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DISCUSSION PAPER

# Our Future in the Anthropocene Biosphere: Global sustainability and resilient societies

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# Our Future in the Anthropocene Biosphere:

## Global sustainability and resilient societies

Discussion Paper for the first Nobel Prize Summit - Our Planet, Our Future[1]

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# Summary

The corona pandemic has exposed the interconnected, tightly coupled and vulnerable globalised world. This White Paper sets the scientific stage for understanding and responding to such crises for global sustainability and resilient societies. We provide a systemic overview of the current situation; where people and nature are dynamically intertwined and embedded in the biosphere, placing shocks and extreme events as part of this dynamic; where humanity has become the major force in shaping the future of the Earth system as a whole; and where the rapid expansion of the human dimension has caused climate change, simplification of life on earth, growing inequalities, and loss of resilience to deal with uncertainty and surprise. Taken together, human actions are challenging the biosphere foundation for a prosperous development of civilisations. The Anthropocene reality, of rising turbulence, calls for transformative change towards sustainable futures. Emerging technologies, social innovations, broader shifts in cultural repertoires, as well as a diverse portfolio of active stewardship of human actions in support of a resilient biosphere are highlighted as essential parts of such transformations.

# Content

# Introduction

Organisms have profoundly affected earth's environment from the evolution of photosynthetic cyanobacteria that resulted in a dramatic rise in oxygen concentrations in the atmosphere 2.4 billion years ago. Humans only became an important species in environmental transformations very recently on the time scale of the planet. Major human influence on environmental conditions began with megafauna extinctions from hunting, the rise of agriculture some 10 000 years ago and intensified with the start of the Industrial Revolution 250 years ago. Discernible human influence on global environmental conditions, however, became abundantly clear during the great acceleration in human activity over past 75 years.

Humans are now the dominant force of change on the planet – giving rise to a proposed new epoch referred to as the Anthropocene. This new epoch has profound meaning for humanity and one in which we are only now beginning to fully comprehend. Depending on the collective actions of humanity, future environmental conditions could be either beneficial or hostile for sustaining human life and well-being.

We now know that society needs to be viewed as being part of the biosphere, and not separate from it. In the Anthropocene, humans not only constitute the largest force of change on Earth, but also have the power to change the environment on which humanity depends. *Whether humanity has the collective wisdom to navigate the Anthropocene to sustain a livable biosphere for humanity, as well as for the rest of life with which we share the planet, is the most formidable challenge currently and urgently facing humanity.*

The Nobel Prize Summit will explore the challenges and opportunities for global sustainability and evidence-based solutions at this critical juncture. Global sustainability integrates scales and processes from local communities to the globalized world and from local ecosystems to the functioning of the biosphere and the Earth system as a whole, and does so in ways that intertwine society and the living planet. It places development in the context of global environmental change and Earth resilience, focusing on solutions for societal transformations towards biosphere stewardship and sustainable futures for present and future generations.

This paper provides a systemic overview and background of identified key core themes of the global sustainability agenda in focus of the Nobel Prize Summit, namely climate and biodiversity, inequality and global sustainability, and technologies causing social transitions and disruptions that bear on sustainability and inequality. Four major pathways towards global sustainability are emphasized:

- Recognize that societal development is embedded in and critically dependent on the biosphere and the broader Earth system for prosperity and wellbeing.
- Create incentives and design policies that enable societies to collaborate towards just and sustainable futures within planetary boundaries.
- Transform the current pathways of social, economic, cultural development into stewardship of human actions that enhance the resilience of the biosphere.
- Make active use of emerging and converging technologies for enabling the societal transformation.

## The Biosphere and the Earth system foundation

### Humanity as part of the Biosphere

The Universe is immense; estimates suggest at least two trillion galaxies (Conselice et al. 2017). The Milky Way, our galaxy, holds some 100 to 400 billion stars. One of those stars, our sun, has eight planets orbiting it. One of those, planet Earth, has a biosphere, a thin layer of life at its surface. The thickness of this layer is only about twenty kilometres (twelve miles)[3]. That's the only place where we know life exists, indeed where there is a complex web of life. We humans are embedded in the biosphere. We have emerged and evolved within the biosphere. Our societies and economies are part of it. It is our home.

Across the oceans and the continents, the biosphere integrates all living beings, their diversity, and their relationships (Odum 1989, Pace 1997). There is a dynamic interaction between the living biosphere and the broader Earth system, with the atmosphere, the hydrosphere, the lithosphere, the cryosphere, and the climate system (Steffen et al. 2004). Life in the biosphere is shaped by the global atmospheric circulation, jet streams, atmospheric rivers, water vapour and precipitation patterns, the spread of ice sheets and glaciers, soil formation, upwelling currents of coastlines, the ocean's global conveyer belt, the distribution of the ozone layer, movements of the tectonic plates, earthquakes, and volcanic eruptions. Water serves as the bloodstream of the biosphere, and the carbon, nitrogen and other biogeochemical cycles are essential for all life on Earth (Falkenmark 2017, Falkenmark et al. 2019, Gleeson et al. 2020, Steffen et al. 2020). Societies, cultures and the globalised world exist as embedded part of the complex dynamics of the Earth system and its biosphere (Clark and Munn 1986, Folke et al. 2016).

The biosphere has existed for about 3.5 billion years. Modern humans (*Homo sapiens*) have effectively been around in the biosphere for some 250 000 years (Delson 2019, Mounier and Lahr 2019). Powered by the sun, the biosphere and the Earth system coevolves (Lenton 2016) with human actions as an integral part of this coevolution (Palumbi 2001, Jörgensen et al. 2019).

Human societies are reliant on a healthy and resilient biosphere providing suitable living conditions. At the same time, human actions are now a major force in influencing the dynamics of the whole biosphere and more recently also the broader Earth system (Turner et al. 1990, Foley et al. 2005, Rockström et al. 2009, Folke et al. 2016, Steffen et al. 2018, Dasgupta 2020). Social conditions, health, culture, democracy, power, justice, inequity, matters of security, and even survival are interwoven with the Earth system and its

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[3] Almost all life exists between about 500 meters (1,640 feet) below the ocean's surface to about 6 kilometers (3.75 miles) above sea level. There is also a 'deep biosphere' – a zone of life under Earth's surface – dominated by two forms of microbes (bacteria and archaea) estimated to make up 70 percent of all Earth's bacteria and archaea. Science Alert https://www.sciencealert.com/scientists-lift-lid-on-massive-biosphere-of-life-hidden-under-earth-s-surface

biosphere in a complex interplay of local, regional, and worldwide interactions and dependencies.

Existing as part of the biosphere means that the environment is not something outside the economy or society, or a driver to be accounted for when preferred, but rather the very foundation that civilizations exist within and rely upon (Figure 1).

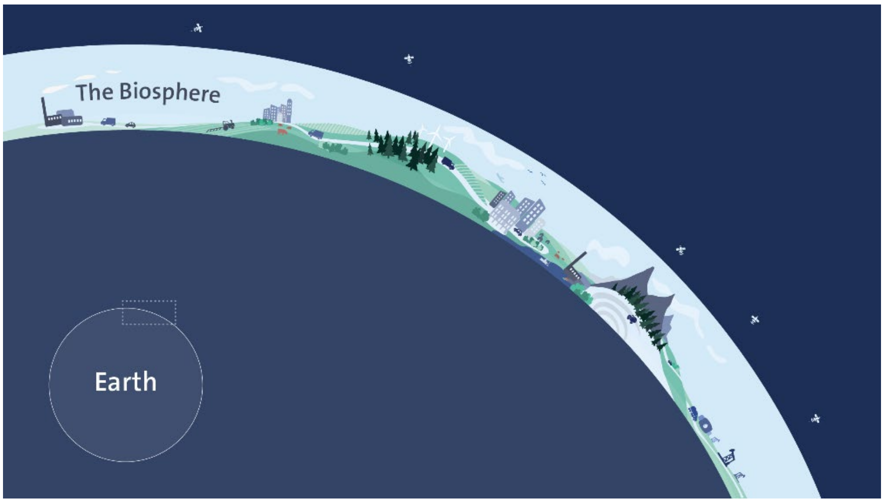

Figure 1. The home of humankind. Our economies, societies and civilizations are embedded in the Biosphere, the thin layer of life on planet Earth. There is a dynamic interplay between the living biosphere and the broader Earth system, with the atmosphere, the hydrosphere, the lithosphere, the cryosphere, and the climate system. Humans have become a major force in shaping this interplay.

### A dominant force in Earth system dynamics

The human population reached one billion around 1800. It doubled to two billion around 1930, and doubled again to four billion around 1974. It is now approaching 8 billion people on Earth and is assumed to stabilize around 11 billion toward the end of this century (UN 2019).

During the past century, and especially since the 1950s, there has been an amazing acceleration and expansion of human activities into a converging globalized society (Figure 2). This has been made possible through the discovery and use of fossil energy and innovations in social organization, technology and cultural evolution (McNeill 2000, van der Leeuw 2019). The world's interdependence, through cross-border trade in goods and services, technology, and flows of people, information, and investment, has sped up to an unprecedented pace since the 1990s, with public policy changes and communication technology innovations as important driving factors.

The globalized world connects people, places and cultures in new ways. Globalization has helped focus attention on human rights, international relations and agreements leading to greater collaboration and trust and, rather remarkably, it appears at least so far to have counteracted large-scale conflict between states that have plagued civilisations from time immemorial. Boundaries between developed and developing regions are less clear and global economic activity is increasingly dispersed across production networks that connect metropolitan areas around the world (Coe et al. 2004, Liu et al. 2015). Health and material standards of living for many people on Earth have improved. More people live longer, healthier lives than at any time in history (Rosling 2015).

Despite vast and growing inequalities as well as too many people still in poverty (Dasgupta 1995, Stiglitz 2012, Piketty 2014), the remarkable acceleration appears to continue with a rise of an affluent middle class in a rapidly urbanizing world (Meng et al. 2018) and with information technology, nano-technology, synthetic biology, molecular revolution and health science more broadly accelerating with unknown potentials, challenges, and futures.

