Lessons from COVID-19 for managing transboundary climate risks and building resilience

Andrew K. Ringsmuth [a,b,*], Ilona M. Otto [a,c], Bart van den Hurk [d], Glada Lahn [o],
Christopher P.O. Reyer [c], Timothy R. Carter [i], Piotr Magnuszewski [j,k],
Irene Monasterolo [q], Jeroen C.J.H. Aerts [e], Magnus Benzie [f,g], Emanuele Campiglio [h],
Stefan Fronzek [i], Franziska Gaupp [c,j], Lukasz Jarzabek [k], Richard J.T. Klein [l,m],
Hanne Knaepen [n], Reinhard Mechler [p], Jaroslav Mysiak [r], Jana Sillmann [s],
Dana Stuparu [d], Chris West [t]

[a] Wegener Center for Climate and Global Change, University of Graz, Brandhofgasse 5, 8010 Graz, Austria
[b] Complexity Science Hub Vienna, Josefstädter Straße 39, 1080 Vienna, Austria
[c] Potsdam Institute for Climate Change Research (PIK), Member of the Leibniz Association, Telegrafenberg, P.O. Box 601203, 14412 Potsdam, Germany
[d] Deltares, Delft, The Netherlands
[e] Institute for Environmental Studies (IVM), VU University Amsterdam, De Boelelaan 1081, 1087JK Amsterdam, The Netherlands
[f] Stockholm Environment Institute, Linnégatan 87D, 115 23 Stockholm, Sweden
[g] Department of Social Sciences, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands
[h] University of Bologna, Piazza Scaravilli 2, Bologna 40126, Italy, RFF-CMCC European Institute on Economics and the Environment (EIEE), Centro Euro-Mediterraneo sui Cambiamenti Climatici, Via Bergognone, 34, Milano 20144, Italy
[i] Finnish Environment Institute (SYKE), Latokartanonkaari 11, 00790 Helsinki, Finland
[j] International Institute for Applied Systems Analysis (IIASA), Schloßplatz 1, 2361 Laxenburg, Austria
[k] Centre for Systems Solutions, Jaracza 80b/10, 50-305 Wroclaw, Poland
[l] Stockholm Environment Institute, P.O. Box 200818, 53138 Bonn, Germany
[m] Linköping University, Centre for Climate Science and Policy Research, 581 83 Linköping, Sweden
[n] European Centre for Development Policy Management, Maastricht, The Netherlands
[o] Chatham House (the Royal Institute of International Affairs), London, United Kingdom
[p] International Institute for Advanced System Analysis, Vienna, Austria
[q] EDHEC Business School, EDHE-Risk Institute, Nice, France
[r] Euro-Mediterranean Centre on Climate Change and University Ca' Foscari Venice, Via della Libertà 12, 30175 Venice, Italy
[s] Center for International Climate Research (CICERO), Pb. 1129 Blindern, 0318 Oslo, Norway
[t] Stockholm Environment Institute York, Department of Environment and Geography, University of York, YO10 5NG, United Kingdom

ARTICLE INFO

ABSTRACT

COVID-19 has revealed how challenging it is to manage global, systemic and compounding crises. Like COVID-19, climate change impacts, and maladaptive responses to them, have potential to disrupt societies at multiple scales via networks of trade, finance, mobility and communication, and to impact hardest on the most vulnerable. However, these complex systems can also facilitate resilience if managed effectively. This review aims to distil lessons related to the transboundary management of systemic risks from the COVID-19 experience, to inform climate change policy and resilience building. Evidence from diverse fields is synthesised to illustrate the nature of systemic risks and our evolving understanding of resilience. We describe research methods that

* Corresponding author.

aim to capture systemic complexity to inform better management practices and increase resilience to crises. Finally, we recommend specific, practical actions for improving transboundary climate risk management and resilience building. These include mapping the direct, cross-border and cross-sectoral impacts of potential climate extremes, adopting adaptive risk management strategies that embrace heterogenous decision-making and uncertainty, and taking a broader approach to resilience which elevates human wellbeing, including societal and ecological resilience.

1. Introduction

The cascade of impacts set in motion by the COVID-19 pandemic has raised concerns about the resilience of our interconnected world against major shocks and pressures that are foreseeable but uncertain in timing and effects (Gössling et al., 2021). Health risks, lockdowns, economic shocks and public recovery packages have shifted societal priorities, perceptions of risk, and the nature of planning. Societies have quickly adapted and developed new norms, such as mask-wearing and working from home, although different levels of adaptive capacity have affected impacts and costs across the globe. The crisis shows that when governments, businesses and communities are taken by surprise, they can sacrifice and adapt at speed. However, the measures taken tend to focus on the economy at national and local levels, over the short term. Cross-border and long-term impacts on health, job security, wellbeing, the environment, and social equality are often overlooked and may actually be exacerbated by short-term crisis management. The pandemic fallout shows a need for greater multilateral and regional attention to resilience, particularly in trade, fiscal policies, evidence-based communication and social safety nets. This context is a useful new starting point when planning for future crises, pandemic or otherwise.

Like COVID-19, climate change impacts, and maladaptive responses to them, have potential to disrupt societies at multiple scales via networks of trade, finance, mobility and communication, and to impact vulnerable groups most heavily. The handling of the pandemic adds to evidence that the world is ill-prepared for accelerating and interconnected societal and environmental risks induced by climate change (Manzanedo and Manning, 2020). It has also shown that disruptions that may cascade across geographical and political boundaries need risk management strategies that treat the world as a complex adaptive system. Understanding where and how to intervene in the system to best reduce potentially cascading impacts is becoming an essential part of resilience planning.

This paper aims to distil lessons related to the transboundary management of systemic risks from the COVID-19 experience, to inform climate change policy and resilience building. In Section 2, we take stock of the pandemic's transboundary impacts on health, economies, sociopolitical trends and the natural environment. Section 3 discusses how the high level of connectivity in our global systems has influenced the pandemic and what this implies for climate risk management. Section 4 summarises current theory of systemic resilience and how it depends on network properties including connectivity. Section 5 analyses what the successes and shortcomings of responses to the pandemic can teach us about building resilience. In Section 6, we survey research methods that can capture systemic complexity adequately to inform effective management and crisis preparedness. Finally, in Section 7 we synthesise our findings to recommend specific, practical actions for improving transboundary climate risk management and resilience building.

2. Transboundary impacts of COVID-19

In the two years since its first detection in Wuhan, China, in December 2019, COVID-19 has spread to all but a few countries (Dong et al., 2021; Hubbard, 2021), with over 272 million infections and over 5.3 million deaths reported worldwide (Dong et al., 2021). For many patients, the health impacts have continued after the acute phase as 'long COVID', with more than half reporting one or more persistent symptoms within the first six months after diagnosis and ~37% at least one symptom between three and six months after (Taquet et al., 2021). Beyond the direct effects of infection, COVID-19 has disrupted public health by demanding healthcare resources that have become unavailable for other health issues (Chudasama et al., 2020; Masroor, 2020), impacting healthcare workers' physical and mental wellbeing (Shaukat et al., 2020), raising public avoidance of healthcare services (Baugh et al., 2021; Hartnett et al., 2020), increasing risks to immunosuppressed (Al-Quteimat and Amer, 2020) and elderly (Banerjee, 2020) patients, and inflating other health risks due to the physical inactivity (Pinto et al., 2020; Crisafulli and Pagliaro, 2020; Sallis et al., 2021) and mental stressors (Pancani et al., 2021; Pieh et al., 2021) associated with measures such as lockdowns and social distancing. Despite the rapid development of effective vaccines (USCDC, 2021) and administration of over 8.5 billion doses globally (Dong et al., 2021), infection rates remain high (Dong et al., 2021). New viral variants continue to emerge, some with the potential to circumvent previously effective control measures and present unpredictable new challenges at all scales from individual to global. Perceptions of uncertainty at various stages of the pandemic, and responses to them, such as panic buying, have amplified impacts throughout the system (Szczygielski et al., 2021).

The pandemic has shown that most communities are able and willing to respond drastically to crises during the period when they perceive a high level of threat and are supported by institutions in collective action to reduce the threat (Botzen et al., 2021). Together, governments have announced stimulus spending of an unprecedented $17.2 trillion (Vivid Economics & F4B, 2021). Foreign aid rose to its highest level ever in 2020, with donors providing more emergency funds for developing countries suffering from the crisis. However, this barely compensated for losses; in the same year, total external private finance to developing countries fell by 13% and trade volumes declined by 8.5% (OECD, 2021). Debt levels relative to GDP, particularly in those countries facing the double hit of

lockdown and declining export revenues, have risen (Adam et al., 2020). Labour markets have been disrupted on an unprecedented scale - with losses of $3.7 trillion in income (before any benefits) globally in 2020, the equivalent of around 255 million full-time jobs (International Labour Organization, 2021). Forecasts of prolonged economic downturns and the prospect of rising public debts have the potential to trigger new sovereign debt crises, in both developing and industrialised countries (Dunz et al., 2021).

The COVID-19 experience has also added (Sachs, 2020) to the evidence that socioeconomic inequalities tend to erode resilience against multiple shocks (Hart et al., 2016; Pickett and Wilkinson, 2010). Three countries - the United States, Brazil, and Mexico - account for one third (32%) of the world's reported COVID-19 deaths (Dong et al., 2021) although they contain only 8.6% of the global population (2021). These countries also have very high levels of income and wealth inequality (Sachs, 2020; Roser and Ortiz-Ospina, 2013). Although a systematic analysis of this correlation is needed, it is consistent with prior evidence that economic inequalities can strongly influence societies' resilience to shocks and crises (Hart et al., 2016; Pickett and Wilkinson, 2010). At the global level, unequal vaccine access due to hoarding by rich countries leaves the poorest, most vulnerable nations to bear the brunt of the pandemic while also promoting continued viral evolution and emergence of dangerous mutant strains, thereby prolonging risks to all nations (Asundi et al., 2021; Amaro, 2021; Ritchie et al., 2021). While the pandemic has hit the most vulnerable groups hardest (International Labour Organization, 2021; Kharas, 2020; Lenhardt, 2020; Chi, 2021), the rich have not been immune to its effects. The wealth of the world's top 1000 billionaires decreased by almost 30% in the early months of the pandemic. However, their fortunes have proven more bouyant, taking just nine months to return to pre-pandemic heights (Berkhout et al., 2021). While it is too early to gather conclusive evidence, international experts warn that global inequalities are expected to further increase as a result of the pandemic, including capital, income, gender, political and racial inequalities (Ferreira, 2021). Most national governments so far have no plans in place to resolve these inequalities. Instead, business continuation has been the main priority in societal recovery plans (Berkhout et al., 2021).

