC) treat the FABLE domains. According to the NDC, Sweden has committed to reducing its GHG emissions by 40% by 2030 compared to 1990. This includes emission reduction efforts from energy, industrial processes, agriculture, forestry, and other land use. Envisaged mitigation measures from agriculture and land-use change include food productivity improvement and dietary change towards low-carbon foods, adoption of regenerative agricultural practices such as conservation tillage, utilization of low carbon energy sources, afforestation, and expansion of protected forest areas. Under its current commitments to the UNFCCC, Sweden does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
(EU) NDC (2016)	1990	n/a	2030	At least 40% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Forests

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source: EU (2016)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets included in the National Biodiversity Strategies and Action Plan (NBSAP) from 2011, as listed on the CBD website (CBD, 2020), which are related to at least one of the FABLE Targets. In comparison with FABLE targets, the NBSAP targets are however less restrictive in quantifying the targets, especially in reducing the deforestation target.

Table 2 | Overview of the latest NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
The milestone target on environmental consideration in forestry is that by 2015 the expectations of society on environmental considerations in forestry are clarified and known to the forestry industry so that they can be applied in practice.	**DEFORESTATION:** Zero net deforestation from 2030 onwards
The milestone target on varied forestry is that provisions have been clarified so that by 2015 there are good conditions for varied forestry.	**DEFORESTATION:** Zero net deforestation from 2030 onwards
The milestone target on the protection of land areas, freshwater areas and marine areas is that at least 20 per cent of Sweden's land and freshwater areas, and 10 per cent of Sweden's marine areas, by 2020 contribute to achieving national and international biodiversity targets.	**BIODIVERSITY:** At least 30% of the global terrestrial area protected by 2030

Brief Description of National Pathways

Among possible futures, we present three alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Sweden.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth from 10.1 million in 2020 to 12.4 million in 2050, limited constraints on agricultural expansion, no afforestation target, no change in the extent of protected areas, low productivity increases in the agricultural sector, no change in diets and a minimum (10%) reduction in food waste and post-harvest losses (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to food self-sufficiency envisioned in the national food policy by improving productivity and competitiveness of the agri-food sector (MoEI, 2017). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for wheat, barley, oats, potato, sugar beet, peas, beans, apple, tomato, and onion (see Annex 2).

Our Sustainable Medium Ambition Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to a higher consumption of plant-based foods such as cereals, pulses and nuts, improvement in agriculture productivity and expansions of forest lands and protected areas, but a lower intake of red meat such as beef, pork and lamb, and reduction of food waste and post-harvest losses (see Annex 2). This corresponds to a future based on the conscious choice of healthy foods and the practice of low carbon agriculture that would also see considerable progress with regards to competitiveness and sustainability of the agricultural sector by adopting innovative technologies and ensuring a high level of environmental and animal welfare standards (OECD, 2018). With the other FABLE country teams, we embed this Sustainable Medium Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Our Sustainable High Ambition Pathway represents a future in which cropland use declines through the reduction in food waste and post-harvest losses (50%) and improvement in crop productivity. This pathway assumes an expansion of forest lands by 250,000 ha by 2050, even though the country has no commitments in this regard in national and international committees, e.g. the Bonn Challenge. For protecting the space for nature as in Baillie & Zhang (2018), this high ambition pathway explores the possible enlargement of the protected area network to 30% ecoregion coverage by 2030. This pathway thus corresponds to the highest boundary of feasible action. Compared to the Sustainable Medium Ambition Pathway, we assume that this future would lead to a further increase in areas of forest lands and protected areas and even more reduction in food waste and post-harvest losses (see Annex 2). As in the Sustainable Medium Ambition Pathway, we embed this Sustainable High Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

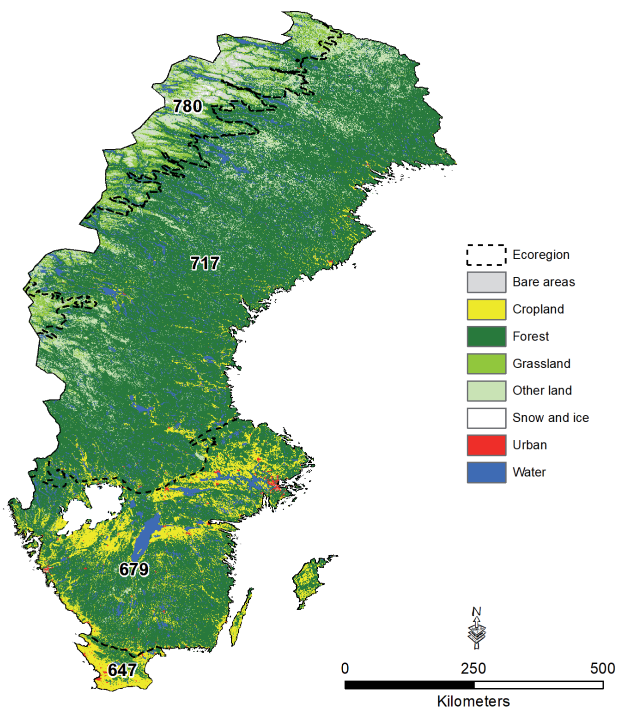
Land and Biodiversity

Current State

In 2010, Sweden was covered by 6.5% cropland, 1.1% grassland, 66.8% forest, 0.5% urban and 25.1% other natural land. Most of the agricultural area is in southern Sweden, while forest and other natural land are mainly concentrated in the northern part of the country (Map 1). In Sweden, abandonment of farmland and pastoral systems, intensified forestry and eutrophication are the major threats to the terrestrial and wetland biodiversity (MoE, 2014). Thus, the Swedish government has prioritized the restoration of forests and wetlands with high nature value to enhance connectivity and integration of protected areas into the landscape (OECD, 2018).

We estimate that land where natural processes predominate[2] accounted for 62% of Sweden's terrestrial land area in 2010 (Map 2). The 780-Scandinavian Montane Birch forest and grassland holds the greatest share of land where natural processes predominate, followed by 717-Scandinavian and Russian taiga and 679-Sarmatic mixed forest (Table 3). Across the country, while 6,3 Mha of land is under formal protection, falling short of the 30% zero-draft CBD post-2020 target, only 19.9% of the land where natural processes predominate is formally protected. This indicates that the 647/679-Baltic and Sarmatic mixed forests are important for establishing the connectivity of protected areas across the country.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

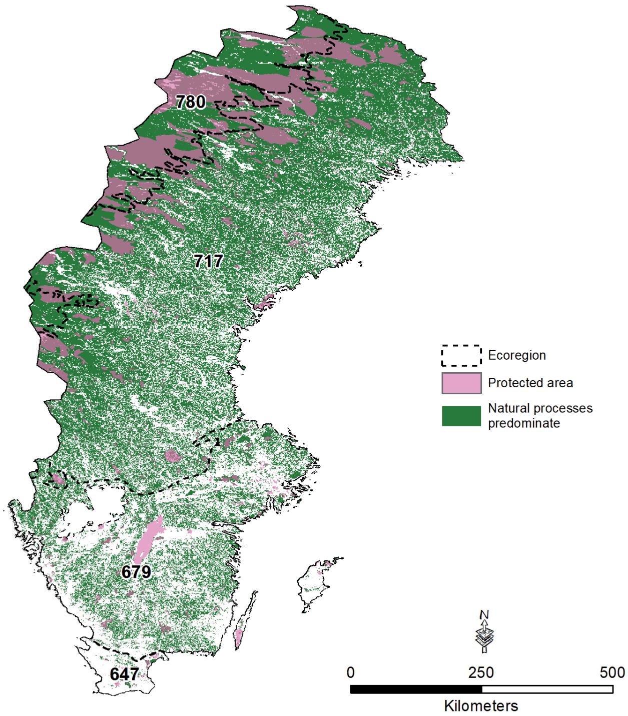


Notes. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. ccountries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 47.2% of Sweden's cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in 679-Sarmatic mixed forest, followed by 717-Scandinavian and Russian taiga and 647-Baltic mixed forests. The regional differences in the extent of biodiversity-friendly cropland can be explained by regional production intensity and urban development on farmland (Hallgren, 2015).

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Notes. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
647	Baltic mixed forests	864.5	7.4	11.1	28.6	71.4	489.0	22.0
679	Sarmatic mixed forests	11,984.0	6.3	36.3	7.5	92.5	2,527.9	47.9
717	Scandinavian and Russian taiga	2,5933.3	11.2	70.0	14.3	85.7	556.1	65.5
780	Scandinavian Montane Birch forest and grasslands	5,030.9	50.2	93.1	51.2	48.8	10.4	97.1

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

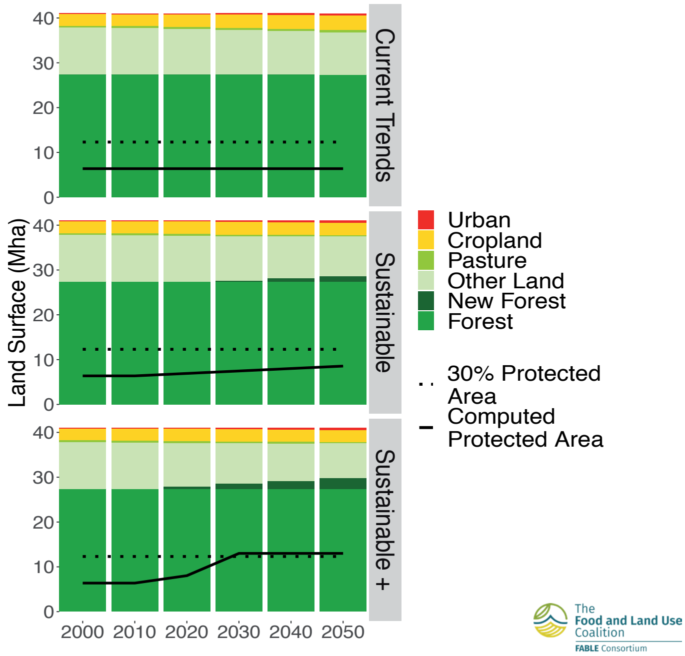
Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, no planned afforestation or reforestation, and protected areas remain at 6.4 Mha, representing 11% of total land cover (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase of cropland, pasture and urban area and a decrease in other land areas. This trend evolves over the period 2030-2050: cropland, pasture and the urban area further increase and other land areas further decrease (Figure 1). The expansion of the planted area for barley, wheat and oats explains 75% of total cropland expansion between 2010 and 2030. For barley, 32% of the expansion is explained by an increase in exports and demand for animal feed. For wheat, 31% of the expansion is due to an increase in internal demand for food and animal feed. Finally, for oats, 11% results from an increase in demands for feed and exports. Pasture expansion is mainly driven by the increase in internal food consumption of milk and beef while livestock productivity per head and ruminant density per hectare of pasture remain constant over the period 2020-2030. Between 2030-2050, cropland expansion is explained by an increase in demands of cereal grains, particularly barley, oats and wheat in export and domestic feed markets, and an increase in domestic consumption of wheat and sugar beet. This results in a reduction of land where natural processes predominate by 5% by 2030 and by 10% by 2050 compared to 2010, respectively.

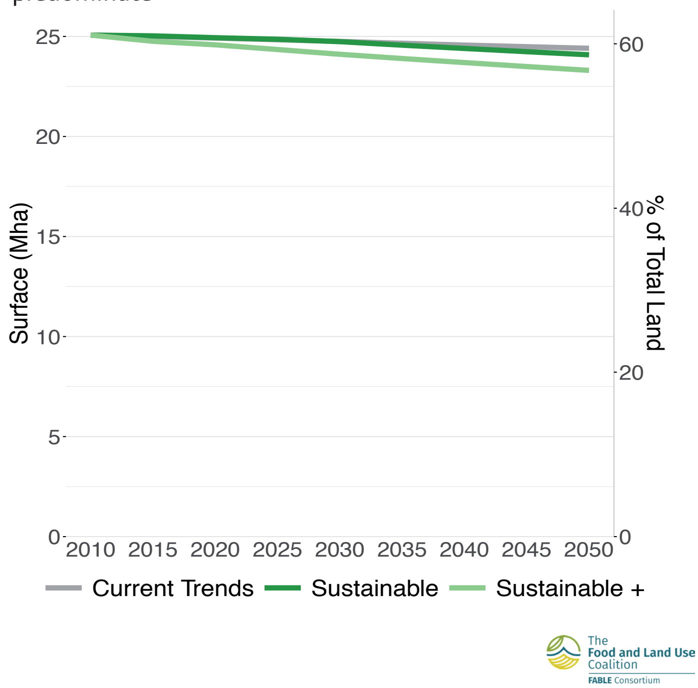
In the Sustainable Medium Ambition and Sustainable High Ambition Pathways, assumptions on protected areas have been changed to reflect a better management of protected areas and the creation of additional

Figure 1 | Evolution of area by land cover type and protected areas under each pathway



Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

Figure 2 | Evolution of the area where natural processes predominate



areas unavailable for agricultural expansion. The main assumptions include protected areas increase from 11% of the total land in 2010 to 30% in 2030 (cf. Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Sweden in the Sustainable Medium Ambition and Sustainable High Ambition Pathways: (i) a reduction in cropland, (ii) an increase in the expansion of urban cities, and (iii) an increase in protected areas and forest land. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by a decrease in the production of barley and wheat due to lower demand in the export market and high reduction in demand for animal products internally and globally. In the Sustainable Medium Ambition and Sustainable High Ambition Pathways, the area predominated by natural processes is decreased by 2-4% between 2025 and 2050, due to expansion of protected forest areas in shrubland and intact areas of sparse vegetation and trees (Figure 2).

GHG emissions from AFOLU

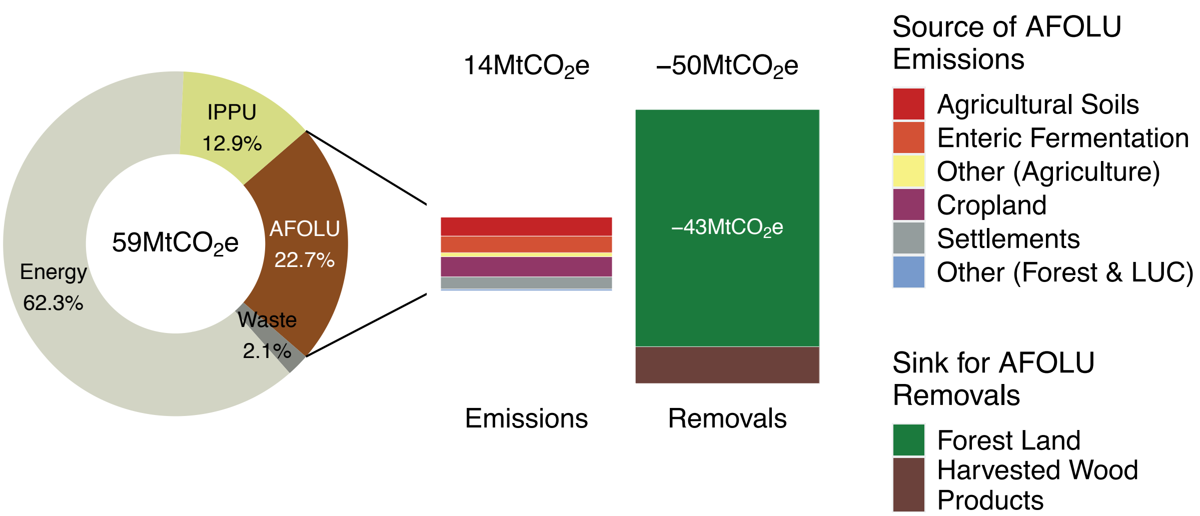
Current State

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 22.7% of total emissions in 2010 (Figure 3). Cropland is the principal source of AFOLU emissions, followed by agricultural soils, enteric fermentation, and settlements. This can be explained by increasing consumption of red meat and dairy products, expansion of farmland on drained peatlands and urban development on farmlands (Hallgren, 2015; Jordbruksverket, 2014).

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU rise to 8.3 $MtCO_2e$/yr in 2030, before reaching 9 $MtCO_2e$/yr in 2050 due to an increase in the production of grains and oilseed crops such as barley, wheat, oats, rye and rapeseed (Figure 4). In 2050, the livestock sector is the largest source of emissions (4.5 $MtCO_2e$/yr) while biofuel acts as a sink (-0.5 $MtCO_2e$/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for the agriculture sector (27%), while a reduction is computed for land-use change in other lands such as shrubland and other vegetation (2.1%).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2010



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

In comparison, the Sustainable Medium Ambition Pathway leads to a reduction of AFOLU GHG emissions by 71% and the Sustainable High Ambition Pathway to a reduction by 110% by 2050 compared to Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Medium Ambition Pathway is dominated by a reduction in GHG emissions from land-use change and livestock sectors (Figure 5). The most important drivers of this reduction are dietary shifts towards plant-based foods, an increase in livestock productivity, a decrease in exports of agricultural commodities, increased afforestation and, an expansion of protected forest areas. Under the Sustainable High Ambition Pathway, GHG emissions from land-use change are further reduced thanks to higher levels of afforestation and of expansion of protected areas.

Compared to Sweden's commitments under the UNFCCC (Table 1), our results show that AFOLU could contribute by as much as 12% of the country's total GHG emissions reduction objective by 2030. Such reductions could be achieved through dietary changes to low-carbon foods, agricultural productivity improvement, afforestation, and the expansion of protected forest areas. These measures could be particularly important in contributing to full-fill the GHG mitigation target in the NDC (see Table 1), and to achieve the national climate targets of zero net GHG emissions by 2045, and thereafter negative emissions.

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

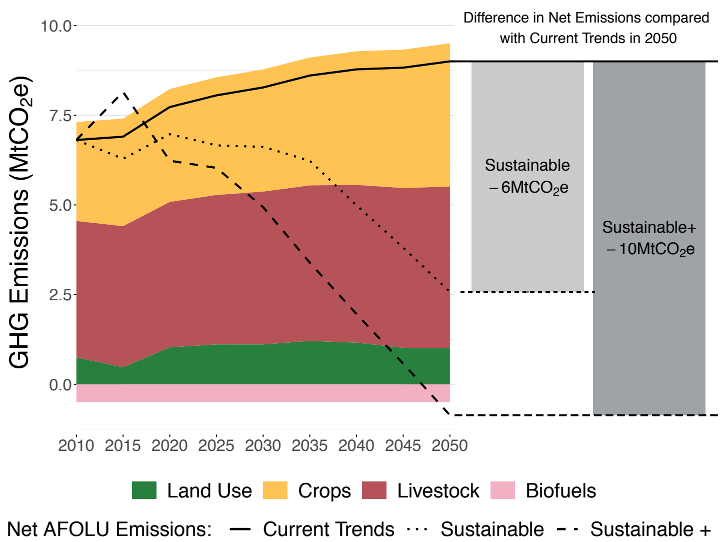
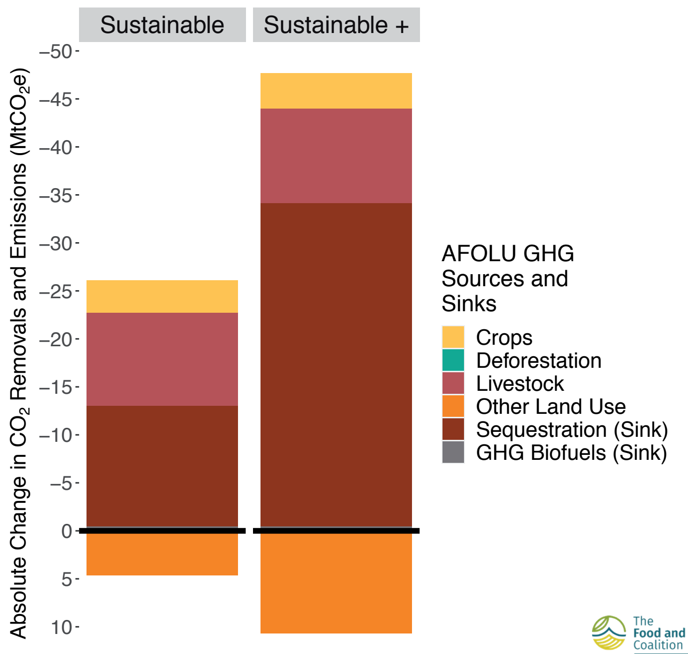


Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



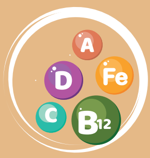
Food Security

Current State

The "Triple Burden" of Malnutrition

Undernutrition

2.5% of the population were undernourished in 2016. This share has been constant since 2000 (FAO, 2020).



Micronutrient Deficiency

15.4% of women suffered from anemia in 2016, which can lead to maternal death (FAO, 2020).

5.2% of the population is deficient in vitamin A, which can notably lead to blindness and child mortality, and 1.2% were deficient in iodine, which can lead to developmental abnormalities (IHME, 2017).

Overweight/ Obesity

11.4% of the population and 18.3% of adults and 4.4% of children were obese in 2015.

28.7% of the population, and 39.3% of adults and 18.1% of children, were overweight in 2015. These shares have increased since 1990 (IHME, 2017).

Disease Burden due to Dietary Risks

14.9% of deaths were attributable to dietary risks, or 137.3 deaths per year (per 100,000 people) in 2017.

4.2% of the population suffers from diabetes and 18.6% from cardiovascular diseases, which can be attributable to dietary risks (IHME, 2017).

Table 4 | Daily average fats, proteins, and kilocalories intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways in 2030 and 2050

	2010	2030			2050		
	Historical Diet (FAO)	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition
Kilocalories (MDER)	2,752 (2,091)	2,734 (2,081)	2,795 (2,081)	2,795 (2,081)	2,734 (2,079)	2,858 (2,079)	2,858 (2,079)
Fats (g) (recommended range)	116 (61-92)	116 (61-91)	112 (62-93)	112 (69-93)	116 (61-91)	109 (64-95)	109 (64-95)
Proteins (g) (recommended range)	96 (69-241)	94 (68-239)	88 (70-245)	88 (70-245)	94 (68-239)	81 (71-250)	81 (71-250)

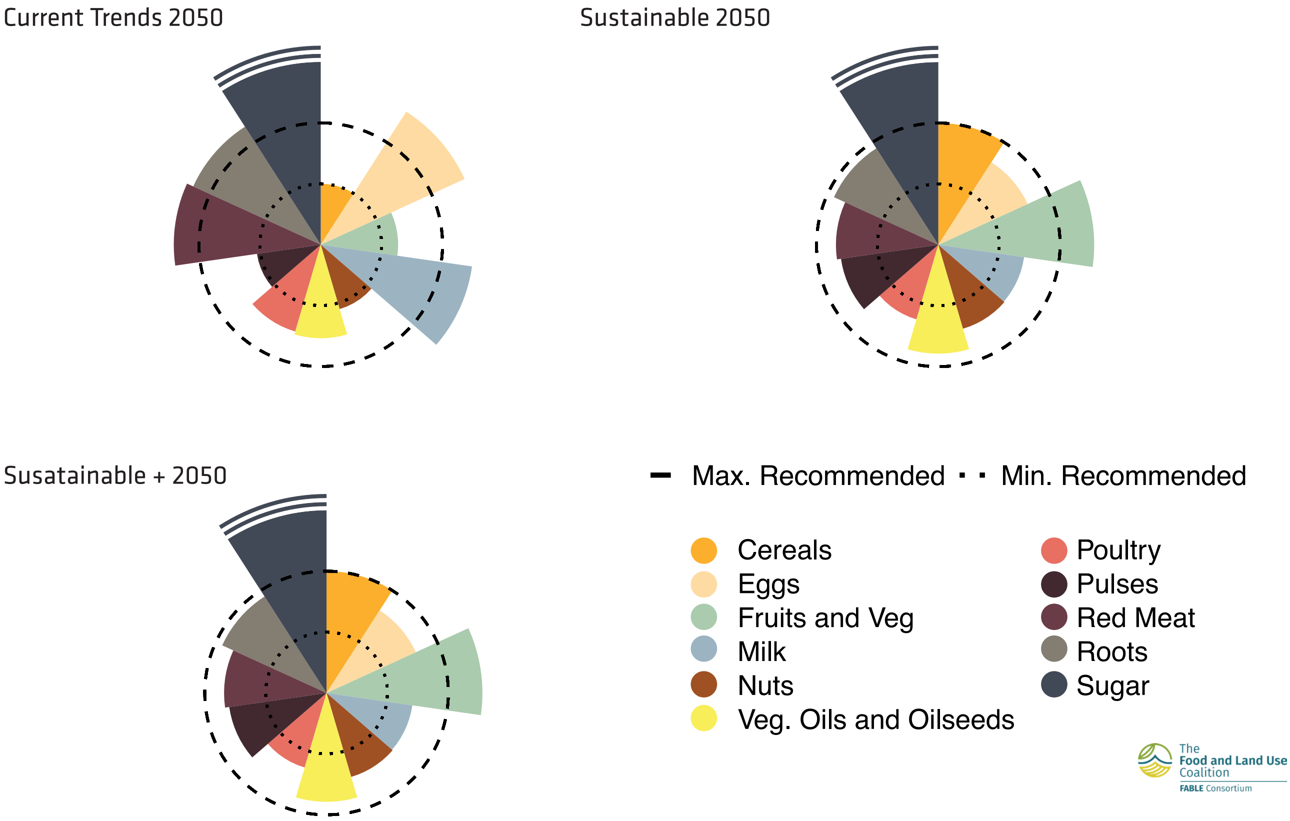
Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the popula-tion projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014).For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, the computed average calorie intake is 31% higher in 2030 and 2050 (Table 4). The current average intake is mostly satisfied by cereals, dairy, oilseed products, added sugar and red meat (pork and beef), representing 25%, 16%, 16%, 15% and 11% of the total calorie intake, respectively. The consumption of fruits, vegetables, pulses and nuts on aggregate represents less than 10% of the total calorie intake. Under the Current Trends Pathway, we assume that the consumption of food diets will remain stable between 2010 and 2050. Compared to the EAT-*Lancet* recommendations (Willett et al., 2019), red meat, sugar, eggs, fish and milk are over-consumed while cereals, nuts and pulses are consumed in the lower part of the recommended range in 2050 (Figure 6). Fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050, while protein intake per capita is sufficient to meet the minimum recommendations. This can be explained by excess consumption of animal products such as milk, eggs and red meat, and added sugar, but a lower intake of plant-based foods such as cereal grains, fruits, vegetables, pulses and nuts (Figure 6).

