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Relationships between physical effects of climate change on forests and economic impacts by world region

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Abstract: This study projects the macroeconomic consequences of impacts of climate change on forests by world regions under the three Representative Concentration Pathways, RCP2.6, RCP4.5, and RCP8.5 until 2100. It is based on assessments of the impacts of the mortality of trees in forest plantations in 27 countries. The forestry sectors in these country covers about 75 percent of the value of timber production in the world. To address the macroeconomic consequences, the estimated effects of climate change on forest mortality were generalized to 11 world regions, and implemented in the computable general equilibrium model GRACE, to address adaptation in the management of forests, resulting market effects and impacts on macroeconomic indicators. With few exceptions, climate change will lead to slower growth of forests in most regions, but there are large variations, which must be explained by other factors than the increase in temperature, such as an apparent dependency on changes in precipitation. The economic impacts are moderated substantially by an increase in the value of felled trees. While the felling is reduced on the world scale, the total value of the felling increases. Combined with the adaptation within the forestry sector, this leads to an even higher increase in the contributions to the gross domestic product from the forestry sectors on the world scale

Language of Report: English

This report has been written with support from Ortec Finance to develop their Systemic Climate Risk-Aware Scenarios Sets to help inform their clients' future investment decisions. Ortec Finance is collaborating with Cambridge Econometrics to develop climate damage inputs for their E3ME macro-econometric model. The aim of this study is to provide assessments of impacts on prices and quantities for forestry in world regions, based on the results from a master thesis by students at Nicholas School of the Environment at Duke University, which assesses effects of climate change on forests in 27 countries.

Contents

Introduction

The integrated assessment models that include impacts of climate change are typically based on relationships between selected climate indicators, usually the change in mean temperature, and gross domestic products (GDP) by region, such as E3ME, (Pollitt et al. 2015), DICE (Nordhaus, 2014), FUND (Anthoff and Tol, 2013), and PAGE (Hope, 2011). Adaptation among economic agents and resulting market effects are thereby considered given. Possible dependencies on how production possibilities change under specific climatic changes, and what implications impacts to one sector have for other sectors because of market effects are thereby ignored. These problems add to many other challenges in deriving impacts of climate change on national economic aggregates, such as GDP, from studies of physical effects. One is related to the transformation of physical quantities to economic quantities used to analyse economic behaviour. Another is to estimate the impacts on the aggregates in the national accounts with reference to studies of physical effects, which are usually focusing on selected geographical areas.

An alternative to using functional relationships between climate indicators and GDP is to link these indicators to economic factors that will be affected by climate change. Then, the economic consequences can be estimated by a description of how economic agents respond from basic theory of economic behaviour. The resulting shifts in supply and demand give rise to market effects, with combinations of changes in prices and quantities. This study makes such an assessment for the impacts of climate change on forestry in different world regions. The aim is to derive the economic consequences of assessments of physical impacts on forests, and to provide a more comprehensively founded relationship between changes in climate indicators, effects on forests and impacts on GDP, which can be used in integrated assessment models based on so-called damage functions.

The next section gives a short presentation of the general equilibrium model used in this study, GRACE (Aaheim et al. 2018), and shows how impacts on forests are integrated. Then follows a presentation of the forestry module in GRACE, with an explanation to how it relates to the standard model. The following section summarises the data used to estimate the physical effects of climate change on forests in different countries. Data are available for 27 countries, which covered approximately 73 percent of the total value of harvested forests in the world in 2014 (Jia et al., 2020). The section discusses strengths and weaknesses of data used for the economic assessment. It is partly related to lack of information of importance for modelling economic behaviour, and partly to information available in the dataset, which we were unable to utilize in this study. It explains how a dataset for countries are used to estimate the biological characteristics of forests for the 11 world regions in GRACE and shows how the impacts of climate change are estimated. We present two alternative impact functions, one related only to temperature change and one related to combinations of changes in temperature and precipitation. The last section shows the impacts of climate change by world region. As the aim of the study is to provide input to other integrated assessment models, the impacts are isolated to impacts on forests, and estimated in a static mode. The estimated impacts thereby refer to climatic changes as if they occurred “today”, without any dynamic effects of policies, population growth, economic growth or climate change.

1 Economic impacts of climate change assessed by GRACE

GRACE is a computable general equilibrium (CGE) model, which integrates effects of climate change on primary input factors (labour, capital and natural resources), and on the demand for specific goods and services, such as energy, health services and tourist related activities. In the version of the model used in this study, the impacts of climate change are limited to impacts on forests. Figure 1 illustrates how these impacts affect the economy in CGE models. These models are based on data from the national accounts on the flows of goods and services between economic sectors, and on deliveries from the economic sectors to consumption and to investments. The grey boxes on the lower side contain the value of deliveries from sectors listed in the green box, to sectors listed in the red box and to final deliveries, shown in the orange box. The red line thereby shows the demand for goods from one sector, here forestry, in all other sectors in the economy and for consumption and investments. The green, vertical line shows the use of goods from other sectors in each sector, here highlighted by the forestry sector. In addition to these deliveries, the sectors also use labour, capital, and natural resources as input in the production of their final output.

The national accounts data are used to calibrate demand-functions for all goods in all production sectors and consumption. The demand in the production sectors is derived from the production functions in each sector, based on the data along the green line. In global models, like GRACE, the goods and services are demanded also from other regions, measured by exports and imports, respectively. Deliveries between two sectors represent costs to one sector and income to another. Therefore, the income generated by each sector, the value added, is attributed only to the use of labour, capital, and natural resources. It is assumed that all income from these primary input factors is used to demand goods and services. This is a weakness in most general equilibrium models, which is due to a lack of data on the value of, and thereby demand for, property on national scales.

The economic activity in a region is thereby constrained by the availability of the three primary input factors. A change in the availability of forests can be represented as an exogenous change in the input of natural resources in the forestry sector, which leads to a shift in the supply curve on the right-hand side in the figure.