The pandemic has also raised awareness of the extent to which economic health, as measured by conventional metrics, depends on increasing product consumption, mobility and pollutant emissions. Simultaneously, it has shown the potential for demand-side actions to mitigate a broad range of environmental impacts and reduce global CO_2 emissions at a rate approaching the 7.6% per year now required to prevent average global warming of more than 1.5 °C, in line with the Paris Agreement (Tollefson, 2021). Total global emissions in 2020 are estimated to have fallen by 5.8% relative to the 2019 level (IEA, 2021), with a global reduction of 8.8% during the first half of the year (Liu et al., 2020). This correlated with a 4% reduction in energy consumption, 50% of which came from the transport sector (IEA, 2021). The average peak of daily reductions across individual countries was as high as 26% (Le Quéré et al., 2020). These reductions were larger than during previous economic downturns and World War 2 (Liu et al., 2020; Ritchie and Roser, 2020), and were accompanied by other environmental benefits such as large reductions in other air pollutants, water pollution, noise pollution and reduced human encroachment into wildlife habitats (Kumar et al., 2020; Arora et al., 2020). However, emissions are now projected to increase by 4.9% in 2021 (Friedlingstein et al., 2021), returning almost to pre-pandemic levels, driven by economic recoveries in a few advanced economies while the developing world continues to struggle under the pandemic (World Bank, 2021). Adverse effects of the resulting overheating of rich economies, such as increased fuel prices, are further adding to the burden on the poor (McHugh et al., 2021). We discuss implications of these findings for building climate resilience in Section 4.

The abatement of environmental damage due to the pandemic was in part caused by pervasive behavioural changes. These included a large reduction in air travel (accompanied by a widespread switch to online conferencing) (Jack and Glover, 2021; Puttaiah et al., 2020), reduced overall personal mobility, increased use of active transportation modes like walking and cycling (Borkowski et al., 2021; Kim, 2021), and reduced discretionary spending (Puttaiah et al., 2020). Despite the pandemic's many negative impacts on citizens, societal responses have also brought benefits to some, such as fewer road crashes and health benefits from cleaner air and increased exercise by those using more active transportation (Kim, 2021). These widely appreciated upsides of the difficult COVID-19 experience have motivated public investments in, for example, cycling infrastructure upgrades (Frost, 2021; Puttaiah et al., 2020), and inspired calls for a persistent shift to online conferencing (Jack and Glover, 2021). Notably, the conditions that enabled these silver linings were created by strong regulations that affected everyone more or less equally. They did not allow exceptions based on, for example, a market in tradeable permits to violate lockdown rules, which may have helped to preserve the status quo and reinforce inequalities (e.g. online conference attendance may be disadvantageous if others, who can afford to, meet in person (Jack and Glover, 2021).

3. Complexity of systemic risks in a connected world

A complex system comprises many components whose interactions, with each other and their environment, give rise to 'emergent' system properties that cannot be deduced from the components' properties alone (Thurner et al., 2018). The climate, societies and economies are quintessential complex systems with networked interactions from local to global scales. The interconnectedness of these systems provides some measures and mechanisms for resilience to local crises: rapid spread of information, trade, regional and global security arrangements, and financial transfers can provide resilience to disruptions by enabling fast responses and fallback options. Examples include international assistance in cases of natural disaster, the ability to import food from alternative suppliers if one source cannot deliver, and international insurance markets (Altenberg, 2020). Trade (e.g. in medical equipment) helped to meet shortages during the COVID-19 crisis (Altenberg, 2020).

The same interconnectedness can, however, enable propagation of negative impacts from a crisis like COVID-19 between organisations, regions or sectors (Valdez et al., 2020; Liu et al., 2020). The virus' rapid spread was facilitated by international trade and travel. The subsequent response, in the form of lockdowns and mobility restrictions, affected consumer demand, supply networks, company revenues, poverty levels and national economies, with impacts spreading through networks (Fig. 1), many of which were designed to maximise short-term profits and consumer choice rather than societal resilience (Kharrazi et al., 2020). For instance,

automated trading on international markets, just-in-time long-distance supply chains and globalised mass-tourism promote over-exploitation of resources (Myklebust, 2020; Gössling and Peeters, 2015) and concentrate market power in the hands of few, increasing vulnerability of the overall system (Klimek et al., 2015).

These challenges resulting from economic connectivity are aggravated by an unprecedented level of social connectivity, particularly through online social media. This has driven human collective behaviour into a regime that is significantly altered from the conditions of our evolutionary past, for which we may be maladapted. The functional consequences are emerging in real time as we struggle to understand and manage them without a developed scientific framework (Bak-Coleman et al., 2021). This emerging regime of social connectivity includes many benefits, such as rapid spread of evidence-based information, and transnational and trans-disciplinary collaborations. However, these are accompanied by harmful phenomena such as ideological echo chambers and polarisation, eroded trust in government, and rapid spread of fake news and misinformation that can undermine collective intelligence (Bak-Coleman et al., 2021). In the case of the COVID-19 pandemic, this has hindered public acceptance of evidence-based safety measures such as mask wearing, widespread testing and vaccination (Zarocostas, 2020; Roozenbeek et al., 2020). In the case of climate change, it has contributed to overrepresentation of climate contrarians, public confusion, political inaction, and stalled support for or rejection of mitigation policies (Bak-Coleman et al., 2021; Lamb et al., 2020; Treen et al., 2020).

The same combination of network connectivity, emergent collective behaviour, political responses, and social vulnerability has potential to spread and amplify climate change impacts. These will likely take diverse, more diffuse forms than COVID-19, although health issues and disease spread across borders may be among them. Indeed, although the current pandemic is not clearly attributable to climate change, its likelihood was elevated by large-scale human impingement on natural habitats, biodiversity loss and ecosystem degradation (Johnson et al., 2020; Shield, 2020), and possibly also by a climate change-driven increase in bat species[1] richness in southern China (Beyer et al., 2021). Some climate-driven disruptions of global socio-economic networks may arise from a single climatic event (Lenton et al., 2019). Others may emerge from multiple scattered, smaller events and their interactions with each other and other social-ecological dynamics (Raymond et al., 2020). For example, simultaneous crop losses due to droughts in key production regions can drive up global food prices, potentially triggering mass human displacement (UNFCCC, 2017) and unrest (Gaupp et al., 2020).[2] These in turn can influence politics in consumer and migrant-receiving regions. In such a case, pre-existing inequalities and lack of social safety nets in food importing countries would weaken the ability to cope and intensify the crisis.

Linked collections of climate change impacts should be understood as systemic risks (Aglietta and Espagne, 2016), which are characterised by the potential for cross-sectoral impacts to reverberate across geographical and political boundaries (Folke et al., 2011). They are likely to materialise as a result of cascading failures (Pescaroli and Alexander, 2015; Valdez et al., 2020) whereby impacts accumulate, impairing or triggering breakdown of entire systems (McGlade et al., 2019). Risks are greatest where there is strong interdependence between conditions that amplify risk (Willner et al., 2021), trigger secondary disasters (Jongman et al., 2014) and affect critical nodes such as infrastructure or major hubs of trade or finance (Mandel et al., 2021). A growing number of public and private financial institutions, including central banks, banks (Carlin et al., 2021), and insurance and asset managers (BlackRock, 2021), recognise that climate risks could affect their portfolios' performances and have destabilising effects on the international financial system. Accordingly, interest in and pressure to disclose, assess and respond to climate-related financial risks is growing (Smith, 2021). This could lead to positive or negative revaluation of entire asset classes due to 'physical risks' such as exposure to climatic hazards, or 'transition risks' such as decarbonization. Climate-related financial risks have been recognized by the European Commission (European Commission, 2018) and financial supervisors, including over 90 central banks and financial regulators that have joined the Network for Greening the Financial System (Elderson and Heemskerk, 2020; Basel Committee on Banking Supervision, 2021; NGFS, 2019). In terms of more general theoretical understanding, the dependence of systemic resilience on network properties including connectivity remains only partially characterised and is a subject of ongoing research (Liu et al., 2020; Kharrazi et al., 2020).

4. Systemic resilience and its dependence on network properties

Different fields of study define resilience in different ways and its meaning in relation to social-ecological systems has evolved in recent years. While it was initially conceptualised as the capacity to absorb disturbances and continue to function as before, it is now understood as the ability to cope with disturbances not just by withstanding and recovering from them but also through adaptive changes and, if necessary, transformation into a qualitatively different state (Walker, 2020). In this sense, resilience is a process rather than simply a property. For example, resilient coastal towns may at first withstand and recover from a single flooding event, then adapt to more frequent flooding due to sea level rise by raising the heights of sea walls, but eventually find it necessary to relocate to higher ground (Liu et al., 2020; Walker, 2020).

Studies of a wide range of systems have identified redundancy, diversity and modularity as key properties that contribute to systemic resilience (Kharrazi et al., 2020). Redundancy is the inclusion of replicated pathways, functions or components, which increases fault tolerance. Diversity may refer to the number of categorical types in a system (e.g. economic sectors), the distribution of

---

[1] Bats are the likely zoonotic origin of several coronaviruses, including that which causes COVID-19 (SARS-CoV-2). However, significant evolutionary gap between SARS-CoV-2 and the closest known animal viruses suggests decades of evolutionary divergence, and a more immediate animal reservoir for SARS-CoV-2 has not been identified (Beyer et al., 2021; Holmes et al., 2021).

[2] When discussing the effects of direct climate impacts such as drought, it is important to recognize the role of historical political governance and resource management dynamics, including failure of resilience and adaptation measures, in the shape and severity of ensuing human impacts and responses.