Under the Sustainable Medium Ambition Pathways, we assume that diets will transition towards plant-based foods, with increased consumption of cereals and pulses, but decreases consumption of red meat. Similar assumptions are made under the Sustainable High Ambition Pathway. The ratio of the computed average intake over the MDER increases to 34% in 2030 and 37% in 2050 under the Sustainable Medium and High Ambition Pathways. Compared to the EAT-Lancet recommendations, the consumption of cereals, sugars, fruits and vegetables remains outside of the recommended range with the consumption of red meat, starchy roots, eggs, milk and fish being now within the recommended range (Figure 6). Moreover, the fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050, showing some improvement compared to the Current Trends Pathway. The protein intake per capita hardly meets the lower bound of the recommended range (Table 4). An increase in consumption of pulses, nuts and poultry may improve the protein intake.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



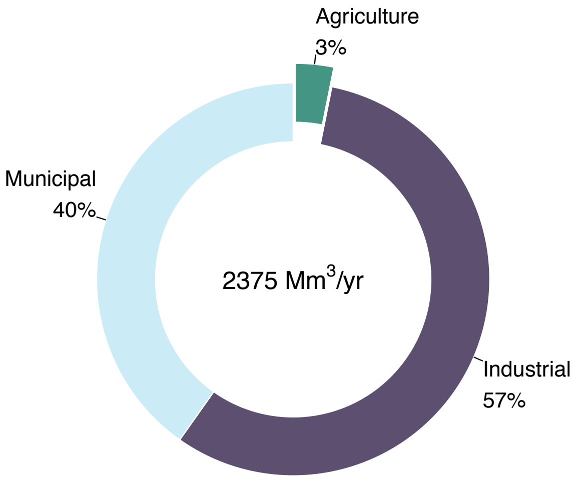
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings) i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring.

Water

Current State

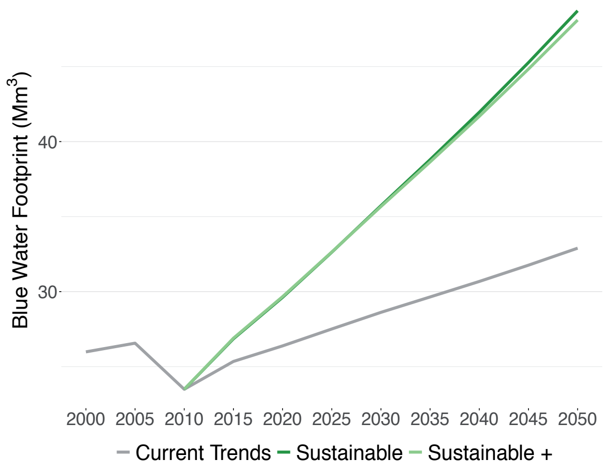
Sweden is characterized by the cool temperate climate with 624 mm average annual precipitation that mostly occurs over the period June - August. The agricultural sector represented 3% of total water withdrawals in 2010 (Figure 7). In 2016, 2% of agricultural land was equipped for irrigation, representing 34% of estimated-irrigation potential (Jordbruksverket, 2018). The three most important irrigated crops - potato, sugar beet and cereals, account for 89% of the total harvested irrigated area. These crops are the most traded crops in Sweden. In 2016, about 30% of cereals, 8% of sugar beet, and 3% of potato were exported (Chatham House, 2018). About 70-80% of their acreages are irrigated in Sweden (Jordbruksverket, 2018).

Figure 7 | Water withdrawals by sector in 2010



Source. Adapted from AQUASTAT Database (FAO, 2017)

Figure 8 | Evolution of blue water footprint in the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen & Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Pathways and Results

Under the Current Trends Pathway, annual blue water use decreases between 2000-2010 (26 and 23.5 Mm^3/yr), before reaching 28.6 Mm^3/yr and 32.9 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with vegetables, sugar beet and potato accounting for 39%, 31% and 29% of computed blue water use for agriculture by 2050[4]. In contrast, under the Sustainable Medium Ambition Pathway, the blue water footprint in agriculture reaches 35.7 Mm^3/yr in 2030 and 48.7 Mm^3/yr in 2050, respectively. Under the Sustainable High Ambition Pathway, the blue water footprint further decreases to 48.1 Mm^3/yr in 2050. This is primarily explained by the impact of climate change over time (Annex 2) that influences the crop productivity and consumption of irrigation water. Under the Sustainable Pathways, the supply of irrigation water increases, due to sustainable intensification scenarios for crop and livestock productions (see Annex 2). This scenario assumes to increase crop yields by closing the yield gaps between the current and potential yields, which may require increased use of irrigation water without significant environmental drawbacks. However, the footprint of greywater would remarkably decrease under the Sustainable Pathways with a reduced production of animal products, mostly milk and pork in Sweden. As the droughts are projected to occur more frequently and severely in Northern Scandinavia (Spinoni, Vogt, Naumann, Barbosa, & Dosio, 2018), we could expect more requirements of irrigation water, particularly in arid and drought-stricken regions to close the potential yield gaps under the Sustainable Pathways.

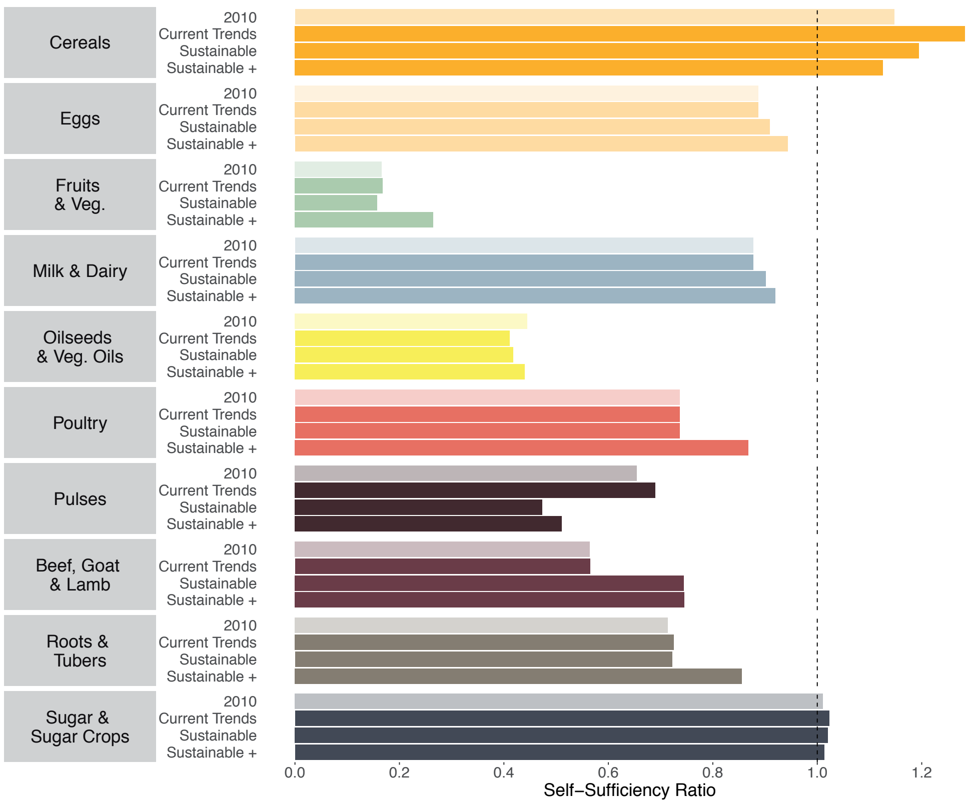
Resilience of the Food and Land-Use System

The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Sweden's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

About half of the Swedish food consumption is domestically produced, by which we can infer the degree of self-sufficiency to about 55-60% (Eriksson et al., 2016). In the national food strategy, the Swedish government has stressed for the improvement in food self-sufficiency through an increase in domestic food production (MoEI, 2017). However, strict environmental indicators and animal welfare can increase the cost of local production. In 2012, Sweden was self-sufficient in the supply of dairy, potatoes, sugar beet and cereal grains, particularly oats, wheat, barley and rye, but heavily reliant on imports of red meat (beef and pork), fish and seafood, and animal feed (Eriksson et al., 2016; McNitt, 1987).

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

Under the Current Trends Pathway, we project that Sweden would be self-sufficient in cereals and sugar crops such as sugar beet in 2050, with self-sufficiency by product group remaining stable for the majority of products from 2010 – 2050 (Figure 9). The product groups which the country depends the most on imports to satisfy internal consumption are fruits and vegetables, oilseeds and vegetable oils, and red meat (beef, goat and lamb) and this dependency will remain stable until 2050. Under the Sustainable Medium Ambition Pathway, the self-sufficiency has been relatively improved for red meat by 2050. Similar results have been found for fruits and vegetables, poultry meat and starchy roots and tubers under the Sustainable High Ambition Pathway, as can be seen in the vertical bars of these food commodities that approach the horizontal dotted line for 2050 (Figure 9). This is explained by changes in crop productivity and food diets.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

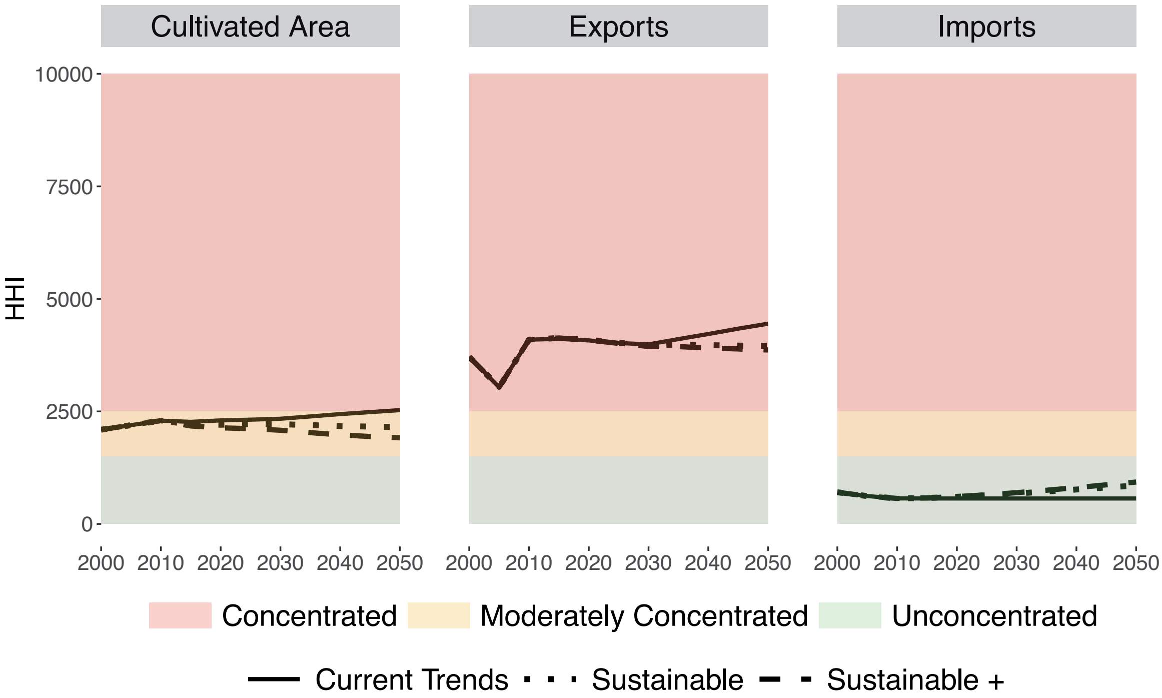
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, a moderate concentration between 1,500 and 2,500, and a high concentration above 2,500.

In 2010, the diversification of crop species, as shown by the HHI of planted area in Figure 10, was moderately concentrated on few major crops such as potato, barley, wheat, oats, rye and sugar beet. A similar trend was observed on the exports of crops, which was concentrated on a few crop products. However, the imports of food commodities were unconcentrated in the same year. This indicates that in 2010 a wide range of Swedish food items relied on the import market.

Under the Current Trends Pathway, we project a high concentration of crop exports and planted areas in 2050. The trends have constantly increased over the period 2010 - 2050. This indicates low levels of diversity across the national production system and exports. In contrast, under the Sustainable Medium and High Ambition Pathways, we project relatively low concentration of crop exports, and medium concentration in the range of crops planted in 2050, indicating moderate levels of diversity across the national production system. The crop exports are highly concentrated, but the level of diversity is high for crop imports across three pathways (Figure 10). This is largely explained by the transformation of meat-based to plant-based diets.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

In Sweden, we find two main drivers of unsustainable food and land-use systems. First, food is generally overconsumed and the dietary mix is moderately unhealthy and dominated by red meat, added sugar and animal fats. There is also a substantial food loss and waste challenge. Additionally, the increasing intensification of agricultural activities is primarily responsible for the ongoing loss of natural vegetation and ecosystems. This has led to an enormous impact on the environment, including biodiversity loss and overuse of natural ecosystem services in many places through eutrophication and land-use change.

To mitigate these environmental and health issues and increase local ecosystem resilience, we investigated the potential of alternative sustainable pathways within various country-specific determining factors, including future estimated economic and population growth, alternative diets with more healthy food, sustainable agricultural productivity to achieve national and international climate and environmental policies, as well as biodiversity conservation. Next to the Current Trends Pathway, two alternative variants of Sustainable Pathways are defined with medium and high levels of ambition in achieving sustainable indicators. These pathways aim at bringing a dietary shift from the current red meat-based diet towards more plant-based foods. Additionally, the sustainable high ambition pathway considers an increase of protected forest areas to 30% of terrestrial land by 2030 and halving of the food waste from the current level by 2050. Moreover, a socio-economic conversion to the high ambition pathway would make it possible to achieve the zero net-emission target by 2050.

The results show that a dietary change under the two Sustainable Pathways reduces the cur-rent trend of unhealthy diets and overconsumption of red meat, pork, milk and animal fats, while increasing the intake amount of grains, nuts, and pulses. The Swedish diet under the Sus-tainable Pathways shows that, compared to the EAT-Lancet recommendations (Willett et al., 2019), the consumption of cereals, fruits and vegetables, and sugars remains outside the recommended range.

Next to the dietary changes for public health, a transformative change in the management of ecosystem services to achieve the proposed Sustainable Pathways also has implications on environmental sustainability. Cropland use and blue water consumption can markedly decrease under these Sustainable Pathways, mainly due to dietary changes, followed by an increase in agricultural productivity and improvement in water-use efficiency. Compared to the Current Trends, the Sustainable Pathways lead to a substantial reduction of GHG emissions by 2050, especially AFOLU emissions. Here, afforestation and expansion of protected areas are the most important drivers of this reduction. Additionally, self-sufficiency of commodities as fruits, vegetables, eggs, poultry meat and starchy roots are relatively improved. However, these pathways still require an increase in local production to close yield gaps. Currently, Swedish consumption relies on high imports of grains, pulses, nuts, fruits and vegetables that would be diminished when implementing the Sustainable Pathways.

We hope that this present study can enable policymakers and stakeholders to understand the current trends and ambitious pathways for the transformative changes in dietary patterns, land-use change, and footprints of natural resources (cropland and blue water). Specifically, it could inform setting new national targets to fulfil signed national goals in international com-mitments such as the Paris Agreement, the CBD's Aichi targets or the national SDGs. On a global scale, the FABLE Scenathon measures various environmental indicators such as GHG emissions and evaluates the contribution of the Sustainable Pathways to the Paris Agreement goal of limiting the rise in global temperature below 2Ð above pre-industrial levels and the CBD's strategic plan for biodiversity.

Even though the FABLE Calculator covers many components of the food and land-use system for developing Sustainable Pathways, it still faces limitations for certain country-specific char-acteristics that cannot be covered adequately. For example, the Swedish Parliament has al-ready set goals to achieve 30% organic farmland and 60% organic food purchases in the public sector by 2030 as part of the national food policy (European Commission, 2019; Pekala, 2020). In this context, the Swedish team may further utilize the FABLE Calculator in analyzing the tri-lemma of organic farming, food security, and environment. Similarly, an alternative inclusion of insect-based feeds could be a more extreme, out-of-the-box scenario for reducing the Swe-dish dependency of chicken and bovine feed market on external imports of conventional soy meal. This alternative animal feed diet scenario cannot be implemented in the current scenario analysis, which could result in an increased food supply.

In the future, the present study could be further expanded to integrate risk due to uncertainty in the food supply chain, a topic of particular relevance with the ongoing outbreak of COVID-19. Such an assessment could help inform policymakers on the resilience of our food and land-use system and their ability to cope with extreme events. Finally, in future Scenathons, we will also aim to incorporate stakeholders' perspectives by working with them to co-develop a stakehold-er-specific pathway for a sustainable food and land-use system in Sweden.

Annex 1. List of changes made to the FABLE Calculator to adapt it to the national context

Following changes are made in the FABLE Calculator to adapt it to the national context:

- A new food diet scenario is defined for a new plant-based diet. This diet assumes low consumption of red meat, but more intake of grains, pulses, vegetables, and fruits. This diet is defined based on the normative decisions made by stakeholders, including representatives from farmers' unions, producers, retailers, government agencies, and environmental organizations (Karlsson et al., 2017; Wood et al., 2019).
- Animal feed diets are re-calibrated to historical observations, based on the Swedish feed requirement data available at (Cederberg et al., 2009). In this process, new feed ingredients such as palm kernel and sunflower cake, vegetable oil, potato, sugar beet and rye are also added.
- In the "customized import" scenario under the Sustainable Medium Ambition and Sustainable High Ambition Pathways, trends of food imports are customized for each product, based on their demands on study diets (e.g. sufficiency diet). In this process, we assumed a 20% reduction in import quantity if the commodities are consumed 20% less in the selected diet, in otherwise case a 50% reduction is imagined. A stable import is defined for the food items, which largely increase in the diet scenario (e.g. fruits and vegetables).
- A sustainable intensification scenario is defined to increase crop yields equivalent to 75-95% of their potentials, depending upon low-performing to highly productive areas (Clark, Hill, and Tillman, 2018). To execute this, we computed the additional productivity as business-as-usual plus 50% yield gaps of high growth scenario.
- A new scenario for the expansion of protected areas is defined to achieve the Aichi Biodiversity targets. The Sustainable Medium Ambition Pathway is defined for a target of achieving 17% protected areas of terrestrial land by 2030. An ambitious target of 30% protected areas by 2050 is assumed under the Sustainable High Ambition Pathway. These scenarios are implemented in the FABLE Calculator with a reference to Müller et al. (2020).
- The expansion of urban areas is calibrated as a function of GDP growth.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
No change in current policies to influence demographics. 12.4 million population is projected by 2050. (SSP2 scenario selected)	Incentives to influence demographics in the direction which is supposed to improve the sustainability of the system. 12.8 million population is projected. (SSP1 scenario selected)	Same as Sustainable Medium Ambition Pathway

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Free expansion of productive land under the total land boundary. No constraint on the expansion of the agricultural land outside beyond existing protected areas and under the total land boundary.	Free expansion of productive land under the total land boundary. No constraint on the expansion of agricultural land outside beyond existing protected areas and under the total land boundary.	Free expansion of productive land under the total land boundary. No constraint on the expansion of agricultural land outside beyond existing protected areas and under the total land boundary.
LAND Afforestation or reforestation target (1000 ha)		
No active afforestation / reforestation.	Medium level of afforestation to contribute to the Bonn Challenge. 100,000 ha areas will be forested by 2050.	High ambition of afforestation. 250,000 ha areas will be forested by 2050.

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
No expansion of protected areas beyond the current. Currently, Sweden has 11% protected areas of total terrestrial areas, including inland waters (Statistics Sweden, 2017).	Better management of protected areas and/or creation of additional protected areas. Protected areas are extended to 17% of terrestrial and inland water by 2030 and remain stable afterward.	Protected areas are extended to achieve an ambitious target of 30% of terrestrial land by 2030. These additional areas are protected to make them unavailable for agricultural expansion (Müller et al., 2020).

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
PRODUCTION Crop productivity for the key crops in the country (in t/ha)		
Medium pace of technological change in agriculture. Yield growth mainly due to an increase in input use. The current business-as-usual (BAU) trend of productivity growth is assumed. By 2050, productivity of major crops increases as below, while that for other crops remains the same: • 4.2 t/ha for barley. • 31.7 t/ha for potato. • 66.2 t/ha for sugar beet. • 2.2 t/ha for rapeseed. • 4.9 t/ha for wheat. • 26.2 t/ha for vegetables. Source: Authors' calculation based on FAO statistics.	Crop yields improve more moderately, equivalent to 75-95% of their potentials, depending on low-performing to highly productive areas (Clark et al., 2018). By 2050, productivity of major crops increases as below, while that for other crops remains the same: • 4.3 t/ha for Barley. • 32.5 t/ha for potato. • 66.4 t/ha for sugar beet. • 2.8 t/ha for rapeseed. • 5.3 t/ha for wheat. • 31.5 t/ha for vegetables. Source: Authors' calculation based on assumptions of productivity growths.	Same as Sustainable Medium Ambition Pathway
PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)		
Animal productivity growth mostly concentrated in pig and poultry sectors driven by structural change towards industrial livestock production. The current trend growth is assumed (BAU growth). By 2050, livestock productivity reaches: • 90 kg/head for beef. • 28 kg/head for chicken. • 60 kg/head for eggs. • 7.3 t/head for milk. • 250 kg/head for pork. Source: Authors' calculation based on FAO statistics.	Animal productivity growth is driven by structural change in industrial livestock production. High productivity growth is favored for the low-GHG production system. By 2050, livestock productivity reaches: • 90 kg/head for beef. • 33 kg/head for chicken. • 73 kg/head for eggs. • 9.6 t/head for milk. • 300 kg/head for pork. Source: Authors' calculation based on productivity growth assumptions by 10-25% for mutton, beef and milk, 50% for egg and 85-100% for chicken and pork by 2050.	Same as Sustainable Medium Ambition Pathway
PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)		
No change in the management of the permanent pasture area. Average ruminant livestock stocking density is 3.49 livestock units/ha pasture land. Based on FAO (2020).	Same as Current Trends Pathway	Same as Current Trends Pathway
PRODUCTION Post-harvest losses		
No change in the current scenario of post-harvest losses. Constant share of supply available lost during storage and transportation after 2010 (up to 8% post-harvest losses for fruits and vegetables). Source: authors' calculation.	Medium reduction of post-harvest losses reduced by 30% based on dry matter production of modeled products in 2010. Based on FOLU (2019)	High reduction of post-harvest losses halved by 2050 compared to BAU. Regulatory frameworks, R&D, and investment for improved storage and processing. Based on FAO (2018)

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
No policy changes, imports may increase up to 30% of the 2010 levels by 2050 for major food commodities such as cereal grains, fruits, vegetables, red meat (pork and beef) and dairy products. For production feasible commodities, the import shares of total consumption reduce: • Up to 25 % by 2050 for pork, milk, chicken, eggs, potato, and other cereals. • 36% by 2050 for rapeseeds. • 45 % by 2050 for beef. • 60-100% by 2050 for mutton, tropical fruits, vegetables, cereals, sunflower, soybeans. Source: Authors' calculation.	Reduction of trade barriers, reduced imports by up to 50% by 2050 if consumptions decrease in scenario diet. High demand for food commodities in the scenario diet is supplied by increased domestic production. For production feasible commodities, the import shares of total consumption reduce by: • Up to 25 % by 2050 for pork, milk, chicken, eggs, potato, other cereals, and rapeseeds. • 25 % by 2050 for beef and mutton. • 60-100 % by 2050 for tropical fruits, vegetables, cereals, and soybeans. Source: Authors' calculation.	Reduction of trade barriers, reduced imports by 50% by 2050 with increase domestic production. For production feasible commodities, the import shares of total consumption reduce by: • Up to 15 % by 2050 for pork, milk, chicken, eggs, potato, rapeseeds, and other cereals. • 25 % by 2050 for beef and mutton. • 35-45% by 2050 for apple, beans and other fruits and oilseeds. • 60-100 % by 2050 for tropical fruits, vegetables, cereals, and soybeans. Source: Authors' calculation.

TRADE Evolution of exports for key exported products (1000 tons)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
No major changes in trade policy, double exports by 2050 as follows: • 1275 k tons by 2050 for barley. • 283 k tons by 2050 for wheat. • 235 k tons by 2050 for oats. • 99 k tons by 2050 for rye. • 22 k tons by 2050 for peas. Source: Authors' calculation.	No major changes in trade policy, increase exports by 50% by 2050 as follows: • 728 k tons by 2050 for barley. • 173 k tons by 2050 for wheat. • 169 k tons by 2050 for oats. • 74 k tons by 2050 for rye. • 31 k tons by 2050 for peas. Source: Authors' calculation.	No changes in trade policy, stable exports by 2050 as follows: • 481 k tons by 2050 for barley. • 112 k tons by 2050 for wheat. • 115 k tons by 2050 for oats. • 50 k tons by 2050 for rye. • 31 k tons by 2050 for peas. Source: Authors' calculation.

FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
High levels of consumption and share of livestock products, sugar, and fat in the diet. Food demand directly linked to population growth unless no intervention is made (SSP2 scenario). The average daily calorie consumption/cap remains stable at 2752 kcal over the study period 2010-2050 and is: • 586 kcal for cereals. • 383 kcal for dairy milk. • 383 kcal for vegetable oils. • 357 kcal for added sugars. • 284 kcal for red meat (pork and beef). • 148 kcal for fruits and vegetables. • 122 kcal for fish and poultry. • 48 kcal for eggs. • 55 kcal for pulses and nuts. • 84 kcal for roots. • 148 kcal for animal fat. Based on FAO (2020)	More sustainable and healthy diets. Livestock products' share decreases with more consumption of plant-based foods such as cereal grains, fruits, vegetables, pulses, and nuts. By 2050, the average daily calorie consumption/cap reaches to 2858 kcal and is: • 711 kcal for cereals. • 108 kcal for dairy milk • 171 kcal for vegetable oils. • 23 kcal for added sugars. • 132 kcal for red meat (pork and beef). • 358 kcal for fruits and vegetables • 55 kcal for fish and poultry. • 19 kcal for eggs. • 432 kcal for pulses and nuts. • 57 kcal for roots. • 1 kcal for animal fat. Based on Karlsson et al. (2017)	Same as Sustainable Medium Ambition Pathway

FOOD Share of food consumption which is wasted at household level (%)

No change in the current scenario of food loss and waste, a business-as-usual (BAU) scenario. A slow reduction in food loss and waste, that is, 10% by 2050.	Regulatory frameworks, R&D and investment for improved storage and processing, and consumer awareness drastically reduce food loss and waste in 2050 by 25% of the share compared to the 2010 level (Searchinger et al., 2018).	Regulatory frameworks, R&D and investment for improved storage and processing, and consumer awareness drastically reduce food loss and waste in 2050 by 50% compared to the share in 2010 (Wood et al., 2019). However, a breakthrough in technology may be required for a 50% reduction in food loss and waste (Searchinger et al., 2018).