If the demand curve remains unaffected, this shift leads to a change both in the quantity and in the price of products from this sector. The price effect leads to a substitution with alternative goods, which differ depending on sector. It thereby affects the demand for all goods and services, firstly in sectors that use products from the forestry sector. When these sectors are affected, the effects

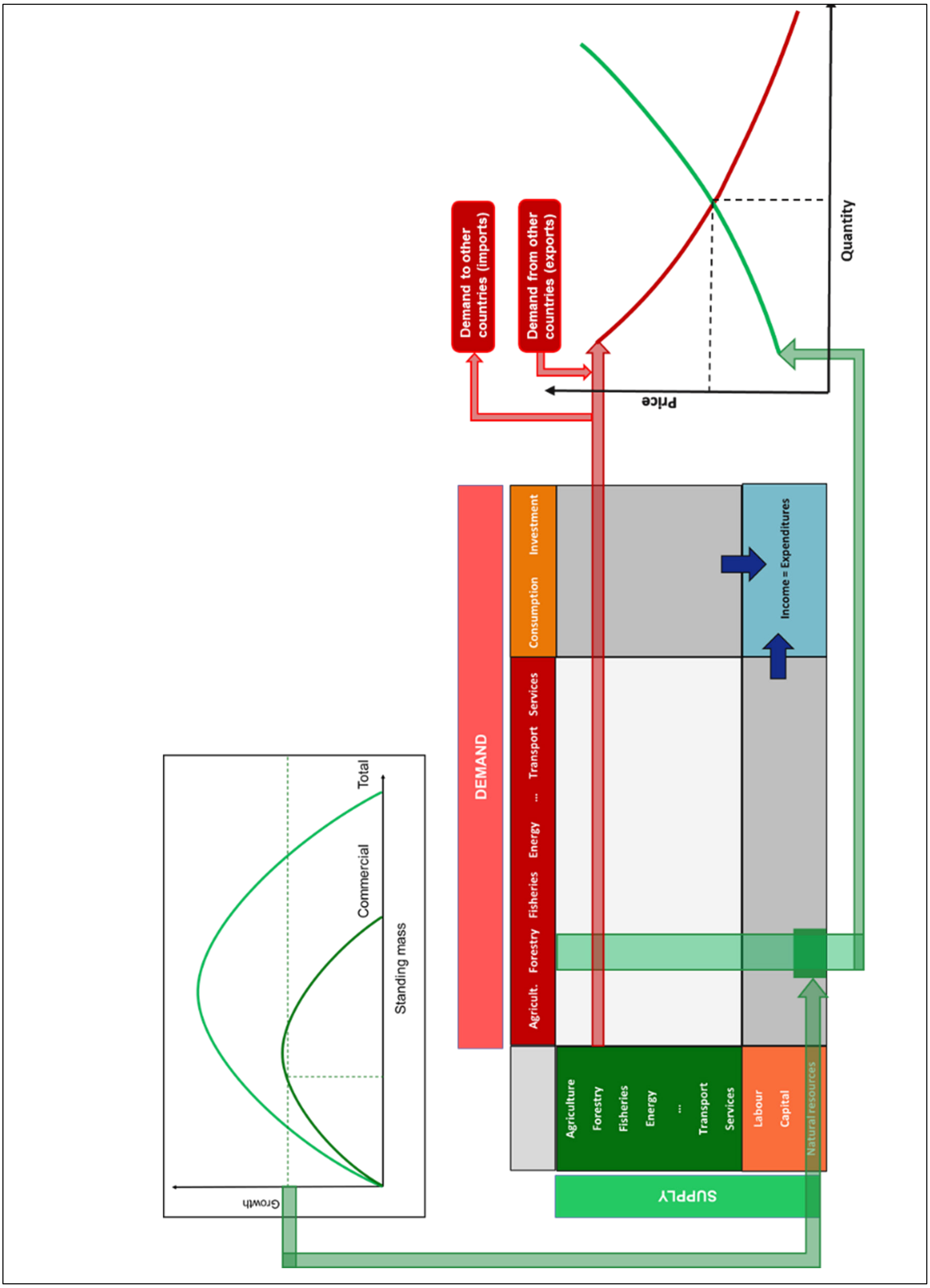

Figure 1. Main flows and relationships in GRACE

Name	Short	Comprises
Western Europe	WEU	EU15, Nordic countries, Iberia and Greece
Central and Eastern Europe	CEE	Sovereign countries of the former Warsaw pact, Baltic states, former Jugoslavia
Former Soviet Union	FSU	Other former Soviet states
Middle East & North Africa	MEA	Mediterranian Africa, and countries in the triangle Turkey – Saudi Aarabia – Iran
Sub-Saharan Africa	AFR	States in Sahara and southern Africa
South Asia	SAS	Afghanistan, Pakistan, India, Nepal, Bangladesh, Nepal, Maldives, Bhutan
East Asia	EAS	China, Mongolia, North Korea
Other Pacific Asia	PAS	Asian peninsula and island states
Pacific OECD	PAO	Japan, South Korea, Australia, New Zealand
North America	NAM	USA and Canada
Latin America	LAM	Carribbean, Mexico and further south

Table 1. Regions in GRACE

penetrate throughout the economy. CGE models thereby estimate the "global footprints" of shifts like this, but include the market responses of the initial shift.

The "input of forests" by region in GRACE is taken from the GTAP database v10 (Aguiar et al, 2019). It is estimated by dividing the value added in each sector into values generated by the use of labour, capital, and natural resources. The value generated by labour is measured by the reported compensations to labour. It is far more problematic to distinguish the values of capital use and utilization of natural resources, but in this study, we use the GTAP data as reported. It is this number, which appears in the green box in figure 1, that will be affected in GRACE by the impacts of climate change on forests.

To relate this number to the assessments of the physical impacts, we replace the number with a module for forests, which is illustrated by the curves on the upper right-hand side of the figure. The module uses relationships between standing biomass and growth to determine the economic optimal harvesting of forests, from which the value of the extracted forests can be estimated. For further use in GRACE,

these curves refer to values, but they are based on estimates of the physical characteristics of the forests. They thereby enable a description of forests on the basis of the physical assessments, which can be transformed and used in the economic analyses. Further details about this module is given below.

2 The forestry module

GTAP provides information on the value of harvested forests in the base-year 2014. This is an estimate of the value of the sales of timber products when all the costs of cutting timber and bringing it to the market are covered, including a normal return on investments in real capital, such as machinery and transport equipment. The value of harvested forests can, therefore, be interpreted as the return on the wealth of forests in a country. Physical effects of climate change will affect this return.

The standard approach in integrated assessment models, to establish a fixed relationship between mean temperature and GDP, can be interpreted as an estimate of the impact of climate change on this return. This is based on two strong assumptions. First, the managers of the forests continue as before, without adapting to the changes. Second, the effects on forests do not affect the composite of sectors in the economies, meaning that the markets are unaffected by the impacts. The forestry module in GRACE allows us to relax both assumptions, and to establish relationships between forest management and the physical characteristics of forests. The relationships are calibrated by the values from GTAP, under the assumption that forest management meets the optimality conditions for the utilization of forests in each country.

The physical characteristics are described by a relationship between growth of the biomass in a country or region, $\dot{s}$, and the stock of the biomass, s, according to the function

$$\dot{s} = (a - bs)s \tag{1}$$

where a and b are positive parameters. Below, we call this function the bio-mass curve, which is a simple specification of Faustmann's formulae (Erickson et al., 1999).