Interconnected cascading crises of COVID-19 and illustrative climate change impacts
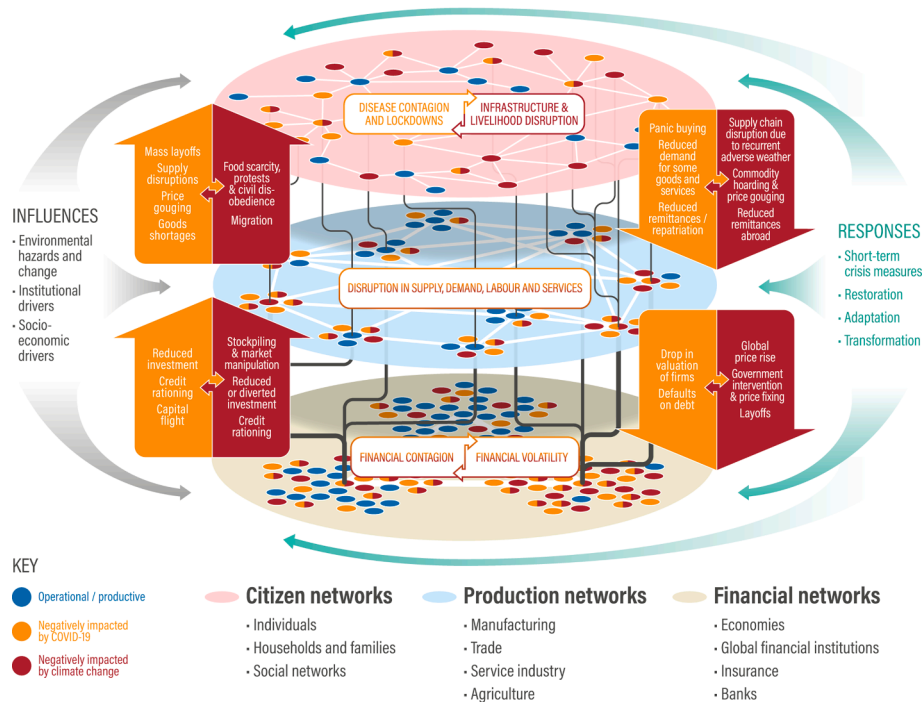

Fig. 1. Interconnected cascading crises of COVID-19 and examples of climate change impacts that illustrate parallels to, and interactions with, the pandemic. Impacts spread and interact within and between networks of citizens, production systems and financial systems, which are also subject to multiple influences and impact responses.

something across available categories (more even distribution means greater diversity), or the disparity between the categories themselves (larger differences means more diversity). Diversity can enable more flexible responses to system shocks. Modularity is the extent to which a network's structure is partitioned into modules (or communities) in which node connections are much stronger than connections between nodes in different modules. More modular systems are better able to contain stresses or contagions within modules, thereby protecting the rest of the system. While redundancy, diversity and modularity are known to individually contribute to systemic resilience in some cases, less is known about how tradeoffs between them, and scaling effects, may affect resilience; these are important subjects for future work (Ringsmuth et al., 2019; Kharrazi et al., 2020).

5. Building resilience to systemic crises

COVID-19 has revealed how challenging it is to manage systemic and compounding crises. Institutional mechanisms were not aligned, national and global disaster risk reduction networks were not prepared, and access to reliable and verifiable data were, at least initially, poorly facilitated (Mechler et al., 2020). Although civil society organisations have been able to mobilise their constituencies to monitor systemic and compound risk (Shaw et al., 2020), this has only partially addressed the gaps left by the state. Similarly, responsibilities within many current governmental structures to identify, track and build resilience to climate risks, which are still often treated as external risks (Benzie and Persson, 2019), are unclear. Effective risk management requires a clear and endorsed 'ownership' of the risk (Young and Jones, 2018; Young and Jones, 2017): an organisational unit that takes responsibility to implement risk mitigation measures. For complex and systemic risks with multiple drivers and stakeholders – such as COVID-19 or climate change – this is challenging. It requires the development of resilience measures that include incentives to enable networks of government, market actors and civil society to co-generate timely, flexible, and actionable solutions (e.g. cost/benefit standards that factor in future generations' costs and benefits). In practical economic terms, resilience can be framed as a "portfolio of dividends": a collection of risk management options and investments which work across different sectors, regions, generations, etc. to minimise overall risk (Mechler and Hochrainer-Stigler, 2019). In this portfolio, we can increase the overall resilience of the global system by spreading investments and targeting the most vulnerable subsystems. These procurements should reduce nations' risks related to the economic, ecological and/or political fragility in countries that supply essentials such as energy, raw materials, labour or food.

The pandemic has shown the importance of impact monitoring and openly sharing data across boundaries for building resilience. This enables faster detection, earlier notification to others, and more informed management of cascading impacts. It also allows experts

around the world to research challenges that arise, analyse associated risks, and share their findings for collective benefit. For example, surveillance systems detected clusters of pneumonia cases as early as December 2019 and the novel coronavirus genome sequence was released by mid January 2020, enabling a global research effort into tests, treatments and vaccines (European Commission, 2021). Researchers used online preprint servers to share research results more quickly than is usually possible through academic journals (Fraser et al., 2021; Taraborelli, 2020) (although the absence of peer review means that sharing results in this way requires safeguards against overinterpretation of preliminary findings, including careful communication and management of uncertainties). Despite these efforts, the International Panel for Pandemic Preparedness and Response concluded that the international alert system did not work fast enough (European Commission, 2021). The European Commission has since recommended that a new global surveillance system be put into place, with capabilities to share data at the earliest possible stage (European Commission, 2021). Investing in a similarly global system for monitoring climate impacts and openly sharing data across boundaries would enable better risk management and resilience across system levels. The practice of frequent 'event attribution studies' (Otto et al., 2018; van Oldenborgh et al., 2021), identifying the contribution of anthropogenic climate change to the intensity or probability of adverse weather events, is a potential contribution to such a climate impact monitoring system.

However, as also demonstrated by the pandemic, plans to respond to threats detected through monitoring do not amount to preparedness without dedicated resources. Many governments were forced to respond to COVID-19 with ad hoc, temporary measures because pandemic response preparedness was under-resourced (European Commission, 2021). This speaks to the importance of putting adequate resources in place for climate impact response preparedness. There have been a variety of initiatives, including from governments, civil society and multilateral institutions, to allocate resources in this direction, and to sustainability more broadly, by using the pandemic as an opportunity to 'reset' the global economy and spur 'green recovery'. These initiatives are based on the understanding that investments in resilience and growth areas such as transport infrastructure, circular economy, digital transformation (European Commission, 2020), and renewable energy will create jobs and prepare for future competitiveness by investing in and up-skilling the global population. Meaningful government and corporate action on this is currently impeded by the lack of sustainability impact criteria applied in the allocation of recovery funds. Only 10.6% of this public money is estimated to be earmarked for projects that help to reduce emissions or restore the natural environment (Vivid Economics & F4B, 2021). Much more is tabled for projects which would appear to stimulate consumption and emissions. For example, the EU funds have been criticised for at least partly preserving business as usual in some countries, rather than being deployed for transformational change to enable low-carbon economies (Climate Action Network Europe, 2021). To be sustainable, such investment would also have to be accompanied by far-reaching reforms in areas such as taxation, subsidy and environmental regulation (OECD, 2020).

Adoption of such policies at the scale and rate required for adequate climate action has been deliberately delayed (Lamb et al., 2020) and also hindered by misinformation about climate change, particularly through nontraditional, digital media (Treen et al., 2020). Recent research has found that lower susceptibility to misinformation about both COVID-19 and climate change is associated with higher risk perception, higher capacity to think deliberately and critically, a tendency to update prior beliefs based on new evidence, and higher trust in scientists and mass media (Roozenbeek et al., 2020; Gruener, 2021). There is also evidence that susceptibility to misinformation about one subject is correlated with susceptibility to misinformation about another subject (Gruener, 2021), so measures taken to counteract misinformation on one subject may also help to counteract it elsewhere. Such measures include educational approaches, 'inoculation', technological solutions, corrective and collaborative approaches, and regulation, although all are subject to criticisms and caveats (Treen et al., 2020).

The impacts of the pandemic on different countries and social groups have shown that a well-functioning social security and public health system can act as insurance against various types of future risks. Reducing economic and other social inequalities, and investing in systems that care for the most vulnerable in society, improves resilience to a wide spectrum of possible risks. For example, higher numbers of beds and staff in hospitals than are needed on average (or increased flexibility to quickly scale this capacity up and down) can greatly reduce the effects of unforeseeable crises and disasters. The need to support the costs of such public services further emphasises that changes in taxation and subsidy flows are likely needed. A higher contribution from the wealthiest and measures against tax havens and tax avoidance may be crucial. At the same time, it is now widely recognized that underlying health conditions including chronic lung diseases, heart conditions, cancer and obesity increase the chances of severe or fatal effects of the virus (USCDC, 2021). Given that these also remain the top causes of death globally, it would seem that a much more integrated approach to public health, with greater attention to prevention and well-being, would both increase societal resilience and reduce long-term costs.

Many already existing internationally agreed policy processes stress the need for enhancing resilience, including the Sustainable Development Goals (SDGs) (United Nations, 2021), the Paris Agreement (United Nations, 2015), and the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015). However, progress in interpretation, uptake and implementation of their various recommendations has thus far been slow and ineffective. It has been argued that if the SDGs, for example, had been fully embraced and implemented, the world would have been in a much better position to respond to the COVID-19 pandemic, which may have been less likely to occur in the first place (Ottersen and Engebretsen, 2020). Counterfactual speculation aside, crucial resilience-building may come from diagnosing and overcoming reasons behind the limited effectiveness of existing policy processes rather than developing entirely new ones.

On the other hand, a number of researchers have recently argued that the limited effectiveness of climate change mitigation efforts to date is due mainly to more fundamental sociometabolic dynamics[3] intrinsic to the global economic system, and therefore largely

---

[3] Stocks and flows of energy, matter and entropy that are needed to support societal functioning (Fischer-Kowalski and Haberl, 2015; Smil, 2008).

immune to policy that does not address these dynamics (Hagens, 2020; King, 2020; Leiva and Schramski, 2020; Garrett et al., 2020). Since the creation of the United Nations Framework Convention on Climate Change in 1992, annual global CO_2 emissions have risen every year during periods of GDP growth, except in 2015, when emissions fell by 0.08% (Ritchie and Roser, 2020), a relative reduction 73 times smaller than was achieved by economic restraint in 2020. Although the fraction of global primary energy supplied by renewable sources grew rapidly before the pandemic, fossil fuel consumption also grew over the same period (BP, 2020) such that global energy growth outpaced decarbonisation and emissions continued to climb (Jackson et al., 2018). That is, renewables have so far not displaced fossil fuels but rather only added to them (BP, 2020), to support the energetic demands of global economic growth.