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Medium technology development of renewables, first-generation biofuels maintained at current target levels. Assume a No Change (Stable biofuel demand as 2010).	OECD-AGLINK Scenario, moderate growth in the supply of biofuels from agriculture. By 2050, biofuel production accounts for: • 4109 kt of wheat production. • 4107 kt of corn production. • 12187 kt of sugar beet production. • 8854 kt of rapeseed production.	Same as Sustainable Medium Ambition Pathway

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland<50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm - millimeters

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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UK

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in the UK. It presents three pathways for food and land-use systems for the period 2020-2050: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition (referred to as "Current Trends", "Sustainable", and "Sustainable +" in all figures throughout this chapter). These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including from the Department for Food, Agriculture and Rural Affairs (Defra), the Department for Business, Energy and Industrial Strategy (BEIS), the Department for International Trade (DIT), the Department for Agriculture, Environment and Rural Affairs in Northern Ireland (DAERA), the Scottish Government, the Welsh Government, the Committee on Climate Change, the Royal Society, the Royal Academy of Engineering, and UK Research and Innovation (UKRI), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how the UK's Nationally Determined Contribution (NDC) and Long Term Low Emissions and Development Strategy (LT-LEDS) treat the FABLE domains; note that we give details of the EU NDC and LT-LEDS as the UK has not yet released its own versions. According to the NDC/LT-LEDS, the UK/EU has committed to reducing its GHG emissions by 80% by 2050 compared to 1990. The UK also has a national commitment through the 2008 Climate Change Act to reduce emissions by 80% from a 1990 baseline by 2050, and in June 2019 this was updated to a new target of net zero GHG emissions by 2050 (BEIS, 2019; Climate Change Act, 2008). This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include increasing tree and hedgerow-planting, increased agricultural productivity and dietary change (reduced consumption of ruminant meat and dairy produce) (CCC, 2018, 2020). Under its current commitments to the UNFCCC, the UK (EU) does not mention biodiversity conservation (EU, 2015).

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC, LT-LEDS and the UK net zero target.

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
(EU) NDC (2016)	1990	n/a	2030	At least 40% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Forests
LT-LEDS (2018)	1990	780.3	2050	80% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	Y	N	food, water, forests
UK net zero	NA	NA	2050	Net zero GHG emissions	all	Y	Y	N	food, forests

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019).
Source: EU (2016)

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Table 2 provides an overview of the targets listed in the latest National Biodiversity Strategies and Action Plans (NBSAPs) for each of the four devolved nations in the UK which are related to at least one of the FABLE Targets (CBD, 2020). The NBSAP for England (Defra, 2011) includes nine Outcomes which will be delivered by 22 Priority Actions from 2011-2020. Among these targets, only two are quantified (both for marine biodiversity). Three explicitly refer to agriculture, but none refer to climate change. The NBSAP for Scotland (Scotland & Scottish Government, 2013) contains ten Outcomes and the Welsh NBSAP (Welsh Government, 2015) contains six Objectives and associated actions; these are not quantified but refer to the Aichi targets, the EU Biodiversity Strategy and parallel national policies and programs that may have quantitative targets. A number of the seven goals and 57 actions in Northern Ireland's NBSAP (DOENI, 2015) are quantified, including targets to increase woodland cover from 8% to 12% and restore 240 ha of ancient woodland. Climate change and agriculture are referred to in several places in these NBSAPs. Many of the targets are linked to the FABLE Targets on deforestation and biodiversity (Table 2) but as most of the NBSAP targets are not quantified they cannot be compared directly.

Table 2 | Overview of the NBSAP targets in relation to FABLE Targets (CBD, 2020)

NBSAP Target	Global FABLE Target
England	
(3.3) **Bring a greater proportion of our existing woodlands into sustainable management and expand the area of woodland in England.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(1A) **Better wildlife habitats with 90% of priority habitats in favourable or recovering condition and at least 50% of Site of Special Scientific Interest (SSSIs) in favourable condition, while maintaining at least 95% in favourable or recovering condition.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(1B) **More, bigger, and less fragmented areas for wildlife, with no net loss of priority habitat and an increase in the overall extent of priority habitats by at least 200,000 ha.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(1C) **By 2020, at least 17% of land and inland water, especially areas of particular importance for biodiversity and ecosystem services, conserved through effective, integrated and joined up approaches to safeguard biodiversity and ecosystem services including through management of our existing systems of protected areas and the establishment of nature improvement areas.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate **BIODIVERSITY:** At least 30% of global terrestrial area protected by 2030
(2A-2C) **By 2020, we will have put in place measures so that biodiversity is maintained, further degradation has been halted and where possible, restoration is underway, helping deliver good environmental status.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(3.8) **Reform the water abstraction regime. The new regime will provide clearer signals to abstractors to make the necessary investments to meet water needs and protect ecosystem functioning. We will also take steps to tackle the legacy of unsustainable abstraction more efficiently.**	**WATER:** Blue water use for irrigation <2453 km3yr-1

Table 2 | Overview of the NBSAP targets in relation to FABLE Targets (CBD, 2020) (continued)

NBSAP Target	Global FABLE Target
(1D) **Restoring at least 15% of degraded ecosystems as a contribution to climate change mitigation and adaptation.**	**GHG EMISSIONS:** Zero or negative global GHG emissions from LULUCF by 2050 **BIODIVERSITY:** A minimum share of earth's terrestrial land supports biodiversity conservation
Northern Ireland	
(10) **Expand a wide range of forest types and area of broadleaf trees from 8% to 12% of Northern Ireland land area.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards
(16) **Deliver peatland and wetland habitat restoration.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(26) **Protection, enhancement, and management of 4,400 hectares of designated land for biodiversity benefit.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(27) **Management of the remaining 5,900 hectares of non-designated land to maintain and enhance priority habitats and species.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(43) **Positive management of 700 hectares of land for biodiversity benefit.**	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
(48) **Restore 240 hectares of ancient woodland.**	**DEFORESTATION:** Zero net deforestation from 2030 onwards **BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
Wales	
Objective 2: Safeguard species and habitats of principal importance and improve their management; Objective 3: Increase the resilience of our natural environment by restoring degraded habitats and habitat creation; Objective 4: Tackle key pressures on species and habitats	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
Scotland	
Outcomes include: Quality and quantity of our wildlife is improving and flourishing; Sustainable land and water management; Ecosystems are restored to good health.	**BIODIVERSITY:** No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate

The UK's policies for safeguarding agrobiodiversity have until recently derived from mechanisms within the Common Agricultural Policy, EU environment legislation and local implementation policies. Strategies to support landscape-scale species recovery and wider ecosystem services now derive from the English Government's 25 Year Environment Plan and equivalent measures in devolved administrations, for example to reduce and reverse the decline in pollinators in Wales funded by the Welsh government's nature fund.

Brief Description of National Pathways

Among possible futures, we present three alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in the UK.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 67 million inhabitants in 2020 to 75 million in 2050), no constraints on agricultural expansion, a low afforestation target, no change in the extent of protected areas, low productivity increases in the agricultural sector, no change in diets or food waste, and continued urban expansion in line with UK government house building targets (cf. Annex 2). This corresponds to a future based on current policy and historical trends but with a levelling off of historical crop and livestock productivity improvements, except for milk yield where a modest improvement continues. Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for rapeseed, sugar beet and wheat (see Annex 2).

Our Sustainable Medium Ambition Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future would lead to higher rates of tree planting, higher agricultural productivity, an extra 0.5Mha of protected areas, and lower food waste and consumption of ruminant meat and dairy produce (see Annex 2). This corresponds to a future based on the adoption and implementation of measures corresponding to the medium ambition scenario in the CCC land use and climate change report, a key document informing UK government policy (CCC, 2018). With the other FABLE country teams, we embed this Sustainable Medium Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Our Sustainable High Ambition Pathway represents a future in which very ambitious climate targets are achieved, in line with the UK government commitment for net zero GHG emissions by 2050 and corresponds to the highest boundary of feasible action. Compared to the Sustainable Medium Ambition Pathway, we assume that this future would lead to much higher rates of tree planting, higher agricultural productivity, a higher protected area of natural habitats, lower rates of urban expansion, lower food waste and lower consumption of meat and dairy produce (see Annex 2). As in the Sustainable Medium Ambition Pathway, we embed this Sustainable High Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

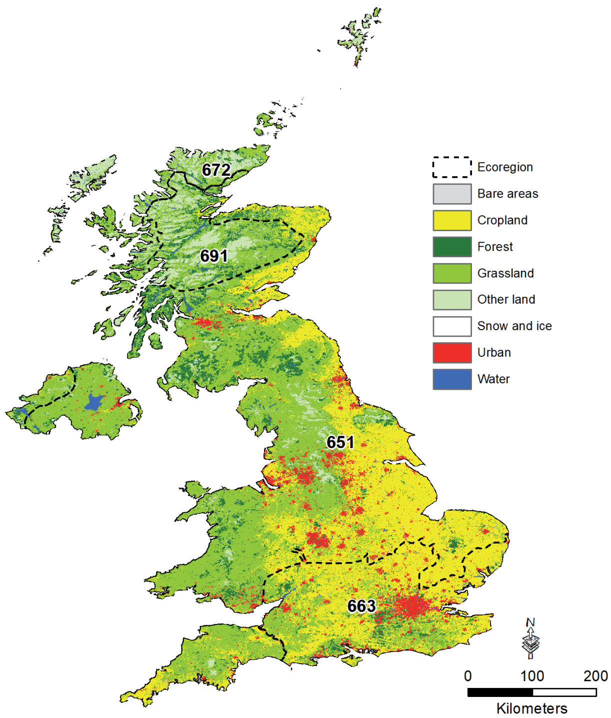
Land and Biodiversity

Current State

In 2015, according to FAOSTAT land cover data (the default FABLE dataset), the UK was covered by 24% cropland, 46% grassland, 12% forest, 4% urban and 12% other natural land. These figures are slightly different from the main national dataset, the UK Land Cover Map (Rowland et al., 2017), but we use FAO data because it provides a consistent historic time series. Arable land is concentrated in eastern, central and southern England, with pasture predominating in western England, Wales, Northern Ireland and southern Scotland (Map 1). Forest and other natural land are highly dispersed across the country but larger areas are found in the upland parts of Wales, Scotland, and northern and south-western England. Biodiversity in the UK faces a range of threats including fragmentation and loss of habitat for housing and infrastructure development, soil and water pollution and nutrient enrichment from agriculture, use of pesticides, climate change impacts and invasive species.

We estimate that land where natural processes predominate[2] accounted for 21% of the UK's terrestrial land area in 2015 (Map 2). The 672-North Atlantic moist mixed forests and the 691-Caledon conifer forests ecoregions, both in Scotland, hold the greatest share of land where natural processes predominate, with far less in the other eco-regions (Table 3). Across the country, while 6.7 Mha (27.6%) of land is under formal protection, falling just short of the 30% zero-draft CBD post-2020 target, only 64% of land where natural processes predominate is formally protected. This indicates that many areas important for biodiversity may be at risk without action to better protect them.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

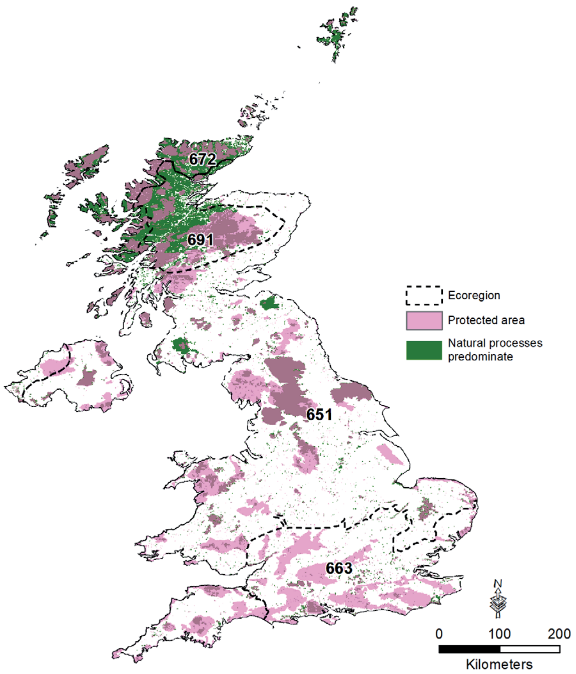


Notes. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 33% of the UK's cropland was in landscapes with at least 10% natural vegetation in 2019. These areas are most widespread in the 672-North Atlantic moist mixed forests and the 691-Caledon conifer forests ecoregions where much of the land is unsuitable for producing crops, due to poor soil conditions and a cool and wet climate.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



Notes. Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[3]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within $1km^2$ (%)
651	Celtic broadleaf forests	15,291	23	13	80	20.2	4,528	32
663	English Lowlands beech forests	4,498	32	7	71	28.7	2,240	35
672	North Atlantic moist mixed forests	2,023	44	70	51	49.5	23	85
691	Caledon conifer forests	2,166	46	68	53	46.8	58	59

Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

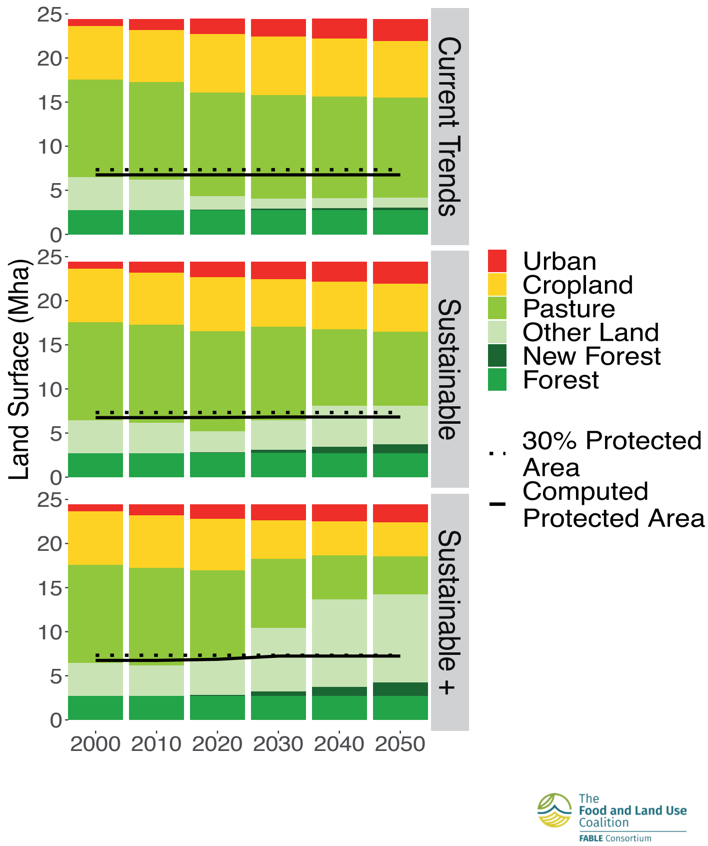
3 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, a target of 360Mha reforested or afforested by 2050 (of which only 326 ha is achieved, due to a shortage of available 'other natural land'; see below), and protected areas remaining at 6.7Mha, representing 27.6% of total land cover (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase of urban, forest, cropland and pasture area and a large decrease of other natural land area (such as heathland, scrub, bog and wetland) so that all the unprotected other natural land is lost by 2025, meaning that afforestation targets cannot be achieved. This trend evolves over the period 2030-2050: urban and new forest area further increase, and cropland and pasture area decrease slightly due to continued afforestation and urban development coupled with productivity increases, with no further loss of other natural land because all the remaining land is protected (Figure 1). The expansion of the planted area for wheat, barley and rapeseed explains 92% of total cropland expansion between 2010 and 2030. For wheat, 48% of expansion is explained by an increase of internal demand for biofuels and non-food products and 32% by an increase of demand for animal feed. For barley, 69% of expansion is due to an increase of demand for animal feed and 51% an increase of demand for non-food products (these shares add up to more than 100% because they are partly offset by a decrease in exports). Finally, for rapeseed, 100% of the expansion results from an increase of demand for non-food products. Pasture expansion is driven by the increase in food consumption of beef, lamb, and milk while livestock productivity per head remains

Figure 1 | Evolution of area by land cover type and protected areas under each pathway



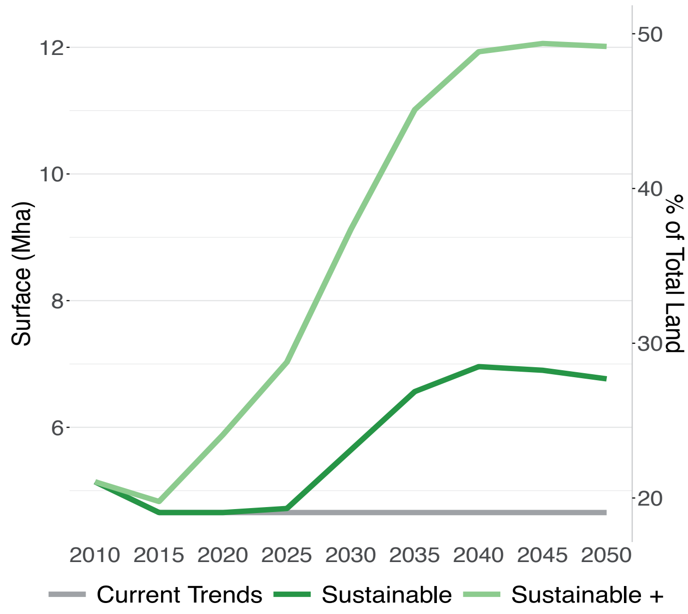
Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

constant for meat but increases for milk, and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, further expansion of farmland to meet the growing demand for food is impossible because the only remaining land is either urban, forest (it is assumed that deforestation is not allowed) or protected areas. The continued growth in urban areas coupled with the continued steady afforestation rate then drives a contraction of farmland. This results in a decrease in food consumption per capita, although this does not drop below the minimum needed for a healthy diet. Land where natural processes predominate therefore stabilizes at 19% from 2030 onwards, compared to 21% in 2010. This includes protected areas plus existing forest.

In the Sustainable Medium Ambition and Sustainable High Ambition Pathways, assumptions have been changed to reflect UK scenarios for afforestation to meet climate change commitments (CCC, 2018, 2020), and plans to set aside land for nature recovery (HM Government, 2018). The main assumptions include 1 and 1.5Mha reforested or afforested by 2050, and protected areas increase from 27.6% of total land in 2020 to 29.7% and 31.4% in 2050 (see Annex 2). Note that the FABLE Calculator assumes that around 80% of the new 0.5Mha protected area in the Sustainable Medium Ambition Pathway is farmland (based on the current mix of land use types in UK protected areas), and this is excluded from the protected area shown in Figure 1. In contrast, the additional 0.42Mha protected area in the Sustainable High Ambition Pathway is all peatland.

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in the UK in the Sustainable Medium Ambition and Sustainable High Ambition Pathways: (i) no change in deforestation because we assume no deforestation is allowed in any scenario, (ii) reversal of the loss of natural land, (iii) decrease in agricultural land, and (iv) increase in reforested/afforested land, as well as (v) lower increase in urban expansion in the Sustainable High Ambition Pathway. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by increased agricultural productivity coupled with decreased demand for meat and dairy

Figure 2 | Evolution of the area where natural processes predominate



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consumption due to a shift to healthier and more sustainable diets. This leads to an increase in the area where natural processes predominate: the area stops declining by 2025 and increases by 27% between 2025 and 2050 in the Sustainable Medium Ambition Pathway and by 57% in the Sustainable High Ambition Pathway (Figure 2).

GHG emissions from AFOLU

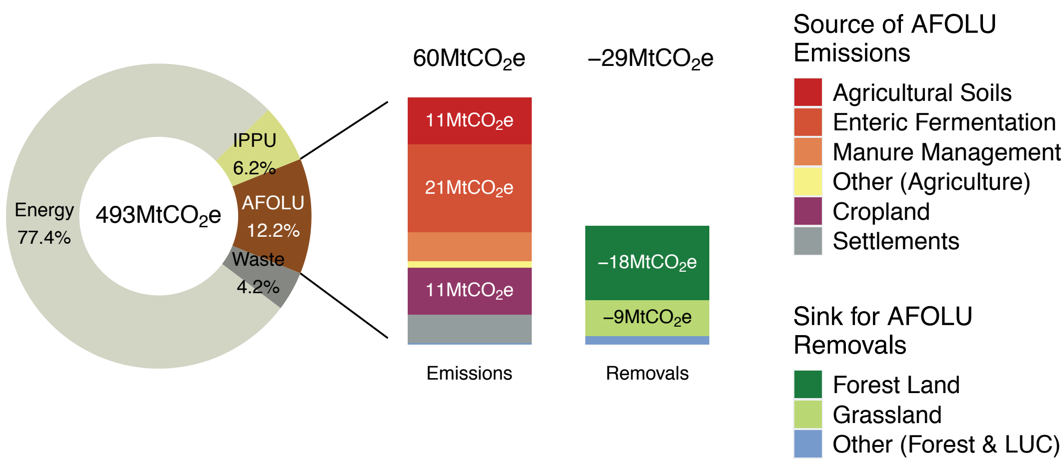
Current State

Direct GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) accounted for 12% of total emissions in 2017 (Figure 3). Enteric fermentation is the principle source of AFOLU emissions, followed by emissions from cropland and agricultural soils, manure management and settlements. This can be explained by the high population density in the UK which leads to a high proportion of land area being occupied by farmland, coupled with ongoing losses due to settlement expansion. Forestry is currently less significant: forest cover is gradually increasing from a very low base (Forest Research, 2019), though existing woodlands are still lost due to major infrastructure development (Woodland Trust, 2019).

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decline from 52 $MtCO_2e$/yr in 2015 to 43.6 $MtCO_2e$/yr in 2030, and 38.5 $MtCO_2e$/yr in 2050, because agricultural emissions decline as farmland is converted to urban areas or afforested. Over the period 2020-2050, emissions from agriculture decrease by 3.6% due to the loss of farmland. This is partly offset by land use change emissions as farmland and natural land are converted to urban areas (Figure 4). In 2050, agriculture is the largest source of emissions (40 $MtCO_2e$/yr, of which 27 $MtCO_2e$ is from livestock and the rest from crops), while carbon sequestration from afforestation acts as a sink (-2.4 $MtCO_2e$/yr).

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2017



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

In comparison, the Sustainable Medium Ambition Pathway leads to a reduction of AFOLU GHG emissions by 36% and the Sustainable High Ambition Pathway leads to a reduction by 123% (i.e. turning net emissions into a net sink) by 2050 compared to the Current Trends Pathway (Figure 4). The potential emissions reductions under the Sustainable Medium Ambition Pathway are dominated by increased sequestration from afforestation and regeneration of farmland to natural land, and a reduction in GHG emissions from agriculture. Increased agricultural productivity and dietary change are the most important drivers of this reduction, because they reduce direct emissions from ruminant livestock as well as freeing up farmland for afforestation and regeneration to natural land (Figure 5). Under the Sustainable High Ambition Pathway, GHG emissions from agriculture are further reduced due to ambitious dietary change and productivity improvements, and sequestration from regeneration of farmland to natural land and afforestation is also increased.

Compared to the UK's commitments under UNFCCC (Table 1), our results show that AFOLU could contribute up to 9% (27 $MtCO_2e$) of its total GHG emissions reduction objective of reducing emissions by 40% by 2030 under the Sustainable High Ambition Pathway. Such reductions could be achieved through ambitious policy measures: a shift to the Eatwell national healthy diet; improved agricultural productivity; protection and restoration of peatland, forests, semi-natural grassland and other natural land; new woodland creation at a rate of 50 kha per year; and reducing the land required for new housing developments by half. These measures could be particularly important when considering options for NDC enhancement and achieving the UK Net Zero target.

Figure 4 | Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the Current Trends Pathway

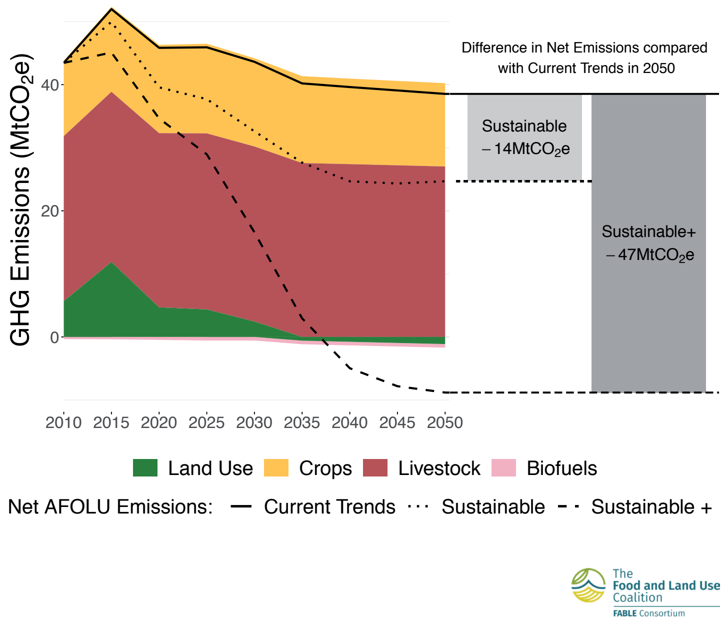
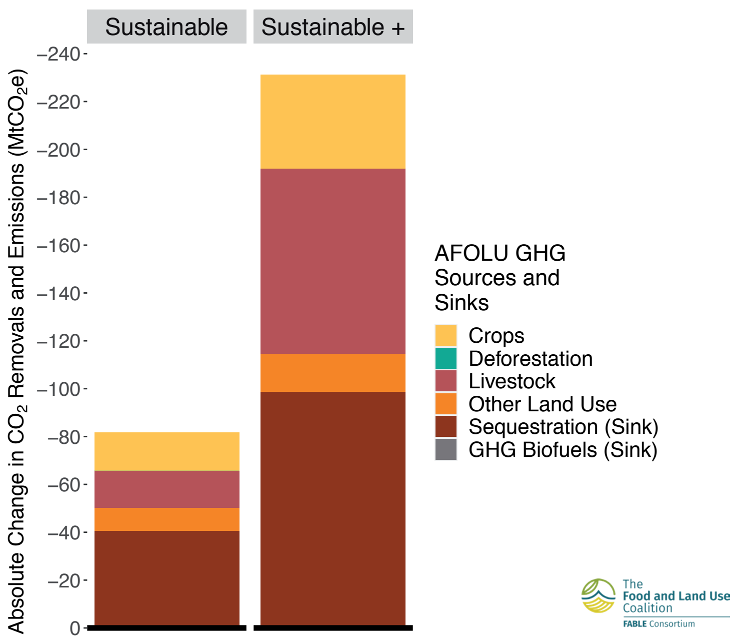


Figure 5 | Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

The “Triple Burden” of Malnutrition

Undernutrition

0.6% of the population undernourished in 2017. This share has increased from 0.5% in 2000 (Institute for Health Metrics and Evaluation [IHME], 2020).

No data on children under 5 stunted and wasted, but 10% of children live with adults who report severe food-insecurity (The Food Foundation, 2017).

Micronutrient Deficiency

9.8% of women and 9.5% of children under 20 suffer from dietary iron deficiency in 2017, (IHME, 2020).