Forest management aims at maximizing the present value of the stock over an infinite time horizon. To find a combination between the growth and the stock, we impose two assumptions. First, the value of harvesting one unit of timber is fixed, and independent on how much is harvested. Second, the observed stock represents a stable, sustainable stock if there are no effects of climate change. Under these assumptions, observed combinations of stock and growth can be interpreted as a stable, long-term equilibrium, where there is no deforestation. To maximize the economic benefit of the forests, harvesting then equals the growth of forests, which can be interpreted as a realization of the return on the wealth of the forest stock. The optimal combination of growth and stock is, then, where the managers of forests are indifferent to owning and utilizing the forests and having the value of the forest invested in capital elsewhere. If the stock is lower, the return of letting the stock grow exceeds that of investing the wealth of the forest in another sector. If higher, the stock should be reduced to the point where the returns are equal. When described by equation (1), the stock is found where the normal return on investments (the discount rate) equals the rate of change in the biomass, or the derivative of the biomass function with respect to the stock:

$$r = a - 2bs \tag{2}$$

3 The data on forests and forestry

Table 2 summarizes information on the forestry sectors in the 27 countries covered in the survey of physical impacts of climate change by Jia et al. (2020).[1] The value of forests harvested in these countries covered 73 percent of the total value of forests harvested in the world in 2014, according to the GTAP database. The economic utilization of forests depends on the quality, including genus, and the cost of extraction, which may vary a lot across countries as well as within countries. To assess the value of forests one ideally has to distinguish between commercial forests and non-

Country	Region in GRACE	Total forest area	Forest plantations		Value of extraction
			Area	Growth	
		$1000\ km^2$	$1000\ km^2$	$Mill\ m^3$	Mill. US$
Denmark	WEU	21.4	18.40	12.05	32.9
France	WEU	234.3	158.18	107.63	466.5
Germany	WEU	128.3	0.27	0.22	512.9
Italy	WEU	105.0	24.66	25.23	152.1
Netherlands	WEU	7.0	0.02	0.02	31.9
Norway	WEU	131.0	0.00	0.00	116.4
Spain	WEU	183.2	123.06	109.62	134.7
Sweden	WEU	291.0	0.01	0.01	427.6
Switzerland	WEU	15.6	0.13	0.09	81.0
United Kingdom	WEU	69.8	34.32	25.57	171.8
Russia	FSU	7748.0	198.00	159.29	992.1
Turkey	MEA	91.1	4.35	7.21	164.8
India	SAS	45.5	37.86	34.45	2815.4
China	EAS	1521.8	191.82	188.74	4978.6
Taiwan	PAS	181.7	3.94	5.89	18.7
Thailand	PAS	192.5	1.50	2.35	94.5
Philippines	PAS	135.2	3.16	5.06	279.0
Indonesia	PAS	1402.9	32.86	73.62	682.3
Malaysia	PAS	209.7	6.66	11.26	330.2
Australia	PAO	396.5	9.87	15.46	338.7
Japan	PAO	261.1	89.10	75.35	381.0
New Zealand	PAO	117.4	20.88	21.76	193.9
South Korea	PAO	53.1	9.32	8.22	138.4
USA	NAM	2767.1	250.78	514.18	1922.4
Canada	NAM	4242.0	4.20	3.84	920.0
Brazil	LAM	1760.6	72.79	100.82	678.1
Mexico	LAM	512.7	14.71	15.31	220.1

Table 2. Main indicators for forests covered by the assessment of physical impacts by country

commercial forests. In some countries, most of the economic utilization of forests take place in plantations, for which data are available. Other countries base their forestry mainly on utilization of natural forests, but we have no information that allows us to distinguish between commercial and non-commercial natural forests.

[1] The survey also includes Saudi Arabia and Singapore, which are excluded in this report.

We therefore have to base the quantifications on information about plantations, for which data are available for forested area and growth in all 27 countries, as shown in Table 2. For India, China, Japan, USA and Mexico, we also have data on sub-regions. Plantations are thereby assumed to be representative for all commercial forests in all countries. This may be reasonable for some countries, such as Denmark, France, India, and Spain, where plantations constitute 2/3 or more of the total forested area. It is much more problematic for other countries, such as Canada, Germany, Netherlands, Norway, Sweden, Switzerland, and Thailand, where plantations constitute less than 1 percent of the total forested areas. Moreover, forested area is assumed to be an indicator for the stock of biomass. This may imply further biases in the calibration of the two parameters.

3.1 Calibration of biomass curves

With data on area, growth and an assumption about the normal return on investments, the parameters a and b can be calibrated from Equations (1) and (2) for each country. Then,

$$b = \frac{1}{s}\left(\frac{\dot{s}}{s} - r\right) \tag{3}$$

$$a = r + 2bs \tag{4}$$

To estimate a and b for the 11 regions in GRACE based on the national estimates, further assumptions are needed. First, the curves for each country or country-regions within a country must be aggregated to the regions in GRACE. Second, the harvested amount derived from the biomass-curves, which is based on the estimated growth measured in m^3, must be translated to the economic equivalents used in GRACE. Third, the curves used in GRACE must also include countries not covered by the survey. Figure 2 shows the value of harvested forests in countries covered by the survey in each region, and the total value of harvested forest in each region from the GTAP data. East Asia and North America are fully covered, but there are no countries in Africa south of Sahara (AFR) or in Central Europe East (CEE) covered by the assessment.

Finally, note that the optimality condition for the stock of biomass in equation (2) is independent on prices. This is based on the strong assumption that the unit cost of harvesting timber and bringing it to the place where it can be delivered is fixed, as there is no information about the dependencies between the amount harvested and the costs. To estimate the biomass curve for a region, based on information from different countries within the region, we can take possible differences between countries in the unit costs of harvesting into account, however. Instead of estimating the biomass curves from the aggregated stocks and growths for all countries covered by the survey in one region from (3) and (4), we therefore derived a and b for the GRACE regions from the estimated changes in stock and growth for each country or regions within countries.