Given that large and compounding emission reductions are now needed *immediately* to remain within an agreed safe carbon budget (IPCC, 2021), prospects for decoupling GDP from emissions at the scale and rate required are negligible (Haberl et al., 2020; Hagens, 2020; Hickel and Kallis, 2020; Ward et al., 2016). Serious commitment to climate risk reduction should therefore make us question whether returning to sustained GDP growth at the global level is a sound goal for pandemic recovery. Moreover, the possibility of an approaching decline in net energy yields from primary energy sources, whether fossil-fuelled or renewable, suggests that the world may soon face protracted energetic constraints to economic activity (Brockway et al., 2019; Capellán-Pérez et al., 2019; King and van den Bergh, 2018). This is another reason to consider alternatives to GDP growth as the prime objective and performance measure for economies.

A growing literature is now exploring options for so-called degrowth, which aims to promote human wellbeing and ecological resilience without requiring GDP growth (Hickel et al., 2021; Kallis, 2017; Keyßer and Lenzen, 2021; Wiedmann et al., 2020; Kallis, 2020). The experiences of the last few years, including COVID-19, may have shifted public understanding and opinion on these issues, especially in richer countries, which are best placed to lead with new policies. In a recent survey of people in G20 countries, 74% of respondents supported the idea that their country's economic priorities should move beyond profit and increasing wealth to focus more on human wellbeing and ecological protection (Gaffney et al., 2021). Overcoming the research-implementation gap remains a challenge, however. We do not yet know how degrowth policies could be adopted at scale or how they would interact with our current economic processes and patterns of behaviour. Nonetheless, our climate predicament demands openness to new approaches. To better understand the options, further research into basic relations between societal metabolism and social-ecological wellbeing is crucial (Haberl et al., 2019; Hagens, 2020; King, 2020; Leiva and Schramski, 2020; Schramski et al., 2015; West, 2018; Fischer-Kowalski and Haberl, 2015; Garrett et al., 2020; Giampietro et al., 2013; Ringsmuth et al., 2016). Although the many challenges and risks associated with a fundamental economic transition are formidable, arguably, they may be overcome on the time scale of a human life (decades).[4] Conversely, the risks associated with ever more radiative forcing as we avoid adequately reducing emissions include transitions of the Earth system to inhospitable states that may not be reversible on the time scales of civilisations (centuries to millennia) (Lenton et al., 2019; Steffen et al., 2018). The growing literature on tipping dynamics in socioeconomic systems may offer reasons for optimism about societies' potentials for a timely rise to the challenge of systemic transformation (Otto et al., 2020; Lenton, 2020).

6. Research methods for assessing and managing complex systemic risks

In order to build overall systemic resilience and preparedness for cascading impacts of climate change, we need to understand how they may affect systems and how systems can adapt. Existing conceptual frameworks lay the groundwork for such assessments by, for example, making it possible to distinguish between the initial impact of a climate trigger and its downstream consequences as the impact propagates through an impact transmission system (Carter et al., 2021). Simulating and visualising the risks and impacts of interventions can support policy actions to limit systemic risks and understand the dependencies on internal and external interactions.

A major challenge in managing the rapidly shifting climate risk landscape is the development of mental and formal models that adequately capture systemic complexity. Integrated Assessment Models (IAMs), either cost-benefit optimization models such as DICE-style IAMs (Nordhaus, 1992) or process-based simulation models (Kriegler et al., 2013; McCollum et al., 2018; Rogelj et al., 2019) have been used to inform climate policy and the Intergovernmental Panel on Climate Change (IPCC). They vary in terms of structure, assumptions and outcomes (Krey et al., 2019), such as the optimal cost of carbon, and climate mitigation trajectories compatible with 2 °C-aligned carbon budgets (Weyant, 2017). Despite their ubiquity, IAMs face several limitations for the analysis of complex and compound shocks that embed nonlinearity. IAM economic modules can range from partial to computable general equilibrium models. They embed representative agents with perfect foresight and forward-looking expectations (i.e. it is assumed that they know perfectly what will happen in the future), and solve to equilibrium (Balint et al., 2017; Mercure et al., 2016). Such models cannot capture nonlinear dynamics that emerge from interactions between heterogeneous agents who are subject to imperfect information and have adaptive expectations about the future, which amplifies the complexity of decision making and uncertainty over outcomes (Monasterolo, 2020; Arthur, 2021). IAMs have been criticised for neglecting agents' heterogeneity, which is important for modelling the complexity of societal transitions, and for over- or under-representing technological change (Keppo et al., 2021). Furthermore, IAMs do not embed finance and its complexity; there are no financial actors that decide whether to allocate capital based on risk assessment, which translates into financing costs for high or low-carbon investments (Battiston et al., 2021). Given the importance of these dynamics in the real world, it may be useful to complement or integrate IAMs with models such as dynamical systems/system dynamics models (Lade et al., 2022; Sterman, 2000), agent-based models (Andersson et al., 2021; Haer et al., 2020; Steinbacher et al., 2021), adaptive network models (Wunderling et al., 2021; Thurner et al., 2018), or Bayesian networks (Kaikkonen et al., 2021), that can more

---

[4] The collapse of the Soviet country bloc at the end of the 20th century is an example of a large-scale economic system transition that took place on this time scale.

fully accommodate the complexity of nonequilibrium, nonlinear, networked systems like societies, economies, ecosystems and Earth systems(Balint et al., 2017; Farmer et al., 2015). Moreover, incorporating alternative economic performance metrics into these models and considering degrowth scenarios can assist with understanding potential future pathways that have not usually been taken into account by integrated assessment modellers (Keyßer and Lenzen, 2021).

Policymakers and managers tend to use mental models that may have been valid when the risk landscape was more stable, leading to expectations that the world will change only incrementally and 'go back, more or less, to normal' soon after a shock such as the COVID-19 pandemic or an extreme weather event. Such models now diverge ever further from reality. Even if carbon emissions are reduced, atmospheric concentrations will continue to rise, and extreme climate events and sea level rise will stay with us for decades to come (IPCC, 2021)(). There is no longer a stable 'normal' climate on which to base planning decisions. Managers would therefore do well to adopt mental models in which climate risks cannot always be quantified, and extreme and cascading impacts are ever more likely (Shepherd et al., 2018). Such a change in mental models can be supported by interactive tools such as crisis simulators (Smith, 2004), serious games (Mochizuki et al., 2021; Solinska-Nowak et al., 2018), event storylines (Sillmann et al., 2021) or policy simulations (Duke and Geurts, 2004), in which managers are confronted with severe climate triggers leading to inter-connected, acute impacts and must respond to them. Outcomes from these processes, in the form of storylines and policy responses, can provide input for formal complex system models, which in turn produce results that help to build, in a process of iterative development, real-world adaptation pathways.

While crisis simulation can be an essential tool in building preparedness to shocks and resilience for the new normal, it is equally important to include a long-term perspective in the mental models of managers and policy makers. Policy simulation - also known as policy exercise - is an interactive, participatory method to develop strategic insight. This approach allows stakeholders to explore real policy issues, using design elements known from serious games to structure communication (Duke, 2011) as well as to include feedback that participants receive based on their decisions. Participants work with real world data and take roles that often represent their roles in the real-life system (Harvey et al., 2009). Simulation experience helps to understand how problems emerge in complex systems and where points of policy intervention may lie. They can explore possible strategies, or "pathways" for their specific internal group of actors embedded in a range of external scenarios (Zurek and Henrichs, 2007; OECD, 2006). Such scenarios can be drawn, for example, from Shared Socioeconomic Pathways (Riahi et al., 2017), event storylines rooted in historic events (Sillmann et al., 2021), or other global scenarios. Within these scenarios, stakeholders use their knowledge and available data in a deliberative manner to develop strategies that can lead them to responses that are consistent with desirable future developments, identifying challenges, seeking solutions, and negotiating trade-offs.

Policy simulations have been successfully used in multiple areas including systemic liquidity crises in banking (Gai et al., 2010), climate policy as a business opportunity for venture capital in Europe (Kasemir et al., 2000) and river floodplain management (Stefanska et al., 2011). The Cascading Climate Impacts (CCI) policy simulation (Jarzabek et al., 2020) was developed in 2020 to account for cascading effects and systemic interconnection[5]. It brings together stakeholders from different thematic areas: Trade, Supply & Value Chains; Security, Development, and Foreign Policy; and Business and Finance. The simulation is based on a storyline - a series of climate triggered events cascading across continents with final impacts on Europe. Although the objective is not to predict specific events, quite often the future that unfolds is quite close to proposed storylines - for example a Suez Canal blockade was part of the simulated series of events in April 2020, shortly before one happened in the real world.

7. Recommendations for improving transboundary climate risk management

Based on the lessons learned, we draw three recommendations from COVID-19 that are relevant to climate risk management.

First, acknowledge the systemic nature of climate change impacts. Most climate risk assessments and adaptation strategies focus on nations and sectors, addressing clearly identified risks, actors and options to reduce risk. However, the systemic, cross-sectoral and transboundary nature of many climate change drivers and impacts requires broad, systemic transformation and better preparation for the unavoidable impacts of climate change. Complex interactions and impact cascades will shape the overall risk profile. Actions to approach climate change as a systemic rather than a localised risk include:

1) Understanding and mapping the direct, cross-border and cross-sectoral impacts of potential climate extremes (including compound events) to guide effective risk mitigation strategies. Cross-sectoral model intercomparison projects such as the Intersectoral Impact Model Intercomparison Project (ISIMIP) (Frieler et al., 2017) and recent conceptual advances defining compound climatic events (Zscheischler et al., 2020) and cross-border impacts (Carter et al., 2021) provide the foundations for modelling and developing scenarios of plausible impact chains affecting key regions (e.g. reduced water availability, extreme temperatures and population increase) with local stakeholders to analyse regional risks (such as conflict dynamics and migration), and trans-regional impacts;

2) Redefining the goals of climate adaptation plans, including a wider definition of resilience and the targeted scope of these actions. For example, at the international level, these could include developing or sharpening legal or fiscal interventions that increase the resilience of global trade, finance, development cooperation and food security networks (such as EU regulations on corporate transparency, dedicated stress-tests and policy that directs sustainable international collaboration). At both the regional and national levels, they may look to increase the modularity of energy and food systems;

---

[5] Video material presenting the simulation is available at https://youtu.be/QBXHm1SVMQ4

3) Reorganising risk management procedures and institutions to establish responsibility for systemic risks. For example, exploring mandates for risk mitigation strategies at international and cross-sectoral levels, by designing appropriate risk contingency programs involving public and private institutions (Benzie and Persson, 2019).