2% of the population are deficient in vitamin A (GBD), which can notably lead to blindness (WHO, n.d.) and child mortality, and 1.5% are deficient in iodine, which can lead to developmental abnormalities (IHME, 2020).

Overweight/ Obesity

29% of adults and 15% of children were obese in 2018. These shares have increased since 1993 but have been stable since 2000 (NHS, 2020).

63% of adults and 28% of children were overweight in 2018. These shares have increased since 1993 but have been stable since 2000 (NHS, 2020).

Disease Burden due to Dietary Risks

14.8% of deaths are attributable to dietary risks (IHME, 2020).

Dietary risks also lead to/cause 1.6 million disability-adjusted life years (DALYs), or years of healthy life lost due to an inadequate diet (IHME, 2020).

9.6% of the population suffers from diabetes and 11.4% from cardiovascular diseases (responsible for 29% of all UK deaths), which can be caused by dietary risks (IHME, 2020).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways in 2030 and 2050

	2010	2030			2050		
	Historical Diet (FAO)	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition
Kilocalories (MDER)	2,983 (2,086)	2,896 (2,078)	2,972 (2,078)	2,727 (2,078)	2,736 (2,075)	2,974 (2,075)	2,149 (2,075)
Fats (g) (recommended range)	132 (66-99)	129 (66-99)	132 (66-99)	108 (61-91)	124 (66-99)	133 (66-100)	53 (48-72)
Proteins (g) (recommended range)	87 (75-261)	84 (75-261)	86 (75-261)	86 (68-240)	80 (75-261)	85 (75-261)	86 (54-189)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

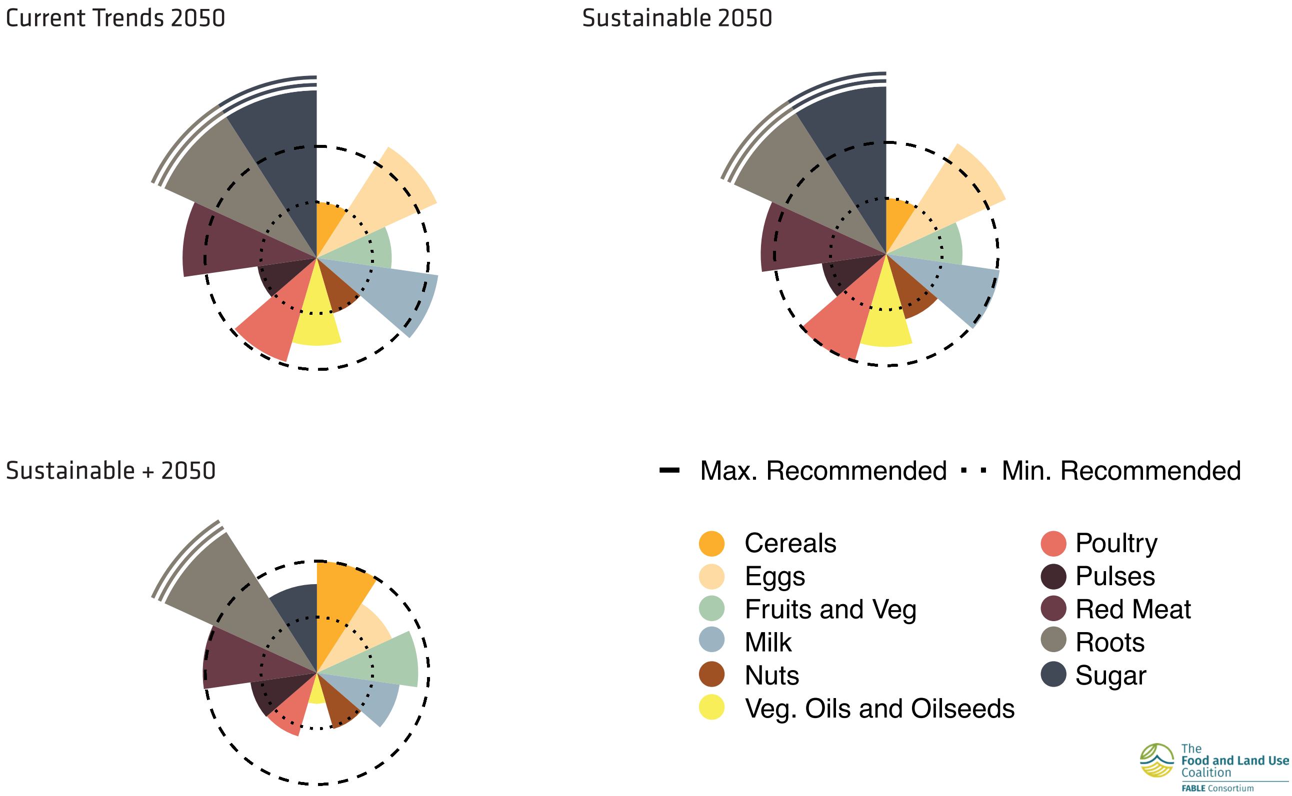
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 39% higher in 2030 and 32% higher in 2050 (Table 4). The current average calorie intake is mostly satisfied by cereals, oils and sugar, and animal products represent 31% of the total calorie intake. We assume that diets will remain constant between 2020 and 2050. Compared to the EAT-Lancet recommendations (Willette et al., 2019), roots, sugar, red meat, eggs, and milk are over-consumed while no food categories are under-consumed in 2050 (Figure 6). Moreover, fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050 (Table 4).

Under the Sustainable Medium Ambition Pathway, we assume that diets will transition towards the CCC "medium ambition" diet, in which consumption of ruminant meat and milk decreases by 20%, being replaced by pork and chicken (CCC, 2018). Under the Sustainable High Ambition Pathway, we assume that diets transition towards the UK "Eatwell" diet, which is a healthy diet according to UK government guidelines, with a much lower intake of sugar and animal products, and higher intake of pulses, fish, fruit and vegetables. The excess of the computed average intake over the MDER increases slightly to 43% in 2030 and 2050 under the Sustainable Medium Ambition Pathway (which is designed to meet climate objectives rather than health guidelines), and decreases to 32% in 2030 and 4% in 2050 under the Sustainable High Ambition Pathway. Compared to the EAT-Lancet recommendations, in the Sustainable Medium Ambition Pathway only the consumption of milk changes to fall within the recommended range, while in the Sustainable High Ambition Pathway the consumption of sugar, eggs, red meat, and milk fall within the recommended range by 2050 (Figure 6), the consumption of vegetable oils falls below the minimum recommended amount (because the Eatwell diet was modelled to be as close as possible to the current UK diet but this is based on surveys which under-report consumption of some foodstuffs), and the fat intake per capita is lower than the dietary reference intake (DRI) in 2050 (Table 4), showing a major improvement compared to the Current Trends Pathway.

Comprehensive policy measures will be important to promote this shift in diets, building on the range of existing UK actions (WCRF, 2020) such as further marketing of the Eatwell diet, integrating nutrition advice into education and primary care, refining guidelines for public sector purchasing of food and improving access to affordable plant-based food choices, as well as supply-side measures such as supporting UK growers and processors of plant-based protein sources (nuts, beans, and pulses).

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



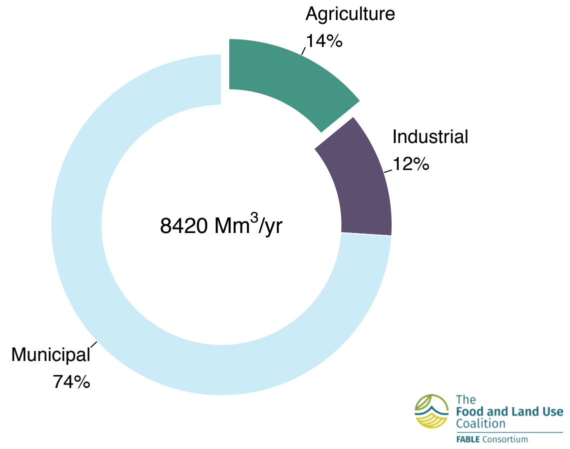
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and roots indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

The UK is characterized by a temperate oceanic climate with 1220 mm average annual precipitation that occurs all year round, but with more in the months of October to January (Met Office, 2019). According to the default FABLE dataset (used for this round of modeling), the agricultural sector represented 14% of total water withdrawals in 2016 (Figure 7; FAO, 2017), though more recent UK data indicates a share of 9% (Environment Agency, 2020). In 2016, only 3% of arable land was equipped for irrigation (FAO AQUASTAT, 2016). The two most important irrigated crops, potatoes and other vegetables, accounted for 52% and 27% of total harvested irrigated area in 2007 (FAO, 2017). The UK exported 7% of potatoes and 12% of other vegetables in 2010 (FAO, 2020).

Figure 7 | Water withdrawals by sector in 2016

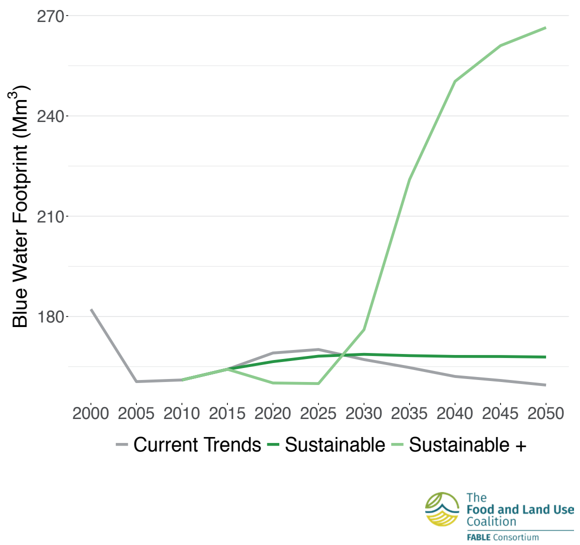


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use decreases between 2000-2015 (182 and 164 Mm^3/yr), before reaching 167 Mm^3/yr and 160 Mm^3/yr in 2030 and 2050, respectively (Figure 8), with potatoes and other vegetables accounting for 47% and 42% of computed blue water use for agriculture by 2050[4]. Under the Sustainable Medium Ambition Pathway, blue water footprint in agriculture reaches 169 Mm^3/yr in 2030 and 168 Mm^3/yr in 2050, respectively. Under the Sustainable High Ambition Pathway, the blue water footprint increases to 266 Mm3/yr in 2050. The increase in water use in the Sustainable High Ambition Pathway is due to greater production of potatoes and other vegetables. We did not assume any changes in the water-use efficiency of irrigation.

Figure 8 | Evolution of blue water footprint in the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways



4 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

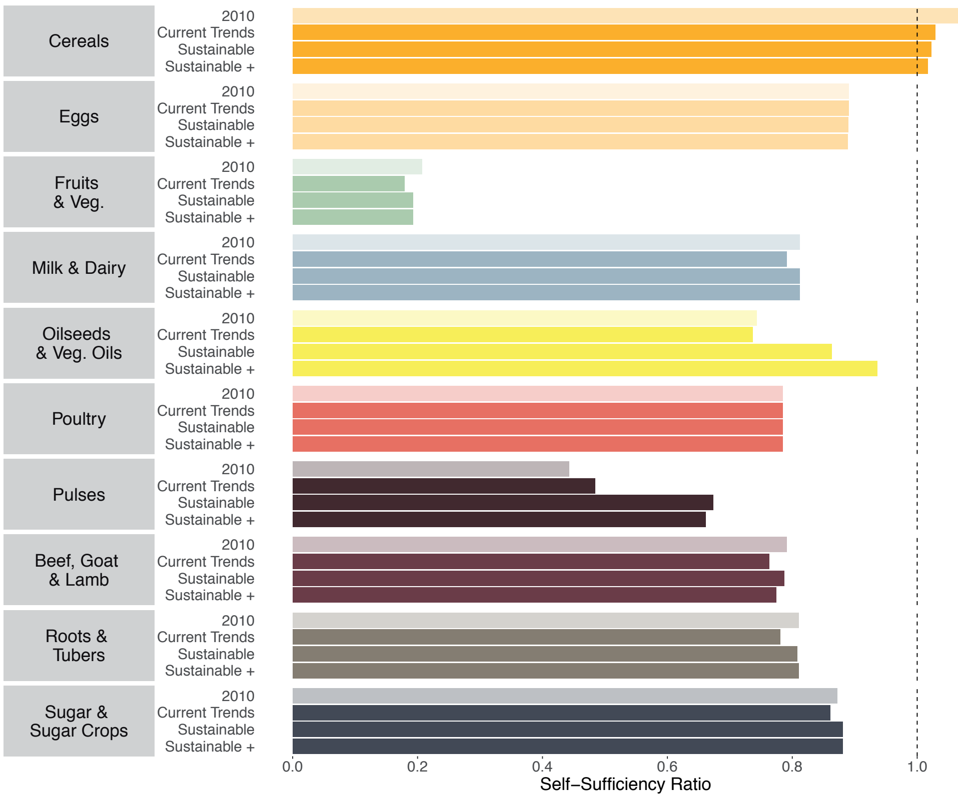
Resilience of the Food and Land-Use System

The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge the UK's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Self-sufficiency has been declining since a peak in 1984, when the UK produced 78% of all foodstuffs consumed, and 95% of indigenous foodstuffs (those that can be produced in the UK). In 2010 the UK was 62% self-sufficient in all foods and 78% in indigenous foods, and this downwards trend is still continuing (DTI, 2014). The highest reliance on imports is for fruit and vegetables, oilseeds, and spices (FAO, 2020).

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1.

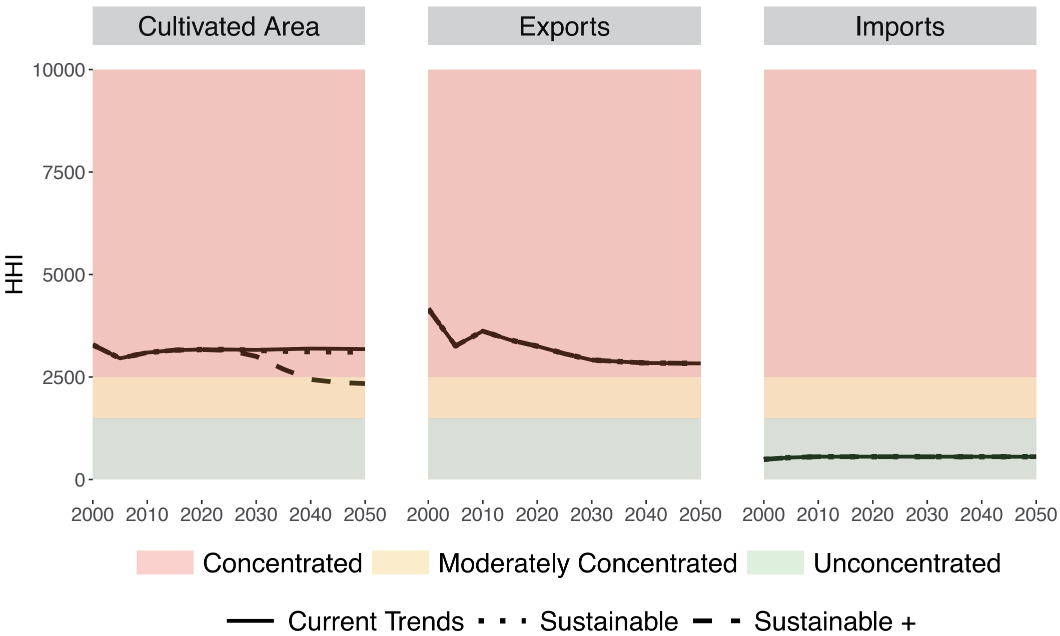
Under the Current Trends Pathway, we project that the UK would continue to be self-sufficient only in cereal production in 2050, with self-sufficiency by product group decreasing slightly for the majority of products from 2010 – 2050 (Figure 9). The product groups where the country depends the most on imports to satisfy internal consumption are fruit and vegetables, and this dependency will increase until 2050. Under the Sustainable Medium Ambition and Sustainable High Ambition Pathways, there are slight improvements in self-sufficiency for most food groups, and especially for oilseed and pulses, as land for food production is freed up and demand for feed crops is reduced due to dietary change and productivity improvements.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- ❑ **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- ❑ **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

According to the HHI (Figure 10), the planted crop area in 2010 is concentrated on just a few crops (wheat, barley, and oilseed rape), and exports are also concentrated on these crops. However, imports are not concentrated, reflecting the high dependence of the UK on imports across many food groups.

Under the Current Trends Pathway, we project concentration of crop exports to decrease slightly over the period 2010 – 2050 while imports remain un-concentrated and the range of crops planted remains concentrated. This indicates low levels of diversity across the national production system and exports. In contrast, under the Sustainable Medium Ambition and the Sustainable High Ambition Pathways, we project a slight decrease in the concentration of the range of crops planted in 2050, indicating higher levels of diversity across the national production system (Figure 10). This is explained by a reduction of the large proportion of crop area previously needed to grow barley for animal feed.

Discussion and Recommendations

The FABLE results for the UK show that our land-use system faces extreme pressure. With our Current Trends Pathway, urban development and afforestation compete strongly with land for food production, resulting in increased food imports to meet demand from a growing population. Although GHG emissions from AFOLU remain stable at 2015 levels, global emissions will rise as the UK imports more food. In contrast, the Sustainable Pathways show how emissions could be reduced by between 36% and 123%, enabling the AFOLU sector to contribute up to 9% of the UK target of a 40% reduction by 2030. This is consistent with scenarios developed for the UK government (CCC, 2018), designed to deliver AFOLU GHG reductions of between 35% and 80%, as a key part of the UK commitment to Net Zero emissions by 2050. Even with the very ambitious assumptions of the Sustainable High Ambition Pathway, however, it is clear that the majority of emission reductions need to come from decarbonising the economy.

The impacts of future land use change on biodiversity are dramatic. Under the Current Trends Pathway, all the non-forest natural land (semi-natural grasslands, wetlands, heathland, and shrub) except for that which is in protected areas is lost to urban development, afforestation, and expansion of farmland by 2030. This would undermine UK NBSAP targets for protecting and expanding the area of priority habitats and creating nature recovery networks. In addition, the UK would be responsible for additional environmental impacts globally to satisfy the demand for increased food imports. However, our Sustainable Pathways illustrate how dietary change and productivity improvements can free up land for biodiversity and carbon storage, enabling a transition to a healthy and sustainable food supply system.

The results highlight key trade-offs and synergies in UK food and land-use systems, especially the strong dependence of climate, food, and biodiversity targets on dietary change, and the synergy between climate mitigation and healthy diets. However, there are potential trade-offs between afforestation and biodiversity targets, due to the pressure on other types of natural land. In the 'current trends' scenario, despite a relatively modest amount of afforestation, all other types of natural land are eliminated except for that in protected areas. Current targets for expansion of housing and infrastructure may also have significant impacts on our ability to meet climate and biodiversity targets in the face of growing demand for food, if the expansion includes greenfield as well as brownfield development. In the sustainable scenarios, productivity increases help to reduce the trade-offs by enabling more food to be produced per unit area, but these involve ambitious assumptions which are highly uncertain.

It is still too soon to say how the experience of COVID-19 will affect the UK food and land-use system over the next five years. Although global commodity trade has shown resilience (as of November 2020), peaks in demand for certain goods have stressed supply chains and there has been a shortage of migrant workers for production of labor-intensive crops. The pandemic has also highlighted how consumer habits can change rapidly and has raised the profile of nutritional health. Future outcomes are uncertain, but the disruption may create an opportunity to influence and shape the UK food system as society and economy recover over the next five years. Key questions include whether "de-globalization" will lead to political pressure to grow more food locally even when market forces favor imports, whether public perceptions will shift to allow more state intervention to achieve societal goals beyond those produced by the market, whether changes in consumer habits that have emerged during the lock-down might lead to fundamental changes in consumer preferences and nutrition, and what effect may this have on land use. And uncertainty over Brexit still remains, with the threat of 'no deal' disruption at the end of 2020 and the unknown outcomes of ongoing trade negotiations with non-EU countries. Exploring scenarios about future food supply and land use has never been more important.

To tackle these challenges and trade-offs we recommend that:

- Existing and emerging national policies within each of the four UK nations of England, Wales, Scotland and Northern Ireland that affect land use (for example, for England these include the 25 Year Plan for the Environment, Environmental Land Management schemes, the Environment and Agriculture Bills and the National Food Strategy) should consider the strong evidence of the essential role that the Eatwell diet and related initiatives could play in reducing GHG emissions and protecting biodiversity. Various evidence-based tools are already available to policy makers to help bring this about. Modelling consumer behavior is likely to become even more important.

- UK farmers, growers and producers should be supported in transitioning to a sustainable food system. A dietary shift towards more fruit and vegetable consumption could present an opportunity to expand this highly profitable sector in the UK.

- Housing and infrastructure development targets should take account of their impacts on the ecosystem services provided by different types of land. The presumption in favor of brownfield development will reduce pressure on other land uses.

- Biodiversity, agriculture, and forestry policies should consider the impact of large-scale afforestation on biodiversity and on food production, as well as using native species or natural regeneration where possible and aligning with nature recovery networks.

- Unprotected peatland should be protected in order to achieve benefits for both biodiversity and carbon. The 0.5Mha nature recovery land in the 25 Year Environment Plan should be given effective protection in the planning system, to avoid encroachment by development.

- The Sustainable Pathways illustrate emissions reduction due to reduced agricultural land area and improved productivity, but land/soil management (including manure management) will also be important on remaining agricultural lands.

The analysis has certain limitations. There is considerable uncertainty over some input parameters and assumptions, including future trends in crop and livestock productivity, the impacts of climate change on yield and future livestock stocking densities. For example, stakeholders advise that policy may shift towards lower stocking densities to reduce environmental impacts, rather than the high densities assumed in our sustainable pathways. There are many differences between actual UK statistics and the global FAOSTAT database that is used as the default in FABLE. In some cases, we have adjusted the input parameters to match more closely UK statistics but in general we use the FAOSTAT figures to ensure consistency with other country teams. Imports and exports were assumed to be fixed at current levels, due to uncertainty over Brexit negotiations (except for the global trade balancing adjustments). The model is not spatial and does not take account of the different contexts of the four devolved nations of the UK. It also does not distinguish between different types of forest (native vs non-native; semi-natural vs commercial plantations) which have different impacts on biodiversity and climate mitigation, or between semi-natural and improved grassland.

We hope to address some of these issues in future work. In particular we aim to secure funding to develop versions of the FABLE Calculator for the UK Devolved Administrations. We would like to extend the UK version of the FABLE Calculator to include peatland emissions, UK-relevant bioenergy crops (coppice and miscanthus) and water efficiency targets and investigate whether agroforestry and hedgerow creation can be included. Distinguishing between improved and semi-natural grassland and semi-natural vs plantation forest would enable the impacts of land use change on biodiversity to be assessed in more detail. We also plan to undertake sensitivity analyses to explore the impact of key assumptions, e.g. on productivity. Finally, we would like to secure funding to explore the spatial implications of the scenarios by developing high resolution spatially-explicit models of the UK food and land-use system coupled to global trade.

Annex 1. List of changes made to the model to adapt it to the national context

- Added in alternative diets: the CCC medium ambition scenario diet and the Eatwell diet (see Annex 2).
- Altered livestock productivity calculation to allow a specific increase above the 2015 value to be set, rather than using the default extrapolation. This allows more precise control over the scenarios.
- Altered crop productivity calculation to allow a specific increase above the 2015 value to be set, rather than using the default extrapolation.
- Added forest planting implementation rate such that the historical values were correct and consistent between pathways; and such that the future values could be specified more precisely based on stakeholder input.
- Altered Protected Area calculation to allow a specified increase in absolute area to be defined (we wanted to be able to include +500 kha of protected land in our scenarios).
- Added in a scenario on Urban Expansion, such that we could differentiate between pathways instead of assuming the same expansion policy between all three.
- Added in custom implementation rate curves for the Post Harvest Loss scenarios, such that we could control these more precisely in line with the stakeholder input.

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
The population is expected to reach 75.4 million by 2050 (UN medium projections). Based on UNDESA (2017) (UN Medium Projection scenario selected).	As for Current Trends.	As for Current Trends.

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
We assume that there will be no constraint on the expansion of the agricultural land beyond existing protected areas and under the total land boundary. Based on lack of any UK policy to constrain expansion.	As for Current Trends.	As for Current Trends.
LAND Afforestation or reforestation target (1000 ha)		
We assume total afforested/reforested area to reach 326Mha by 2050. Based on continuation of average rate of tree planting 2014-2016, i.e. 9,000ha/y (CCC, 2018).	We assume total afforested/reforested area to reach 990Mha by 2050. Based on CCC medium ambition scenario, i.e. 30,000ha/y (CCC, 2018).	We assume total afforested/reforested area to reach 1490Mha by 2050. Based on CCC high ambition scenario, i.e. 50,000ha/y (CCC, 2018).
LAND Urban expansion		
Increase of urban area from 7% of UK land area in 2015 (1.6Mha) to 10.2% (2.5Mha) by 2050, at a rate of 26,000ha/y, based on government projections for future housing needs (CCC, 2018; MHCLG, 2019).	As for Current Trends.	Increase of urban area from 7% of UK land area in 2015 (1.6Mha) to 8.3% (2.0Mha) by 2050, at a rate of 13,000ha/y, based on assumption that land take could be half of Current Trends, e.g. if developments were more compact, following the approach used in (Thomson et al., 2018).

BIODIVERSITY Protected areas (% of total land)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Protected areas remain stable: by 2050 they represent 27.6% of total land. Based on (WDPA, 2020). Includes National Parks, AONBs, local and national nature reserves, SSSIs, Ramsar sites and Natura sites (SACs and SPAs). Within these areas, the FABLE Calculator distinguishes between forests and other natural land, which are assumed to be unavailable for expansion of food production, and farmland, where production can continue.	Protected areas increase: by 2050 they represent 27.9% of total land. Based on assumption that 0.5Mha of land will be set aside for nature recovery, as expressed in 25 Year Environment Plan for England and Wales (HM Government, 2018), and that this area will be protected. Note that the FABLE Calculator currently assumes that this land is the same mix of forest, farmland and other natural land as in currently protected areas. This means that only about 20% of the new protected area is recognized as natural or forest.	Protected areas increase: by 2050 they represent 29.6% of total land. Based on assumption that in addition to the 0.5Mha extra protected land for nature recovery, all unprotected peatland is protected, adding a further 0.42Mha of natural protected land (calculations by UK FABLE team).