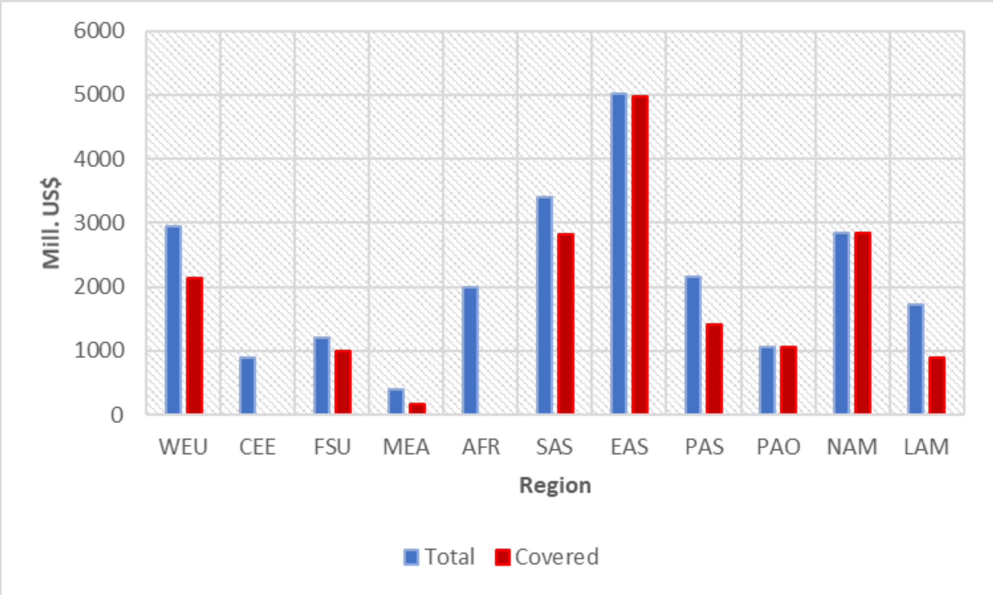

Figure 2. Value of harvested forests by region in GRACE and in countries covered by the survey. Source: GTAP

Let $S = \sum_{i=1}^{n} s_i$ denote the stocks of biomass in n countries covered by the survey that belong to the same region. For each country, we have the estimates of a_i and b_i, meaning that we can assess the optimal stock under different rates of return in each country from equation (2). Denoting the chosen discount rates by r_0 and r_1 and the corresponding stocks in country i by s_{i0} and s_{i1}, respectively, the parameters for an aggregate of countries are:

$$b = \frac{n(r_1 - r_0)}{2(\sum_i s_{i0} - \sum_i s_{i1})} \quad (5)$$

$$a = r_0 + 2b \sum_i s_{i0} \quad (6)$$

Now, all parameters are estimated using the data from the country survey, meaning that they give relationships between physical growth and forested area. To apply in GRACE, the assessments of growth has to be transformed to values, interpreted as the value of harvesting. This is done simply by attaching a fixed conversion factor, v_i. to the estimated growth, based on the value of harvested forests in each country in the forestry sectors, Q_i, from GTAP:

$$v_i = \frac{Q_i}{\dot{s}_i} \quad (7)$$

Note that although this conversion factor may be interpreted as the value per m^3 of timber in a base year, the value of timber will change depending on economic conditions, which are addressed in GRACE. Figure 3i shows the aggregated biomass functions by region in countries covered by the national survey. Figure 3ii shows the aggregated biomass function for all countries in all regions, which are based on the transformation (7). Figure 3ii includes functions for Central and Eastern Europe (CEE) and Africa south of Sahara (AFR), but there are no countries covered by survey in these regions. We have used the curve for Western Europe to describe forests in Central and Eastern Europe, and the curve for Latin America to describe African forests. Both curves are scaled to match the harvesting in the two regions reported in GTAP, but they do not reflect the biological properties in these regions.

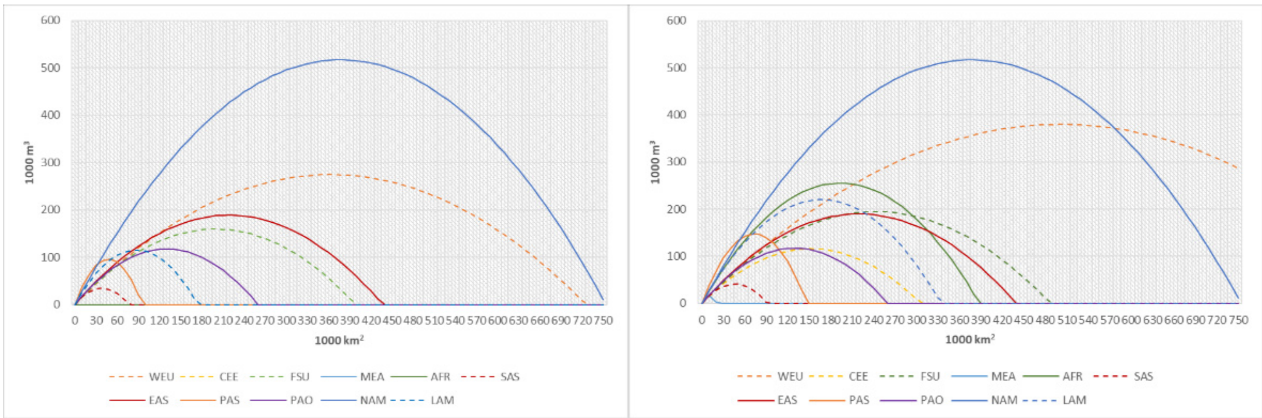

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Figure 3. Biomass functions by GRACE region for countries covered by survey (i) and for all countries (ii)

3.2 The impacts of climate change

The impacts of climate change are calculated from the changes in forested area and growth in plantations under RCP4.5 and RCP8.5 in 2100 relative to the growth and area in 2100 under the baseline. An estimate of the direct economic impact is given by multiplying these changes with the value per m^3, which is given by the value of harvested forests in GTAP divided by the growth in the baseline in each region. Figure 4 shows the impacts on the economic value of the physical changes under the three RCPs. Some regions gain under the moderate changes under RCP2.6, but most regions gain less or lose more with the increasing climatic changes under RCP4.5 and RCP8.5. In Asia, the pattern is not as clear, except in East Asia (EAS). In South Asia (SAS), for example, the large loss under RCP2.6 is reduced substantially under RCP4.5, and further under RCP8.5.

In GRACE, these impacts are represented by changes in the parameters of the bio-mass functions, which become dependent on changes in climate indicators. The dependencies are calibrated by re-estimating *a* and *b* under impacts of climate change. Most integrated assessment models are based on impacts of changes in temperature, but the impact of a given change in temperature depends also on changes in precipitation. Below, we therefore calibrate the impacts of changes both in temperature alone, and on combinations of changes in temperature and precipitation.