Second, accept limitations to predictability of impacts, develop models that account adequately for systemic complexity, and adopt adaptive risk management strategies that embrace uncertainty. In a highly interconnected world, quantitatively analysing how systemic hazards propagate to societal impacts is a challenge. While probabilistic assessments of local and near-term climate-related impacts are generally feasible, the ability to map indirect and cascading effects of shocks proves to be limited. Nonetheless, there is potential for going beyond current models with methods that can more fully account for systemic complexity and incorporate alternative economic performance metrics. Furthermore, we need to develop adaptation strategies that accommodate heterogeneous decision makers working under uncertain conditions, to be able to adjust to new insights, developments and risk management options over time. For instance, the concept of 'dynamic adaptation policy pathways' (Haasnoot et al., 2013) is designed to incorporate deep uncertainty into decision making, by identifying short-term actions and a framework to guide future actions towards the desired goal, whilst allowing for adaptation over time to meet changing circumstances. Steps to adopt adaptive risk management strategies include:

1) Visualising dynamic and responsive pathways and storylines to anticipate unknown events and prioritise options and measures. For instance, digesting lessons learned from COVID-19 and other systemic crises into a representative set of cause-effect networks, or exploring potential evolution of historic shocks under possible future (climate) conditions (Sillmann et al., 2021);
2) Exploring adaptation strategies to unprecedented but plausible risk pathways for 'critical entities' (critical services, supplies and infrastructure (Haasnoot et al., 2020; European Commission, 2020). For example, co-developing adaptive risk strategies for selected services and institutions (such as urban water management or power supply).

Third, build resilience at multiple, interconnected levels. Resilience against system shocks is desired but difficult to achieve. A redefinition of strategic economic objectives can be helpful: from an efficiency-focussed paradigm towards a forward looking, multi-objective approach that takes into account social and intergenerational equity. Incentives for building resilience can be developed by:

1) Redefining performance metrics to have a long-term focus and target human wellbeing, including societal and ecological resilience. For example, understanding the multidisciplinary SDGs as performance indicators applicable to economies at different scales, including citizens, private business organisations, sectors and multi-level governments;
2) Redesigning international and national solidarity mechanisms that help to recover from shocks of various kinds. For instance, operationalising the Global Goal on Adaptation (United Nations, 2015) and ensuring international support and cooperation under the Paris Agreement to achieve just and systemic resilience to current and future climate change, including by building rapid crisis response capacity and making sufficient financial and political investments in societal resilience at all scales.
3) Establishing the study of human collective behaviour in the digital era as a 'crisis discipline'[6] tasked with developing methods for ethical stewardship (Bak-Coleman et al., 2021), particularly in the face of crises, even though a complete understanding of system dynamics is not available. Leveraging the benefits of global digital communication tools, while also effectively navigating and mitigating their pathologies, will be crucial to future risk and crisis management.
4) Jointly utilising COVID-19 recovery packages to meet the interconnected goals of fiscal and financial stability, societal resilience and environmental quality. For example, improving public health care systems and expanding investment in integrated public health with greater emphasis on disease prevention, social protection and labour laws, strengthening corporate tax policy and making fiscal measures that support carbon-intensive businesses conditional on alignment with international climate targets (Battiston et al., 2020).

8. Conclusions

This review has aimed to distil lessons related to the transboundary management of systemic risks from the COVID-19 experience, to inform climate change policy and resilience building. We have identified challenges that arise from highly interconnected and adaptive global systems. These include risks of transboundary cascades of both climate impacts and maladaptive responses to them (Raymond et al., 2020; Carter et al., 2021), as well as reduced response effectiveness due to pathologies in human collective behaviour, such as widespread digital misinformation and discourses of action delay (Bak-Coleman et al., 2021; Lamb et al., 2020; Treen et al., 2020). The massive stimulus spending so far announced (Vivid Economics & F4B, 2021) has the potential to contribute to a 'new normal' of increased climate resilience, but until now has strongly favoured the recovery of consumption and, accordingly, emissions (Vivid Economics & F4B, 2021). The large drop in emissions in the early months of the pandemic (Liu et al., 2020) demonstrated the potential for demand-side restraint to reduce emissions at the scale and rate now required for effective climate action (Tollefson, 2021). The rapid resumption of emissions along with rebounding economic growth following the lifting of lockdown restrictions calls

---

[6] 'Crisis disciplines' have been described as distinct from other fields of urgent, evidence-based research in their need to consider the degradation of an entire complex system without a complete description of the system's dynamics (Bak-Coleman et al., 2021). Examples include medicine, conservation biology and climate science. Such a discipline for the study of collective human behaviour would need to take a transdisciplinary approach, drawing on many established fields from within and also beyond the social sciences (Bak-Coleman et al., 2021).

into question the soundness of a return to global GDP growth as a goal for economic recovery (Hickel et al., 2021; Keyßer and Lenzen, 2021).

Social-ecological resilience building is essential to climate impact preparedness, and it is important to think of resilience as an adaptive and/or transformative process, rather than simply a capacity to persist (Liu et al., 2020; Walker, 2020). COVID-19 has shown the value of impact monitoring and open data sharing for building resilience, and there have since been calls to develop an integrated global monitoring system to guard more effectively against future pandemics (European Commission, 2021). A similarly global system for monitoring climate impacts and openly sharing data across boundaries would enable better climate risk management and resilience across levels. However, dedicated resources for responding to impacts detected through monitoring must also be put in place (European Commission, 2021). Developing strategies for ethical stewardship of human collective behaviour would further help to build climate impact resilience (Bak-Coleman et al., 2021), as would effectively diagnosing and overcoming reasons for the limited effectiveness of existing policy processes.

Effective risk management through clear and endorsed risk 'ownership' (Young and Jones, 2018; Young and Jones, 2017) is difficult for complex and systemic risks with multiple drivers and stakeholders, so resilience measures need to include incentives that enable diverse stakeholders to co-generate timely, flexible, and actionable solutions. Reducing economic and other social inequalities, and investing in systems that care for the most vulnerable groups, would also improve resilience to a wide spectrum of possible risks. Based on the pandemic experience, we recommend that decision makers must take into account the systemic nature of climate change impacts, adopt adaptive risk management strategies that embrace uncertainty, and implement a range of strategies for building resilience at multiple, interconnected system levels. The suite of transdisciplinary tools and methods reviewed here can support these endeavours.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

References

Adam, C., Henstridge, M., Lee, S., 2020. After the lockdown: macroeconomic adjustment to the COVID-19 pandemic in sub-Saharan Africa. Oxf Rev Econ Policy. Sep 28;36(Supplement_1):S338–58.

Aglietta, M., & Espagne, É. (2016). *Climate and finance systemic risks, more than an analogy?: the climate fragility hypothesis*. CEPII, Centre d'etudes prospectives et d'informations internationales. Available from: http://www.cepii.fr/PDF_PUB/wp/2016/wp2016-10.pdf.

Al-Quteimat, O.M., Amer, A.M., 2020. The Impact of the COVID-19 Pandemic on Cancer Patients. Am. J. Clin. Oncol. 43 (6), 452–455.

Altenberg, P., 2020. Improving economic resilience through trade. National Board of Trade Sweden., ISBN:978-91-88201-75-1

Amaro, S., 2021. WTO chief 'very concerned' about the unequal distribution of Covid vaccines. Available from: CNBC https://www.cnbc.com/2021/12/02/covid-vaccines-wto-chief-very-concerned-about-unequal-distribution-.html.

Andersson, D., Bratsberg, S., Ringsmuth, A.K., de Wijn, A.S., 2021. Dynamics of collective action to conserve a large common-pool resource. Sci. Rep. 11, 9208. https://doi.org/10.1038/s41598-021-87109-x. https://www.nature.com/articles/s41598-021-87109-x.

Arora, S., Bhaukhandi, K.D., Mishra, P.K., 2020. Coronavirus lockdown helped the environment to bounce back. Sci. Total Environ. 742, 140573.

Arthur, W.B., 2021. Foundations of complexity economics. Nat Rev Phys 3 (2), 136–145.

Asundi, A., O'Leary, C., Bhadelia, N., 2021. Global COVID-19 vaccine inequity: The scope, the impact, and the challenges. Cell Host Microbe 29 (7), 1036–1039.

Bak-Coleman, J.B., Alfano, M., Barfuss, W., Bergstrom, C.T., Centeno, M.A., Couzin, I.D., et al., 2021. Stewardship of global collective behavior. Proc. Natl. Acad. Sci. 118 (27), e2025764118.

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., Sapio, A., 2017. Complexity and the economics of climate change: a survey and a look forward. Ecol. Econ. 138, 252–265. https://doi.org/10.1016/j.ecolecon.2017.03.032.

Banerjee, D., 2020. The impact of Covid-19 pandemic on elderly mental health. Int J Geriatr Psychiatry 35 (12), 1466–1467.

Basel Committee on Banking Supervision. (2021). Climate-related financial risks: measurement methodologies. Bank for International Settlements. Available from: https://www.bis.org/bcbs/publ/d518.htm.

Battiston S, Billio M, Monasterolo I. Pandemics, Climate and Public Finance: How to Strengthen Socio-Economic Resilience across Policy Domains. In: A New World Post COVID-19. Venice: Fondazione Università Ca' Foscari; 2020. Accessed July 16, 2021. Available from: https://edizionicafoscari.unive.it/libri/978-88-6969-443-1/pandemics-climate-and-public-finance/.

Battiston, S., Monasterolo, I., Riahi, K., van Ruijven, B.J., 2021. Accounting for finance is key for climate mitigation pathways. Science 372 (6545), 918–920.

Baugh, J.J., White, B.A., McEvoy, D., Yun, B.J., Brown, D.F.M., Raja, A.S., et al., 2021. The cases not seen: Patterns of emergency department visits and procedures in the era of COVID-19. Am. J. Emerg. Med. 46, 476–481.

Benzie, M., Persson, Å., 2019. Governing borderless climate risks: moving beyond the territorial framing of adaptation. Int Environ Agreem Polit Law Econ 19 (4–5), 369–393.

Berkhout, E., Galasso, N., Rivero Morales, P.A., Taneja, A., Vazquez Pimental, D.A., 2021. The Inequality Virus: Bringing together a world torn apart by coronavirus through a fair, just and sustainable economy. Accessed August 23, 2021. Available from: Oxfam https://policy-practice.oxfam.org/resources/the-inequality-virus-bringing-together-a-world-torn-apart-by-coronavirus-throug-621149/.