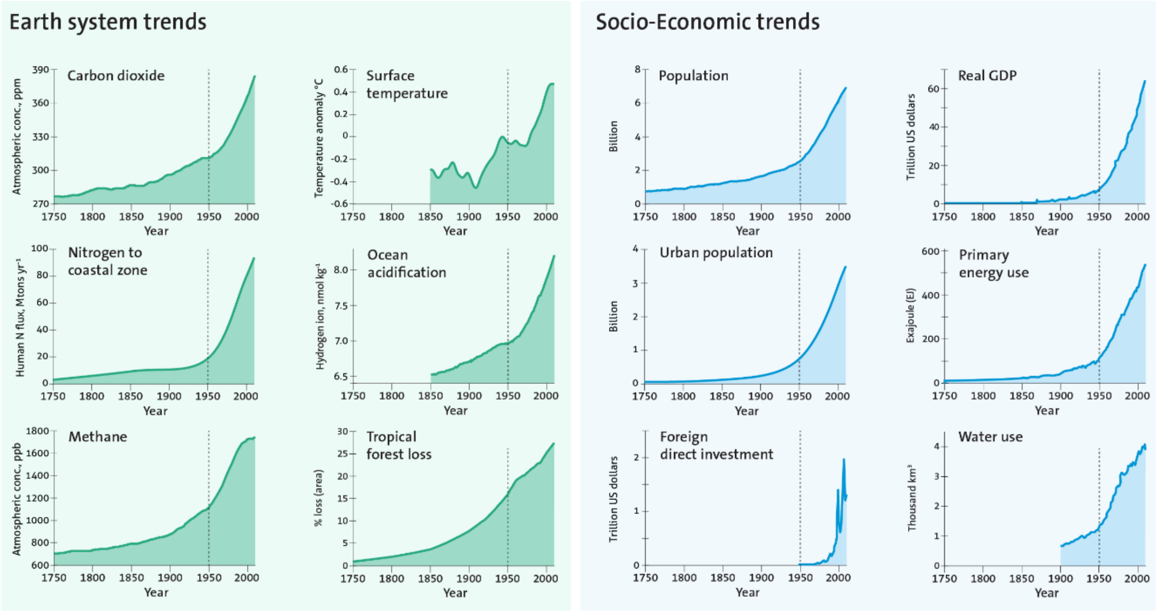

Fig. 2. The Great Acceleration since mid-1900 (modified from Steffen et al. 2015b)

In this context, it is important to recall that all human civilizations have developed within an unusually favourable interglacial period of the last 11 700 years of a relatively stable climate and a resilient planet Earth - the Holocene geological epoch (Figure 5). This stability made agriculture feasible, settlements multiplied and the human dimension accelerated into a globalised society (Redman 1999, Ellis 2015, Kavanagh et al. 2018, van der Leeuw 2019). It is the only state of the Earth system that we know for sure can accommodate contemporary society (Steffen et al. 2011).

Now, there is ample evidence that the cumulative human culture has expanded to such an extent that it has become a significant global force affecting the operation of the Earth system and its biosphere at the planetary level. As a reflection of this unprecedented expansion, a new geological epoch – the Anthropocene, the age of mankind - has been proposed (Crutzen and Stoermer 2000, Steffen et al. 2007, Waters et al. 2016). In a binding vote, the Anthropocene Working Group of the International Commission on Stratigraphy has recommended that the Anthropocene be formalised as a new epoch in the Geological Time Scale, with a base (starting date) around the mid-20th century, terminating the Holocene at that time (AWG 2019).

The biosphere in the Anthropocene is currently characterised by features like human-driven land-use change (50 % of Earth's land area has been transformed into agriculture, cities, roads and other infrastructure) and massive loss of species (on trajectory of losing 1 million of 8 million known species) (Diaz et al. 2019), resulting in the global homogenisation of flora and fauna. A single species (*Homo sapiens*) is commandeering the dominant part of net primary production by plants and mining fossil net primary production (fossil fuels) to break through the photosynthetic energy barrier, as well as directing evolution of all other species (Vitousek et al. 1997, Williams et al. 2015, Jörgensen et al. 2019).

It is further characterised by a tightly interconnected globalised world operating at high speed with hyper-efficiency in several dimensions. These dimensions include the globalised food production and distribution system, extensive trade and transport systems, strong connectivity of financial and capital markets, internationalized supply and value chains, widespread urbanization and movements of people, social innovations, development and exchange of technology and pervasive communication capacities (Peters et al. 2004, Vitali et al. 2011, Helbing 2013, Frank et al. 2014, Liu et al. 2016, Nyström et al. 2019) (Figure 3).

Figure 3. A snapshot of the interconnected world (source Globaia).

In addition, the technosphere (e.g. physical infrastructure, technological artefacts, novel substances and associated social and technological networks) is a recent human-created phenomenon of our planet, one that is developing extraordinarily fast, and an essential feature of the globalised world. It now plays a significant role in shaping global biosphere dynamics and has already left a deep imprint on the Earth system (Palumbi 2001).[4] The rapid transformation of much of Earth's surface mass into the technosphere and its numerous components, their use in the contemporary globalized world, and their side-effects underscores the novelty of the current planetary transformation (Arthur 2009, Galaz 2014, Zalasiewicz et al. 2016, Carpenter et al. 2019).

Humanity has indeed developed into a dominant force in biosphere dynamics altering the physical, chemical, and biological make up of our planet (Vitousek et al. 1997, Worm and Paine 2016), a significant evolutionary force of the biosphere in new ways. This is unique in the history of the living planet (Williams et al. 2016).

In the Anthropocene, where human activities now rival the great forces of nature (Steffen et al. 2007), it seems like the expanding human dimension is confronted with dynamic, interacting and large-scale thresholds and tipping points with pervasive implications for the future wellbeing[5] of people on Earth (Scheffer et al. 2001, 2012, Steffen et al. 2018, Lenton et al. 2019) many of which are encompassed in the planetary boundaries framework (Rockström et al. 2009, Steffen et al. 2015b, Lade et al. 2020). There is truly something new under the sun (McNeill 2000).

In this new reality, it is important to clarify that contemporary growth and development economics, as well as the economics of climate change, have been constructed on the thought that humanity is external to the biosphere (Dasgupta 2020). This has allowed economists to work with models in which technological progress is expected to enable humanity to enjoy ever growing GDP and thus consumption. Arguably, the view of the economy as external to the environment may have been comparatively harmless so long as the biosphere was more than able to supply the demands humanity made of it. That simply is not the case any longer (Dasgupta and Ramanathan 2014). As made clear here, the economy is embedded in the biosphere, and therefore the global economy is bounded, meaning that indefinite growth in GDP and consumption is simply not possible. This fundamental insight has far reaching and profound implications for contemporary models of economic possibilities that many still work with and draw policy conclusions from (Dasgupta 2020).

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[4] Preliminary estimates suggest a technosphere mass (the summed material output of the contemporary human enterprise) of approximately 30 trillion tonnes (Tt), which helps support a human biomass that is only about 300 million tonnes, or 5 orders of magnitude smaller (Zalasiewicz et al. 2016). It includes a growing residue layer, currently only in small part recycled back to sustain energy and material flows of contemporary society. Other impacts include toxic, chemical, medical waste and pollution, as well as diverse kinds of emissions including green-house gasses. Greenhouse gas emissions, untreated urban and rural waste, pollutants from industrial, mining and agricultural activities, oil spills and toxic dumping have had strong negative effects on soil, freshwater and marine water quality and on the global atmosphere.

[5] Human wellbeing can be thought of as a state of being with others, where human needs are met, when individuals can act meaningfully to pursue self-defined goals, and when they can enjoy a satisfactory quality of life. Wellbeing is often related to material wellbeing, quality of life, and relational well-being (Hicks et al. 2016) as well as identity, emotions, beliefs (Brown et al. 2019, Ives et al. 2020).

Hence, although there are beliefs and values of humans and nature as separate entities that have emerged with economic development, technological change, cultural evolution and the amazing expansion of the human dimension, it has certainly not changed the fact that humans are living within and are dependent upon a resilient biosphere and a stable, Holocene-like dynamics of the broader Earth system.

## The intertwined planet of people and nature

The Earth as transformed by human actions and the speed, spread, and connectivity of the Anthropocene epitomize contemporary - not just linked but intertwined - systems of people and nature[6], intertwined across levels and scales (Turner et al. 1990, Reyers et al. 2018, Nyström et al. 2019).

Local events can escalate into global challenges and local places are shaped by global dynamics (Adger et al. 2009, Crona et al. 2015, 2016, Liu et al. 2016, Kummu et al. 2020). The tightly coupled human interactions of globalisation allow for the continued flow of information, capital, goods, services, and people, but also create global systemic risk (Centeno et al. 2015, Galaz et al. 2017, Tu et al. 2019). However, this interplay is not only global between people and societies but coevolving with biosphere dynamics (Walker et al. 2009, Biggs et al. 2011, Homer-Dixon et al. 2015, Bai et al. 2016).

For example, extreme-weather and geopolitical events, interacting with the dynamics of the food system, can spill over multiple sectors and create synchronous challenges among disconnected areas and rapidly move across countries and regions (Rocha et al. 2018, Cottrell et al. 2019). The rise of antibiotic resistance, the rapid spread of the recent corona-pandemic, or altered moisture recycling across regions expose the intertwined world (Galaz et al. 2011, Jörgensen et al. 2018, Keys et al. 2019).

Extensive urbanisation plays a central role in the dynamics of the Anthropocene. Indeed, we live on an urban planet with over 50% of the population now living in cities. This is projected to reach about 70% by 2050 (UN DESA 2018) as the world adds the equivalent of one new city of one million people every five days. Power relations, inequalities, behaviours and choices of urban dwellers shape landscapes and seascapes and their diversity around the world through, e.g., markets, institutions, and global infrastructures (Turner et al. 2007, Lambin and Meyfroidt 2011, Seto et al. 2012, Andersson et al. 2014, Cumming et al. 2014, Elmqvist et al. 2019).

The stunning acceleration of the human dimension over continents and in the oceans (Steffen et al. 2015b, Jouffray et al. 2020) has escalated into a concentration of wealth and power in the hands of a few ‘keystone actors’ that have a disproportionate capacity to influence biosphere dynamics (Österblom et al. 2015, Folke et al. 2019). It also reflects rising inequality and social tension challenging smooth transformations towards global sustainability (Piketty 2014, Carpenter et al. 2019, UNDP 2019). Clearly, there is need for

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[6] also referred to as human-environment systems, social-ecological systems, social-environmental systems, socio-natural systems, coupled human-natural systems (Berkes and Folke 1998, Turner et al. 2003, Ostrom 2009, Fischer et al. 2015, Matson et al. 2016, van der Leeuw 2019, Liu et al. 2007).

greater collaboration among existing institutions, as well as new institutions, to help construct and provide a social contract for global sustainability (Lubchenco 1998, Young et al. 2006, O'Brien et al. 2009, Walker et al. 2009, Ebbesson 2010, Biermann et al. 2012, De Fries et al. 2012, Brondizio et al. 2016, Dannenberg and Barrett 2018, Lubchenco and Gaines 2018).