Let a_0 and b_0 be the estimated parameters in the baseline, and τ^a and τ^b, the impact parameters for changes in temperature. For the impacts on temperature change alone, the parameters of the biomass function are then replaced by

$$a(\Delta T) = a_0 + \tau^a \Delta T \qquad (8)$$

$$b(\Delta T) = b_0 + \tau^b \Delta T \qquad (9)$$

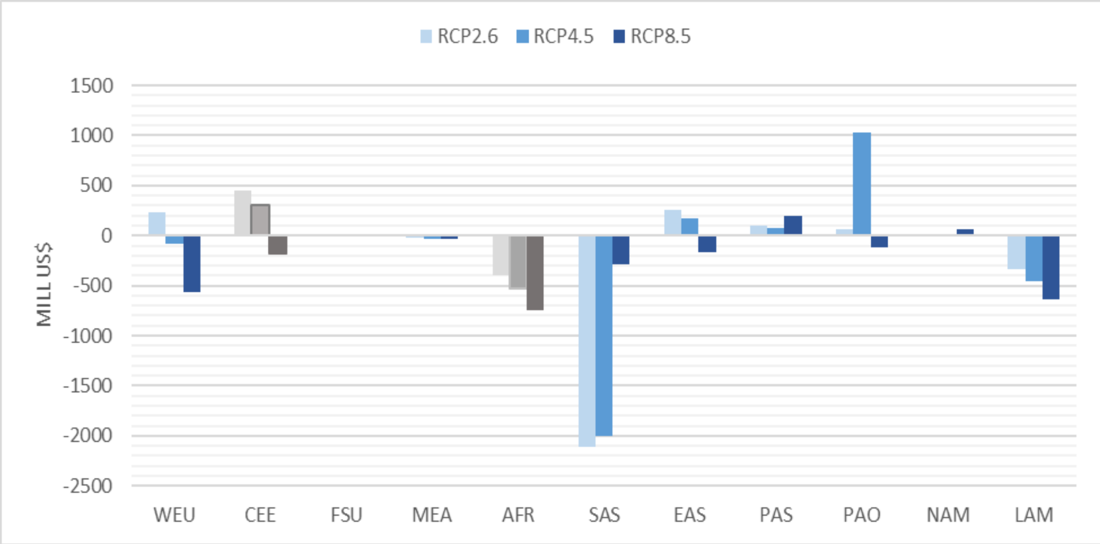

Figure 4. Direct impacts on the value of harvested forests by region in 2100 in RCP2.5, RCP4.5 and RCP8.5.

For combinations of changes in temperature and precipitation, we have

$$a(\Delta T, \Delta P) = a_0 + \tau_c^a \Delta T + \pi_c^a \Delta P \quad (10)$$

$$b(\Delta T, \Delta P) = b_0 + \tau_c^b \Delta T + \pi_c^b \Delta P \quad (11)$$

where $\tau_c{}^n$ is the impact on temperature change in parameter n, and $\pi_c{}^n$ is the respective impact of change in precipitation.

τ^a and τ^b are calibrated from the reported impacts on forests from the temperature changes under RCP8.5 in 2100, while $\tau_c{}^n$ and $\pi_c{}^n$ are calibrated from the impacts of temperature changes and changes in precipitation under RCP4.5 and RCP8.5 in 2100. Table 3 shows estimated parameters in the bio-mass functions by region, and the underlying projected changes in temperature and precipitation in 2100 under the two pathways. As mentioned, the properties of forests in Central Europe East and Africa South of Sahara are copied from Western Europe and Latina America, respectively. The scaling implies a change in parameter b also for these regions, while parameter a is the same.

The relevance of including both temperature and precipitation is indicated by using the impact functions based only on the temperature change, which are based on RCP8.5, to estimate the impacts in 2100 under RCP4.5. This is shown in Figure 5. The resulting biases are notable for Pacific Asia (PAS), Pacific OECD countries (PAO), and Latin America (LAM), where the relative differences in precipitation between RCP4.5 and RCP8.5 in 2100 are large.

The parameters in table 3 were implemented in the forestry module in GRACE. The model was run under seven cases in a static mode. This implies, as mentioned earlier, that dynamic effects under the different pathways are ignored. The impacts thereby show the difference between the baseline economies and the same economies where forests are impacted by climate change in six alternatives.

	Baseline		Temperature effect		Temperature and precipitation effects			
	a_0	b_0	τ^a	τ^b	τ_c^a	π_c^a	τ_c^b	π_c^b
WEU	1.5137	0.0015	-0.0252	0.0000	-0.046492	-0.007662	0.000032	0.000004
CEE	1.5137	0.0049	-0.0252	0.0001	-0.046389	-0.007617	0.000940	0.000312
FSU	1.5996	0.0033	0.0006	0.0000	0.020262	-0.011076	0.000035	-0.000016
MEA	3.3279	0.1598	0.0348	0.0066	0.173425	0.039793	0.012200	0.001650
AFR	2.6343	0.0068	-0.0004	0.0007	-0.000610	-0.000168	0.000504	-0.000170
SAS	1.8050	0.0197	0.0061	0.0015	-0.002960	-0.001594	-0.007972	-0.001695
EAS	1.7281	0.0039	-0.0039	0.0000	0.006210	-0.002284	0.000130	-0.000025
PAS	4.0048	0.0272	-0.0806	0.0040	-0.018863	-0.001651	-0.001528	0.000136
PAO	1.8036	0.0069	-0.0042	0.0002	-0.029891	-0.006439	0.001234	0.000265
NAM	2.7425	0.0036	-0.0157	-0.0001	-0.014970	-0.000343	-0.000055	0.000002
LAM	2.6343	0.0079	-0.0058	0.0108	-0.001068	0.000207	-0.000575	-0.000724

Table 3. Regional parameters of the biomass functions and changes in temperature and precipitation in 2100 under RCP4.5 and RCP8.5

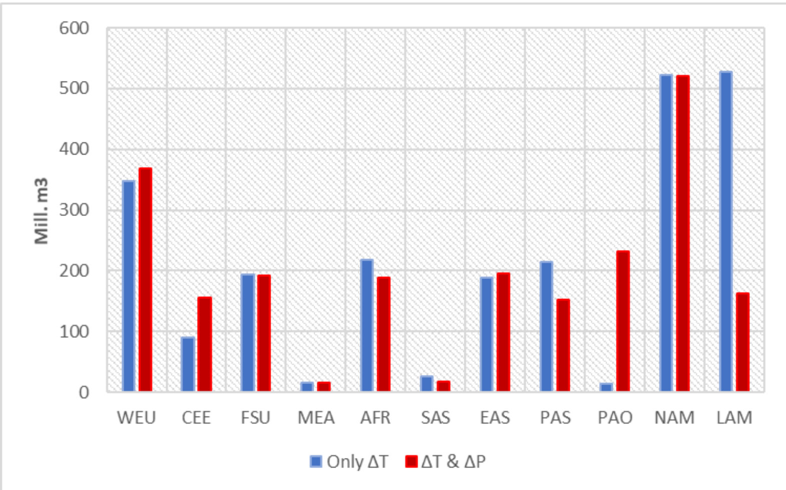

Figure 5. Estimated growth under RCP4.5 in 2100 by region, with impact functions based on change in temperature only and change in temperature and precipitation

The alternatives show the economic impacts of climatic change in RCP2.6, RCP4.5 and RCP8.5 in 2100, using the impact functions based on the change in temperature only and the impact functions based on the combination of changes in temperature and precipitation. Table 4 shows the changes in temperature and precipitation in 2100 under the different RCPs, which are taken from ISIMIP.