Beyer, R.M., Manica, A., Mora, C., 2021. Shifts in global bat diversity suggest a possible role of climate change in the emergence of SARS-CoV-1 and SARS-CoV-2. Sci. Total Environ. 767, 145413.

BlackRock. (2021). Climate risk and the transition to a low-carbon economy. Available from: https://www.blackrock.com/corporate/literature/publication/blk-commentary-climate-risk-and-energy-transition.pdf.

Borkowski, P., Jażdżewska-Gutta, M., Szmelter-Jarosz, A., 2021. Lockdowned: Everyday mobility changes in response to COVID-19. J. Transp. Geogr. 90, 102906.

Botzen, W., Duijndam, S., van Beukering, P., 2021. Lessons for climate policy from behavioral biases towards COVID-19 and climate change risks. World Dev. 137, 105214.

BP (2020). Statistical review of world energy 2020. Available from: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf.

Brockway, P.E., Owen, A., Brand-Correa, L.I., Hardt, L., 2019. Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. Nat. Energy 4 (7), 612–621.

Capellán-Pérez, I., de Castro, C., Miguel González, L.J., 2019. Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies. Energy Strategy Rev 26, 100399.

Carlin, David, Peters, Glen, Sognnæs, Ida, 2021. Pathways to Paris: A practical guide to climate transition scenarios for financial professionals. UN Environment.

Carter, T.R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., et al., 2021. A conceptual framework for cross-border impacts of climate change. Glob Environ Change 69, 102307.

Chi, Y.-L., 2021. The Collateral Health Impacts of COVID-19: a Disproportionate Impact on Girls and Women. Available from: Center for Global Development https://www.cgdev.org/blog/collateral-health-impacts-covid-19-disproportionate-impact-girls-and-women.

Chudasama, Y.V., Gillies, C.L., Zaccardi, F., Coles, B., Davies, M.J., Seidu, S., et al., 2020. Impact of COVID-19 on routine care for chronic diseases: A global survey of views from healthcare professionals. Diabetes Metab Syndr Clin Res Rev 14 (5), 965–967.

Climate Action Network Europe. (2021). Rallying cry for climate friendly spending of EU funding: NGOs highlight good, bad and ugly measures in spending plans. Accessed Aug 23, 2021. Available from: https://caneurope.org/rallying-cry-for-climate-friendly-spending-of-eu-funding-ngos-highlight-good-bad-and-ugly-measures-in-spending-plans/.

Crisafulli, A., Pagliaro, P., 2020. Physical activity/inactivity and COVID-19. Eur J Prev Cardiol 19, 2047487320927597.

Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. Lancet Infect Dis; published online Feb 19, 2020. https://doi.org/10.1016/S1473-3099(20)30120-1. Accessed Dec 19, 2021 at: https://coronavirus.jhu.edu/map.html.

Duke, R.D., 2011. Origin and Evolution of Policy Simulation: A Personal Journey. Simul Gaming 42 (3), 342–358.

Duke, R.D., Geurts, J., 2004. Policy Games for Strategic Management. Dutch University Press.

Dunz, Nepomuk and Mazzocchetti, Andrea and Monasterolo, Irene and Hrast Essenfelder, Arthur and Raberto, Marco, Macroeconomic and Financial Impacts of Compounding Pandemics and Climate Risks (2021). Available at: https://ssrn.com/abstract=3827853 or https://doi.org/10.2139/ssrn.3827853.

Elderson, F., Heemskerk, I., 2020. Guide for Supervisors: Integrating climate-related and environmental risks into prudential supervision. Network for Greening the Financial System.

Esteban. (2021). 'Population'. Published online at OurWorldInData.org. Accessed August 23, 2021, Available from: https://ourworldindata.org/grapher/population.

European Commission. (2018). Action Plan: Financing Sustainable Growth. COM/2018/097 final. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0097.

European Commission. (2020). Proposal for a directive of the European Parliament and of the Council on the resilience of critical entities. COM(2020) 829 final. Available from: https://eur-lex.europa.eu/resource.html?uri=cellar:74d1acf7-3f94-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF.

European Commission, 2020. Shaping Europe's digital future. European Commission. https://doi.org/10.2759/091014. https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/shaping-europe-digital-future_en#documents.

European Commission. (2021). Drawing the early lessons from the COVID-19 pandemic. COM(2021) 380 final. Available from: https://ec.europa.eu/info/sites/default/files/communication150621.pdf.

Farmer, J.D., Hepburn, C., Mealy, P., Teytelboym, A., 2015. A third wave in the economics of climate change. Environ Resource Econ 62, 329–357. https://doi.org/10.1007/s10640-015-9965-2.

Ferreira, F.H.G., 2021. Inequality in the time of COVID-19. Available from: International Monetary Fund https://www.imf.org/external/pubs/ft/fandd/2021/06/inequality-and-covid-19-ferreira.htm.

Fischer-Kowalski, M., Haberl, H., 2015. Social metabolism: a metric for biophysical growth and degrowth. In: Martinez-Alier, J. (Ed.), Handbook of Ecological Economics. Edward Elgar Publishing, pp. 100–138.

Folke, C., Jansson, Å., Rockström, J., Olsson, P., Carpenter, S.R., Chapin, F.S., et al., 2011. Reconnecting to the Biosphere. Ambio 40 (7), 719.

Fraser, N., Brierley, L., Dey, G., Polka, J.K., Pálfy, M., Nanni, F., et al., 2021. The evolving role of preprints in the dissemination of COVID-19 research and their impact on the science communication landscape. Dirnagl U, editor PLOS Biol. Apr 2;19(4):e3000959.

Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Bakker, D.C.E., Hauck, J., et al., 2021. Global Carbon Budget 2021. Accessed December 20, 2021. Anthroposphere – Energy and Emissions https://essd.copernicus.org/preprints/essd-2021-386/.

Frieler, K., Lange, S., Piontek, F., Reyer, C.P.O., Schewe, J., Warszawski, L., et al., 2017. Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). Geosci. Model Dev. 10 (12), 4321–4345.

Frost, R., 2021. Paris is investing €250 million to become a 100% 'cycling city'. Available from: Euronews https://www.euronews.com/green/2021/10/25/paris-is-investing-250-million-to-become-a-100-cycling-city.

Gaffney O, Tcholak-Antitch Z, Boehm S, Barthel S, Hahn T, Jacobson L, et al. (2021). The global commons survey: Attitudes to planetary stewardship and transformation among G20 countries. The Global Commons Alliance. Available from: https://globalcommonsalliance.org/wp-content/uploads/2021/08/Global-Commons-G20-Survey-full-report.pdf.

Gai P, Haldane A, Kapadia S. Complexity, concentration and contagion. Carnegie-Rochester Conf Public Policy Norm Cent Bank Pract Light Credit Turmoi 12–13 Novemb 2010. 2011 Jul 1;58(5):453–70.

Garrett TJ, Grasselli M, Keen S. Past world economic production constrains current energy demands: Persistent scaling with implications for economic growth and climate change mitigation. Rahmani O, editor. PLOS ONE. 2020 Aug 27;15(8):e0237672.

Gaupp, F., Hall, J., Hochrainer-Stigler, S., Dadson, S., 2020. Changing risks of simultaneous global breadbasket failure. Nat. Clim. Change 10 (1), 54–57.

Giampietro, M., Mayumi, K., & Şorman, A. (2013). *Energy analysis for a sustainable future: multi-scale integrated analysis of societal and ecosystem metabolism*. Routledge.

Gössling, S., Peeters, P., 2015. Assessing tourism's global environmental impact 1900–2050. J Sustain Tour 23 (5), 639–659.

Gössling, S., Scott, D., Hall, C.M., 2021. Pandemics, tourism and global change: a rapid assessment of COVID-19. J Sustain Tour 29 (1), 1–20.

Gruener, S., 2021. Susceptibility to misinformation: a study of climate change, Covid-19, and artificial intelligence. Accessed August 22, 2021. Available from: https://osf.io/x8efq.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob Environ Change 23 (2), 485–498.

Haasnoot, M., Kwadijk, J., van Alphen, J., Le Bars, D., van den Hurk, B., Diermanse, F., et al., 2020. Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. Environ. Res. Lett. 15 (3), 034007.

Haberl, H., et al., 2020. A systematic review of the evidence on decoupling GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ. Res. Lett. 15, 065003. https://doi.org/10.1088/1748-9326/ab842a.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat Sustain 2 (3), 173–184.

Haer, T., Husby, T.G., Botzen, W.J.W., Aerts, J.C.J.H., 2020. The safe development paradox: An agent-based model for flood risk under climate change in the European Union. Global Environ. Change 60, 102009. https://doi.org/10.1016/j.gloenvcha.2019.102009.

Hagens, N.J., 2020. Economics for the future – Beyond the superorganism. Ecol. Econ. 169, 106520 https://doi.org/10.1016/j.ecolecon.2019.106520.

Hart, A., Gagnon, E., Eryigit-Madzwamuse, S., Cameron, J., Aranda, K., Rathbone, A., et al., 2016. Uniting Resilience Research and Practice With an Inequalities Approach. SAGE Open 6 (4), 215824401668247.

Hartnett, K.P., Kite-Powell, A., DeVies, J., Coletta, M.A., Boehmer, T.K., Adjemian, J., et al., 2020. Impact of the COVID-19 Pandemic on Emergency Department Visits — United States, January 1, 2019–May 30, 2020. MMWR Morb. Mortal. Wkly Rep. 69 (23), 699–704.

Harvey, S., Liddell, A., McMahon, L., 2009. Windmill 2009: NHS response to the financial storm. King's Fund, London, p. 68. https://www.kingsfund.org.uk/publications/windmill-2009.

Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., et al., 2021. Urgent need for post-growth climate mitigation scenarios. Nat Energy. https://www.nature.com/articles/s41560-021-00884-9.

Hickel, J., Kallis, G., 2020. Is Green Growth Possible? New Polit Econ 25 (4), 469–486.

Holmes, E.C., Goldstein, S.A., Rasmussen, A.L., Robertson, D.L., Crits-Christoph, A., Wertheim, J.O., et al., 2021. The origins of SARS-CoV-2: A critical review. Cell 184 (19), 4848–4856.

Hubbard K. Places without reported COVID-19 cases. U.S. News; 2021. Accessed December 16, 2021. Available from: https://www.usnews.com/news/best-countries/slideshows/countries-without-reported-covid-19-cases.

IEA. (2021). Global Energy Review: CO2 Emissions in 2020. Available from: https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020.