In the 21st century, people and planet are truly interwoven and coevolve. It becomes evident that it is all about our own future on Earth, as part of the biosphere, which is at stake. It is a new situation with humans in the driver's seat of Earth's dynamics, having the power and responsibility to exert stewardship over our planet.

This insight has major implications for human wellbeing in the face of climate change and loss of biodiversity as elaborated on in the next section.

## Climate change and loss of biodiversity

Contemporary climate change and biodiversity loss are not isolated phenomena but symptoms of the massive expansion of the human dimension into the Anthropocene, the novel, human-mediated state of the Earth System (Steffen et al. 2018).

The climate system plays a central role for life on Earth. It sets the boundary for our living conditions. The climate system is integral to all other components of the Earth system, through heat exchange in the oceans, albedo dynamics of the ice sheets, carbon sinks in terrestrial ecosystems, cycles of nutrients and pollutants, and climate forcing through evapotranspiration flows in the hydrological cycle and greenhouse pollutants. Together these interactions in the Earth system interplay with the heat exchange from the sun and the return flow back to space, but also in significant ways with biosphere-climate feedbacks that either mitigate or amplify global warming. These global dynamics interact with regional environmental systems (like ENSO or the monsoon system) that have innate patterns of climate variability and also interact with one another via teleconnections (Steffen et al. 2020).

The living organisms of the planet's ecosystems and biological diversity play a significant role in these complex dynamics. The fabric of life on Earth has been "woven" by natural processes over many millions of years (Diaz et al. 2019) and the genetic and species diversity of the biosphere allow it to persist and adapt under changing conditions (Mace et al. 2014, Lenton 2016). Earth has been oscillating between colder and warmer periods over a million years (the entire Pleistocene), but the average mean temperature has never exceeded 2°C (inter-glacial) above or 5°C below (deep ice age) the pre-industrial temperature on Earth (14°C), reflecting the importance of biosphere feedbacks as part of regulating the temperature dynamics of the Earth (Willeit et al., 2019) (Figure 5).

The biosphere feedbacks that support human life are currently being challenged by the actions of the human population, including the challenge of climate change.

## Human-induced climate change

Through the discovery of fossil energy, the development of industrial societies and the expansion of human actions, humans have accelerated into a major force that is altering Earth's climate, primarily through the emissions of greenhouse-gases (GHG: carbon dioxide $CO_2$, methane $CH_4$, and nitrous oxide $N_2O$) that trap heat in the lower atmosphere and at the Earth's surface, thus warming the planet. These emissions have caused the global average temperature on Earth to increase by 1.1°C as compared to preindustrial levels (WMO 2020) (Figure 4).

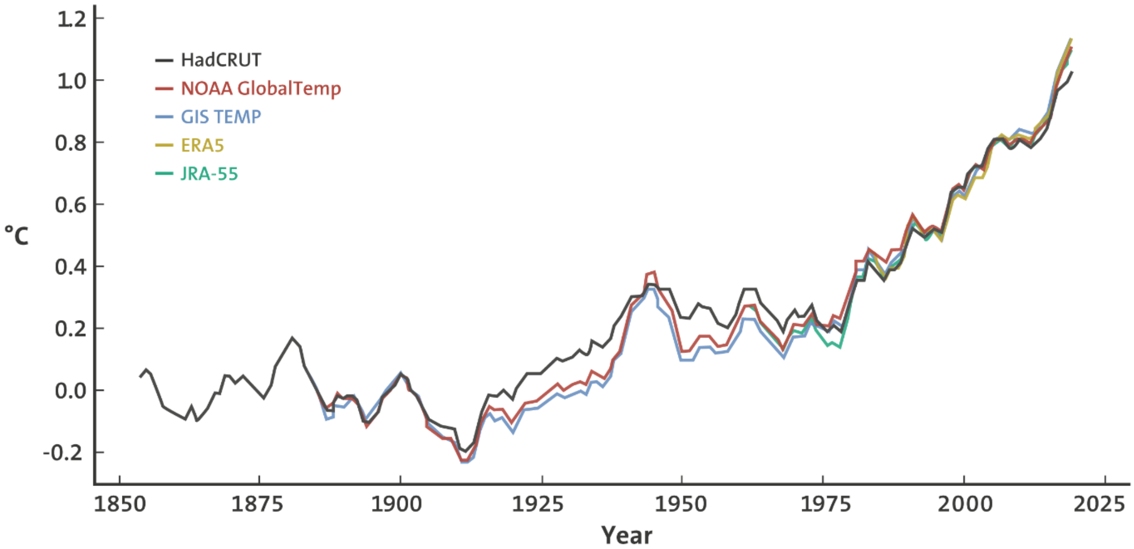

Figure 4. The average global temperature increase on Earth in relation to emissions of greenhouse-gasses and compared to preindustrial levels (1850-1900) (modified from WMO 2019).

Human-induced global warming is unparalleled: for 98% of the planet's surface, the warmest period of the past 2000 years occurred in the late twentieth century (Neukom et al. 2019), side by side with the great acceleration of the human dimension after WWII (Steffen et al. 2015b, Jouffray et al. 2020). Human-induced warming has steadily increased into the 21st century with the average global temperature for 2015-2019 being the warmest of any equivalent period on record (WMO 2020). If efforts to constrain emissions fail, the global average temperature by 2100 is expected to increase 3-5°C (IPCC 2014) above preindustrial levels.

The supply of energy and its use in buildings and transport generate about 55% of global anthropogenic GHG emissions. The remaining 45% comes from emissions that arise from the management of land and the production of buildings, vehicles, electronics, clothes, food, packaging, and other goods and materials (Ellen MacArthur Foundation 2019). The food system itself accounts for about 25% (21-37%) of global anthropogenic GHG emissions (Poore and Nemecek 2018, Mbow et al. 2019). Human driven land-use change through agriculture, forestry and other activities (Lambin and Meyfroidt 2011) causes about 14% of the emissions (Friedlingstein et al. 2019). According to C40 Cities, the cities account for more than 70% of global CO2 emissions. Collectively, the top 10 emitting countries account for three-quarters of global GHG emissions, while the bottom 100 countries account for only 3.5 percent (WRI 2020). Still, and despite local and regional efforts for mitigation and progress in renewable energy, $CO_2$ emissions from fossil-fuel use continue to grow globally (Peters et al. 2020).

$CO_2$ dominates and contributes about 66% of the radiative forcing by long-lived GHG. Methane contributes about 17% of which some 60% derives from anthropogenic sources. Human-driven emissions have increased $CO_2$ levels in the atmosphere from about 280 parts per million (ppm) in the late 1800s to above 410 ppm in early 2020. Significant amounts of $CO_2$ remain in the atmosphere for centuries and in the ocean for even longer, thus locking in ocean acidification and climate change for hundreds of years. The current levels of atmospheric concentrations of carbon dioxide, methane and nitrous oxide are unprecedented in at least the last 800,000 years (IPCC 2014).

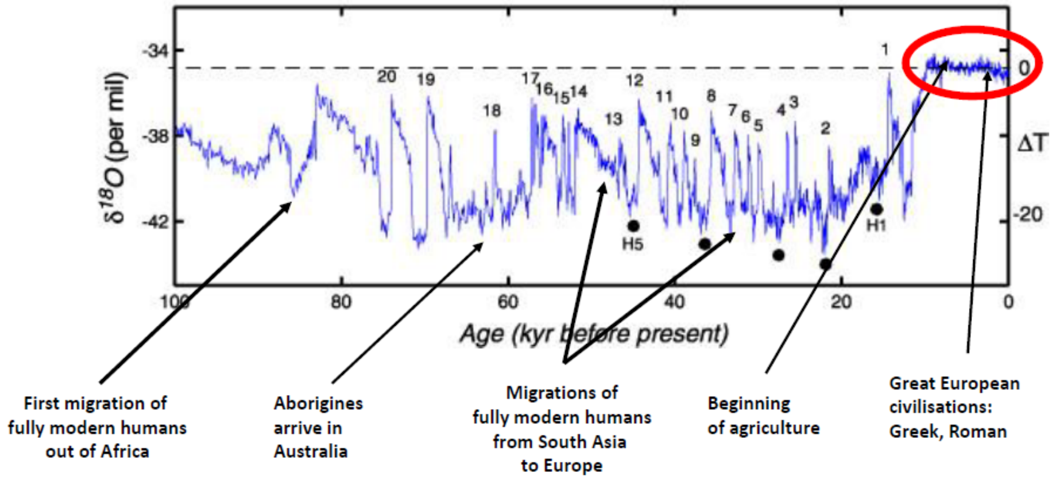

Figure 5. Ice-core data from the last 100 000 years in relation to human migration and civilisation. The red circle marks the last 11 700 years of the accommodating Holocene epoch. Evidence suggest that current levels of anthropogenic warming has already forced the Earth system out of the Holocene climate conditions into the Anthropocene. There is increasing consensus that pushing the Earth system to more than 2°C warming compared to preindustrial levels constitutes unknown terrain for contemporary societies and a severe threat to civilisation (see e.g. Clark et al. 2016, Burke et al. 2018, Steffen et al. 2018).

Already now at 1.1°C it appears we have moved out of the accommodating Holocene environment that allowed agriculture and complex human societies to develop (Steffen et al. 2018). Furthermore, with increased warming humanity risks departing the glacier-interglacial dynamics of the past 2.6 million years (Burke et al. 2018).

During the past 2.6 million years, Earth's mean annual global temperature has not exceeded the preindustrial value by more than 2°C (Willeit et al. 2019). Although higher global temperatures are old terrain in the history of Earth, living in a biosphere with a mean annual global temperature exceeding 2°C of the preindustrial average is largely unknown terrain for humanity and certainly novel terrain for contemporary society.

## Climate change - faster and stronger than predicted

Already at current levels of global warming, evidence suggests that climate change impacts are hitting people harder and sooner than predicted a decade ago. This is especially true for extreme events, like heatwaves, droughts, wildfires, extreme precipitation, floods, storms and variations in their frequency, magnitude and duration (Stott et al. 2004, Coumou and Rahmstorf 2012, Turco et al. 2018, Yin et al. 2018). In particular, synchronous extremes are risky in a globally-connected world, and may cause failure of crops across breadbaskets, causing disruptions in global food production (Cottrell et al. 2019, Gaupp et al. 2020).