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
In 2050, crop productivity remains at: • 7.7 tons per ha for wheat (7.1 with climate change impacts). • 5.7 tons per ha for barley. • 43.9 tons per ha for potatoes. Based on FAOSTAT historic yields for 2010.	By 2050, crop productivity reaches: • 10.7 tons per ha for wheat (10.1 with climate change impacts). • 7.9 tons per ha for barley. • 61 tons per ha for potatoes. Based on assumption that yields for all crops increase by 39% from the 2010 value, in line with the revised CCC medium projection (CCC, personal communication, 2020).	By 2050, crop productivity reaches: • 12.7 tons per ha for wheat (12.0 with climate change impacts). • 9.4 tons per ha for barley. • 72.4 tons per ha for potato. Based on assumption that yields for all crops increase by 65% (from stakeholder discussions).

PRODUCTION Livestock productivity for the key livestock products in the country (in kg/head of animal unit)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2050, livestock productivity *(annual production / average herd size, not carcass weight)* reaches: • 7,971 kg per head for milk. • 85 kg per head for cattle meat. • 13.7 kg per head for chicken meat. Based on assumption that milk yield increases by 18%, half the current rate, while other yields remain at 2015 levels, using UK agriculture statistics (Defra, 2019).	By 2050, livestock productivity reaches: • 7,971 kg per head for milk. • 85 kg per head for cattle meat. • 15.3 kg per head for chicken meat. Based on assumption that milk yield increases by 18%, half the current rate; cattle remains the same as productivity is assumed to increase via changes to stocking density; poultry assumed to increase proportional to the assumed increases in stocking density for cattle.	By 2050, livestock productivity reaches: • 8,669 kg per head for milk. • 85 kg per head for cattle meat. • 15.3 kg per head for chicken meat. Based on increase of 27% for milk yield, 75% of the current rate of increase; no further increase for cattle or chicken, to reflect animal welfare and physiology constraints / limits to further yield increases.

PRODUCTION Pasture stocking rate (in animal units/ha pasture)

By 2050, the average ruminant livestock stocking density is 1.1 TLU/ha. Based on assumption that the stocking density remains unchanged from the value in 2010 according to FAOSTAT (herd numbers divided by pasture area).	By 2050, the average ruminant livestock stocking density is 1.2 TLU/ha. Based on increase of 10% from 2015, the same % increase as in CEH Rothamsted high ambition scenario (Thomson et al., 2018).	By 2050, the average ruminant livestock stocking density is 1.7 TLU/ha. Based on increase of 50% from 2015, the same % increase as in CCC high ambition scenario (CCC, 2018), and guidance on potential densities (AHDB, 2016).

PRODUCTION Post-harvest losses

By 2050, the share of production and imports lost during storage and transportation is 1% for crop products and unknown (assumed zero) for livestock products. Based on FAOSTAT data and assumption of no change from present day, but data is patchy.	By 2050, the share of production and imports lost during storage and transportation is 0.5%. Based on assumption of a 50% reduction in losses compared to 2015, i.e. achieving the SDG 12.3 target to halve consumer and retail waste but by 2050 rather than 2030 (WRAP, 2020).	By 2030, the share of production and imports lost during storage and transportation is 0.5%, i.e. the target is achieved earlier than the Sustainable scenario. Based on assumption of a 50% reduction in losses compared to 2015 in line with the Courtauld 2025 Commitment (reduction of 20% across supply chain between 2015-2025) and SDG 12.3 target (halve consumer and retail waste by 2030) (WRAP, 2020).

TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2050, the share of total consumption which is imported remains at the 2015 values: • 53 % for other vegetables. • 88 % by 2050 for apples. • 25 % by 2050 for beef. Based on stakeholder discussions and agreement that the outcome of Brexit trade negotiations and the design of the replacement agricultural support scheme were too uncertain to allow meaningful projections of future change.	As for Current Trends.	As for Current Trends.

TRADE Evolution of exports for key exported products (1000 tons)

By 2050, the volume of exports remains at the 2015 values: • 1.8Mt by 2050 for wheat. • 1.1Mt by 2050 for barley. • 0.3Mt by 2050 for rapeseed oil. Based on stakeholder discussions and agreement that the outcome of Brexit trade negotiations and the design of the replacement agricultural support scheme were too uncertain to allow meaningful projections of future change.	As for Current Trends.	As for Current Trends.

FOOD Average dietary composition (daily kcal per commodity group)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2030, the average target daily calorie consumption per capita is 2,983 kcal and is: • 168 kcal for fruit and vegetables. • 83 kcal for ruminant meat. • 119 kcal for animal fats. Based on assumption of no change in current diet as in FAOSTAT.	By 2030, the average target daily calorie consumption per capita is 2,894 kcal and is: • 167 kcal for fruit and vegetables. • 78 kcal for ruminant meat. • 119 kcal for animal fats. Based on CCC medium ambition scenario (20% reduction in red meat and milk consumption by 2050) (CCC, 2018).	By 2030, the average target daily calorie consumption per capita is 2,739 kcal and is: • 196 kcal for fruit and vegetables. • 75 kcal for ruminant meat. • 98 kcal for animal fats. Based on meeting the Eatwell diet recommendations by 2050 (PHE, 2020; Scarborough et al., 2016).

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2030, the share of final household consumption which is wasted at the household level is 14%. Based on assumption of no change from current levels (WRAP, 2020).	By 2030, the share of final household consumption which is wasted at the household level is 12.5%. Based on CCC medium ambition scenario in which the share which is wasted decreases linearly by 20% from 2010 to 2050, from 14% to 11% (CCC, 2018).	By 2030, the share of final household consumption which is wasted at the household level is 7 %. Based on Courtauld 2025 Commitment (reduction of 20% across supply chain between 2015-2025) and SDG 12.3 target (halve consumer and retail waste by 2030 (WRAP, 2020).

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2050, biofuel production accounts for: • 226kt of corn production. • 909kt of wheat production. Based on OECD Aglink projections until 2028; stable afterwards. In future this could be modified to reflect UK policy to use coppice wood and miscanthus grass rather than food crops.	By 2050, biofuel production accounts for: • 231kt of corn production. • 1143kt of wheat production. Based on OECD Aglink projections until 2028; stable afterwards.	By 2050, biofuel production accounts for: • 215kt of corn production. • 1053kt of wheat production. Based on OECD Aglink projections until 2028; stable afterwards.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tons

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – ton

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – ton per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- ton per TLU, kilogram per TLU, ton per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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United States of America

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines how sustainable food and land-use systems can contribute to raising climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in the United States (e.g., healthier diets). It presents three pathways for food and land-use systems for the period 2020-2050: Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition (referred to as "Current Trends", "Sustainable", and "Sustainable +" in all figures throughout this chapter). These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways using government sources and academic literature, and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context.

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how the US's NDC and Long-Term Low Emissions and Development Strategy (LT-LEDS) treat the FABLE domains. According to its 2016 NDC and LT-LEDS, the US previously committed to reducing its GHG emissions by 26-28% by 2025 compared to 2005 and to 80% below 2005 levels by 2050, respectively. These emission reduction projections include abatement efforts from agriculture, forestry, and other land use (AFOLU). However, envisaged mitigation measures from agriculture and land-use change are not explicit in the US LT-LEDS or NDC. Under its commitments to the UNFCCC submitted in 2016, the US does not mention biodiversity conservation.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC and LT-LEDS

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2005	5,999 million	2025	26-28% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Food, water, forests
LT-LEDS (2016)	2005	5,999 million	2050	80% reduction	Energy, industrial processes, agriculture, land-use change and forestry, and waste	Y	N	N	Food, water, forests

Note. The NDC "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source: US (2016a) for the NDC and US (2016b) for the LT-LEDS

Although the US helped establish the United Nations Environment Programme that started the negotiations to develop the Convention on Biological Diversity, the US is not a contracting party to the CBD. As a result, the US does not have an NBSAP.

1 We follow the United Nations Development Programme definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Brief Description of National Pathways

Among possible futures, we present three alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in the US.

Our Current Trends Pathway corresponds to the lower boundary of feasible action. It is characterized by medium population growth (from 334 million inhabitants in 2020 to 400.4 million in 2050), no constraints and agricultural expansion, a low afforestation target corresponding to the amount of land remaining in the Conservation Reserve Program (5.7 Mha), no change in the extent of protected areas, medium productivity increases in the agricultural sector, no change in diets, no change in the imports or exports of agricultural commodities, and historic rates of change in ruminant density per hectare of pasture (which is a declining) (see Annex 2). This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to crop and livestock productivity (US Department of Agriculture [USDA], 2020a). Moreover, as with all FABLE country teams, we embed this Current Trends Pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, nuts, peas, rapeseed, rice, soyabean, sugarbeet, sugarcane, sunflower, wheat, and millet (see Annex 2).

Our Sustainable Medium Ambition Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the Current Trends Pathway, we assume that this future experiences the same population growth, no constraints and agricultural expansion, a high afforestation target (40 Mha), an increase in the extent of protected areas from 13.2% to 19.2%, high productivity increases in the agricultural sector, a shift in average diets towards the Healthy-Style Diet for Americans (US Department of Health and Human Services [HSS] & USDA, 2015), no change in the imports of agricultural commodities, but a growth in exports for several agricultural commodities (corn, soybean, wheat, beef, soycake, pork, chicken, milk, and eggs), and slightly higher intensity of ruminant density per hectare of pasture compared to the Current Trends Pathway (see Annex 2). This corresponds to a future guided by the US's LT-LEDS, that would also see considerable progress with regards to healthier diets. With the other FABLE country teams, we embed this Sustainable Medium Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Our Sustainable High Ambition Pathway represents a future in which efforts were made to achieve both reforestation as well as bioenergy needs from the land sector. Compared to the Sustainable Medium Ambition Pathway, we assume that this future would lead to use of the land sector to supply biofuels needed to achieve net zero or net negative emissions for the energy and industrial sectors (Williams et al., Manuscript submitted for publication), while also expanding protected areas to 30% of total land area—all made possible by greater productivity and healthier diets (see Annex 2). As in the Sustainable Medium Ambition Pathway, we embed this Sustainable High Ambition Pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

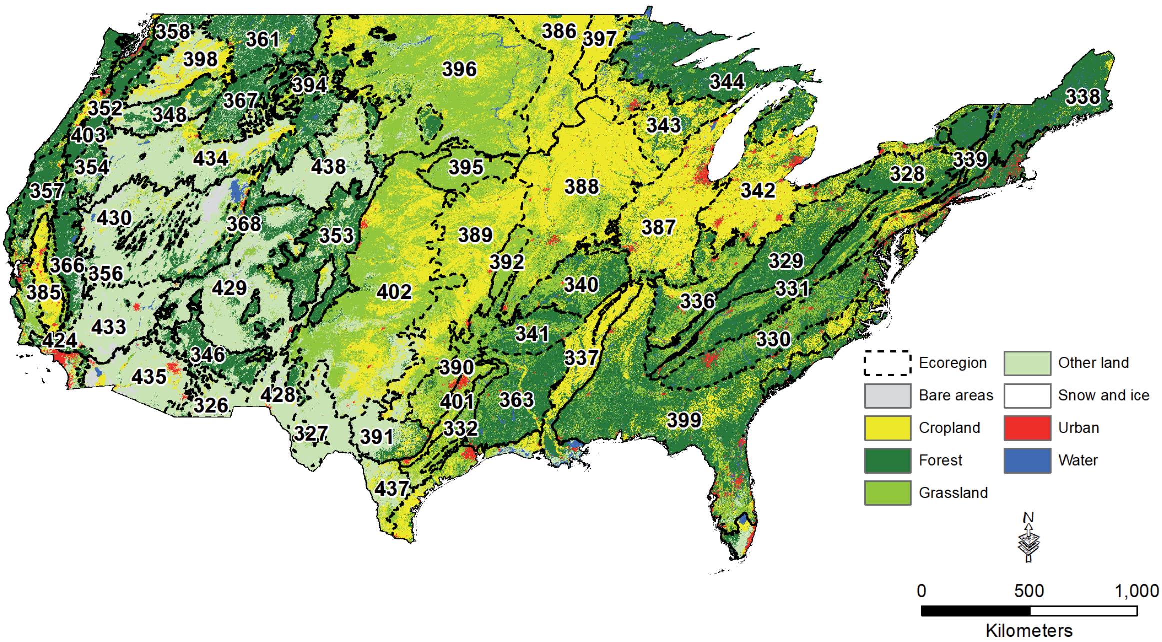
Land and Biodiversity

Current State

In 2010, the US was covered by 17.3% cropland, 27.2% pastureland, 33.2% forest, 1.4% urban, and 22.9% other natural land. Most of the agricultural area is located in the midwestern states while forest and other natural land can be mostly found in western states (Map 1). The greatest threats to biodiversity in the US are habitat loss and habitat degradation. While several policies are in place for biodiversity conservation, the most prominent being the Endangered Species Act, it takes an average of 12 years for species to be listed as endangered or threatened (Puckett et al., 2016) and only 5% of listed species receive adequate conservation funding (Evans et al., 2016).

We estimate that land where natural processes predominate[2] accounted for 45% of the US's terrestrial land area in 2010 (Map 2). The Interior Alaska-Yukon lowland taiga holds the greatest share of land where natural processes predominate, followed by the Great Basin shrub steppe and Colorado Plateau shrublands (Annex 4). Across the country, while 121.4 Mha of land is under formal protection (or about 13.2%), falling short of the 30% zero-draft CBD post-2020 target, only 25.8% of land where natural processes predominate is formally protected.

Map 1 | Land cover by aggregated land cover types in 2010 and ecoregions

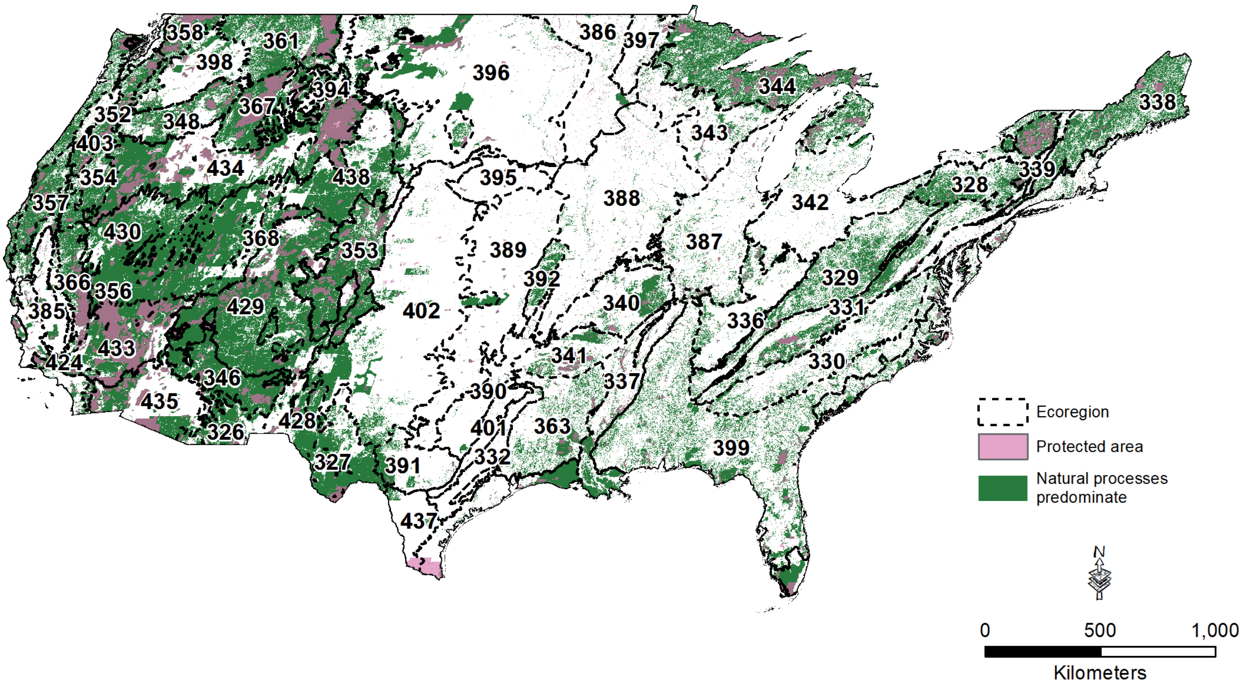


Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); land cover – ESA CCI land cover 2015 (ESA, 2017)
Notes: The map does not display Alaska and Hawaii, which are included in the national statistics (Annex 4). Correspondence between original ESACCI land cover classes and aggregated land cover classes displayed on the map can be found in Annex 3.

2 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".

Approximately 33.9% of US cropland was in landscapes with at least 10% natural vegetation in 2010. These relatively biodiversity-friendly croplands are most widespread in Northern Shortgrass prairie, followed by Central-Southern US mixed grasslands and Western shortgrass prairie.

Map 2 | Land where natural processes predominated in 2010, protected areas and ecoregions



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FABLE Consortium

Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)
Note: Protected areas are set at 50% transparency, so on this map dark purple indicates where areas under protection and where natural processes predominate overlap.

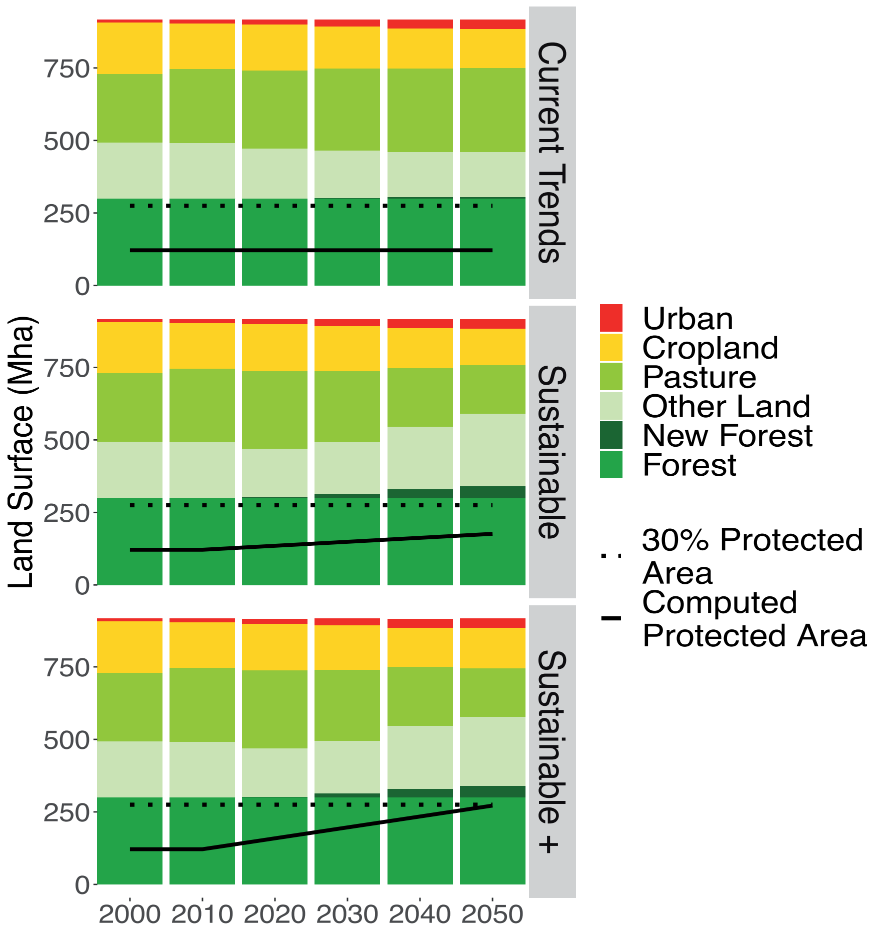
Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no constraints on land conversion beyond protected areas, 5.7 Mha reforested or afforested by 2050, and protected areas remain at 121.4 Mha, representing 13.2% of total land cover (see Annex 2).

By 2030, we estimate that the main changes in land cover in the Current Trends Pathway will result from an increase in pastureland area and a decrease in cropland area. This trend evolves over the period 2030-2050: pastureland area continues to increase and cropland area continues to decrease, but at lower rates (Figure 1). Pasture expansion is mainly driven by the increase in demand for beef due to population growth while livestock productivity per head remains constant and ruminant density per hectare of pasture remains constant over the period 2020-2030. Between 2030-2050, continued cropland reduction, pastureland expansion, and other land reduction are explained by the steady growth of urban areas, modest reforestation, increases in beef demand and no change in ruminant density per hectare of pasture, and continued increases in crop productivity. This results in a slight reduction in land where natural processes predominate by 4% by 2030 and by 5% by 2050 compared to 2010, respectively.

In the Sustainable Medium Ambition and Sustainable High Ambition Pathways, assumptions on protected areas have been changed from 13% under the Current Trends Pathway to 19% and 30%

Figure 1 | Evolution of area by land cover type and protected areas under each pathway

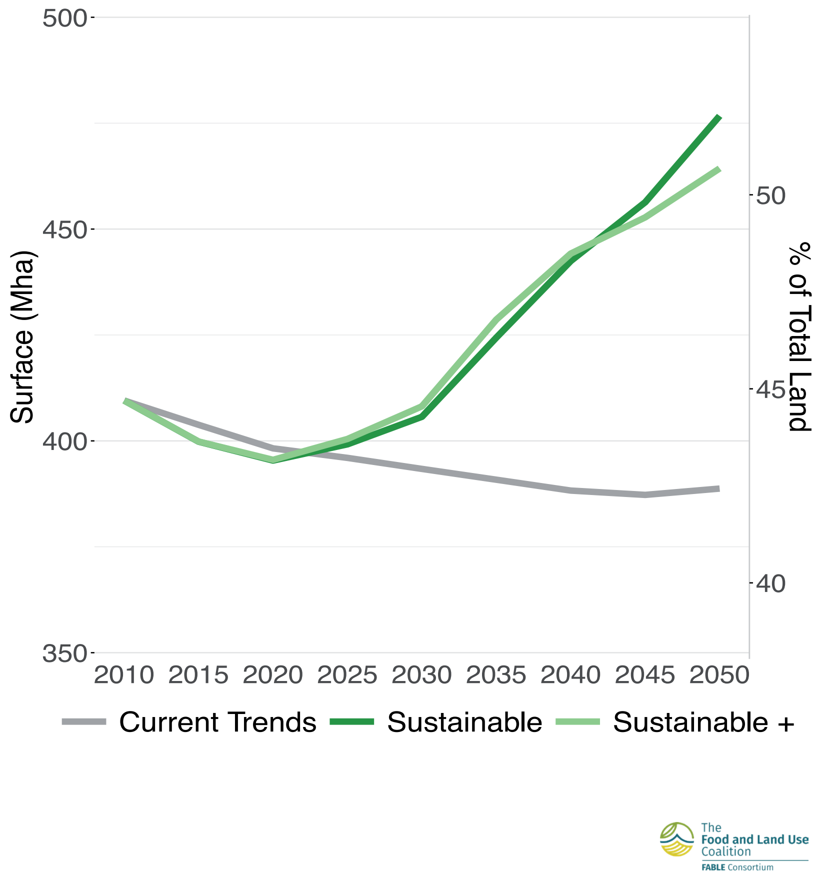


Source. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas (UNEP-WCMC & IUCN, 2020) for protected areas for years 2000, 2005 and 2010.

protection by 2050, respectively, the latter of which is informed and inspired by the 30x30 challenge, or protecting 30% of land and ocean by 2030. The only other assumptions changed under the Sustainable High Ambition Pathway is the use of land for growing dedicated bioenergy feedstocks, miscanthus and switchgrass, consistent with US Deep Decarbonization Pathways assumptions for achieving economy-wide net zero emissions by 2050 (see Annex 2).

Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in the US in the Sustainable Medium Ambition and Sustainable High Ambition Pathways: (i) significant growth in forested land due to reforestation policies, (ii) significant growth in the area of other land, (iii) significant reduction in the extent of pastureland, and (iv) very slight decline in the extent of cropland by 2050 with a slight increase between 2020 and 2040. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are largely explained by dietary shifts and crop productivity improvements. Changes in dietary preferences and crop productivity lead to an increase in the area where natural processes predominate: the area stops declining by 2030 and increases by 16% between 2010 and 2050 (Figure 2).

Figure 2 | Evolution of the area where natural processes predominate



GHG emissions from AFOLU

Current State

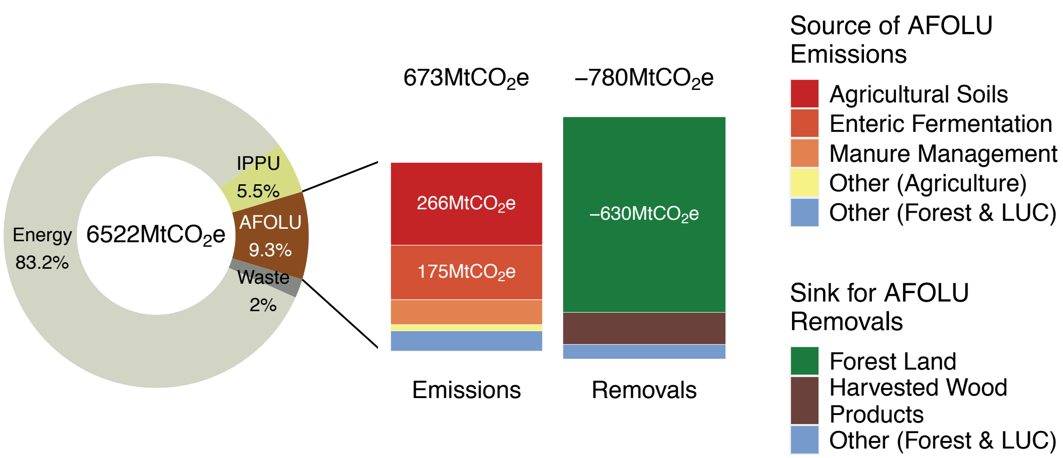
Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 9.3% of total emissions in 2010 (Figure 3). Agricultural soils (e.g., N_2O) is the principle source of AFOLU emissions, followed by enteric fermentation, croplands, and manure management; together enteric fermentation and manure management due to livestock encompasses the largest share of AFOLU emissions. Emissions from agricultural soils (non-CO_2) can be explained by the widespread use of fertilizers, nitrogen-fixing crops, soil drainage properties, how crops are irrigated (US Environmental Protection Agency, 2015), and the growth in consumption of livestock products.

Pathways and Results

Under the Current Trends Pathway, annual AFOLU GHG emissions reported by the FABLE Calculator stand at 408 Mt CO_2e/yr) in 2020, decrease to 326 Mt CO_2e/yr in 2030, and further decrease to 181 Mt CO_2e/yr in 2050 (Figure 4). In 2050, livestock remains the largest source of emissions (249 Mt CO_2e/yr) while land use change, including slower growth of pastureland coupled with a continued increase in reforestation, acts as a sink (-144 Mt CO_2e/yr). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for livestock (1.5%) while emissions reductions are observed for crop production and due to land use change (13.8% from crops, 283% from land use change).