International Labour Organization. (2021). ILO Monitor: COVID-19 and the world of work. 7th edition - Updated estimates and analysis. Available from: https://www.ilo.org/global/topics/coronavirus/impacts-and-responses/WCMS_767028/lang–en/index.htm.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021.

Jack, T., Glover, A., 2021. Online conferencing in the midst of COVID-19: an "already existing experiment" in academic internationalization without air travel. Sustain Sci Pract Policy 17 (1), 292–304.

Jackson, R.B., Le Quéré, C., Andrew, R.M., Canadell, J.G., Korsbakken, J.I., Liu, Z., et al., 2018. Global energy growth is outpacing decarbonization. Environ. Res. Lett. 13 (12), 120401.

Jarzabek L, Krolikowska, K, Sliwa A, Magnuszewski P. Report from Core Workshop 1, delivered in Task 7.4. CASCADES: Cascading climate risks- towards adaptive and resilient European societies; 2020. Available from: https://www.cascades.eu/.

Johnson CK, Hitchens PL, Pandit PS, Rushmore J, Evans TS, Young CCW, et al. Global shifts in mammalian population trends reveal key predictors of virus spillover risk. Proc R Soc B Biol Sci. 2020 Apr 8;287(1924):20192736.

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J.W., et al., 2014. Increasing stress on disaster-risk finance due to large floods. Nat. Clim. Change 4 (4), 264–268.

Kaikkonen, L., Parviainen, T., Rahikainen, M., Uusitalo, L., Lehikoinen, A., 2021. Bayesian Networks in Environmental Risk Assessment: A Review. Integr Environ Assess Manag 17 (1), 62–78.

Kallis, G., 2017. Radical dematerialization and degrowth. Philos Trans R Soc Math Phys Eng Sci 375 (2095), 20160383.

Kallis, G., 2020. The case for degrowth. Polity Press, Cambridge, UK.

Kasemir, B., Toth, F., Masing, V., 2000. Climate Policy, Venture Capital and European Integration. JCMS J Common Mark Stud 38 (5), 891–903.

Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., et al., 2021. Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. Environ. Res. Lett. 16 (5), 053006.

Keyßer, L.T., Lenzen, M., 2021. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat. Commun. 12(1):2676.

Kharas, H., 2020. The impact of the COVID-19 on global extreme poverty. Available from: Brookings https://www.brookings.edu/blog/future-development/2020/10/21/the-impact-of-covid-19-on-global-extreme-poverty/.

Kharrazi, A., Yu, Y., Jacob, A., Vora, N., Fath, B.D., 2020. Redundancy, Diversity, and Modularity in Network Resilience: Applications for International Trade and Implications for Public Policy. Curr Res Environ Sustain 2, 100006.

Kim, K., 2021. Impacts of COVID-19 on transportation: Summary and synthesis of interdisciplinary research. Transp Res Interdiscip Perspect 9, 100305.

King, C.W., 2020. The Economic Superorganism. Springer Nature.

King, L.C., van den Bergh, J.C.J.M., 2018. Implications of net energy-return-on-investment for a low-carbon energy transition. Nat. Energy 3 (4), 334–340.

Klimek, P., Obersteiner, M., Thurner, S., 2015. Systemic trade risk of critical resources. Sci. Adv. 1 (10), e1500522.

Krey, V., Guo, F., Kolp, P., Zhou, W., Schaeffer, R., Awasthy, A., et al., 2019. Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. Energy 172, 1254–1267.

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., Klein, D., 2013. Is atmospheric carbon dioxide removal a game changer for climate change mitigation? Clim. Change 118 (1), 45–57.

Kumar, A., Malla, M.A., Dubey, A., 2020. With Corona Outbreak: Nature Started Hitting the Reset Button Globally. Front. Public Health 24 (8), 569353.

Lade, S.J., Anderies, J.M., Currie, P., Rocha, J.C., 2022. Dynamical systems modelling. In: Biggs, R., de Vos, Alta, Preiser, R., Clements, H., Maciejewski, K., Schlüter, M. (Eds.), The Routledge Handbook of Research Methods for Social-Ecological Systems. Routledge, pp. 359–370.

Lamb, W.F., Mattioli, G., Levi, S., Roberts, J.T., Capstick, S., Creutzig, F., et al., 2020. Discourses of climate delay. Glob Sustain 3, e17.

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., et al., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Change 10 (7), 647–653.

Leiva, B., Schramski, J., 2020. Why the energy transition is not enough. Accessed September 27, 2021. In Review. Submitted for publication. https://www.researchsquare.com/article/rs-66396/v1.

Lenhardt, A., 2020. Pushing people further into poverty: the impact of Covid-19 in lower- and middle- income countries. Available from: ODI https://odi.org/en/insights/pushing-people-further-into-poverty-the-impact-of-covid-19-in-lower-and-middle-income-countries/.

Lenton, T.M., 2020. Tipping positive change. Philos Trans R Soc B Biol Sci 375 (1794), 20190123.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., et al., 2019. Climate tipping points — too risky to bet against. Nature 575 (7784), 592–595.

Liu, Z., Ciais, P., Deng, Z., Lei, R., Davis, S.J., Feng, S., et al., 2020. Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. Nat. Commun. 11 (1), 5172.

Liu X, Li D, Ma M, Szymanski BK, Stanley HE, Gao J. (2020). Network resilience. ArXiv200714464 Q-Bio. Accessed August 9, 2021. Available from: http://arxiv.org/abs/2007.14464.

Mandel, A., Tiggeloven, T., Lincke, D., Koks, E., Ward, P., Hinkel, J., 2021. Risks on global financial stability induced by climate change: the case of flood risks. Clim. Change 166 (1), 4.

Manzanedo, R.D., Manning, P., 2020. COVID-19: Lessons for the climate change emergency. Sci. Total Environ. 742, 140563.

Masroor, S., 2020. Collateral damage of COVID-19 pandemic: Delayed medical care. J. Card. Surg. 35 (6), 1345–1347.

McCollum, D.L., Wilson, C., Bevione, M., Carrara, S., Edelenbosch, O.Y., Emmerling, J., et al., 2018. Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles. Nat. Energy 3 (8), 664–673.

McGlade, J., Bankoff, G., Abrahams, J., Cooper-Knock, S. J., Cotecchia, F., Desanker, P., ... & Wood, M. (2019). Global assessment report on disaster risk reduction 2019.

McHugh, D., Barry, C., McDonald, J., Pollastri, T., 2021. Energy crunch hits global recovery as winter approaches. Available from: Associated Press https://apnews.com/article/coronavirus-pandemic-lifestyle-business-russia-health-70b97e36da53f62eba588b44f2b394bc.

Mechler, R., Hochrainer-Stigler, S., 2019. Generating Multiple Resilience Dividends from Managing Unnatural Disasters in Asia: Opportunities for Measurement and Policy. Available from: SSRN Electron J https://www.ssrn.com/abstract=3590874.

Mechler, R., Singh, C., Ebi, K., Djalante, R., Thomas, A., James, R., et al., 2020. Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. Sustain. Sci. 15 (4), 1245–1251.

Mercure, J.-F., Pollitt, H., AndreaM, B., JorgeE, V., Edwards, N.R., 2016. Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. Glob Environ Change 37, 102–115.

Mochizuki, J., Magnuszewski, P., Pajak, M., Krolikowska, K., Jarzabek, L., Kulakowska, M., 2021. Simulation games as a catalyst for social learning: The case of the water-food-energy nexus game. Glob Environ Change 66, 102204.

Monasterolo, I., 2020. Embedding Finance in the Macroeconomics of Climate Change. Research Challenges and Opportunities Ahead Res Rep 8.

Myklebust, T., 2020. High-Frequency Trading as an Impediment to Long-Term and Sustainable Finance: Identifying a Regulatory Gap that Can Put the Goals of the European Action Plan on Financing Sustainable Growth at Risk. Oslo Law Rev 7 (02), 63–83.

Nordhaus, W.D., 1992. An Optimal Transition Path for Controlling Greenhouse Gases. Science 258 (5086), 1315–1319.

NGFS, A. (2019). A call for action: Climate change as a source of financial risk. *Network for Greening the Financial System: London, UK*.

OECD. (2006). Schooling for Tomorrow: Think scenarios, rethink education. OECD, Paris. Available from https://www.oecd.org/education/school/thinkscenariosrethinkeducation.htm#HTO.

OECD. (2020). The Covid-19 crisis: A catalyst for government transformation?. OECD Policy Responses to Coronavirus (COVID-19). Available from: https://www.oecd-ilibrary.org/social-issues-migration-health/the-covid-19-crisis-a-catalyst-for-government-transformation_1d0c0788-en.

OECD. (2021). COVID-19 spending helped to lift foreign aid to an all-time high in 2020 but more effort needed. Available from: https://www.oecd.org/newsroom/covid-19-spending-helped-to-lift-foreign-aid-to-an-all-time-high-in-2020-but-more-effort-needed.htm.

Ottersen, O.P., Engebretsen, E., 2020. COVID-19 puts the Sustainable Development Goals center stage. Nat. Med. 26 (11), 1671–1673.

Otto, I.M., Donges, J.F., Cremades, R., Bhowmik, A., Hewitt, R.J., Lucht, W., et al., 2020. Social tipping dynamics for stabilizing Earth's climate by 2050. Proc. Natl. Acad. Sci. 117 (5), 2354–2365.

Otto, F.E.L., Philip, S., Kew, S., Li, S., King, A., Cullen, H., 2018. Attributing high-impact extreme events across timescales—a case study of four different types of events. Clim. Change 149 (3–4), 399–412.

Pancani, L., Marinucci, M., Aureli, N., Riva, P., 2021. Forced Social Isolation and Mental Health: A Study on 1,006 Italians Under COVID-19 Lockdown. Front. Psychol. 21 (12), 663799.

Pescaroli, G., Alexander, D., 2015. A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. Planet@ risk 3 (1), 58–67.

Pickett, K., Wilkinson, R., 2010. The spirit level: Why equality is better for everyone. Penguin UK.

Pieh, C., Budimir, S., Delgadillo, J., Barkham, M., Fontaine, J.R.J., Probst, T., 2021. Mental Health During COVID-19 Lockdown in the United Kingdom. Available from: Psychosom Med 83 (4) https://journals.lww.com/psychosomaticmedicine/Fulltext/2021/05000/Mental_Health_During_COVID_19_Lockdown_in_the.5.aspx.