The impacts of extreme events are often region-specific. For example, Europe has seen a particularly strong increase in heat extremes and the risk for wild fires in Australia has increased by at least 30% since 1900 as a result of anthropogenic climate change (van Oldenborgh et al. 2020). The US National Climate Assessment finds that the number of heat waves, heavy downpours, and major hurricanes, and the strength of these events, has increased in the United States. Some 220 million more heatwave exposures by vulnerable elderly persons occurred in 2018 compared to the period 1986-2008. The largest economic losses have been associated with tropical cyclones (WMO 2019). Climate variability and extremes, like drought conditions, are negatively affecting food security (FAO). Pandemics, like the COVID-19 outbreak and associated health responses, intersect with climate hazards all around the world and will exacerbate and be exacerbated by the economic crisis and long-standing socioeconomic and racial disparities, both within countries and across regions (Phillips et al. 2020). Extreme events also have the prospect of widening existing inequalities within and between countries and regions (UNDP 2019).

The warming of the Arctic is increasingly linked to extreme winter and summer climates at mid-latitudes (Cohen et al. 2018, Coumou et al. 2018). Greenland and parts of Antarctic ice sheets are showing signs of destabilizing sooner than expected (Millilo et al. 2019, Lenton et al. 2019, IPCC 2019). Coastal cities and even whole nations, such as low-lying island states, are threatened. Ocean heat is at record levels (Cheng at al. 2020) and there have been widespread marine heatwaves (Oliver et al. 2018). Sea water is 26 percent more acidic than at the start of the industrial era and ocean acidification is proceeding at a pace not seen in over 300 million years (Hönisch et al. 2012, Barange et al. 2018). The existence of vital marine ecosystems like coral reefs are being challenged (Hughes et al. 2018). Climate trends cause abrupt shifts in ecosystems crucial for livelihoods including forests, grasslands, wetlands, freshwaters, coastal waters and coral reefs (Turner et al. 2020).

Vulnerability to climate change impacts is particularly high in countries and parts of the human population with low incomes (Morton 2007, Cutter and Finch 2008). Changes to glaciers, snow and ice in mountains will likely influence water availability for over a billion people downstream by mid-century (Pihl et al. 2019). Some areas will experience increased precipitation, while other areas are expected to see less due to shifting patterns of rainfall and moisture feedback. Depending on scenarios of population growth and warming, over the coming 50 years 1-3 billion people could experience a Sahara-like mean annual temperature and thereby be left outside the climate conditions that have served humanity well over the past 6000 years (Xu et al. 2020). There is significant concern that climate driven events exacerbate conflict because they affect economic insecurity which, in itself, has been shown to be a major cause of violent conflict and unrest (Adger et al. 2014, Collier and Hoeffler 2004, Mach et al. 2019, Ide et al. 2020).

In general, the Anthropocene presents humanity with a new context and new intertwined dynamics of people and planet, where the scale, speed and connectivity of the changes become truly significant. Probabilities and consequences of the changes are not only scale-dependent, but also changing over time as a result of human actions, where those actions can either exacerbate or mitigate the likelihood or consequences of a given event (Levin et al. 2020).

Some of these changes happen continuously and gradually over time, while others take the form of more sudden and often potentially catastrophic change. In addition, some are to some extent predictable, while others are more uncertain (Brock and Hansen 2017, Levin et al. 2020). A recent analysis of a large database of social-ecological shifts suggests that in the intertwined world one change may lead to another, or that events can co-occur because they simply share the same driver (Rocha et al. 2018). Large-scale transitions can unfold when a series of linked elements are all close to a tipping point, making it easier for one transition to set off the others (Scheffer et al. 2012).

### The climate and the biosphere interplay

The climate and the biosphere operate as a complex dynamic system with human actions playing a central part in these dynamics. There is a delicate interplay between the climate system and the biosphere. For example, at current global average temperature the oceans absorb about 25% of annual carbon emissions (Global Carbon Project, Gruber et al. 2019) and absorb over 90% of the additional heat generated from those emissions. Land-based ecosystems like forests, wetlands, and grasslands draw down carbon dioxide through growth, and all in all sequester close to 30% of anthropogenic $CO_2$ emissions (Global Carbon Project 2019).

The total amount of carbon stored in terrestrial ecosystems is huge, almost 60 times larger than the current annual emissions of global GHG ($CO_2$ equivalents, 2017) by humans. About 70% (1500-2400 Gt C) is found in soil (Ciais et al. 2013). The soil carbon (including permafrost) is about 4.5 times larger than the atmospheric pool and about 5 times larger than the carbon found in living plants and animals (Oelkers and Cole 2008). The ocean holds a much larger carbon pool, at about 38,000 Gt of carbon (Houghton 2007).

Thus far, terrestrial and marine ecosystems serve as important sinks for carbon dioxide and thereby contribute significantly to stabilizing the climate. These living systems reflect the delicate dynamics of the climate system and the operation of the biosphere. However, this important ecosystem service (Ehrlich and Daily 1993), or Earth system service (Steffen et al. 2011), cannot be taken for granted (Lade et al. 2019). Recent research has shown that not only human land-use change but also climate impacts, like extreme events and temperature change, increasingly challenge those sinks (Anthony et al. 2018, Harper et al. 2018). For example, the vast fires in Borneo in 1997 released an equivalent of 13-40% of the mean annual global carbon emissions from fossil fuels at that time (Page et al. 2002, Folke et al. 2011).

The Earth system contains several biophysical sub-systems that can exist in multiple states (depending on climate and global environmental changes), and which contribute to regulate the state of the planet as a whole. These so-called tipping elements, or sleeping giants (Figure 6), have been identified as critical in maintaining the planet in favourable Holocene-like conditions (Lenton et al. 2008). These are now challenged by global warming and human-driven biosphere degradation, threatening to trigger self-reinforcing feedbacks and cascading effects that could push the Earth System toward a planetary threshold that, if crossed, could prevent stabilization of the climate at intermediate global warming and cause self-reinforced warming along a "Hothouse Earth" pathway even as human emissions are reduced (Steffen et al. 2018).

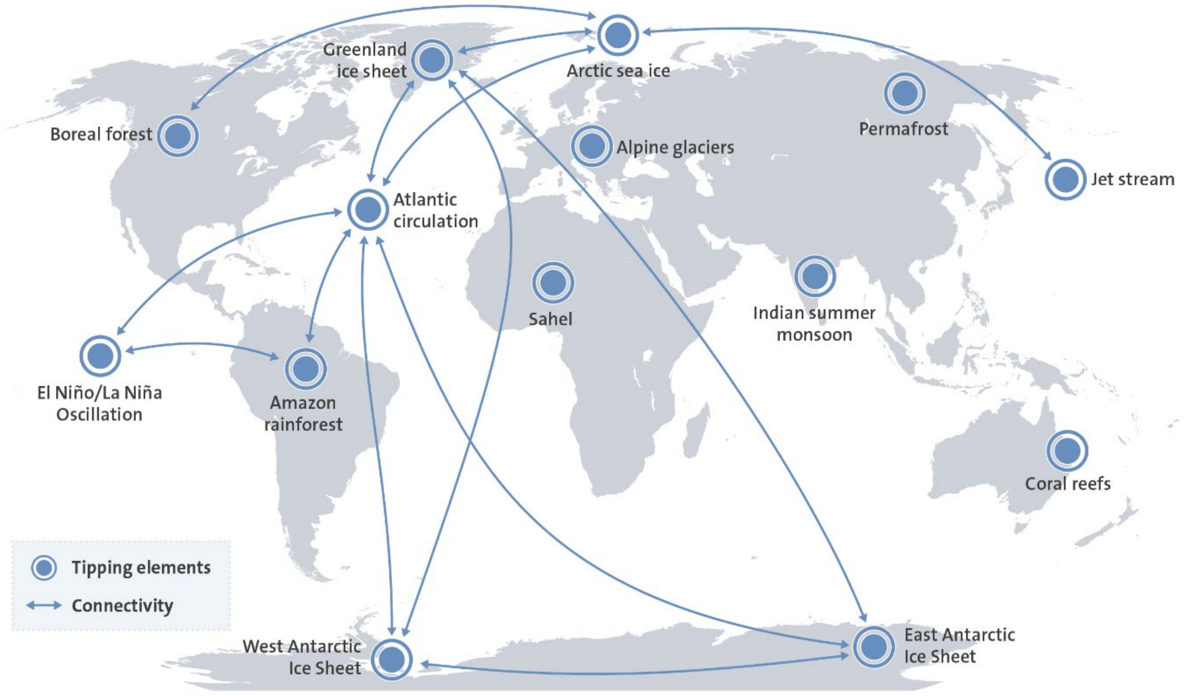

Figure 6. Tipping elements central in regulating the state of the planet, and identified interactions among them that, for humanity, could cause serious cascading effects and even challenge planetary stability (based on Lenton et al. 2008, 2019, Steffen et al. 2018).

Observations suggest that nine of these known sleeping giants are already starting to wake up at the current levels of warming, with possible domino effects to come. That is, of a suite of tipping elements identified a decade ago (Lenton et al. 2008), and thought to be reasonably stable at that time, nine are now actively undergoing large-scale changes (Lenton et al. 2019).

The world's remaining emissions budget to have a 50:50 chance of staying within 1.5°C of warming is about 500 Gt of $CO_2$. Permafrost emissions could take an estimated 20% (100 Gt $CO_2$) off this budget. Amazon dieback could release another 90 Gt $CO_2$ and boreal forests a further 110 Gt $CO_2$ (Lenton et al. 2019), that is removing a further 40% of the remaining budget.

It has become clear that the scale, connectivity and speed of the stunning acceleration of the human dimension into a globalised world in less than a century are now manifested in a significant imprint on the biosphere and the Earth system as a whole. Climate change is a symptom of those actions, now rapidly challenging the future of humanity on Earth.

The significance of the challenge of holding global warming in line with the Paris climate target is obvious. In 2019, the European Union (the European Parliament) declared a climate emergency along with many other countries and municipalities. Collective human action is urgently required to steer the Earth system away from the potential threshold, from potential runaway climate change, and work towards stabilizing it in a habitable interglacial-like state (Steffen et al. 2018).

In fact, the challenge is broader than climate alone. It is about navigating towards a safe-operating space that depends on maintaining a high level of Earth resilience. Obviously, incremental tweaking and marginal adjustments will not suffice. Major transformations towards just and sustainable futures are the bright way forward.