In comparison, the Sustainable Medium Ambition Pathway leads to a reduction of AFOLU GHG emissions by 325% and the Sustainable High Ambition Pathway to a reduction by 374% by 2050 compared to the Current Trends Pathway

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2017



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

(Figure 4). The potential emissions reductions under the Sustainable Medium Ambition Pathway is dominated by a reduction in GHG emissions primarily from livestock and crops in addition to 40 Mha reforestation leading to -600 Mt CO_2e/yr by 2050 (Figure 5). Dietary changes that reduce the demand for red meat, increased crop productivity, and ambitious reforestation targets are the most important drivers of this reduction. Under the Sustainable High Ambition Pathway, GHG emissions are further avoided from fossil fuels due to an increase in biofuels production. However, the GHG benefits due to miscanthus and switchgrass biomass feedstocks are modest (-21 Mt CO_2e/yr).

Compared to US commitments under UNFCCC (Table 1), our results show that AFOLU mitigation interventions tracked by the FABLE Calculator (agricultural emissions and land use change, not including the current land use sink) could contribute to as much as 12.3% and 14.1% of its total GHG emissions reduction objective by 2050 in the Sustainable Medium Ambition and Sustainable High Ambition Pathways, respectively. Such reductions could be achieved through the following policy measures: setting ambitious reforestation targets, encouraging shifts towards a healthier diet, and increasing crop productivity to relax extensive margin pressure on agricultural land use. It is important to note that our analysis only considers mitigation opportunities through land use change and crop production shifts. This approach misses important mitigation opportunities through improved forest management (Baker et al., 2017; Van Winkle et al., 2017), forest planting to increase stand productivity (Wade et al., 2019), mitigation strategies on working agricultural lands such as conservation tillage, and livestock sector mitigation strategies to reduce enteric fermentation emissions or capture methane emissions from hog and dairy operations (Murray et al., 2005). Thus, mitigation potential represents a lower bound for these land use and crop production trajectories.

Figure 4 | Potential AFOLU emissions reductions by 2050 by trajectory compared to Current Trends

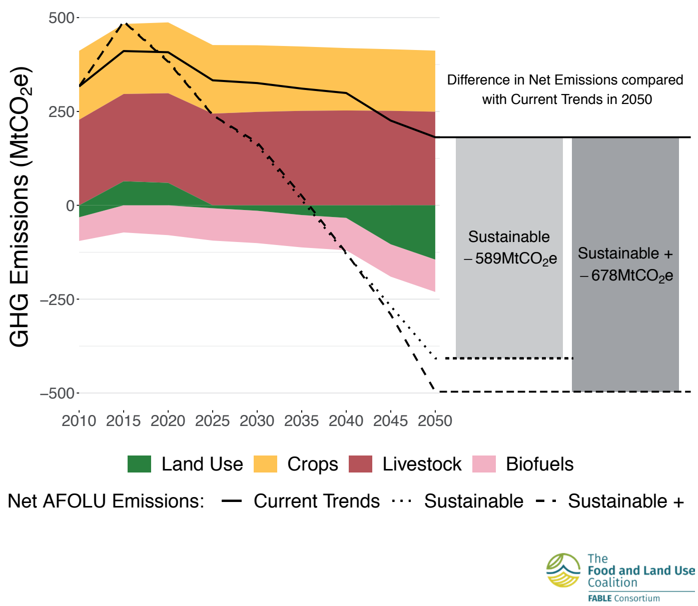
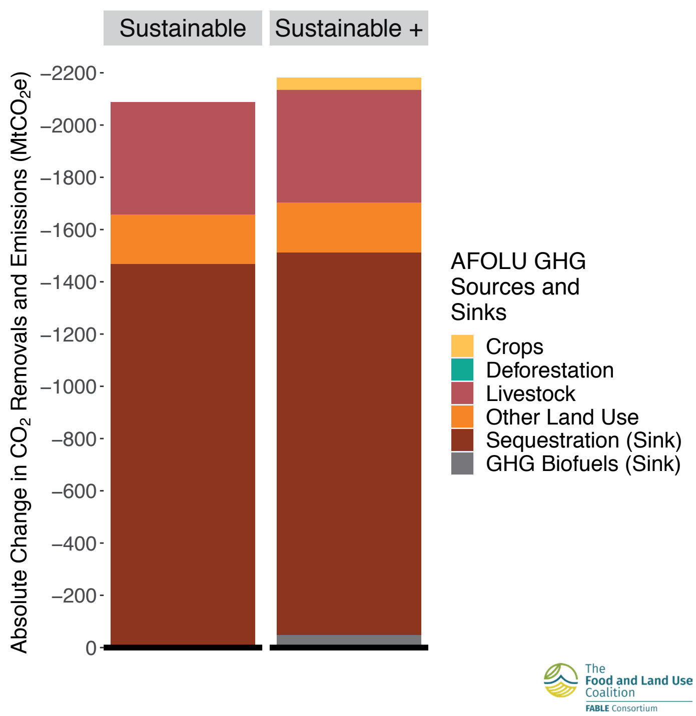


Figure 5 | Cumulated GHG emissions reduction computed over 2020–2050 by AFOLU GHG emissions and sequestration source compared to the Current Trends Pathway



Food Security

Current State

Undernutrition

- 3-4.5% of the population undernourished in 2015. (USDA, 2019a; World Bank, 2019)
- 2.1% of children under 5 stunted and 0.4% wasted in 2012 (World Bank, 2020a, 2020b).

Micronutrient Deficiency

- 13.3% of women and 8.5% of children suffer from anemia in 2016, which can lead to maternal death (World Health Organization, 2020).
- 49% of adults do not meet the Estimated Average Requirement of vitamin A (Fulgoni et al., 2011), and 12% are deficient in iodine, which can lead to developmental abnormalities (Caldwell et al., 2011).

Overweight/ Obesity

- 24.4% of the population, and 39.6% of adults and 18.5% of children were obese in 2015. These shares have increased since 1980 (Hales et al., 2017; Ng et al., 2014).
- 70.9% of adults were overweight in 2013-2016. These shares have increased since 1988 (Centers for Disease Control and Prevention [CDCP], 2020b).

Disease Burden due to Dietary Risks

- About 20% of deaths are attributable to dietary risks, or 170.7 deaths per year (per 100,000 people) in 2017 ((Afshin et al., 2019) supplementary info Table 7).
- Dietary risks also lead to/cause 3,982 disability-adjusted life years (DALYs), or years of healthy life lost due to an inadequate diet ((Afshin et al., 2019) supplementary info Table 7).
- 10.5% of the population suffers from diabetes (CDCP, 2020a) and 48% of adults suffer from cardiovascular diseases, which can be due to/caused by dietary risks (Benjamin Emelia J. et al., 2019).

Table 3 | Daily average fats, proteins, and kilocalorie intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition Pathways in 2030 and 2050

	2010	2030			2050		
	Historical Diet (FAO)	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition	Current Trends	Sustainable Medium Ambition	Sustainable High Ambition
Kilocalories (MDER)	2,872 (2,079)	2,867 (2,075)	2,753 (2,075)	2,753 (2,075)	2,866 (2,078)	2,544 (2,089)	2,544 (2,089)
Fats (g) (recommended range)	139.9 (64-96)	141 (64-96)	126 (61-92)	126 (61-92)	141 (64-96)	99 (57-85)	99 (57-85)
Proteins (g) (recommended range)	93 (72-251)	92 (72-251)	90 (69-241)	90 (69-241)	92 (72-251)	86 (64-223)	86 (64-223)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (HSS and USDA, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

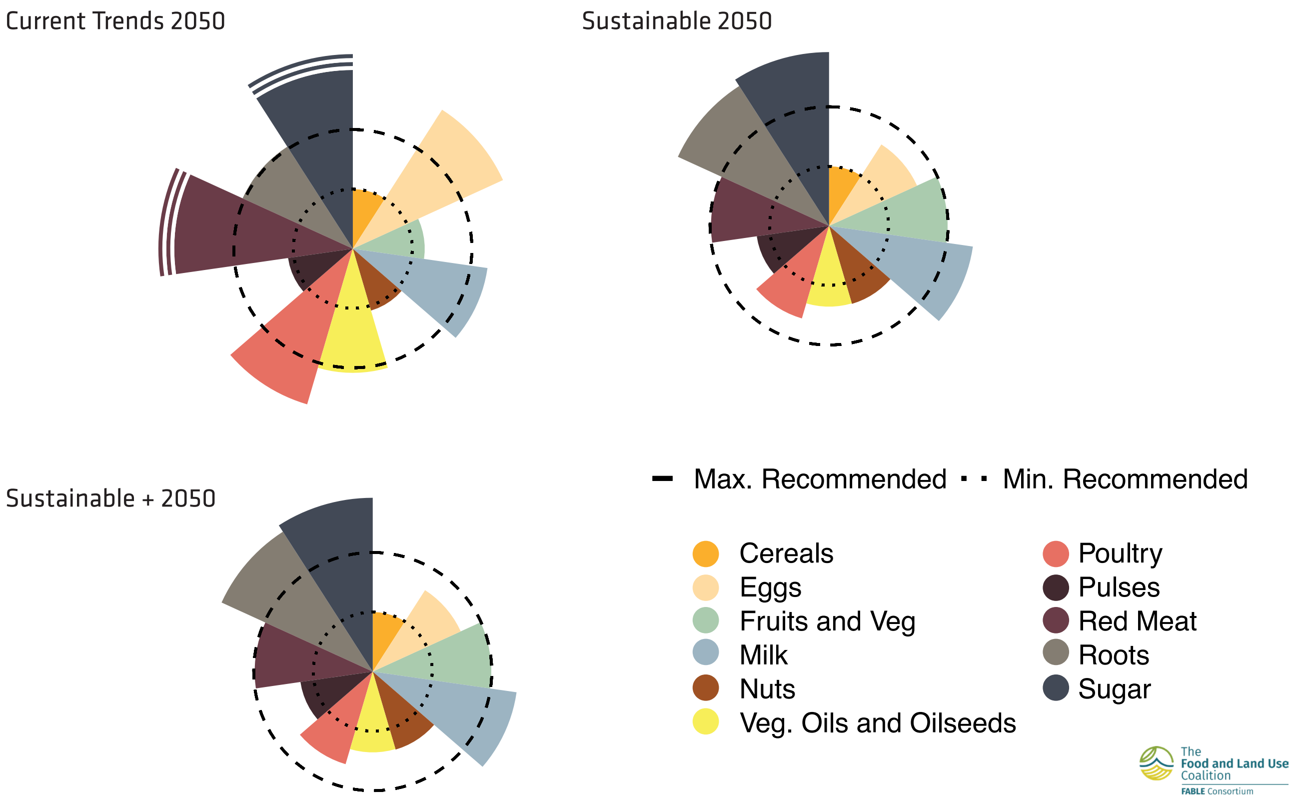
Pathways and Results

Under the Current Trends Pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 38% higher in both 2030 and 2050 (Table 3). The current average intake is mostly satisfied by cereals, oil and fat, and milk and animal products, which represent 32% of the total calorie intake. We assume that the consumption of animal products per capita will stay the same between 2020 and 2050. Compared to the EAT-Lancet recommendations (Willett et al., 2019), red meat, pork, milk, oils and fats, poultry, sugar, eggs, animal fats, and eggs are over-consumed while cereals, fish, fruits and vegetables, pulses, and nuts are under-consumed in 2050 (Figure 6). Moreover, fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050 (Table 3). This can be explained by high consumption of oils and fats and animal fats (Figure 6).

Under the Sustainable Medium Ambition Pathway, we assume that diets will transition towards a "Healthy US-Style Pattern" as determined in the Dietary Guidelines for Americans by the USDA and Department of Health and Human Services (HSS & USDA, 2015). The same assumptions are made under the Sustainable High Ambition Pathway. The ratio of the computed average intake over the MDER decreases to 32% in 2030 and 22% in 2050 under the Sustainable Medium Ambition and Sustainable High Ambition Pathways. Compared to the EAT-Lancet recommendations, only the consumption of roots and milk remains outside of the recommended range with the consumption of red meat, sugar, eggs, and poultry being now within the recommended range in 2050 (Figure 6). Moreover, the fat intake per capita is closer to being within the dietary reference intake (DRI) in 2030, showing some improvement compared to the Current Trends Pathway.

Implementing dietary interventions with quantified food preference impacts such as pricing strategies and product placement at retailers; menu labeling and healthy default choices in restaurants; adding more vegetables and fruits to the Supplemental Nutrition Assistance Program; and providing plant-based meat alternatives in workplaces and schools will be particularly important to promote this shift in diets (Anderson Cheryl A.M. et al., 2019).

Figure 6 | Comparison of the computed daily average kilocalorie intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



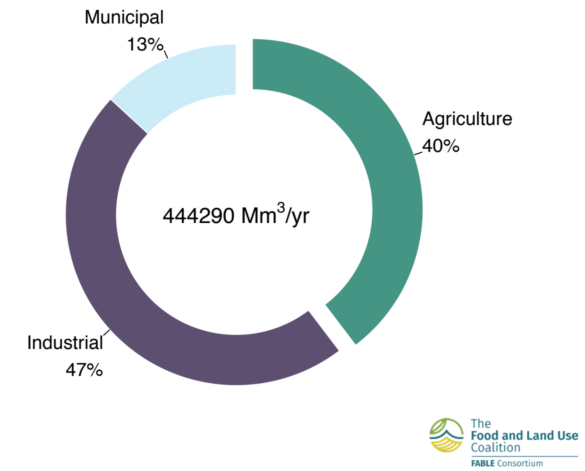
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings) i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of the sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

The US is characterized by temperate climatic conditions suitable for agricultural production with 715 mm average annual precipitation that mostly occurs over the period April to September in the Midwest, where most of the agricultural land is located. The agricultural sector represented 40% of total water withdrawals in 2015 (FAO AQUASTAT) (Figure 7). Moreover, in 2012, about 7.6% of agricultural land was equipped for irrigation (FAO AQUASTAT). The three most important irrigated crops, corn, hay and forage production, and soybeans, account for 25%, 18%, and 14% of total harvested irrigated area (USDA, 2019c). The US exported 14.3% of corn, 48% of soybean in 2018/2019 and 2017/2018, respectively (Iowa Farm Bureau, 2019; US Grains Council, 2020).

Figure 7 | Water withdrawals by sector in 2015

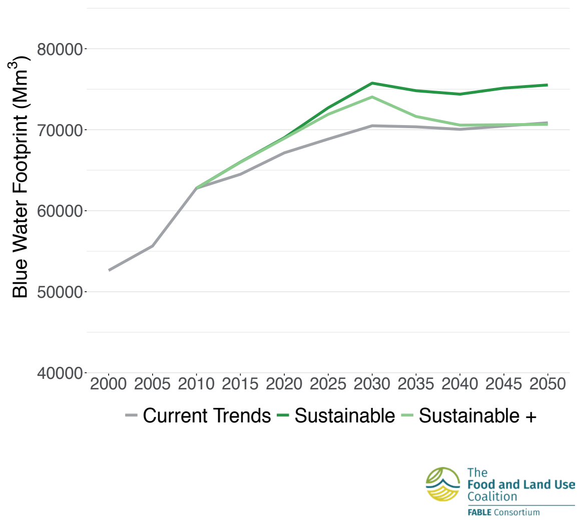


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Under the Current Trends Pathway, annual blue water use increases between 2000 and 2015 (52,600 Mm³/yr and 64,500 Mm³/yr), before reaching 70,500 Mm³/yr and 70,900 Mm³/yr in 2030 and 2050, respectively (Figure 8), with corn, rice, and soybean accounting for 37%, 12%, and 10% of computed blue water use for agriculture by 2050[3]. In contrast, under the Sustainable Medium Ambition and Sustainable High Ambition Pathways, the blue water footprint in agriculture reaches, respectively, 75,800 Mm³/yr and 74,000 Mm³/yr in 2030, and 75,500 Mm³/yr and 70,700. Mm³/yr in 2050. This is explained by changes in the crop composition across pathways such as shifts to production of corn and soybean due to a decline in internal food demand despite increasing exports, as well as climate change impacts.

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable Pathways



3 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Koekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

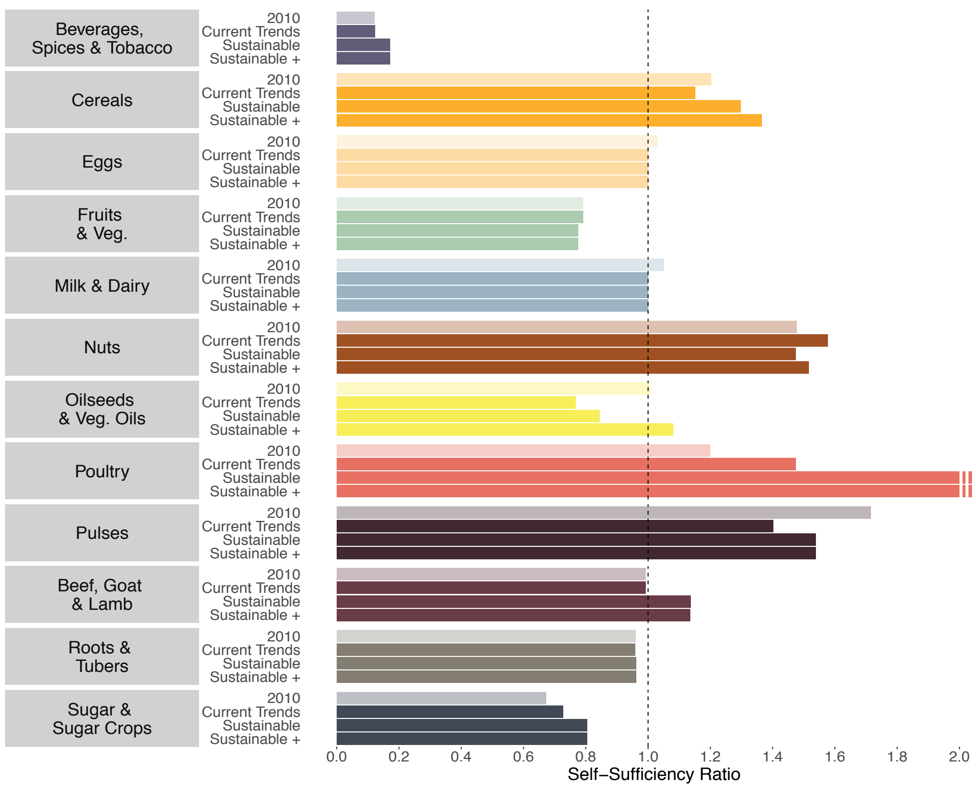
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge the US's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

Currently (as of 2010), the US is self-sufficient in the vast majority of key product groups, with the notable and critical exceptions being fruits and vegetables and sugar.

Under the Current Trends Pathway, we project that the US would be self-sufficient in cereals, eggs, milk and dairy, nuts, poultry, pulses, beef, and roots in 2050, with self-sufficiency by product group remaining stable for the majority of products (except oil seeds and vegetable oils) from 2010 – 2050 (Figure 9). The product groups where the country

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of the figure, as appear for poultry, indicate a high level of self-sufficiency in this category.

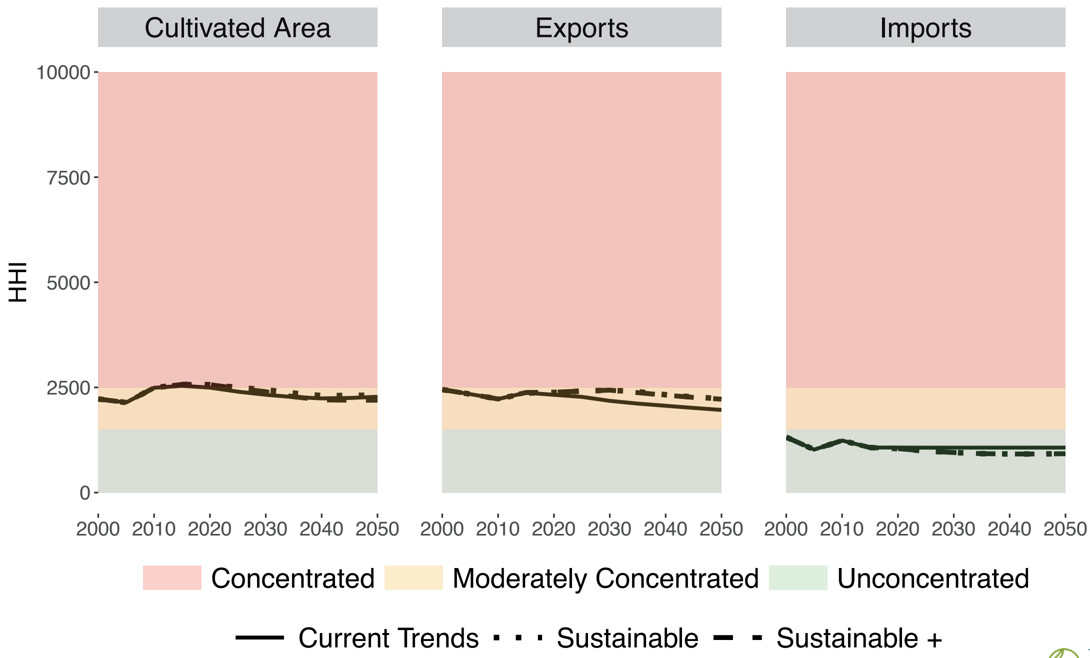
depends the most on imports to satisfy internal consumption are beverages, spices and tobacco, fruits and vegetables, oilseeds and vegetable oils, and sugar, and this dependency will remain stable until 2050. Under the Sustainable Medium Ambition Pathway, the US remains self-sufficient in all the same products as under Current Trends by 2050, representing the same level of self-sufficiency. Finally, under the Sustainable High Ambition Pathway, self-sufficiency resembles the Sustainable Medium Ambition Pathway, except that the US would be self-sufficient in oilseeds and vegetable oils, since no changes to volume of imports and exports, productivity, food crop cultivation, diets were assumed.

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



We use the same thresholds as defined by the US Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

According to the HHI, the diversity of planted crop area in 2010 is concentrated, and moderately concentrated and unconcentrated for crop exports and imports, respectively. Under the Current Trends Pathway, we project moderate and low concentrations of crop exports and imports, respectively, and high to moderate. concentration in the range of crops planted in 2050, trends which generally decrease or stabilize over the period 2010 - 2050. This indicates moderate levels of diversity across the national production system and imports and exports. In contrast, under the Sustainable Medium Ambition Pathway, we project moderate-high and very low concentrations of crop exports and imports, respectively, and moderate-high concentration in the range of crops planted in 2050, indicating overall moderate levels of diversity across the national production system and imports and exports. Finally, under the Sustainable High Ambition Pathway, we project a similar concentration of crop exports and imports, and a slightly lower moderate concentration in the range of crops planted in 2050, indicating moderate levels of diversity across the national production system and imports and exports (Figure 10). This is explained by a change in the share of grains typically used for livestock feed relative to the Current Trends Pathway.

Discussion and Recommendations

This analysis presents a unique assessment of sustainable land use possibilities in the United States, considering potentially competing policy objectives related to healthier diets, climate change mitigation, biodiversity protection, and water conservation. The analysis was conducted in collaboration with the global FABLE community with global sustainable development goal targets in mind, and in the context of calibrated bilateral trade flows using the global FABLE Linker Tool. Broadly, these results show that it is possible for the US to reduce GHG emissions from crop and livestock systems, increase carbon sequestration through reforestation/afforestation, protect biodiversity, and decrease agricultural water footprints while expanding food production to meet the demands of a growing population under alternative dietary preference assumptions and increases in productivity. While these results do not offer insight into the potential economic costs and benefits of sustainable land use scenarios in the US, these projections have several key policy implications that warrant further analysis and consideration.

First, we show that healthier diet assumptions in the US that follow official government agency guidelines (HSS & USDA, 2015) could have important implications for agricultural land use and management trends, offering a range of environmental benefits in addition to improving health outcomes. This result is consistent with recommendations from the EAT-Lancet Report and other US-focused literature on shared socioeconomic pathways and US land use projections (e.g. (Jones et al., 2019)). However, further analysis is needed to understand the potential spatial distribution of land use impacts due to reduced feed grain production and meat consumption and a higher proportion of crop area devoted to fruits, vegetables, and nuts, as spatial detail is necessary to inform land use planning, policy, and management at the regional, state, and sub-state level.

Our results suggest that large scale investments in reforestation/afforestation are possible without substantial sacrifices to crop production if tree planting investments are concentrated on pasturelands and marginally productive croplands—and in particular, alongside dietary preference changes. Changes in land use and crop mixes result in emissions reductions of approximately 589 Mt CO_2e per year by mid-century in the Sustainable Medium Ambition Pathway, or roughly 12.3% of the US LT-LEDS (80% reduction below 2005 levels), though this only allows for mitigation at the extensive land use margin and should be considered as a lower-end estimate of abatement potential from the AFOLU sectors. Intensive margin abatement opportunities, including improved forest management or abatement technologies on working agricultural lands (e.g., soil organic carbon; livestock emissions reduction strategies; (Archibeque et al., 2012; Fargione et al., 2018)), can further contribute to climate mitigation goals. Also, this analysis uses a simplified approach to represent mitigation potential from land use change, assuming a constant sequestration rate for land shifting to forestry in the US In reality, carbon sequestration rates vary considerably across space, forest type, and management regime (Nielsen et al., 2014).

Finally, we do not include emissions displacement from bioenergy in the Sustainable Medium Ambition Pathway, but do include bioenergy emissions displacement from only switchgrass and miscanthus (Langholtz et al., 2016; Williams et al., Manuscript submitted for publication) in the Sustainable High Ambition Pathway which further boosts the US land use sector contributions to LT-LEDS to 678 Mt CO_2e. However, we caution that the bioenergy requirement assumptions by feedstock are highly uncertain as they are dependent on the Billion Ton study's supply curve (Langholtz et al., 2016), whereas the results of energy pathways modeling specify dry tonnes of biomass (biogenic carbon) by price range independent of feedstock (Williams et al., Manuscript submitted for publication). As a result, though the Sustainable High Ambition Pathway is more ambitious from a carbon perspective, by requiring purpose-grown biomass feedstocks, we caution that it is not necessarily more sustainable from a land use or conservation perspective (despite a higher target for protected areas in the High Ambition Pathway). More spatially refined partial equilibrium analyses can improve mitigation projections for bio energy, extensive land use decisions, and intensive margin investments in abatement technologies and other natural climate solutions and to better understand the opportunity costs of these investments (Havlík et al., 2014; Herrero et al., 2013). Nonetheless, this analysis demonstrates how the land use sectors can play a role in long term climate action while considering other policy constraints related to biodiversity and diets.

Future US modeling efforts will focus on additional spatial detail to advance sustainable land use projections. This will include building on the GLOBIOM partial equilibrium model to add US spatial detail for more accurate and spatially-resolved analysis, as well as multi-model assessments in collaboration with other modeling teams (e.g., the US Forest and Agricultural Sector Optimization Model). Future efforts will also focus more on comparing economic outcomes across different scenario assumptions to better quantify potential tradeoffs.