4 Economic consequences

The impacts on quantities, prices and values of harvested forests and on products delivered by the forestry sectors in each region are shown in the six tables in the Appendix. As for the estimated direct economic losses displayed in Figure 4, it is difficult to draw general conclusion for the impacts when expected adaptation in the management of forests and market effects are included. Again, the Asian regions turn out on the extremes, however. From table 4, this may be explained by the expectations of cooling under moderate climate change and low increases in temperature under the strong climatic change in RCP8.5. This is subject for further examination, however, because our estimates are based on a survey of the physical impacts of climate change, which could not be related stringently to projections of the climate.

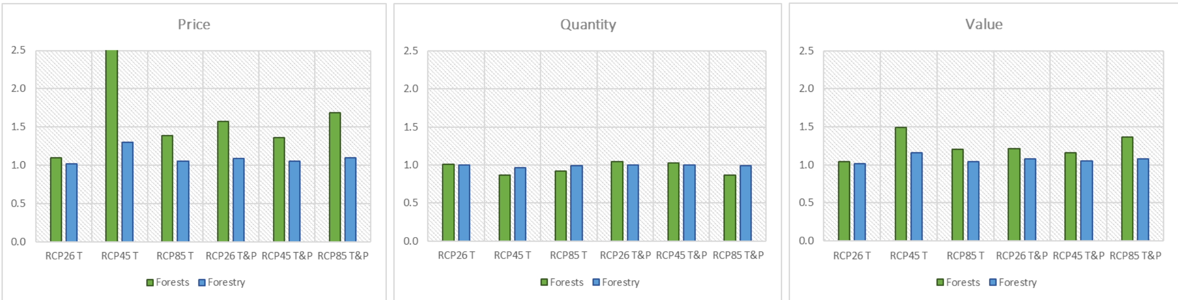

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Figure 6. Indexes for prices, quantities, and value (price*quantity) in extracted forests and the forestry sector by region under RCP2.6, RCP4.5 and RCP8.5, estimated based on changes in only temperature and on changes in both temperature and precipitation in 2100. Baseline = 1.0.

Figure 6 shows the impacts on prices, quantities, and values on the averages in the different alternatives addressed here. The impacts on the quantities are affected rather moderately, and with relatively small differences across the RCPs. Increasing climatic changes also increase the reductions in the quantities of forests, except if calculated based on changes in temperature only, when the reduction in the global average of quantities is reduced from RCP4.5 to RCP8.5. For the forestry sector, the impacts on the quantities are smaller, in general, where the global impact under RCP4.5 is a reduction of 4 percent.

The impacts on global average prices are much stronger, and more sensitive to the underlying climatic changes and to the choice of estimates. Climate change implies an increase in prices with use of both estimates, and regardless of RCP. The increase turns out very high under RCP4.5, if based only on changes in temperature. By including the changes in precipitation, the impacts on the global price is reduced significantly. For the two other RCPs, the impacts on the shadow prices on extracted forest are notably higher when the estimates are based on changes in both temperature and precipitation than when based only on changes in temperature.

As for the quantities, the prices of products in the forestry sector are much less affected than the forests themselves. In terms of economic value, the forestry sector is 15 times larger than the forests, however. In absolute terms, the economic impact on the forestry sector therefore dominates. For forests, the impact ranges between 1.20 and 8.02 bill US$, depending on RCP and use of climate indicators. For the forestry sector the corresponding figures are between 229 and 65.43 bill. US$. The total impacts on the quantities in forests and in the forestry-sector are negative in all cases, except under RCP2.6 when only temperature is referred to, the impacts on value are positive for all cases.

Table 4 compares the impacts under the different RCPs for the world, estimated with the different approaches and with focus on the two different forest-related economic sectors examined in this report. While the physical impacts on forests on the global scale are negative in all RCPs, impacts estimated with the economic models are positive in all RCPs, but they differ considerably

	RCP2.6 (2100)		RCP4.5 (2100)		RCP8.5 (2100)	
	dT	dP	dT	dP	dT	dP
WEU	0.53	-10.03	1.83	-9.72	4.38	-12.18
CEE	0.53	-10.03	1.83	-9.72	4.38	-12.18
FSU	2.29	5.59	4.17	8.09	8.14	14.43
MEA	0.79	-7.97	2.07	-11.46	5.02	-17.72
AFR	-0.06	-14.97	1.36	-10.17	5.94	-5.83
SAS	-2.22	-17.62	-1.02	-12.59	1.40	-7.78
EAS	-0.74	9.77	0.71	13.44	3.80	17.15
PAS	-3.25	-35.10	-2.42	-25.55	-0.46	-18.35
PAO	0.32	-21.61	1.33	-18.02	3.74	-14.82
NAM	2.03	8.79	3.67	11.23	7.33	15.95
LAM	-3.20	1.23	-2.02	-2.27	0.43	-6.72

Table 4. Changes in temperature (dT) and precipitation (dP) from 2016 to 2100 under RCP2.6, RCP4.5 and RCP8.5

depending on method and on the specification of what is meant by “the impacts on forests”. The reason why the direct effects turns positive when considering the economic impacts is partly that forest managers adapt, and partly that prices increase when the supply of wood from forests and products from the forestry sector declines. This price effect is stronger than the effect on the quantities in all alternatives. The impact on values are, therefore, positive.

These are the global impacts. As it appears in tables A1 – A6 in the appendix, the impacts vary significantly across regions, in particular for forests. In general, the variations are particularly large regions in Asia (PAO, PAS, SAS). The increase in prices, which is the mostly affected variable, is also the variable that varies the most, depending on the alternative. An extreme example is the price increase in Pacific OECD countries (PAO) under RCP4.5 is ten times the initial price, when estimated on the basis of changes in temperature, only. If estimated on the basis of changes in both temperature and precipitation, the price is 1/3 of the initial price. The main lesson is, however, that the Asian regions are more sensitive to climatic changes than the other regions, according to this study. One apparent explanation is that forestry plays an important role in the economies in these regions and is important also in a global context. Secondly, the climatic changes, or more specifically the increases in temperature, are lower in these regions than in other regions, as it appears in Table 3.

5 Conclusions

This study aims at bridging results from assessments of the effects of climate change on forests to assessments of the economic consequences on a global scale. The point of departure is an assessment of the effects on forests in 27 countries, which contributes to nearly 75 percent of the total value of harvested forests in the world. The results are aggregated and divided into impacts on forests in 11 world regions and used in economic models to assess the adaptation among producers in the forestry sector. These models are integrated in a global computable general equilibrium model, GRACE, to address how the impacts on forests affect the forestry sector and penetrates further to the rest of the economies, in order derive the economic consequences on the world scale.