## Biological diversity in Biosphere and Earth system dynamics

The interactions and diversity of organisms within and across the planet's ecosystems play critical roles in the coevolution of the biosphere and the broader Earth system. It is this complex adaptive interplay between living organisms, the physical climate and the broader Earth system that has evolved into a resilient biosphere. Human societies and civilizations have evolved with and are part of this dynamic. Development and wellbeing depend on ecosystem services, or nature's contributions to people (Daily 1997, Diaz et al. 2018).

For example, major biomes like tropical and temperate forests and their biological diversity transpire water vapour that connects distant regions through precipitation. Nearly a fifth of annual average precipitation falling on land is from vegetation-regulated moisture recycling, with several places receiving nearly half their precipitation through this ecosystem service. Such water connections are critical for semi-arid regions reliant on rain-fed agricultural production and for water supply to major cities like Sao Paulo or Rio de Janeiro (Keys et al. 2016).

As much as nineteen megacities depend for more than a third of their water supply on water vapour from land, a dependence especially relevant during dry years (Keys et al. 2018). In some of the world's largest river basins, precipitation is influenced more strongly by land-use change taking place outside than inside the river basin (Wang-Erlandsson et al. 2018).

The biosphere is an array of life-supporting ecosystems supplying essential ecosystem services that underpin human wellbeing and socioeconomic development. For example, the biosphere strongly influences the chemical and physical composition of the atmosphere, and biodiversity contributes through its influence in generating and maintaining soils, controlling pests, and participating in biogeochemical cycles. These services represent critical life-supporting functions for humanity (Odum 1989, Folke 1991, De Groot 1992, Ehrlich and Ehrlich 1992, de Bello et al. 2010, Isbell et al. 2017). Biological diversity thus plays fundamental roles in nature's contributions to people (Daily 1997, Diaz et al. 2018).

As an example, the role of biodiversity in pollination is of significance in food production and ecosystem functioning (Buchmann and Nabhan 1996, Dainese et al. 2019). Nearly 90% of wild flowering plants depend at least to some extent on pollination by insects, birds, or vertebrates. These plants are critical for the continued functioning of ecosystems as they provide food, other resources and form habitats for a wide range of species (IPBES 2016). Pollinator-dependent species encompass many fruit, vegetable, seed, nut and oil crops, which supply major proportions of micronutrients, vitamins and minerals in the human diet. More than three quarters of the leading types of global food crops rely to some extent on animal pollination for yield and/or quality (IPBES 2016). Maintaining the biodiversity of ecosystem service providers is vital to sustain the flow of key agroecosystem benefits to society (Dainese et al. 2019). High diversity of wild, native pollinators can stabilize ecosystem services against environmental change, like buffering the impacts of climate change (Rader et al. 2013). Similarly, national food production of crops is stabilized by crop diversity (Renard and Tilman 2019).

The ocean's foodwebs, continental shelves and estuaries support the production of seafood, serve as a sink for greenhouse gases, maintain water quality, and hedge against unanticipated ecosystem changes from natural or anthropogenic causes. Marine ecosystems with high diversity have slower fisheries collapse rates and higher rates of fisheries recovery than marine ecosystems with lower diversity (Worm et al. 2006, Levin and Lubchenco 2008, Palumbi et al. 2009).

## Biodiversity performing vital roles in Biosphere resilience

Organisms do not just exist and compete in ecosystems; they perform critical functions in ecosystem dynamics and in creating and providing resilience (Walker 1992, Jones et al. 1994, Naeem an Li 1997, Tilman et al. 2014). Resilience refers to the capacity of a system to persist with change, to continue to develop with ever changing environments (Holling 1973, Carpenter et al. 2001, Folke 2006, Folke et al. 2010).

In many ecosystems, like lakes, coral reefs, oceans, forests or arid lands, smooth responses to gradual change can be interrupted by sudden drastic switches to a contrasting state, often referred to as a regime shift (Scheffer et al. 2001, Gunderson and Pritchard 2002). Regime shifts are usually due to a combination of a shock such as a drought or flood, and slow changes in underlying variables and internal feedbacks that change the domains of attraction of the different regimes (Gordon et al. 2008, Rocha et al. 2015). Humans are key players in these dynamics (Folke et al. 2004, Biggs et al. 2009). Although diverse events, like a climate-induced shock, can trigger such shifts, numerous studies have shown that a loss of resilience through human actions is usually the pre-cursor for a state change or different pathway of development (Scheffer et al. 2001, 2012, Cumming and Peterson 2017).

Biodiversity plays significant roles in the operation of ecosystems, in buffering shocks and extreme events, and in regime shift dynamics (Peterson et al. 1998, Folke et al. 2004). The diversity of functional groups and traits of species and populations appears to be critical for resilience and for the generation of ecosystem services (Chapin et al. 1997, Luck et al. 2003, Hooper et al. 2005, Diaz et al. 2007, Sterk et al. 2013). Functional traits are important ecological attributes by which different organisms and biological communities shape ecosystem services through their effects on underlying ecosystem processes (de Bello et al. 2010). Species perform essential functions in ecosystems, for example, pollinate, graze, predate, fix nitrogen, spread seeds, decompose, generate soils, modify water flows, open up patches for reorganization, and contribute to the colonization of such patches (Walker et al. 1999, Bartomeus et al. 2013).

Although species redundancy is essential, variation in responses of species performing the same function, to change like shocks or extreme events, is particularly critical in resilience (Chapin et al. 1997, Nyström 2006, Oliver et al. 2015). Such 'response diversity', serves as insurance for the capacity of ecosystems to regenerate and continue to develop after disturbance (Elmqvist et al. 2003, Bellwood et al. 2004, Bottom et al. 2009, Winfree and Kremen 2009, Chillo et al. 2011), for example, for the resilience of grasslands in performing carbon sequestration (Sasaki et al. 2019). The extent to which ecosystems possess response diversity across landscapes and seascapes is central to their capacity to renew following disturbance, like extreme events, and prevents shifts to undesirable ecosystem states (Bengtsson et al. 2003, Hughes et al. 2007, Mori et al. 2013, Nash et al. 2016, Allen et al. 2016).

The likelihood of ecosystem shifts has increased where humans reduce resilience by such actions as reducing species that confer response diversity, removing whole functional groups of species, or removing whole trophic levels; impacting on ecosystems through emissions of waste and pollutants and from climate change; and altering the magnitude, frequency, and duration of shocks and events. The combined and often synergistic effects of those pressures make ecosystems more vulnerable to changes that previously could be absorbed. They have lost resilience (Folke et al. 2004).

The Amazon rainforest is a prime example. Conserving a diversity of plants species may enable the Amazon forests to adjust to new climate conditions and protect the critical carbon sink function (Sakschewski et al. 2016). Frequent extreme drought events have the potential to destabilize large parts of the Amazon forest but the risk of self-amplified forest loss is reduced with increasing heterogeneity in the response of forest patches to reduced rainfall (Zemp et al. 2017). However, continuous deforestation and simultaneous warming is likely to push the forest towards wide-ranging tipping points (Hirota et al. 2011, Staver et al. 2011). It has been estimated that loss of biodiversity and deforestation exceeding 40% of the forest area or a temperature increase of 4°C may shift the Amazon into a large-scale savanna (Nobre et al. 2016) and with synergies between deforestation, climate change, and extensive use of fire possibly already at 20-25% deforestation (Lovejoy and Nobre 2018). Also, with greater climate variability tree longevity is shortened, thus influencing carbon accumulation and the role of the Amazon forest as a carbon sink (Brienen et al. 2015). A large-scale shift of the Amazon would cause major impacts on wellbeing far outside the Amazon basin through changes in precipitation and climate regulation, and by linking with other tipping elements in the Earth System (Steffen et al. 2018, Lenton et al. 2019, Figure 6).

Hence, the resilience of multifunctional ecosystems across space and time, and in both aquatic and terrestrial environments, depends on the contributions of many species, and their distribution, redundancy, and richness at multitrophic levels performing critical functions in ecosystems and biosphere dynamics (Folke et al. 1996, Isbell et al. 2017, Lefcheck et al. 2015, Reich et al. 2012, Gamfeldt et al. 2013, Nash et al. 2016, Soliveres et al. 2016, Hisano et al. 2019).

It becomes clear that species and biological diversity perform vital roles in Earth resilience, from local ecosystems to the whole planet. They mediate biospheric processes, generate ecosystem services and sustain nature's contributions to people, and adapt and evolve with changing conditions. As a matter of fact, biodiversity and a resilient biosphere is a reflection of life continuously being confronted with uncertainty and the unknown. Diversity builds insurance and keeps systems resilient to changing circumstances.

The acceleration of the human dimension has in several ways eroded the critical role of biodiversity in Earth resilience and thereby increased social and economic vulnerability to changing conditions. These are findings at a time of human-induced climate change where diversity would be needed more than ever to buffer shocks and disturbances.

## The Anthropocene Biosphere and biodiversity loss

Anthropogenic biomes, also known as Anthromes or human biomes, describe the terrestrial biosphere in its contemporary, human-altered form using global ecosystem units defined by global patterns of sustained direct human interaction with ecosystems (Figure 7). They show that more than 75% of Earth's ice-free land is directly altered as a result of human residence and land use, with nearly 90% of terrestrial net primary production and 80% of global tree cover under direct human influence (Ellis and Ramankutty 2008).

Similarly, in the oceans no area is unaffected by human influence and a large fraction (41%) is strongly affected by multiple human drivers (Halpern et al. 2008). Just like the great acceleration on land (Steffen et al. 2015b), there has been a more recent acceleration in the oceans, the blue acceleration (Jouffray et al. 2020). As part of the blue acceleration, the increase of countries claiming an extended continental shelf beyond their exclusive economic zone, to explore and exploit seafloor resources, leaves less than 50% of the vast seabed as humanity's global commons in the oceans (Jouffray et al. 2020).