The US food supply system remains strong and analysis at the time of this writing suggests that the COVID-19 pandemic likely will not impact the US food supply. Longer term, however, the picture is less clear. As the import, export, and crop diversity metrics indicate, the US has moderate to high levels of crop variety concentration—making it possibly more susceptible to disruptions in supply chains and international trade as well as more likely to cause food availability issues in its major trade partners. For example, border restrictions impacting migrant workers, plus recent outbreaks in meat processing plants could create labor shortages, limiting food supplies. Already, temporary meat packing plant closures have contributed to short-lived meat price increases throughout the US. If risks of COVID-19 infection to workers at these facilities continue, then this could cause longer-term market impacts and households could face higher meat and dairy prices for prolonged periods. Finally, supply chain disruption resulting from food type preference shifts due to lower commercial and restaurant demand and increased household demand (grocery store purchases) will result in increased post-harvest losses in the short term.

The US FABLE team is also beginning stakeholder engagement with the US policy community focused on land use, sustainability, climate, and agriculture and food systems. Most notably, a SDSN-USA initiative during the second half of 2020 called the "Deep Decarbonization Action Plan" (DDAP) aims to present specific federal and state/local policy proposals for deep decarbonization in the United States in time for the 2020 election season. Anchored in technical pathways for the energy sector from SDSN's and Institute for Sustainable Development and International Relations' (IDDRI) Deep Decarbonization Pathways project (Deep Decarbonization Pathways Project, 2015) and in FABLE's pathway for sustainable land use, the DDAP Land Working Group will bring together policy expertise from across both academia and nonprofit partners. Outreach has already begun to involve policy experts at the US Climate Alliance, American Forests, and other partners with significant policy expertise and working relationships to policymakers, allowing the DDAP Land Working Group to aim for specific policy proposals informed by the FABLE modeling work.

Annex 1. List of changes made to the FABLE Calculator to adapt it to the US context

- Crop productivity updates for corn, soybean, and wheat
- Livestock productivity: chicken productivity updates by adding post-harvest losses
- Grazing intensity (stocking intensity): Modified the livestock stocking density scenarios to add one called "LowerIntensity" which achieves 0.34 TLU/ha by 2050 using a -0.3% rate of change.
- Bioenergy assumptions for corn, soybean; added miscanthus and switchgrass as crops using productivity assumptions from the Billion Ton study (Langholtz et al., 2016).
- Export adjustments for beef and several other commodities
- Added Healthy Style Diet for Americans
- Customized implementation timing

Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
SSP2 – The population is expected to reach 400 million by 2050 (from 322 million in 2015), or a 0.6% increase per year, based on SSP2 scenario. Assumes population follows historical patterns (Medium fertility, medium mortality, medium migration, medium education). Based on the US Census Bureau's report, "Projections of the Size and Composition of the US Population: 2014 to 2060", which predicts 398 million Americans in 2050 (Colby & Ortman, 2015).		

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
We assume that there will be no constraint on the expansion of the agricultural land outside beyond existing protected areas and under the total land boundary, as per lack of current policies restricting agricultural expansion in the US (FreeExpansion scenario selected)		

LAND Afforestation or reforestation target (1000 ha)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
We assume total afforested/reforested area to reach 5.7Mha by 2050, which is the amount of remaining land in the national Conservation Reserve Program, which pays farmers to take ecologically sensitive areas out of production and convert it to natural habitat.	We assume an ambitious increase in reforested area to reach 40Mha by 2050. Based on the US Mid-Century Strategy Report, and assumes no other CO_2 removal technologies are deployed (The White House Council on Environmental Quality, 2016). This is double the target set in the US Mid-Century Strategy Report for Deep Decarbonization in the Benchmark scenario, or roughly consistent with reforestation targets assuming no CO_2 removal technologies are employed, a US government report published in November 2016, which lays out a long-term strategy to decarbonize the US economy by 2050. Though high, this level of afforestation is technically feasible based on recent spatially-explicit analysis (Fargione et al., 2018).	We assume an ambitious increase in reforested area to reach 40Mha by 2050. Based on the US Mid-Century Strategy Report, and assumes no other CO_2 removal technologies are deployed (The White House Council on Environmental Quality, 2016). This is double the target set in the US Mid-Century Strategy Report for Deep Decarbonization in the Benchmark scenario, or roughly consistent with reforestation targets assuming no CO_2 removal technologies are employed,. a US government report published in November 2016, which lays out a long-term strategy to decarbonize the US economy by 2050. Though high, this level of afforestation is technically feasible based on recent spatially-explicit analysis (Fargione et al., 2018).

BIODIVERSITY Protected areas (% of total land)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
Protected areas remain stable: by 2050 they represent 13% of total land. Based on the lack of policies or administrative action to expand protected areas in the US In fact, 90% of all proposals to downsize or eliminate protected areas in the US occurred since 2000 (Golden Kroner et al. 2019).	Protected areas increase: by 2050 they represent 19% of total land. This assumes that ecoregions with the share of protected areas greater than 2% and less than 25% increase their share to 25% by 2050.	Protected areas increase: by 2050 they represent 30% of total land. This assumes that ecoregions with the share of protected areas greater than 0% and less than 45% increase their share to 45% by 2050. It fulfills the US's share of the 30x30 challenge or protecting 30% of land and ocean by 2030. This is not an official target, but an aspiration one set by non-government experts and researchers. This national target is also aligned with the global FABLE target.

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
From 2020 to 2050, crop productivity changes from: • 11.2 to 13.5 tonnes per ha for maize • 3.4 to 4.1 tonnes per ha for soybean • 3.2 to 3.7 tonnes per ha for wheat Based on USDA projections out to 2028 and then a linear leveling off of annual growth rate from 1% to 0% by 2050 (USDA, 2019b).	From 2020 to 2050, crop productivity changes from: • 11.2 to 15.2 tonnes per ha for maize • 3.4 to 4.6 tonnes per ha for soybean • 3.2 to 4.1 tonnes per ha for wheat Based on linear extrapolation out to 2050 of 2028 USDA projections that assume an annual linear growth rate of 1% for corn, 1% for soybean, and 0.8% for wheat (USDA, 2019b).	

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
From 2015 to 2050, livestock productivity increases: • From 374 kg to 400 kg per head for cattle-beef • From 2.8 to 3.2 kg per head for broiler chickens • From 8.6 tonnes to 9.6 tonnes per head of cattle for milk Slower than the historical growth rate from 2000 to 2015 (USDA, 2020a).	From 2015 to 2050, livestock productivity increases: • From 374 kg to 458 kg per head for cattle-beef • From 2.8 to 4 kg per head for broiler chickens • From 8.6 tonnes to 10.8 tonnes per head of cattle for milk Based on applying the average historical growth rate from 2000 to 2015 (USDA, 2020a).	

PRODUCTION Pasture stocking rate (animal units/ha pasture)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
There is no change in pasture stocking rate between 2010 and 2050. By 2050, the average ruminant livestock stocking density is 0.38 TLU/ha for sheep, goats, and cattle.	By 2050, the average ruminant livestock stocking density is 0.34 TLU/ha for sheep, goats, and cattle, declining 0.3% from 0.38 TLU/ha of pasture in 2010. This follows the recent trend in declining livestock stocking rates from 2005 to 2015. Lower intensity grazing is more sustainable because soil organic carbon generally increased with reduced grazing intensity, as does biodiversity of vegetation (Abdalla et al., 2018). A review of several studies in the US of grazing intensity reveals that "light" grazing intensity ranges from 0.29 to 0.44 TLU/ha, depending on the type of animal (heifer or steer) and the region (Reeder et al., 2004; Reeder & Schuman, 2002; Rogers et al., 2005; Schuman et al., 1999)	

PRODUCTION Post-harvest losses		
By 2050, the share of production and imports lost during storage and transportation (which varies between commodities) is held at 2010 rates.	By 2050, the share of production and imports lost during storage and transportation is 50% less than 2010 levels. There is very little available information on 2050 targets or projections for post-harvest losses for the US across all food types.	

TRADE Share of consumption which is imported for key imported products (%)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
The share of total consumption which is imported is assumed to remain stable to 2050 in order to satisfy political economy concerns. By 2050, the share of total consumption which is imported is: • 100% by 2050 for bananas • 100% by 2050 for pepper • 38% by 2050 for fish	The share of total consumption which is imported is assumed to remain stable to 2050 in order to satisfy political economy concerns. It is particularly the case for the sustainability scenarios in which production of several types of commodities have decreased due to dietary shifts. Rather than for the changes to demand to be made up by increases with imports, we assume that the agricultural sector domestically can respond to these shifts in dietary preferences. By 2050, the share of total consumption which is imported is: • 100% by 2050 for bananas • 100% by 2050 for pepper • 38% by 2050 for fish	

TRADE Evolution of exports for key exported products (million tons)		
Current Trends Pathway	**Sustainable Medium Ambition Pathway**	**Sustainable High Ambition Pathway**
The tonnes of exports are kept constant at 2010 levels. For example, by 2050, the volume of exports is: • 48 million tonnes for corn. • 28 million tonnes for soybean • 22 million tonnes for wheat • 5.8 million tonnes for soycake • 1.8 million tonnes for pork	By 2050, the volume of exports is: • 82 million tonnes for corn • 34 million tonnes for soybean • 35 million tonnes for wheat • 13 million tonnes for soycake • 5 million tonnes for pork • 1.1 million tonnes of beef We based these increased export decisions on the trade imbalance after the first iteration of the Scenathon and due to the fact that we had excess production capacity due to reduction in meat intake under this scenario's dietary assumptions.	By 2050, the volume of exports is: • 81 million tonnes for corn • 33 million tonnes for soybean • 34 million tonnes for wheat • 13 million tonnes for soycake • 5 million tonnes for pork • 1.1 million tonnes of beef We based these increased export decisions on the trade imbalance after the first iteration of the Scenathon and due to the fact that we had excess production capacity due to reduction in meat intake under this scenario's dietary assumptions.

FOOD Average dietary composition (daily kcal per commodity group)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2030, the average daily calorie consumption per capita remains at 2,867 kcal and is: • Cereals: 580 • Fish: 22 • Fruit and vegetables: 142 • Pork: 129 • Milk: 327 • Vegetable oils: 610 • Eggs: 54 • Pulses: 37 • Redmeat: 102 • Roots: 67 • Sugar: 299 • Poultry: 181 • Nuts: 30 • Animal fats: 101 • Beverages and spices: 24 • Other: 2 • Alcohol: 167 Based on (FAO 2010).	By 2030, the average daily calorie consumption per capita decreases to 2,544 kcal and is: • Cereals: 666 • Fish: 46 • Fruit and vegetables: 299 • Pork: 46 • Milk: 366 • Vegetable oils: 301 • Eggs: 19 • Pulses: 86 • Redmeat: 50 • Roots: 116 • Sugar: 192 • Poultry: 64 • Nuts: 132 • Animal fats: 65 • Beverages and spices: 15 • Other: 2 • Alcohol: 107 Based on USDA dietary guidelines 2015-2020 (Appendix 3. USDA Food Patterns: Healthy US Style Eating Pattern; HSS & USDA, 2015)	

FOOD Share of food consumption which is wasted at household level (%)

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2030, the share of final household consumption which is wasted at the household level is 30%, unchanged from 2010. Based on USDA Economic Research Service estimates that 31% of food produced in 2010 was wasted at the consumer or retail levels (Buzby et al., 2014).	By 2030, the share of final household consumption which is wasted at the household level is 15%. Based on US EPA and USDA announced a goal of reducing food waste by 50% by 2030, relative to 2010 levels (USDA, 2016).	

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2050, biofuel production accounts for: • 149 million tonnes of corn production • 7.1 million tonnes of soy oil production • 0.75 million tonnes of rape oil production Based on (USDA, 2020b) (NoChange scenario selected)		By 2050, biofuel production accounts for: • 69 million tonnes of corn production • 1.2 million tonnes of soy oil production • 0.75 million tonnes of rape oil production • 180 million tonnes of miscanthus production • 135 million tonnes of switchgrass production Miscanthus and switchgrass values were estimated using absolute dry tonnes of herbaceous biomass selected in the "100% Renewable Energy" scenario in the latest Deep Decarbonization Pathways Project for the US (Williams et al., Manuscript submitted for publication). Since the herbaceous biomass feedstocks were not specified in the DDPP study, we allocated the herbaceous biomass demand to specific feedstocks using the supply curve in the Billion Ton Study (Langholtz et al., 2016),assuming the 2040 supply would hold into 2050. (DedicatedBiomassFeedstocks scenario selected)

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Medium Ambition Pathway	Sustainable High Ambition Pathway
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m^2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m^2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect.	

Annex 3. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland><50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% – herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% – trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Annex 4. Overview of biodiversity indicators for the current state at the ecoregion level[4]

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
0	Rock and Ice	2797.391	62.2	55.2	59.9	40.1	0.082	100
326	Sierra Madre Occidental pine-oak forests	142.646	65.3	92.5	66.8	33.2	1.068	99.2
327	Sierra Madre Oriental pine-oak forests	371.191	15.6	69.3	16.5	83.5	0.277	100
328	Allegheny Highlands forests	7328.939	2.4	48.9	4.2	95.8	212.668	79
329	Appalachian mixed mesophytic forests	18177.539	3	41.8	6.4	93.6	287.68	85.2
330	Appalachian Piedmont forests	16649.703	1.1	19.4	4.3	95.7	143.571	96
331	Appalachian-Blue Ridge forests	16360.194	5.4	35.1	14	86	706.011	66.4
332	East Central Texas forests	5592.954	0.5	1.3	16	84	484.344	87.1
333	Eastern Canadian Forest-Boreal transition	1.203	0	1.9	0	0	0.018	5.6
334	Eastern Great Lakes lowland forests	4048.532	1.3	18.3	3.9	96.1	630.044	63.7
336	Interior Plateau US Hardwood Forests	12375.712	2.8	14.9	15.1	84.9	1177.102	61.8
337	Mississippi lowland forests	11554.262	7.8	29.9	18.2	81.8	6926.191	16.2
338	New England-Acadian forests	16932.843	11.6	65.9	15.8	84.2	214.291	76.5
339	Northeast US Coastal forests	7338.533	3.3	10.8	13	87	449.053	69.4
340	Ozark Highlands mixed forests	10658.501	4	23.6	14.7	85.3	213.286	76.8
341	Ozark Mountain forests	6965.461	12.1	32.1	34.8	65.2	113.739	57.5
342	Southern Great Lakes forests	20317.789	1.1	7.4	7.2	92.8	12314.559	23.6
343	Upper Midwest US forest-savanna transition	13643.006	3.8	14.8	15.5	84.5	5708.151	45.3

4 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
344	Western Great Lakes forests	21544.308	16.3	69.7	21.2	78.8	697.748	66
346	Arizona Mountains forests	11118.532	10.2	90.2	11.2	88.8	14.174	97.9
347	Atlantic coastal pine barrens	1421.599	20	26	56.5	43.5	153.115	62.5
348	Blue Mountains forests	7091.559	10	56.2	16.9	83.1	467.539	54.9
349	British Columbia coastal conifer forests	154.28	96	99.8	96.1	3.9	0.144	100
351	Central Pacific Northwest coastal forests	4067.648	8.3	63.6	12.1	87.9	21.097	83.7
352	Central-Southern Cascades Forests	5886.951	17.9	79.7	21.9	78.1	15.612	91.4
353	Colorado Rockies forests	14591.534	14.3	78.9	17.4	82.6	199.435	93.1
354	Eastern Cascades forests	5328.215	7.1	65.3	9.3	90.7	284.628	51.2
356	Great Basin montane forests	891.288	49.4	97.8	50.5	49.5	11.542	98.5
357	Klamath-Siskiyou forests	4839.941	15.7	83.1	18.7	81.3	197.848	64.5
358	North Cascades conifer forests	2883.045	42.7	85.1	49.1	50.9	33.075	78.6
359	Northern California coastal forests	1359.331	19	73.8	23.6	76.4	9.904	97.2
360	Northern Pacific Alaskan coastal forests	6080.004	41.3	87.8	42.6	57.4	0.048	100
361	Northern Rockies conifer forests	10078.462	12.4	74.8	16.3	83.7	500.118	50
363	Piney Woods	15257.479	3.3	25.5	10.9	89.1	454.661	62.1
364	Puget lowland forests	1691.345	6.8	24.5	18.1	81.9	196.416	48.1
366	Sierra Nevada forests	5319.048	33	78.1	41.4	58.6	77.128	90.2
367	South Central Rockies forests	17676.946	30.5	78.6	38	62	359.8	86.1
368	Wasatch and Uinta montane forests	4575.02	9	63.2	13.3	86.7	86.446	77.3
369	Alaska Peninsula montane taiga	4738.935	82.7	89.6	81.9	18.1	0	0

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within $1km^2$(%)
371	Cook Inlet taiga	2754.208	30.9	90.3	33.3	66.7	10.519	64.4
372	Copper Plateau taiga	1719.222	29.5	98.1	29.8	70.2	0.565	98.9
375	Interior Alaska-Yukon lowland taiga	40375.202	33	98.2	33	67	38.158	45
384	Western Gulf coastal grasslands	7539.74	15.1	27.4	18	82	2921.827	40.2
385	California Central Valley grasslands	4641.757	4.2	10.3	24	76	3333.649	13.4
386	Canadian Aspen forests and parklands	13479.102	2.5	4.5	20	80	9973.446	22.4
387	Central US forest-grasslands transition	22858.296	2.7	8.9	18.6	81.4	15231.917	21.2
388	Central Tallgrass prairie	34277.944	1.6	3	23.1	76.9	22281.066	20
389	Central-Southern US mixed grasslands	27544.796	0.7	1.4	30.4	69.6	13818.664	37.4
390	Cross-Timbers savanna-woodland	8841.934	1.1	2.9	22.4	77.6	778.955	88.6
391	Edwards Plateau savanna	7520.742	1.3	20.5	4	96	700.299	85.3
392	Flint Hills tallgrass prairie	2797.676	1.8	51.6	3	97	366.302	62.5
393	Mid-Atlantic US coastal savannas	7800.107	10.8	31.9	27.3	72.7	1507.429	65.8
394	Montana Valley and Foothill grasslands	8516.214	4	28.2	9.4	90.6	1152.428	69.3
395	Nebraska Sand Hills mixed grasslands	5916.429	1.5	1.4	73.9	26.1	365.128	59.2
396	Northern Shortgrass prairie	49522.636	2	11.3	14.4	85.6	11962.205	47
397	Northern Tallgrass prairie	4502.942	4.6	7.2	39.2	60.8	4106.711	8.8
398	Palouse prairie	8309.87	4.1	20.5	15.9	84.1	3746.626	23.9
399	Southeast US conifer savannas	52180.677	4	27.5	11.3	88.7	5795.546	67.4
400	Southeast US mixed woodlands and savannas	2.761	12.3	24.8	18	82	0.123	57.7
401	Texas blackland prairies	4351.485	0.4	0.6	25.7	74.3	919.079	65.8

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
402	Western shortgrass prairie	48807.714	0.8	12.7	2.7	97.3	13865.852	36
403	Willamette Valley oak savanna	1488.557	1.9	15.2	6	94	674.559	26.2
404	Ahklun and Kilbuck Upland Tundra	5055.961	64.8	97	64.5	35.5	0	0
405	Alaska-St. Elias Range tundra	14073.245	37.8	86.9	34.2	65.8	5.969	96.7
406	Aleutian Islands tundra	1166.35	98	85	97.5	2.5	6.674	91.8
407	Arctic coastal tundra	4869.864	3.9	85.2	4.2	95.8	0	0
408	Arctic foothills tundra	12340.389	20.4	97.6	20.3	79.7	0	0
409	Beringia lowland tundra	14866.532	65.5	88.2	65	35	1.262	98.3
410	Beringia upland tundra	4628.804	20.1	97.7	19.5	80.5	0.009	100
411	Brooks-British Range tundra	13312.139	69.8	99	69.7	30.3	0	0
416	Interior Yukon-Alaska alpine tundra	11445.23	31.2	99.7	31.3	68.7	0.871	97.6
419	Ogilvie-MacKenzie alpine tundra	1067.177	29.3	98.8	29.1	70.9	0	0
420	Pacific Coastal Mountain icefields and tundra	8051.337	48.7	70.4	44.4	55.6	3.052	98.6
422	California coastal sage and chaparral	2100.64	7.7	27.8	24.4	75.6	106.521	69.4
423	California interior chaparral and woodlands	7204.237	5.9	23.9	18	82	817.114	81
424	California montane chaparral and woodlands	1588.158	29.5	79.2	36.5	63.5	54.396	94.4
425	Santa Lucia Montane Chaparral & Woodlands	471.688	26.8	57.2	44.7	55.3	22.783	97
428	Chihuahuan desert	19922.872	6	63.7	8.8	91.2	287.407	49.8
429	Colorado Plateau shrublands	28395.985	11	77.1	13.9	86.1	566.594	62.1
430	Great Basin shrub steppe	30126.797	7.7	84.1	9	91	1021.574	62.6
433	Mojave desert	12761.15	45.5	82	54.8	45.2	48.921	76.1

	Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with at > 10% natural vegetation within 1km²(%)
434	Snake-Columbia shrub steppe	19329.658	15.8	55.9	26.8	73.2	2244.6	34
435	Sonoran desert	11869.828	19.2	47.5	39.4	60.6	634.012	34
437	Tamaulipan mezquital	5368.314	6.4	7.6	3.8	96.2	1363.909	76.1
438	Wyoming Basin shrub steppe	13276.438	3.5	55.9	5.3	94.7	529.427	81.2
581	Everglades flooded grasslands	1988.43	14.7	57.2	24	76	343.81	23.2
612	Bahamian-Antillean mangroves	376.928	86.1	70	94.7	5.3	1.672	82.5
623	Hawai'i tropical moist forests	670.724	13	70	18.2	81.8	84.564	53.8
636	Hawai'i tropical dry forests	659.281	15.7	45.4	29.4	70.6	106.944	36.8
639	Hawai'i tropical high shrublands	185.714	43	97.8	43	57	0	0
640	Hawai'i tropical low shrublands	144.352	8.3	35.8	17.9	82.1	20.888	46.2
641	Northwest Hawai'i scrub	0.049	100	71.4	88.6	11.4	0	0

Sources: countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

m – meter

Mha – million hectares

Mm^3 – million cubic meters

Mt – million tons

t – ton

TLU – Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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7. Annexes

Annex 1 - Indicator for land where natural processes predominate: dataset selection and target terminology

In the FABLE 2020 report, countries sought to achieve the biodiversity target of "no net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate." There are many different spatial datasets that can be used as indicators of areas where natural processes predominate to monitor progress towards this target. The following sections explain our dataset selection process and rationale.

Dataset identification

Members of the FABLE Biodiversity Working Group (a subset of FABLE consortium members comprising 28 members with expertise in biodiversity) compiled a list of four candidate spatially explicit, recent, globally consistent datasets that could serve as proxies for habitat that is ecologically intact. These included key biodiversity areas (BirdLife International, 2019), the human footprint map (Venter et al., 2016), intact forest landscapes (Potapov et al., 2008), and the biodiversity intactness index (Newbold et al., 2016).

We conducted a survey with the FABLE consortium country teams with the aim of using their local knowledge and datasets to assess which of the four candidate global datasets most reliably distinguished ecologically intact areas in each country. Country teams were asked to work with a biodiversity specialist to rate the reliability of each dataset from very bad (1) to very good (5) and explain their reasoning. We invited respondents to suggest any alternative, better global datasets that could be considered.

Dataset selection

Results showed that all four datasets were considered good or very good by some country teams, while 24% of countries rated the biodiversity intactness index as very bad (Figure: Rating of geospatial dataset reliability for detecting ecologically intact land by FABLE country teams). The median ratings were 4, 4, 3.5 and 2.5 respectively for the key biodiversity areas, human footprint map, intact forest landscapes, and biodiversity intactness index, with various reasons given for these ratings (Table: Summary of FABLE country team views on strengths and weakness of compared datasets). Respondents noted that the key biodiversity areas and intact forest landscapes were only useful for detecting specific types of land, not all ecological intact areas, while the human footprint map and biodiversity intactness index had more comprehensive global coverage but missed some of the areas identified in the key biodiversity areas or intact forest landscape datasets. Respondents put forward five newer datasets that we could also consider: the Global Human Modification Index (Kennedy et al., 2019), Low Impact Areas (Jacobson et al., 2019), an updated biodiversity intactness index (v.2), a habitat condition map created as part of CSIRO's global biodiversity modeling work (CSIRO, 2019) and the contextual habitat index (Mokany et al., 2020).

Based on the survey results we decided to use a combination of key biodiversity areas (BirdLife International, 2019), intact forest landscapes (Potapov et al., 2008), and either the human footprint map (Venter et al., 2016) or one of the five newer datasets identified. To help select among the latter datasets, the human footprint and the five other candidate datasets were characterized and qualitatively compared by members of the FABLE secretariat (Table: Comparison of datasets for use as indicators of land contributing to biodiversity conservation (or ‘intact land’) in FABLE). Based on this we determined that the biodiversity intactness index was conceptually in line with what we wanted to measure, explicitly seeking to measure ecological intactness. However we were unable to obtain a copy of the updated biodiversity intactness index from the PREDICTS team, and given the problems identified by the FABLE country teams and others (Martin et al., 2019) with version 1 of this dataset, we excluded it from further consideration. CSIRO’s habitat condition map is conceptually similar to the biodiversity intactness index, but since it was unpublished at the time of analysis and therefore not clearly documented we elected not to use it in this year’s modeling. The contextual intactness index measures intactness in relation to local surroundings, and users can see the proportion of habitat expected to have once supported a similar assemblage of species but now in a worse condition than the focal location. While useful for conservation planning, this dataset is not suitable for setting a meaningful global target since the amount of land identified varies with the threshold set (i.e. setting a threshold of 0.5 identifies which 50% of the world’s land is in a locally relatively better condition than the rest).

Of the remaining three datasets, the Global Modification Index and Low Impact Areas datasets focused on identifying areas of low human disturbance, rather than natural habitat intactness, making them conceptually close to the human footprint map. We considered both datasets as preferable to the human footprint map because they used newer and higher resolution input data, and used the ESA CCI land cover as input data, matching the data used in computing the biodiversity baseline in FABLE. This narrowed the final choice down to between the Global Modification Index and Low Impact Areas datasets. From these two, we selected the Low Impact Areas dataset because it corrects for known errors in the ESA land cover dataset so that strictly protected areas were included, which we considered important as it directly impacts on our indicator results.

The three selected datasets (key biodiversity areas, intact forest landscapes, and low impact areas) were used as default indicators of land where natural processes predominate in FABLE 2020, unless country teams wanted to use their own national datasets (no countries opted to do this).