The underlying purpose of the study is to quantify economic impacts of climate change that are left out in most integrated assessment models, where the impacts of a change in temperature on the value added (gross domestic product) in the forestry sector is assumed fixed. The model used in this report was therefore run in a static mode, meaning that reported impacts of climate change on forests in 2100 under the three pathways RCP2.6, RCP4.5 and RCP8.5 are implemented in the economies of today, without any changes in the socioeconomic conditions in the future. These changes are expected to be taken care of when used in the integrated assessment models.

The impacts highlighted in this report can be divided into the physical effects, which are taken as the point of departure, the effects on the harvesting of wood, the impacts to the forestry sector and the economic consequences on the world economy. Except for the physical effects, the impacts can be divided into effects on quantities and effects on prices.

The physical effects in the 11 world regions in GRACE were estimated on the basis of the study of the 27 countries. They show that climate change limits the access to forests on the world scale as the climatic changes strengthen. There is an increase in some regions under the moderate changes in RCP2.6, however, and to some extent under RCP4.5. Under RCP8.5, the growth declines in most regions, meaning that the general picture is that stronger climatic changes implies a reduction in growth. There are exceptions, though, such as South Asia which loses a lot under RCP2.6, and less under RCP4.5 and RCP8.5.

A possible explanation to the rather diverse picture of the effects on forests in the different regions is that the state of forests depends on several climatic conditions, which will change differently under global warming. To show the implication of this, we assess the economic consequences based on two relationships between climate and forests. One refers to changes in temperature only, and the other to a combination of changes in temperature and precipitation.

The primary economic effects of climate change on forests can be divided into the impacts on the management of forests and the impacts on the output from the forestry sector. The first affects how the owners utilize the forests, e.g. by the intensity of harvesting in a given area. The second affects the delivery of products from the forestry sector.

The harvesting of forests increases by 1 percent on the world scale under RCP2.6, when changes refer to change in temperature, only. It declines by 13.1 percent under RCP4.5 and 8.1 percent in RCP8.5. Relating impacts on forests to changes in both temperature and precipitation gives a quite different picture. There is an increase at 4.6 percent under RCP2.6, which reduces to 2.9 percent in RCP4.5. In RCP8.5, the quantity of harvested forests declines by 13.3 percent.

The variations across regions are large, however, in particular if the impacts are explained only by changes in temperature. This is compensated by higher prices, however. The extreme case is Pacific OECD-countries, where the quantity of harvested forests declines by 88 percent under RCP4.5, while the price of extracted forests increases more than 10 times. The value of extracted forests in this region increases by 32 percent.

	RCP2.6	RCP4.5	RCP8.5
Direct	-1.760	-1.501	-2.477
Value of forests (dT)	1.20	12.84	3.99
(dT & DP)	7.54	5.20	8.02
Value of forestry (dT)	4.29	65.43	13.64
(dT & DP)	28.66	17.42	26.42

Table 5. Alternative estimates of impacts of climate change on all forest in the world under climatic changes in fifferent RCP in 2100. Bill. US$

The forestry sector is less affected. Quantities decline in all RCPs, and by 0.2 percent in RCP2.6 regardless of the choice of impact function. In RCP4.5, the quantity declines by 3.9 percent on the world scale, and by 0.2 percent under RCP8.5 if explained by changes in temperature, only. If explained by temperature and precipitation, the reductions are 0.2 in RCP4.5 and 1.3 percent in RCP8.5. These reductions are more than compensated by increases in prices. The value of the output from the forestry sectors increases in all alternatives, from 1.3 percent under RCP2.6 to 15.9 percent under RCP4.5 when referring only to changes in temperature. When referring to combinations of changes in temperature and precipitation, the increases vary between 5 percent in RCP4.5 to 8.1 percent in RCP8.5. Again, the variations across regions are notable, but far less than for the impacts on extracted wood from forests. When relating impacts to combinations of changes in temperature and precipitation, the value of the production in the forestry sector increases in all regions.

Table 5 sums up the main results on the global scale. The message is that all RCPs give negative direct effects of climate change on the growth of forests, which tend to be weaker under the "moderate" changes under RCP4.5 than under the low changes in RCP2.6. The largest negative effect appears under the strongest climatic changes in RCP8.5. Because of the price effects, the economic consequences turn the other way around, however. On the world scale, the wealth of forests increases in all RCPs, and mostly under moderate changes. This contribute an even larger increase in the value of products from the forestry sector.

There are large differences across regions, however, where the patterns may differ substantially from the global pattern. The table also illustrates the importance of relating assessments of the impacts to adequate climate indicators. In this study, we compared impact functions based on temperature alone with functions based on combinations of temperature and precipitation.

Besides providing estimates of the economic consequences based as far as we can on physical assessments of the impacts, the study also reveals several knowledge gaps worth to fill to provide better estimates. Among the most important, we mention that the survey did not cover any countries in central and eastern Europe or in Africa south of Sahara. Other regions were rather sparsely covered. Moreover, the estimated impacts were based on studies of the effects on plantations only, which constitute a small part of the forestry sector in many countries. A better representation of commercial forests in the different regions would improve the assessment considerably. Another objective should be to better match the output from the physical assessments and the input in the economic assessment. In this study, the impacts on forested area reported in the survey are interpreted as effects to the density of forests, which are needed for the economic assessment. Ideally, economic assessments need information on both density and area. We also assume that the cost of harvesting is independent on scale. Better information on the costs of harvesting would improve the assessments and help to make consistent distinctions between commercial and non-commercial forests. Finally, this study illustrates the importance of specifying climatic conditions that affect the forests by pointing out the differences between explaining the impacts from changes in temperature only and impacts from combinations of changes in temperature and precipitation. Most studies of the economic impacts of climate change on a global scale until now refer to changes in temperature only.