Pinto, A.J., Dunstan, D.W., Owen, N., Bonfá, E., Gualano, B., 2020. Combating physical inactivity during the COVID-19 pandemic. Nat. Rev. Rheumatol. 16 (7), 347–348.

Puttaiah, M.H., Raverkar, A.K., Avramakis, E., 2020. All change: how COVID-19 is transforming consumer behaviour.. Available from: Swiss Re Institute https://www.swissre.com/institute/research/topics-and-risk-dialogues/health-and-longevity/covid-19-and-consumer-behaviour.html.

Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., et al., 2020. Understanding and managing connected extreme events. Nat. Clim. Change 10 (7), 611–621.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Change 42, 153–168.

Ringsmuth AK, Landsberg MJ, Ben Hankamer. Can photosynthesis enable a global transition from fossil fuels to solar fuels, to mitigate climate change and fuel-supply limitations? Renew Sustain Energy Rev. 2016; 62(C):134–63.

Ringsmuth, A.K., Lade, S.J., Schlüter, M., 2019. Cross-scale cooperation enables sustainable use of a common-pool resource. Proc R Soc B 286, 20191943. https://doi.org/10.1098/rspb.2019.1943.

Ritchie, H. and Roser, M. (2020) - "CO₂ and Greenhouse Gas Emissions". Published online at OurWorldInData.org. Accessed Aug 23, 2021. Available from: 'https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions'.

Ritchie H, Mathieu E, Rodés-Guirao L, Appel C, Giattino C, Ortiz-Ospina E, et al. (2021). Coronavirus (COVID-19) Vaccinations. Our World in Data. Accessed on December 22, 2021. Available from: https://ourworldindata.org/covid-vaccinations.

Rogelj, J., Forster, P.M., Kriegler, E., Smith, C.J., Séférian, R., 2019. Estimating and tracking the remaining carbon budget for stringent climate targets. Nature 571 (7765), 335–342.

Roozenbeek, J., Schneider, C.R., Dryhurst, S., Kerr, J., Freeman, A.L.J., Recchia, G., et al., 2020. Susceptibility to misinformation about COVID-19 around the world. R. Soc. Open Sci. 7 (10), 201199.

Roser, Ortiz-Ospina E. 'Income Inequality'. Published online at OurWorldInData.org (2013). Accessed Aug 23, 2021. Available from: https://ourworldindata.org/income-inequality.

Sachs, J. D. Opinion: COVID-19 spreading fast in countries with lots of economic inequality. MarketWatch (2020). Available from: https://www.marketwatch.com/story/covid-19-spreading-fast-in-countries-with-lots-of-economic-inequality-2020-06-29.

Sallis, R., Young, D.R., Tartof, S.Y., Sallis, J.F., Sall, J., Li, Q., et al., 2021. Physical inactivity is associated with a higher risk for severe COVID-19 outcomes: a study in 48 440 adult patients. Br. J. Sports Med. 55 (19), 1099–1105.

Schramski, J.R., Gattie, D.K., Brown, J.H., 2015. Human domination of the biosphere: Rapid discharge of the earth-space battery foretells the future of humankind. Proc. Natl. Acad. Sci. 112 (31), 9511–9517.

Shaukat, N., Ali, D.M., Razzak, J., 2020. Physical and mental health impacts of COVID-19 on healthcare workers: a scoping review. Int J Emerg Med 13 (1), 40.

Shaw, R., Kim, Y., Hua, J., 2020. Governance, technology and citizen behavior in pandemic: Lessons from COVID-19 in East Asia. Prog Disaster Sci 6, 100090.

Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., et al., 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim. Change 151 (3–4), 555–571.

Shield, C., 2020. Coronavirus pandemic linked to destruction of wildlife and world's ecosystems. Available from: Deutsche Welle https://www.dw.com/en/coronavirus-pandemic-linked-to-destruction-of-wildlife-and-worlds-ecosystems/a-53078480.

Sillmann, J., Shepherd, T.G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., et al., 2021. Event-Based Storylines to Address Climate Risk. Earth's Future 9 (2), e2020EF001783. https://doi.org/10.1029/2020EF001783. https://onlinelibrary.wiley.com/doi/10.1029/2020EF001783.

Smil, V., 2008. Energy in Nature and Society. MIT Press.

Smith, D., 2004. For Whom the Bell Tolls: Imagining Accidents and the Development of Crisis Simulation in Organizations. Simul Gaming 35 (3), 347–362.

Smith, P. (2021). The Climate Risk Landscape: A comprehensive overview of climate risk assessment methodologies. UN environment program.

Solinska-Nowak, A., Magnuszewski, P., Curl, M., French, A., Keating, A., Mochizuki, J., et al., 2018. An overview of serious games for disaster risk management – Prospects and limitations for informing actions to arrest increasing risk. Int. J. Disaster Risk Reduct. 31, 1013–1029.

Stefanska, J., Magnuszewski, P., Sendzimir, J., Romaniuk, P., Taillieu, T., Dubel, A., et al., 2011. A Gaming Exercise to Explore Problem-Solving versus Relational Activities for River Floodplain Management: A Game to Explore Problem-Solving vs Relational Activities. Environ Policy Gov 21 (6), 454–471.

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., et al., 2018. Trajectories of the Earth System in the Anthropocene. Proc. Natl. Acad. Sci. 115 (33), 8252–8259.

Steinbacher, M., Raddant, M., Karimi, F., Camacho Cuena, E., Alfarano, S., Iori, G., et al., 2021. Advances in the agent-based modeling of economic and social behavior. SN Bus Econ 1 (7), 99.

Szczygielski JJ, Bwanya PR, Charteris A, Brzeszczyński J. The only certainty is uncertainty: An analysis of the impact of COVID-19 uncertainty on regional stock markets. Finance Res Lett. 2021 Jan;101945.

Sterman, J., 2000. Business dynamics. McGraw-Hill, Inc.

Taquet M, Dercon Q, Luciano S, Geddes JR, Husain M, Harrison PJ. Incidence, co-occurrence, and evolution of long-COVID features: A 6-month retrospective cohort study of 273,618 survivors of COVID-19. Kretzschmar MEE, editor. PLOS Med. 2021 Sep 28;18(9):e1003773.

Taraborelli, D., 2020. How the COVID-19 crisis has prompted a revolution in scientific publishing. Accessed December 21, 2021. Available from:Fast Company. https://www.fastcompany.com/90537072/how-the-covid-19-crisis-has-prompted-a-revolution-in-scientific-publishing.

Thurner, S., Klimek, P., Hanel, R., 2018. Introduction to the Theory of Complex Systems. Oxford University Press.

Tollefson, J., 2021. COVID curbed 2020 carbon emissions - but not by much. Nature 21, 589.

Treen, K.M.D. I., Williams, H.T., O'Neill, S.J., 2020. Online misinformation about climate change. Wiley Interdisciplinary Reviews: Climate Change 11 (5), e665.

UNFCCC. (2017). Climate change is a key driver of migration and food insecurity. Oct 16, 2017. Available from: https://unfccc.int/news/climate-change-is-a-key-driver-of-migration-and-food-insecurity.

United Nations. (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030. Available from: https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf.

United Nations. (2015). The Paris Agreement. 2015. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

United Nations. (2021). The 17 Goals. Accessed Aug 22, 2021. Available from: https://sdgs.un.org/goals.

USCDC. (2021). COVID-19: People with certain medical conditions. United States Centers for Disease Control and Prevention. Accessed Dec 23, 2021. Available from: https://www.cdc.gov/coronavirus/2019-ncov/need-extra-precautions/people-with-medical-conditions.html.

USCDC. (2021). COVID-19 vaccine effectiveness. US Centers for Disease Control and Prevention. Accessed Dec 16, 2021 at: https://www.cdc.gov/coronavirus/2019-ncov/vaccines/effectiveness/how-they-work.html.

Valdez, L.D., Shekhtman, L., La Rocca, C.E., Zhang, X., Buldyrev, S.V., Trunfio, P.A., et al., 2020. Cascading failures in complex networks. Estrada E, editor J Complex Netw. Apr 1;8(2):cnaa013.

van Oldenborgh, G.J., van der Wiel, K., Kew, S., Philip, S., Otto, F., Vautard, R., et al., 2021. Pathways and pitfalls in extreme event attribution. Clim. Change 166 (1–2), 13.

Vivid Economics & F4B (Finance for Biodiversity). Greenness of Stimulus Index: An assessment of COVID-19 stimulus by G20 countries and other major economies in relation to climate action and biodiversity goals. 2021. Available from: https://www.f4b-initiative.net/post/majority-of-17-2-trillion-covid-stimulus-packages-doing-more-harm-than-good-to-environment.

Walker BH. Resilience: what it is and is not. Ecol Soc. 2020;25(2):art11.

Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H., Simmons, C.T., 2016. Is Decoupling GDP Growth from Environmental Impact Possible? Naya DE, editor. PLoS ONE 11 (10), e0164733.

West, G., 2018. Scale: The universal laws of life, growth, and death in organisms, cities, and companies. Penguin.

Weyant, J., 2017. Some Contributions of Integrated Assessment Models of Global Climate Change. Rev Environ Econ Policy 11 (1), 115–137.

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 11 (1), 3107.

Willner, S.N., Glanemann, N., Levermann, A., 2021. Investment incentive reduced by climate damages can be restored by optimal policy. Nat. Commun. 12 (1), 3245.

World Bank (2021). Global Economic Prospects, June 2021. Washington, DC: World Bank. doi:10.1596/978-1-4648-1665-9. License: Creative Commons Attribution CC BY 3.0 IGO.

Wunderling, N., Donges, J.F., Kurths, J., Winkelmann, R., 2021. Interacting tipping elements increase risk of climate domino effects under global warming. Earth Syst. Dyn. 12 (2), 601–619.

Young, C. and Jones, R. (2017) Risk Ownership for Natural Hazards: Summary of Key Research Findings. Project Report. Bushfire and Natural Hazards CRC. Available from: https://vuir.vu.edu.au/36796/.

Young, C., Jones, R., 2018. Valuing recovery through risk ownership. Australian Journal of Emergency Management 33 (1), 48–54.Chicago.

Zarocostas, J., 2020. How to fight an infodemic. The Lancet 395 (10225), 676.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., et al., 2020. A typology of compound weather and climate events. Nat Rev Earth Environ 1 (7), 333–347.

Zurek, M.B., Henrichs, T., 2007. Linking scenarios across geographical scales in international environmental assessments. Technol Forecast Soc Change 74 (8), 1282–1295.