Data processing

We merged data on intact forest landscapes from 2016 and key biodiversity areas with low impact areas to obtain a spatially consistent raster of land where natural processes predominate, at 1x1km resolution. We used the Tabulate tool in ArcGIS to calculate the area of land where natural processes predominate within each ecoregion inside each country, using a computation cell size of 20m. Ecoregions were sourced from (Dinerstein et al., 2017) and countries from GADM v.36. Results are reported in the current context sections of the country chapters and aggregated to biome level in the global overview. For use in the FABLE Calculator, we used the Tabulate tool to calculate the area of land where natural processes predominate within each land cover type, inside each ecoregion and country. Land cover data were sourced from the ESA CCI land cover map for 2010. We used 2010 data to be consistent with the land cover data used in scenario baselines for other outcomes (e.g. carbon, food production) in the FABLE Calculator. Baseline data for other outcomes are based on FAO land cover shares which differ slightly from the ESA land cover shares. Land cover sourced from ESA was aggregated into broader land cover classes for use in the FABLE calculator as shown in the table “Correspondence used to aggregate ESA land cover classes into the broader land cover classes, for use in the FABLE Calculator”.

Table	*Correspondence used to aggregate ESA land cover classes into the broader land cover classes, for use in the FABLE Calculator*

FABLE classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland>50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)
Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Note on target terminology

In 2019, we used this wording for one of the biodiversity targets: "At least 50% of global terrestrial land supports biodiversity conservation by 2050". This indicator was designed to monitor the extent of ecologically intact land. We received feedback from readers of the 2019 FABLE Report that it was not clear what land we were referring to by land supporting biodiversity conservation, since, for example, protected areas aim to support biodiversity conservation but we did not consider these as contributing, and it was unclear what we meant by ecological intact land. FABLE country teams also raised concerns over using the word "intact" because of a lack of clarity as to what it means in practice, e.g. how can we really know the species richness and abundance present in an undisturbed habitat given all habitats are arguably now some extent disturbed, and we lack distribution data on millions of species.

At the same time, our selection of a dataset that focused on human disturbance levels led us to question whether intact land was an accurate term for describing what the indicator would measure. Jacobson et al. (2019) explicitly state their dataset does not necessarily capture intact habitat: Low Impact Areas are "areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes, or faunal assemblages". For this reason, we decided to adjust our biodiversity target wording to match what we were measuring and adopted Jacobson et al (2019) notion of areas where "natural processess predominate".

Figure 23 *Rating of geospatial dataset reliability for detecting ecologically intact land by FABLE country teams*

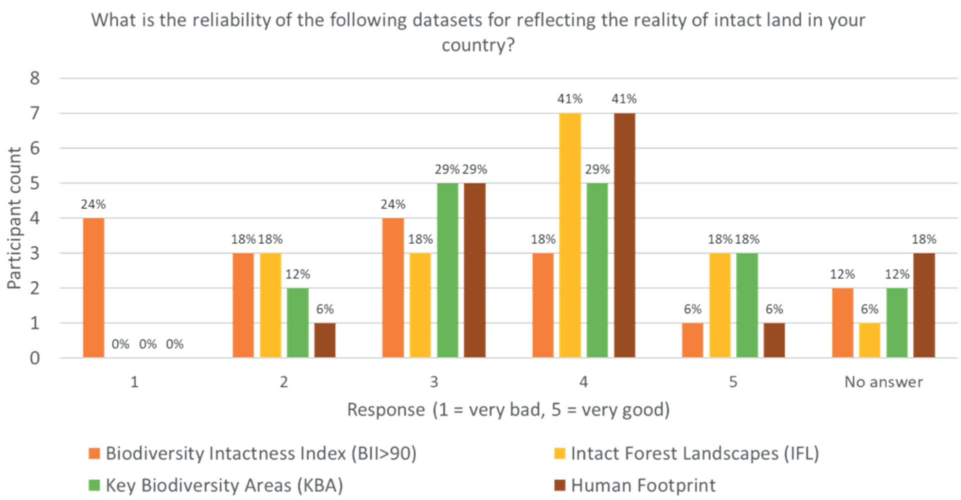


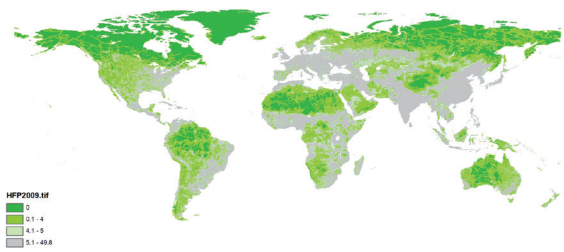
Table *Summary of FABLE country team views on strengths and weakness of compared datasets*

DATASET	STRENGTHS	WEAKNESSES
Biodiversity intactness index v1 (>90)	• Allows a homogenous approach for all FABLE countries • Picks up many areas of intact land not captured by the KBA or IFL datasets • Theoretically the closest dataset to what we actually want to measure	• We apply a threshold. This is expected to produce inaccurate predictions at local scale • Does not distinguish between plantation and natural forest • Favours forests and overlooks natural grasslands • Threshold >90 misses large areas of pristine landscapes and picks up many urban and cropped areas • **44% FABLE countries rated it as unreliable (score of 1 or 2)**
Key biodiversity areas	• **Considered reliable across FABLE countries (median rating 4)**	• The KBA dataset includes Ramsar sites and IBAs, but not other potentially important sites such as SACs, SPAs, NNRs and SSSIs, and LNRs. It includes mostly coasts, estuaries, islands, heaths, moors and mountains: bias towards birds
Intact forest landscapes	• **Considered quite reliable across FABLE countries (median rating 3.5)**	• IFL takes into account areas of plantation forest • Leaves out much of the country's land area that can and should also be included into conservation strategizing
Human footprint	• **Considered reliable across FABLE countries (median rating 4)**	• This appears to use distance from roads as an indicator of intact nature, which doesn't sound particularly useful.
Biodiversity intactness using national land use maps (e.g. SA) or other national intact proxies	• Some countries are poorly represented in global biodiversity datasets and better national data are(sometimes) available	• Would lead to inconsistent input datasets across FABLE countries and potentially inconsistent definitions of land that counts as intact. Maybe ok if care is taken.
CSIRO habitat condition	• Conceptually promising	• Untested across FABLE countries

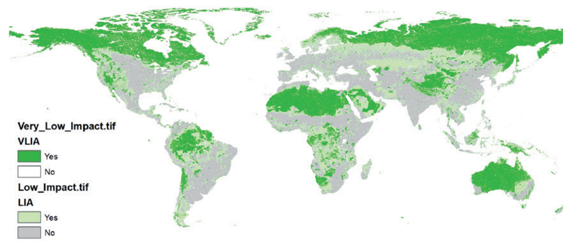
Table *Comparison of datasets for use as indicators of land contributing to biodiversity conservation (or 'intact land') in FABLE*

GLOBAL MAPS

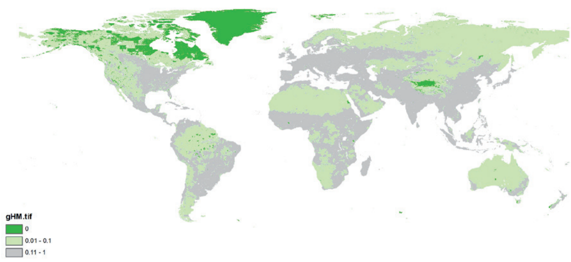
Human footprint map (Venter et al. 2016)



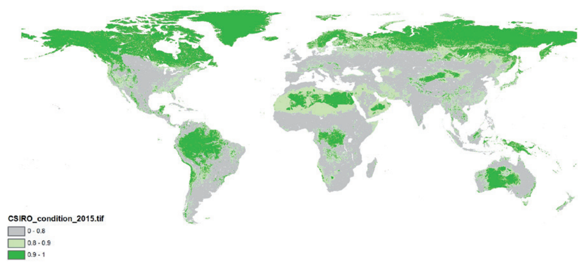
Low impact areas (Jacobson et al. 2019)



Human mofication index (Kennedy et al. 2019)



Habitat condition (CSIRO)



Detailed comparison

DATASET	WHAT DOES IT MEASURE?	BRIEF DESCRIPTION	THRESHOLD TO APPLY FOR FABLE	STRENGTHS	WEAKNESSES	SCIENTIFICALLY ROBUST?	APPROVED BY FABLE COUNTRY TEAMS BASED ON BIODIVERSITY SURVEY COMPLETED 17 JAN 2020?
Human Footprint map (Venter et al., 2016)	Cumulative human pressure on the environment, at 1x1km resolution, for ~1993, 2009	The HF is an index of human pressure (scaled from 0 to 50) based on the summation of eight global data layers: 1) human population density, 2) built-up areas, 3) cropland, 4) pastureland, 5) night-time lights, 6) roads, 7) railroads and 8) navigable rivers.	HF = 0. This captures areas considered unmodified. OR HF <3. Used in Mokany et al. (2019) based on 'extensive experience of the [CSIRO] co-authors'. OR HF <4. It is used in Jacobson et al 2019 as part of his cross-data comparison, but because of % land captured not for biological reasons. OR HF < 5. Adrian Monjeau recommended this as working very well for Argentina.	• Trends can be easily computed because human footprint maps are available from 1993 and 2009	• Includes pressures from data at 10x10km resolution downscaled to 1x1km (this was done to enable analysis through time) • Spatial patterns are driven primarily by road networks, because roads, coastlines and waterways features were buffered and an exponential distance decay effect applied 15km from these features • Weights applied to each stressor were mostly based on expert opinion • Treats each pixel as binary in terms of pressures, irrespective of how much of the pixel is impacted by the pressure • Assumes interactions between pressures are additive, whereas evidence suggests often they are non-additive (but hard to be sure)	Yes, widely used and cited generally positively	Judged reliable for detecting intact land: median score 4 out of 5, on a scale of 1 = very bad, 5 = very good, but some teams raised concerns, e.g. Sweden, India.

DATASET	WHAT DOES IT MEASURE?	BRIEF DESCRIPTION	THRESHOLD TO APPLY FOR FABLE	STRENGTHS	WEAKNESSES	SCIENTIFICALLY ROBUST?	APPROVED BY FABLE COUNTRY TEAMS BASED ON BIODIVERSITY SURVEY COMPLETED 17 JAN 2020?
Low Impact Areas (Jacobson et al., 2019)	"Landscapes that currently have low human density and impacts and are not primarily managed for human needs", at 1x1km resolution, for ~2015	Categorical data set showing humanity's current impact on the terrestrial environment, identifying areas of relatively low human impact as Low Impact Areas. LIAs are derived from 7 global stressor datasets: human population, livestock density, forest change, land cover and nighttime lights. These datasets have variable spatial and temporal resolution. Human impacts are classified as very low, low or other. LIAs are **"areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes, or faunal assemblages".**	Include everything that is classified as having 'very low' or 'low' human impact. This includes 56% of the planet.	• Uses ESA CCI land cover data matching the data used in FABLE for protected area calculations per land cover. • Uses mostly data from 2015 or newer • Explicitly includes some national reserves and protected areas with IUCN I-IV status (strictly protected) to account for errors in ESA land cover classifications and/or where human pressures are very likely to be low	• Three classes only so analysis options are limited (but fine for what we want to do for 2020 in FABLE) • Assumes interactions between pressures are additive, whereas evidence suggests often they are non-additive (but hard to be sure)	NEW - untested	Not checked

DATASET	WHAT DOES IT MEASURE?	BRIEF DESCRIPTION	THRESHOLD TO APPLY FOR FABLE	STRENGTHS	WEAKNESSES	SCIENTIFICALLY ROBUST?	APPROVED BY FABLE COUNTRY TEAMS BASED ON BIODIVERSITY SURVEY COMPLETED 17 JAN 2020?
Global Human Modification Index (Kennedy et al., 2019)	Percentage of land modified by humans, at 1x1km resolution, for ~2015	Based on global data on five stressors (13 stressor datasets) obtained at 1x1km resolution: human settlements (population density, built-up areas), agriculture (cropland, livestock), transportation (roads, tracks, railroads), mining and energy production (mining, oil wells, wind turbines), electrical infrastructure (powerlines, nighttime lights). Stressor data had a median date of 2016. The degree of human modification was calculated as the per-pixel product of spatial stressors (spatial extent and expected intensity of impact) with stressors scaled from 0 to 1 and aggregated by taking the fuzzy algebraic sum (assumes the contribution of a given factor decreases as values from other stressors co-occur).	GHM <=0.1. This represents areas classified by Kennedy et al as having a low human modification.	• More stressors considered than in the Human Footprint • Intensity values for stressors were based on published land use coefficients showing amount of energy required to maintain the human activity • The intensity of impact coefficients are on a ratio scale, rather than ordinal or interval as in the human footprint. Possible to get area of land that scores low on the index using 1x1km pixel percentages, so should be more accurate than using binary 0,1 pixel values as done for Human Footprint. • Used ESA CCI land cover data matching the data used in FABLE for protected area calculations per land cover. • Used fuzzy algebraic sum which assumes interactions among impacts are more commonly non-additive than additive, in line with empirical evidence	• Data on some stressors was taken from OpenStreetMap and was globally incomplete, notably for transportation, mining and energy production. • Biodiversity responses to land use intensity and human activity will be species and region specific	NEW - untested	Not checked

DATASET	WHAT DOES IT MEASURE?	BRIEF DESCRIPTION	THRESHOLD TO APPLY FOR FABLE	STRENGTHS	WEAKNESSES	SCIENTIFICALLY ROBUST?	APPROVED BY FABLE COUNTRY TEAMS BASED ON BIODIVERSITY SURVEY COMPLETED 17 JAN 2020?
CSIRO contextual intactness index (Mokany et al., 2020)	Contextual intactness of each cell on the planet, at 1x1km resolution	"We assessed the contextual intactness of each location (1 km grid cell), by determining the proportion of habitat expected to have once supported a similar assemblage of species but is now in worse condition than the focal location. Locations with the highest contextual intactness are where all other biologically-similar locations are in a worse condition." (Mokany et al. 2019)	0.5?	• Takes into account importance of habitat in local environment so picks up relatively intact areas in managed lands. For example, a location with a higher human footprint can still have a higher contextual intactness value, if it is the 'best-on-offer' in terms of the condition of all other locations with similar expected species assemblages, e.g. remnant habitats in modified regions. • Takes into account large intact areas meeting 'wilderness' classifications, but also partially degraded fragmented habitat • Possible to set the threshold to reach our biodiversity target, i.e. a threshold of 0.5 picks up all areas that are in a better condition than over half of the areas that supported a similar assemblage of species, and hence covers half of the Earth's surface.	• Assumes the same habitat coefficients apply everywhere (?) • Permission to use needs to be agreed with CSIRO (but should be fine) • Data on locations of species assemblages is modelled from environmental variables not actual observations (but this overcomes biases in observation data) • It is unclear how we would set a threshold on this for use in the FABLE calculator. It is probably better suited for conservation planning.	NEW – untested (publication in review at time of FABLE comparison)	Not checked

DATASET	WHAT DOES IT MEASURE?	BRIEF DESCRIPTION	THRESHOLD TO APPLY FOR FABLE	STRENGTHS	WEAKNESSES	SCIENTIFICALLY ROBUST?	APPROVED BY FABLE COUNTRY TEAMS BASED ON BIODIVERSITY SURVEY COMPLETED 17 JAN 2020?
CSIRO habitat condition map	Habitat condition of each cell on the planet, at 1x1km resolution	Habitat condition at 1km resolution derived by combining statistical downscaling of the Land Use Harmonization land-use classes (using finer resolution remote-sensing, abiotic environmental and population covariates) with condition scaling factors or coefficients, from PREDICTS and various other sources. This "habitat condition" layer is essentially the equivalent of the BII from PREDICTS, or the MSA from GLOBIO – i.e. it's a measure of local intactness of each cell on the planet. (Simon Ferrier, pers comm 14 Jan 2020).		• Conceptually close to ecological intactness	• Limited documentation	NEW – untested (publication in review)	Not checked
Biodiversity intactness index v2			BII >90%. This represents areas expected to contain at least 90% of original species assemblages.	• "We believe that measuring the relative intactness of species assemblages with metrics like the BII can be a useful indicator of the state of ecosystems." (Martin et al., 2019)	• We have been unable to get hold of the dataset from the PREDICTs team	NEW - untested, but BII v1 widely cited both positively and negatively	Not checked but BII v1 judged unreliable by several countries

Indicator for biodiversity-friendly cropped landscapes

Dataset selection

We use the proportion of natural or semi-natural vegetation in cropped areas as an indicator of working landscapes supporting biodiversity and ecosystem functioning (Garibaldi et al., 2020). We set the percentage of natural or semi-natural vegetation required to support biodiversity and ecosystem functioning to at least 10% within a ~1x1km window as proposed by Willet et al. 2019 and supported by (Sirami et al., 2019). We compute the proportion of natural or semi-natural habitat in cropped landscapes from ESA CCI land cover data from 2010. We use 2010 land use data to be consistent with the land use extents used in other scenario baselines in the FABLE Calculator.

Data processing

We reclassified ESA CCI land cover into cropland, natural or not relevant classes as shown in the table "Correspondence used to aggregate ESA land cover classes into the broader land cover classes, for use in computing he proportion of natural or semi-natural land in cropped landscapes". Next, we used the focal and mask functions in the R Raster package to compute the number of natural or semi-natural pixels within a 3x3 window around each cropped pixel. The 3x3 focal window was selected since ESA data are available at ~300m resolution, meaning the focal window corresponds to approximately 0.9km2. The output values were converted to proportions by dividing the number of natural or semi-natural pixels identified by the total number of pixels in the focal window (excluding the cropped pixel). We reclassified the output such that 1 indicated at least 10% of the focal window around a cropped pixel was natural or semi-natural and 0 indicated that this value was <10%.

We used the Tabulate tool in ArcGIS to calculate the area of cropland with >10% natural or semi-natural within a ~1x1km window, within each ecoregion inside each country, using a computation cell size of 20m. Ecoregions were sourced from (Dinerstein et al., 2017) and countries from GADM v.36. Results are reported in the current context sections of the country chapters and aggregated to biome level in the global overview.

Table *Correspondence used to aggregate ESA land cover classes into the broader land cover classes, for use in computing he proportion of natural or semi-natural land in cropped landscapes*

Aggregate classes	ESA classes (codes)
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30)
Natural or semi-natural	Mosaic cropland>50% - natural vegetation >50% (40), Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170), Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130), Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Not relevant	Bare areas (200,201,202), Snow and ice (220), Urban (190), Water (210)

Annex 2 - Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed

ESA LULC CODE	ESA LULC NAME	FABLE CLASS
0	No data	No data
10	Cropland rainfed	Cropland
11	Cropland rainfed herbaceous cover	Cropland
12	Cropland rainfed tree or shrub cover	Cropland
20	Cropland irrigated or post-flooding	Cropland
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous) (<50%)	Cropland
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	Cropland
50	Tree cover broadleaved evergreen closed to open (>15%)	Forest
60	Tree cover broadleaved deciduous closed to open (>15%)	Forest
61	Tree cover broadleaved deciduous closed (>40%)	Forest
62	Tree cover broadleaved deciduous open (15-40%)	Forest
70	Tree cover needleleaved evergreen closed to open (>15%)	Forest
71	Tree cover needleleaved evergreen closed (>40%)	Forest
72	Tree cover needleleaved evergreen open (15-40%)	Forest
80	Tree cover needleleaved deciduous closed to open (>15%)	Forest
81	Tree cover needleleaved deciduous closed (>40%)	Forest
82	Tree cover needleleaved deciduous open (15-40%)	Forest
90	Tree cover mixed leaf type (broadleaved and needleleaved)	Forest
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Forest
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	Grassland
120	Shrubland	OtherLand
121	Shrubland evergreen	OtherLand
122	Shrubland deciduous	OtherLand
130	Grassland	Grassland
140	Lichens and mosses	OtherLand
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	OtherLand
151	Sparse tree (<15%)	OtherLand
152	Sparse shrub (<15%)	OtherLand
153	Sparse herbaceous cover (<15%)	OtherLand
160	Tree cover flooded fresh or brakish water	OtherLand
170	Tree cover flooded saline water	OtherLand
180	Shrub or herbaceous cover flooded fresh/saline/brakish water	OtherLand
190	Urban areas	Urban
200	Bare areas	OtherLand
201	Consolidated bare areas	OtherLand
202	Unconsolidated bare areas	OtherLand
210	Water bodies	Water
220	Permanent snow and ice	OtherLand

Annex 3 - GHG emissions

Annex GHG emissions

This annex summarizes how GHG emissions are considered in the FABLE Calculator and in the MAgPIE land-use model. For instance, carbon sequestration is only considered on land that has been afforested or taken out of agricultural production during the simulation period (i.e. after 2000 in the FABLE Calculator). Therefore, removals are substantially lower in our calculations because CO2 accounting for the categories "forest land remaining forest", "grassland remaining grassland", and "woody products" are not represented in our modeling framework (or only partially represented in MAgPIE). Moreover, within the represented categories some products and processes are not accounted for. For example, our pathways only consider deforestation that occurs to produce the commodities included in the models. Our estimates exclude deforestation due to land speculation or driven by products not covered in the FAO statistics. Finally, the FABLE Calculator does not account for all carbon pools: only emissions from biomass change are included, leaving aside emissions/sequestration from changes in dead organic matter and soil carbon.

GHG REPORTING CATEGORY	COVERAGE	FABLE CALCULATOR COVERAGE	MAGPIE COVERAGE
Agriculture			
Enteric fermentation	CH_4 production from herbivores during the digestive process. Animal categories include Cattle, Buffalo, Sheep, Goats, Camels and Lamas, Horses, Mules and Asses, Swine, Poultry, and Other.	Included for cattle (dairy and non-dairy), sheep, and goats	Included for all FAO ruminant livestock categories
Manure management	CH_4 and N_2O produced from the decomposition of manure under low oxygen or anaerobic conditions (i.e. often when large numbers of animals are managed in a confined area).	Included for cattle (dairy and non-dairy), sheep, goats, poultry and swine	Included for all ruminants (dairy and non-dairy), poultry and swine
Rice cultivation	CH_4 emissions from anaerobic decomposition of organic material in flooded rice fields.	Included	Included
Agricultural soils	CH_4 and N_2O emissions and removals from agricultural soil/land and Non-methane volatile organic compounds (NMVOCs) from crops (includes the biological nitrogen fixation, and return of crop residues to the field or to animal production)	N_2O emissions from synthetic fertilizers and return of crop residues to the field	Emissions from organic and inorganic fertilizers, return of crop residues to the field and to the animals, nitrogen fixation, and atmospheric deposition
Other	Field burning of agricultural residues, liming, urea application, other carbon-containing fertilizers, other. Burning of savannas is not included in the inventory total.	Emissions from energy use in agriculture and direct emission savings due to the replacement of fuel by biofuels	Field burning of agricultural residues

GHG REPORTING CATEGORY	COVERAGE	FABLE CALCULATOR COVERAGE	MAGPIE COVERAGE
Land use, Land Use Change, and Forestry (LULUCF)			
Annex 1 parties			
Cropland	Changes in carbon in cropland remaining cropland include changes in biomass in monoculture tree plantations, fruit and nut orchards, and polycultures such as agroforestry systems, changes in soil carbon due to management practices, and burning of agricultural residues	Not included	Not included
	Carbon stock change due to the conversion of land from natural conditions and other uses to cropland includes biomass, dead organic matter, soil carbon, and non-CO_2 emissions from biomass burning	Changes in biomass stock due to the conversion of forest and other natural land to cropland	Changes in carbon stocks including biomass, dead organic matter and soil carbon due to the conversion of forests, pastures and other natural land to cropland
Grassland	Changes in carbon in grassland remaining grassland include variations in cover of woody vegetation, effects of organic matter additions, effects of management and liming, and non-CO_2 emissions from incomplete combustion of biomass in managed grassland	Not included	Not included
	Carbon stock change due to the conversion of land from natural conditions and other uses to grassland includes i) biomass, ii) dead organic matter, iii) soil carbon, iv) non-CO_2 emissions from biomass burning	Changes in biomass stock due to the conversion of forest and other natural land to grassland	Changes in carbon stocks including biomass, dead organic matter and soil carbon due to the conversion of forests, cropland and other natural land to pasture
Forest Land	Changes in carbon in forest remaining forest include gains from total biomass growth, biomass losses from roundwood removal, fuelwood removal, and from disturbances by fire, insects, diseases, and other disturbances, and non-CO_2 emissions from biomass burning	Not included	Changes in biomass carbon stocks due to climate change.
	Carbon stock change through afforestation and reforestation either by natural or artificial regeneration (including plantations and abandoned productive lands)	Changes in biomass dues to active afforestation (e.g. through plantations) Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment are accounted for in Other Natural Land category	Changes in biomass due to active afforestation (e.g. through plantations) Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment are accounted for in Other Natural Land category

GHG REPORTING CATEGORY	COVERAGE	FABLE CALCULATOR COVERAGE	MAGPIE COVERAGE
Settlements	Changes in biomass, dead organic matter (DOM), and soil carbon on lands classified as settlements	Not included	Not included
	Carbon stock change due to the conversion of Forest Land, Cropland, Grassland etc. to Settlements	Changes in biomass stock due to the conversion of forest and other natural land to urban area	Not included
Wetlands	Emissions from managed wetlands e.g. any land that is covered or saturated by water for all or part of the year, that does not fall into the Forest Land, Cropland, or Grassland categories, and where the water table is artificially changed (e.g., drained or raised) or those created through human activity (e.g., damming a river)	Managed wetlands other than for cropland and grassland are included under other natural land	Not included
Other Land	Other land (includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories) remaining other land	Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment	Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment
	Carbon stock change due to the conversion of land to Other land	Not included	Not included
Harvested Wood Products	Includes carbon stored in all wood material (including bark) that leaves harvest sites from Forest Land, Cropland and other types of land use and remains in products for differing lengths of time	Not included	Not included
Non-Annex 1 Parties			
CO_2 emissions and removals from soils	Emissions and removals from i) cultivation of mineral soils, ii) cultivation of organic soils, and iii) liming of agricultural soils	Emissions from the cultivation of organic soils (only included in Finland and Indonesia)	Not included
Changes in forests and other woody biomass stocks	Commercial management, harvest of industrial roundwood (logs) and fuelwood, production and use of wood commodities, and establishment and operation of forest plantations as well as planting of trees in urban, village and other non-forest locations	Not included	Not included
Forest and Grassland conversion	Conversion of forests and grasslands to pasture, cropland or other managed uses	Changes in biomass stock due to the conversion of forest to cropland and grassland	Changes in carbon stocks including biomass, dead organic matter and soil carbon due to the conversion of forest and other natural vegetation to cropland and grassland
Abandonment of managed lands	Lands that regrow into their prior natural grassland or forest condition	Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment (allocated to the Other natural Land category)	Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment (allocated to the Other natural Land category)