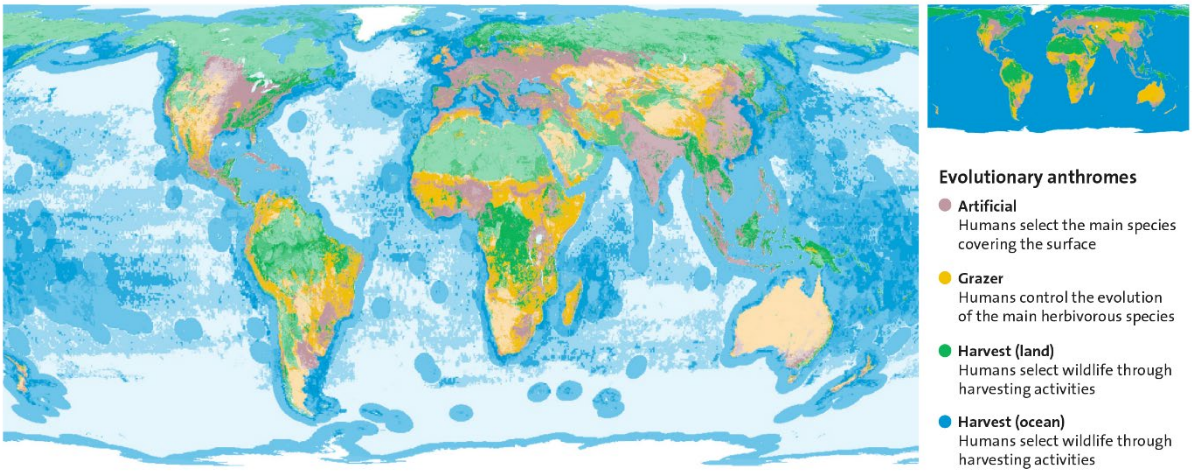

Figure 7. Evolutionary Anthromes, illustrating that human actions not only interact with and shape the Earth's surface, but are also deeply intertwined with all biomes and a major force in setting the stage for evolution on Earth. Darker colors indicate higher intensity of human control (based on Ellis et al. 2010 and modified from Jörgensen et al. 2019).

In addition, as a consequence of rising nutrient loads coupled with warmer temperatures, oxygen concentrations in both the open oceans and coastal waters have been declining since at least the middle of the 20th century. Oxygen is fundamental to life and global cycles of major nutrients and carbon. Oxygen-minimum zones for life in the open ocean have expanded by several million square kilometres (Breitburg et al. 2018, Limburg et al. 2020).

The human dominance is further reflected in the fact that the weight of the current human population is 10 times the weight of all wild mammals. If we add the weight of livestock for human use and consumption to the human weight, only 4% of the weight of all mammals on Earth remain wild mammals. There are about three times more domesticated than wild birds on Earth in terms of biomass (Bar-On et al. 2018).

The human dimension has become a dominant force in shaping evolution of all species on Earth. Through artificial selection and controlled reproduction of crops, livestock, trees, and microorganisms, through varying levels of harvest pressure and selection, through chemicals and pollution altering life-histories of species, and by sculpting the new habitats that blanket the planet, humans, directly and indirectly, determine the constitution of species that succeed and fail (Palumbi 2001, Smith et al. 2014, Jörgensen et al. 2019).

Conversion and degradation of habitats have caused global biodiversity declines and defaunation (human-caused animal loss), with extensive cascading effects in marine, terrestrial, and freshwater ecosystems as a result, altering ecosystem functions and services (Jackson et al. 2001, Worm et al. 2006, Sala and Knowlton 2006, Carpenter et al. 2011, Estes et al. 2011, Newbold et al. 2015, 2018, McCauley et al. 2015).

Rapid and pervasive urbanisation requires large support areas to be sustained (Folke et al. 1997, Grimm et al. 2008). Urbanisation is a force in homogenizing and altering biodiversity in landscapes and seascapes (Seto et al. 2012b, McDonald et al. 2020), and land-use change

(Meyfroidt et al. 2018) accounts for nearly a quarter of all anthropogenic greenhouse gas emissions over the past decade (Arneth et al. 2019). Functional traits in ecosystems, biomass, richness and distributions of species both on land and in the oceans change with climate change (Parmesan 2006, Bjorkman et al. 2018, Pinsky et al. 2018, Lotze et al. 2019, Free et al. 2019).

As a consequence of the human imprint, currently, an average of around 25% of animal and plant species assessed are threatened, suggesting that around 1 million species face extinction, many within decades, and at much higher rates than over the past 10 million years (Diaz et al. 2019). Extinction risks will accelerate with future rises in global surface temperatures (Urban 2015). Extinctions often occur when reductions in populations, restrictions on movement and limitations on the availability of suitable habitats finally take effect (Isbell et al. 2017).

Over the past 50 years of human acceleration, the capacity of nature to support quality of life has declined in 78% of the eighteen categories of nature's contributions to people considered by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). These categories range from pollination and dispersal of seeds and propagules to formation of soils, to regulation of air quality, regulation of extreme events to providing medical, biochemical, and genetic resources, to supporting human identities and maintaining options (Diaz et al. 2019). In addition, such ecosystem simplification and degradation increase the likelihood of disease emergence, including novel viruses (Myers and Patz 2009).

## Homogenization and critical transitions

Much of the Earth's biosphere has been converted into production ecosystems, i.e. ecosystems simplified and homogenised for the production of one or a few harvestable species (Nyström et al. 2019). The increase in homogeneity worldwide denotes the establishment of a global standard food supply, which in regard to crops at the national level is relatively species-rich, but species-poor globally (Khoury et al. 2014). Globally, local varieties and breeds of domesticated plants and animals are disappearing (Diaz et al. 2019). Land-use intensification homogenizes biodiversity in local assemblages of species worldwide (Newbold et al. 2018) and counteracts a positive association between species richness and dietary quality. It also affects other ecosystem services and well-being in low- and middle income countries (Lachat et al. 2018, Vang Rasmussen et al. 2018). In much of the world more than half, up to 90%, of locally adapted varieties of major crop species (e.g. wheat and rice) have been lost due to replacement by single high-yielding varieties (Heal et al. 2004)

The simplification and intensification of production ecosystems and their tight connectivity with international markets has yielded a global production ecosystem that is very efficient in delivering goods to markets, but globally homogenous, highly connected and characterized by weakened internal feedbacks that mask or dilute the signals of loss of ecosystem resilience to consumers (Meyfroidt and Lambin 2009, Bennett et al. 2014, Crona et al. 2016, Ordway et al. 2019, Nyström et al. 2019).

In addition, the global food trade network has over the past 20 years become progressively delocalized as a result of globalization (that is, modularity has been reduced) and as connectivity and homogeneity increase, shocks that were previously contained within a geographic area or a sector are becoming globally contagious and more prevalent (Tamea et al. 2016, Tu et al. 2019, Kummu et al. 2020).

Homogenization reduces the diversity of ways in which species, people, sectors and institutions can respond to change as well as their potential to functionally complement each other (Nyström et al. 2019). In addition, homogeneous landscapes lack the diversity of ecosystem types for resilient responses when a single homogeneous landscape patch, such as a production forest or crop, is devastated by pathogens or declines in economic value (Holling and Meffe 1996). In homogenized systems, resilience, the capacity to live and develop with change and uncertainty, experienced or unknown, gradual or abrupt, has been eroded (Folke et al. 2010, Bennett et al. 2014). Diversity is central in resilience. Loss of resilience implies vulnerability to changing circumstances (Biggs et al. 2012, Grêt-Regamey et al. 2019).

Although these alterations occur at local and regional scales, and increasingly across scales, their cumulative effect is causing global conversion of the Earth's biosphere. In parallel, people, places, cultures and economies are increasingly linked across geographic locations and socioeconomic contexts, making people and planet intertwined at all scales (Folke et al. 2016, Reyers et al. 2018, Nyström et al. 2019).

Evidence suggests that homogenization, simplification, intensification, strong connections, as well as suppression of variance, increase the likelihood of facing critical transitions, or regime shifts, with thresholds and tipping points (Levin 1999, Scheffer et al. 2012, Carpenter et al. 2015). These shifts may interact and cascade, thereby causing change at very large scales with severe implications for the wellbeing of human societies (Hughes et al. 2013, Rocha et al. 2018).

Comparison of the present extent of biosphere conversion with past global-scale regime shifts suggests that global-scale biosphere regime shift is more than plausible. The biotic hallmark for each earlier state change was pronounced change in global, regional and local assemblages of species (Barnosky et al. 2012).

## Planetary boundaries and a safe-operating space for humanity

Staying away from large-scale regional and even global tipping points is clearly in the self-interest of humanity. Therefore, a major challenge is to work towards stabilizing the Earth system and its biosphere in a state that, hopefully, is safe for humanity to operate within, albeit a warmer state than the Holocene and one with a human-dominated biosphere (Rockström et al. 2009, Steffen et al. 2018). Clearly, the climatic system and the biological diversity and functional integrity of the biosphere, as well as their interplay, are foundational for stabilizing and cultivating a resilient Earth system (Barnosky et al. 2012, Steffen et al. 2015, Dasgupta 2020).

Climate and biosphere integrity constitute the two fundamental dimensions of the Planetary Boundaries framework. Together with seven other planetary boundaries (land system change, freshwater use, biogeochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, and novel entities, and their interactions), the framework defines a Holocene-like state of the Earth system (Figure 8). With four of the boundaries, including the two core boundaries, already transgressed, the framework provides a natural-science-based analysis underpinning the observation that global human forcing has already, at the planetary scale, rapidly pushed the Earth system away from the Holocene-like conditions, that have enabled civilisations to emerge and flourish, and onto an accelerating Anthropocene trajectory (Steffen et al. 2015, 2018).