6 Appendix

Impacts on forests

	Baseline	Temperature only			Temperature and precipittion		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
WEU	2.945	3.067	4.050	4.123	2.754	3.111	4.208
CEE	0.898	0.934	1.443	1.247	0.561	0.683	1.276
FSU	1.213	1.219	1.853	1.353	1.289	1.259	1.391
MEA	0.396	0.407	0.497	0.461	0.457	0.458	0.470
AFR	2.000	1.990	2.976	3.495	3.469	2.905	3.552
SAS	3.391	4.743	7.104	3.023	9.191	6.894	4.868
EAS	5.007	4.937	6.745	5.518	5.058	4.984	5.665
PAS	2.163	1.266	1.969	2.049	2.510	2.295	2.150
PAO	1.052	1.064	1.320	1.230	0.583	0.506	1.272
NAM	2.842	2.836	5.974	2.942	3.037	2.912	3.045
LAM	1.726	2.367	2.542	2.182	2.265	2.829	3.757

Table A1. Value of harvested forests under climatic changes in 2100 under RCP2.6, RCP4.5, with impacts explained by change in temperature only and changes in temperature and precipitation. Bill US$ (2014)

	Baseline	Temperature only			Temperature and precipittion		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
WEU	1.000	1.067	1.502	1.733	0.865	1.087	1.766
CEE	1.000	1.066	2.076	1.718	0.397	0.567	1.758
FSU	1.000	1.008	1.535	1.126	1.080	1.050	1.158
MEA	1.000	1.044	1.306	1.267	1.263	1.277	1.295
AFR	1.000	0.989	1.741	2.777	2.698	1.967	2.823
SAS	1.000	1.828	3.401	0.802	6.102	3.530	1.848
EAS	1.000	0.980	1.356	1.140	0.960	0.963	1.171
PAS	1.000	0.366	0.625	0.868	1.103	1.024	0.911
PAO	1.000	1.021	10.333	1.308	0.295	0.243	1.354
NAM	1.000	0.994	2.083	1.014	1.067	1.017	1.049
LAM	1.000	1.691	1.708	1.461	1.482	2.221	3.460

Table A2. Price indexes for harvested forests under climatic changes in 2100 under RCP2.6, RCP4.5, with impacts explained by change in temperature only and changes in temperature and precipitation.

	Baseline	Temperature only			Temperature and precipittion		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
WEU	2.945	2.873	2.697	2.379	3.183	2.861	2.383
CEE	0.898	0.876	0.695	0.726	1.413	1.205	0.726
FSU	1.213	1.210	1.207	1.202	1.193	1.199	1.201
MEA	0.396	0.390	0.381	0.364	0.362	0.359	0.363
AFR	2.000	2.012	1.709	1.258	1.286	1.477	1.258
SAS	3.391	2.596	2.089	3.770	1.506	1.953	2.635
EAS	5.007	5.040	4.973	4.839	5.269	5.177	4.837
PAS	2.163	3.454	3.150	2.360	2.275	2.240	2.361
PAO	1.052	1.042	0.128	0.940	1.975	2.087	0.940
NAM	2.842	2.854	2.869	2.901	2.845	2.862	2.904
LAM	1.726	1.400	1.488	1.494	1.529	1.274	1.086

Table A3. Volumes of harvested forests under climatic changes in 2100 under RCP2.6, RCP4.5, with impacts explained by change in temperature only and changes in temperature and precipitation. Bill. US$

Impacts on the forestry sector

	Baseline	Temperature only			Temperature and precipittion		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
WEU	43.84	44.21	50.40	47.21	44.28	44.45	47.88
CEE	13.43	13.52	15.25	14.32	13.75	13.79	14.51
FSU	17.94	17.96	21.98	18.81	18.32	18.16	19.05
MEA	5.88	5.93	6.66	6.12	6.08	6.05	6.21
AFR	28.86	28.88	32.99	31.17	31.31	30.12	31.47
SAS	47.32	49.27	57.27	47.40	60.49	54.33	50.60
EAS	71.56	71.30	82.31	73.71	73.86	72.65	74.65
PAS	30.50	30.82	38.32	31.40	34.89	32.52	32.41
PAO	16.19	16.20	12.27	16.53	17.57	16.94	16.83
NAM	45.26	45.32	65.03	46.41	46.64	45.92	47.16
LAM	25.24	26.89	28.96	26.56	27.46	28.49	31.64

Table A1. Value products delivered from the forestry sector under climatic changes in 2100 under RCP2.6, RCP4.5, with impacts explained by change in temperature only and changes in temperature and precipitation. Bill US$ (2014)

	Baseline	Temperature only			Temperature and precipittion		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
WEU	1.000	1.011	1.139	1.104	0.998	1.016	1.117
CEE	1.000	1.009	1.167	1.097	0.970	0.984	1.108
FSU	1.000	1.001	1.122	1.027	1.014	1.008	1.034
MEA	1.000	1.008	1.114	1.045	1.039	1.036	1.058
AFR	1.000	1.000	1.139	1.172	1.169	1.092	1.181
SAS	1.000	1.077	1.283	0.990	1.525	1.256	1.096
EAS	1.000	0.997	1.079	1.022	1.009	1.003	1.029
PAS	1.000	0.975	1.175	1.015	1.112	1.050	1.042
PAO	1.000	1.002	2.641	1.035	1.009	0.980	1.050
NAM	1.000	1.000	1.304	1.014	1.020	1.009	1.025
LAM	1.000	1.089	1.138	1.064	1.087	1.164	1.329

Table A2. Price indexes for products delivered from the forestry sector under climatic changes in 2100 under RCP2.6, RCP4.5, with impacts explained by change in temperature only and changes in temperature and precipitation

	Baseline	Temperature only			Temperature and precipittion		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
WEU	43.8	43.7	44.2	42.8	44.4	43.8	42.9
CEE	13.4	13.4	13.1	13.1	14.2	14.0	13.1
FSU	17.9	17.9	19.6	18.3	18.1	18.0	18.4
MEA	5.9	5.9	6.0	5.9	5.8	5.8	5.9
AFR	28.9	28.9	29.0	26.6	26.8	27.6	26.6
SAS	47.3	45.8	44.7	47.9	39.7	43.3	46.2
EAS	71.6	71.5	76.3	72.1	73.2	72.4	72.6
PAS	30.5	31.6	32.6	30.9	31.4	31.0	31.1
PAO	16.2	16.2	4.6	16.0	17.4	17.3	16.0
NAM	45.3	45.3	49.9	45.8	45.7	45.5	46.0
LAM	25.2	24.7	25.4	25.0	25.3	24.5	23.8

Table A3. Volumes of products delivered from the forestry sectors under climatic changes in 2100 under RCP2.6, RCP4.5, with impacts explained by change in temperature only and changes in temperature and precipitation. Bill. US$.

Corrections of data provided by Duke

The study from Duke includes Saudi Arabia and Singapore. Due to a lack of information on some core variables, the two countries were excluded from this study.

The data for India have been corrected because of apparent errors in India C&P-region. We use RCP4.5, which seems to be correct, as reference for the development to 2100, and apply the same relative differences for area and growth in C&P as in the D&Tro&Temp zones.

China is divided in four regions, but the data for C&P zones are lacking. We therefore use the totals from the summary file from Duke on planted forests.

The data used for change temperature refers to temperature in 2016, which was an extaordnary hot year. The projections therefore give a relatively low increase in all RCPs. To adjust for this, we added 0.6 °C to the temperature increase in all RCPs.

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