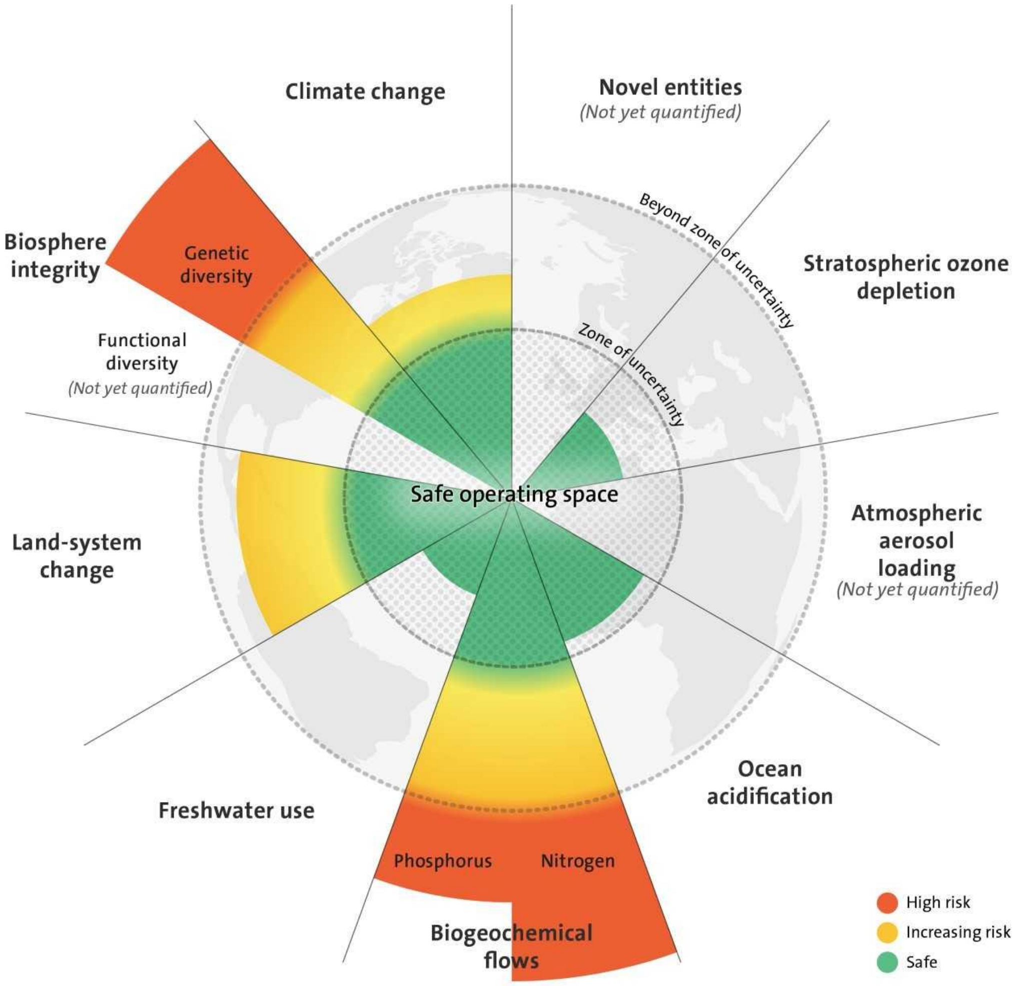

Figure 8. The nine identified planetary boundaries. The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. Processes for which global-level boundaries are not quantified are represented by grey wedges (modified from Steffen et al. 2015).

Within the framework zones of uncertainty have been identified for the nine boundaries. In these potentially dangerous zones of increasing risk, there are likely continental and global tipping points for some of the boundaries, although not for all them. Therefore, it is important to stress that a proposed boundary does not represent a tipping point or a threshold, but is placed upstream of it, that is, well before the risk of crossing a critical threshold. The intent of this buffer between the boundary and a potential threshold in the dangerous zone is to allow society time to react to early warning signs of approaching abrupt or risky change (Rockström et al. 2009b, Steffen et al. 2015).

In recent years, there have been several efforts to further investigate and deepen the understanding of planetary boundaries and the safe-operating space for humanity. These include updates on the biodiversity boundary, the freshwater boundary, and the biogeochemical flows (Carpenter and Bennett 2011, de Vries et al. 2013, Mace et al. 2014, Newbold et al. 2016, Gleeson et al. 2020b), multiple regime shifts and possible links between regional and planetary tipping points (Anderies et al. 2013, Hughes et al. 2013), regional perspectives on the framework (Häyhä et al. 2016, O'Neill et al. 2018) and creating safe operating spaces (Scheffer et al. 2015). There are also propositions for integrating the Planetary Boundaries framework with economic, social and human dimensions (Raworth 2012, Dearing et al. 2014, Downing et al. 2019) as well as tackling the policy and governance challenges associated with the approach (Biermann et al. 2012, Galaz et al. 2012, Sterner et al. 2019, Pickering and Persson 2020).

The Planetary Boundaries framework has attracted considerable interest and discussions within the policy, governance, and business sectors as an approach to inform efforts toward global sustainability. For example, it was highlighted as essential in the report of the United Nations Secretary-General's High-Level Panel on Global Sustainability 'Resilient Planet, Resilient People, A Future worth Choosing'. Another striking example is the EAT-Lancet Commission's report on healthy and sustainable food systems. Here, the global food system is placed within the framework of planetary boundaries to define a safe-operating space for human health and food production aimed at ensuring healthy diets from sustainable food systems for nearly 10 billion people by 2050 (Willett et al. 2019). Finally, recent attempts to quantify interactions between planetary boundaries suggest that cascades and feedbacks predominantly amplify human impacts on the Earth system and thereby shrink the safe operating space for human actions in the Anthropocene (Lade et al. 2020).

In light of the profound challenges of navigating the future of human societies towards a Stabilized Earth state (Steffen et al. 2018), it becomes clear that modest adjustments on current pathways of societal development are not very likely to guide humanity into sustainable futures. Stabilising the Earth System in a safe-operating space will require rapid, transformative changes in many dimension of human actions and relations (Westley et al. 2011, Tallis et al. 2018, Clark and Harvey 2020).

## Inequality and global sustainability

Rising inequality in income, wealth, and political power is a major social concern, largely because of issues regarding fairness, lack of progress on poverty alleviation, and potential negative impacts on democratic processes, and the economy (Stiglitz 2012, Piketty 2014, UNDP 2019).

Additionally, there are also important and complex interconnections between inequality, the environment, and global sustainability (Leach et al. 2018). Greater inequality may make the challenge of achieving global sustainability more difficult. Conversely, global environmental change and unsustainable practices may exacerbate inequalities (Hamann et al. 2018) (Figure 9). Excessive inequality may lead to weaker economic performance and cause economic instability (Stiglitz 2012). Increasing income inequality may also leads to more societal tension and increase the odds of conflict (Wilkinson and Pickett 2009, Durante et al. 2017).

The majority of countries for which adequate data exists have seen rising inequality in income and wealth over the past several decades (Piketty 2014, World Inequality Report 2018). In the U.S., the share of income going to the top 1% rose from around 11% in 1980 to above 20% in 2016, and the top 1% now earn more income than the bottom 50% (World Inequality Report 2018). Wealth tends to be even more unequally distributed. For example, in the U.S. the share of wealth of the top 0.1% more than tripled between 1978 and 2012, and is roughly equal to the share of wealth of the bottom 90% (Saez and Zucman 2016). In the US, Europe, and China, the top 10% of the population own 70% of the wealth, while the bottom 50% own only 2% (World Inequality Report 2018).

Though inequality is rising within countries, global inequality has not increased as rapidly because the economies of many lower- and middle-income countries have been growing faster than the economies of high-income countries. Nevertheless, about 10% of the world population in 2015, or some 740 million people, were living in extreme poverty (World Bank 2019). Furthermore, inequality within cities, the dominant living environment of the human population, is widespread. Seventy-five per cent of the world’s cities have higher levels of income inequalities than two decades ago, and the spatial concentration of low-income unskilled workers in segregated residential areas acts as a poverty trap (UN-Habitat 2016).

Inequality may give rise to perceptions, behaviour, and social norms about status and wealth, and disparities in worth and cultural membership between groups in a society - so called “recognition gaps”. Inclusive cultural membership is an important dimension of collective well-being that often is given less weight than other economic, demographic, and political measures (Lamont 2018). Social norms are also important in supporting actions that may help or hurt in trying to achieve global sustainability in a number of other dimensions ranging from use of energy and other resources to fertility (Nyborg et al. 2016, Barrett et al. 2020). Also, gender inequality may have important reinforcing feedbacks with environmental change (Bongaarts and O’Neill 2018, Fortnam et al. 2019) and has, for example, been shown to change with shifts in tropical land-use in Indonesia (Maharani et al. 2019) or with changes in levels of direct use of local ecosystem services by households in South Africa (Hamann et al. 2015).

If status and self-esteem are tied to relative income and wealth accumulation, there can be a never ending race for higher incomes and greater wealth accumulation as each person strives to climb higher in the social rankings (Veblen 1899, Frank 1985). But since one person's gain in social ranking is another person's loss, further growth in income does not necessarily translate to gains in overall well-being. Greater economic activity may lead to all racing harder to stay in the same place, and lead to globally unsustainable trajectories.

Many sustainability challenges require cooperation to manage common pool resources, from communal pastures, healthy oceans, to climate change (Dietz et al. 2003, Folke et al. 2005, Barrett 2016, Bodin 2017, Bennett et al. 2019). Inequality can have negative impacts on the sense of community and common purpose and make successful management of common pool resources less likely (Ostrom 1990). A consistent theme that has hindered progress in negotiations under the U.N. Convention on Climate Change has been the "north-south" debate among countries over who should bear more of the burden of the costs of reducing greenhouse gas emissions (Anand 2017). These debates involve ethical judgements about differentiated responsibilities related to differential past contributions to atmospheric greenhouse gases, current economic and social circumstances, and likely future growth. It is harder to agree on differentiated responsibilities than it is to agree on proportionally equal responsibilities among parties that are all roughly in the same situation.

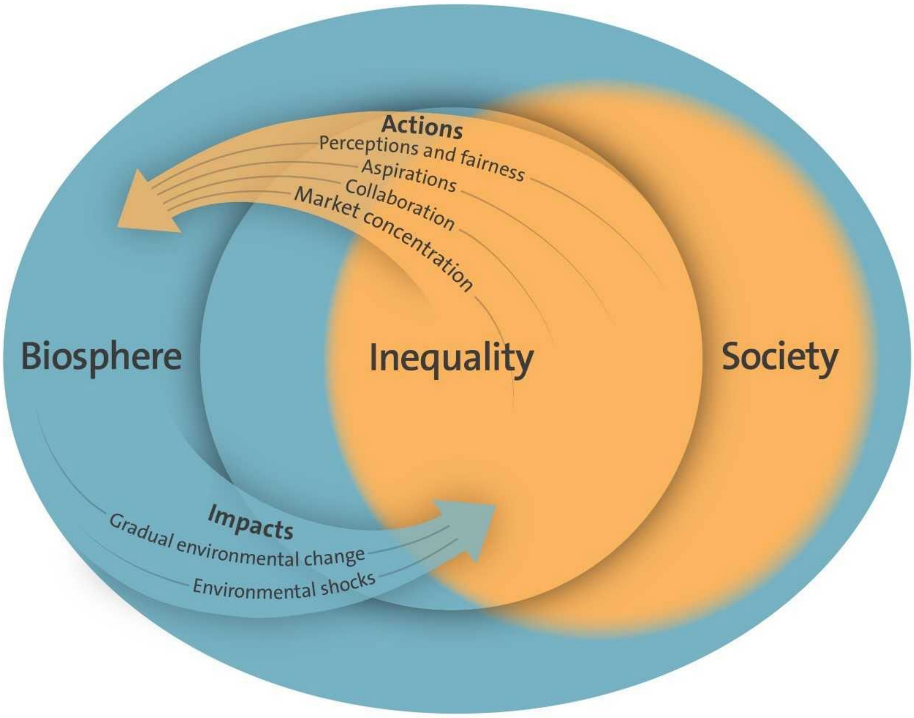

Figure 9. Examples of pathways of interactions between inequality and the biosphere in intertwined systems of people and nature (modified from Hamann et al. 2018).

## Inequality, poverty and climate change

Poor people in low-income countries are highly dependent on their local environment (World Bank 2003, Barbier 2005, Kates and Dasgupta 2007, Leichenco and Silva 2014). Greater inequality can lead directly to more rapid environmental degradation, because low incomes lead to low investment in physical capital and education (human capital). Such situations often cause excessive pressure and degradation of natural capital leading to declining incomes and further degradation in a downward spiral, a poverty trap (Dasgupta 1995b, Bowles et al. 2006, Barrett and Bevis 2015). Furthermore, interventions that ignore nature and culture can reinforce poverty traps (Lade et al. 2017), and economic and environmental shocks, food insecurity and climate change may force people back into poverty (UNDP, Wood et al. 2018).

The poor are more vulnerable to climate change (Althor et al. 2016, Hsiang et al. 2017, UNDP 2019) and to environmental shocks such as floods and droughts (Carter et al. 2008, Hallegatte et al. 2016). The Covid-19 pandemic has further exposed the inequality in vulnerability to shocks among the poor and marginalized, feeding off existing inequalities and making them worse. Because they have less agency and fewer resources at their disposal, the poor have lower capacity to deal with shocks (Brown and Westaway 2011, Brown 2016). Similarly, access to freshwater has built wealth for advantaged communities, whereas poor communities have often been confronted with degraded water quality and infrastructure disinvestments (Keeler et al. 2020). Public investment in universal education in poor countries and communities within countries in the near future is of significance for enhancing societies' adaptive capacity vis-à-vis future climate change (Lutz et al. 2014). Educating girls and having access to contraception have been shown to be significant factors in reducing the number of births per woman and slowing population growth (Jejeebhoy 1995, Kebede et al. 2019).

Poor countries are thought to suffer the bulk of the damages from climate change, not only because of poverty but also due to their location in low latitudes where further warming pushes these countries ever further away from optimal temperatures for climate-sensitive economic sectors (Mendelsohn et al. 2006, King and Harrington 2018). Examples include countries with high numbers of vulnerable, poor or marginalized people in climate-sensitive systems like deltas, semi-arid lands, and river basins dependent on glaciers and snowmelt (Conway et al. 2019).

Climate-related shocks to international agricultural production and food supply chains can, through interaction with multiple other factors, result in food price spikes and reduced access to food for vulnerable groups (Challinor et al. 2017). Under future scenarios of land use and climate change, up to 5 billion people face higher water pollution and insufficient pollination for nutrition, particularly in Africa and South Asia. Hundreds of millions of people face heightened coastal risk across Africa, Eurasia, and the Americas (Chaplin-Kramer et al. 2019). Emerging risks from climate-related displacements of populations affect all countries, even those remote from the risks themselves (Xu et al. 2020).

## Ocean inequity - a special case

While inequality describes an unequal distribution of a scarce resource, benefit, or cost, and does not necessarily represent a normative statement, inequity is a more normative term that evokes an unfair or unjust distribution of privileges across society (Hamann et al. 2018).

In the oceans, inequity manifests, for example, in skewed distribution of commercial fish catches, limited political power of small-scale fishers, particularly women and other minority groups, limited engagement of developing nations in high-seas activities and associated decision-making, and consolidated interests of global supply chains in a few transnational corporations, with evidence of poor transparency and human rights abuses (Bennett et al. 2019, Österblom et al. 2020).

The patterns of inequity are consistent across geographical scales (from local to global) and can be found in all sectors (Österblom et al. 2019). The results of inequity include negative impacts on marine ecosystems and, a loss of livelihoods and limited financial opportunities, and increased vulnerabilities of already marginalised groups, who are facing nutritional and food security challenges (Harper et al. 2013, Hicks et al. 2019). The mechanisms upholding inequity include existing norms and formal social institutions (Crona and Bodin 2010, Felipe-Lucia et al. 2015) as well as historical and colonial legacies, insecure territorial and tenure rights, and limited financial resources or technological capacity (Bourguignon 2015).

Climate change is projected to disproportionally affect marine and coastal ecosystems and communities in least developed countries, particularly small-island development states (Barnett and Campbell 2010), and disproportionally influence disadvantaged groups, especially women, girls and indigenous communities (Islam and Winkel 2017).

A projected rise in developing nations' inequity is not only due to projected climatological changes but also to the sensitivity of coastal communities to shifts in the distribution and abundance of fish stocks crucial to their livelihoods and nutrition (Blasiak et al. 2017). This accentuated sensitivity is coupled with comparatively low levels of adaptive capacity, as remote coastal communities often have limited access to education, health services and alternative livelihoods, all of which could buffer the projected negative impacts from climate change (Cinner et al. 2018).

As a means to improve fish abundance for coastal communities of developing nations, there have been suggestions of closing the high seas to fishing through the use of regulatory "clubs", which refers to groups of states that commit to a set of international rules (Green and Rudyk 2020). It has been suggested that closing the high seas would not only slow the pace of overfishing, but would also cause stocks to migrate into countries' Exclusive Economic Zones (EEZs). It has been estimated that closing the high seas could be catch-neutral while inequality in the distribution of fisheries benefits among the world's maritime countries could be reduced by 50% (Sumaila et al. 2015).

## Wellbeing and sustainability

It has been proposed that many systems tend to self-organise towards a situation where wealth will inevitably be appropriated by a very small fraction of the population unless effective wealth-equalizing institutions emerge at the global level (Scheffer et al. 2017). Measures to counteract such self-organisation, ranging from regulations to economic incentives, or from better corporate governance to investment in public goods, such as education, health, and biosphere stewardship are essential to tackle existing wealth inequalities and prevent further increases in inequality (Stiglitz 2012, Alvaredo et al. 2018, Chapin 2020).

Inclusive (or genuine) wealth aims at capturing the aggregate value of all capital assets to provide a comprehensive, long-term foundation for human wellbeing (Dasgupta and Mäler 2000, Polasky et al. 2015). By incorporating costs associated with externalities in natural capital (renewable and non-renewable natural resources, ecosystem services), human capital (the capacity of people to accomplish their goals through education and training) and social capital (empowerment of people to act collectively to solve problems) (Daly and Costanza 1992, Brondizio et al. 2006), inclusive wealth provides a basis for designing incentives for more sustainable market transactions (Dasgupta 2014, Clark and Harley 2019).

Produced capital and human capital have no doubt increased by many-fold, but as a stock of natural capital the biosphere has shrunk considerably, implying that the huge rise in economic activity has been built upon unsustainable foundations (Costanza 1991, Arrow et al. 1995, Barrett et al. 2020). The ultimate challenge is to shift the trends of preceding decades that have lifted many people out of poverty and extended life spans, but in the process been running down the planet's natural capital and resilience (Dasgupta and Ramanathan 2014, Nyström et al. 2019, Dasgupta 2020). Such a challenge will require actively working to reduce and redirect growing inequalities and develop all-encompassing collaboration and collective action within and between countries.

Reducing inequality and poverty is a central objective of the U.N. Sustainable Development Goals agreed to by national governments. Achieving global sustainability is another important set of objectives in the Sustainable Development Goals. However, simultaneously reducing poverty and achieving global sustainability in a manner that is politically palatable is quite challenging. Raising the entire global population to a decent standard of living requires a large increase in income going to the lower end of the income distribution. In principle this could be done by redistributing income from those who live well above the level needed for a decent standard of living. But redistribution is politically unpopular and may be blocked by those for whom redistribution would take away income or wealth. Without redistribution, however, the scale of the income increase necessary to bring every person on the planet up to a decent standard of living is daunting. For example, trying to increase over a global population estimated to be nearly 10 billion in 2050 (UN 2019) to a per capita income of $50,000 similar to the current per capita income in many developed countries would require increasing global GDP to $500 trillion, which is almost a 6-fold increase from current global GDP of $86 trillion (World Bank 2019). Achieving global sustainability with such a large scale increase in economic activity could only be done by a fundamental transformation of the economy and human impacts on the biosphere (Tallis et al. 2018, Diaz et al. 2019).

## Societal transformation and technological change

Currently, there are signs that human societies are moving out of the industrial revolution era into a new era of development. Science has illustrated that as living systems approach major transitions they tend to start fluctuating more wildly (Scheffer et al. 2012, Carpenter et al. 2019). The interconnected globalized world is currently confronted with uncertain futures, extremes, and turbulent times (pandemics, climate change, political tension, extreme events, rising inequality, fake news, etc.). Information technologies allow information to travel fast, and the participatory nature of new media give it a central role in shaping individual attitudes, feelings and behaviours (Williams et al. 2015, Lazer et al. 2018), can underpin large social mobilization and protests (Steinert-Threlkeld et al. 2015), and influence social norms and policy-making (Barbéra et al. 2019, Stewart et al. 2019).

Clearly, technological change such as information technology, artificial intelligence, and synthetic biology will drastically change economies, human relations, social organisation, culture and civilization, creating new unknown futures. However, technological change alone will not lead to transformations towards sustainability. It could take humanity into diverse directions, pleasant and unpleasant ones, and with different distributional impacts. Therefore, the technological dimension of development has to be deliberately and strategically guided to contribute to sustainable futures (Westley et al. 2011, Galaz 2014).

On the other hand, transformations to sustainability are unlikely to happen without the deployment of technologies that, e.g., help build resilience and development on the ground (Brown 2016, USAID 2018), support transformations of current food production and innovation systems (Gordon et al. 2017, Reardon et al. 2019), and contribute to a shift towards carbon neutral (or even negative) energy systems (Rockström et al. 2017).

### Novel technologies and sustainability

Much of the discussions about the importance to direct technological change towards sustainability has centered on technologies associated with sectors with substantial impacts on the climate system, such as energy production, transportation, and agriculture, including the potential role of technologies that could help actively remove greenhouse gases from the atmosphere.

In general, the following categories of new technologies will and are already having bearing on global sustainability: the diversity of existing and emerging renewable energy technologies, like solar cells, hydrogen energy, wind generators, or geothermal heating; the digital transformation, with Artificial Intelligence (AI), satellite monitoring, quantum computing, and precision agriculture; synthetic biology, including biotechnology and genetic and molecular engineering, by redesigning and using organisms to solve problems in medicine, manufacturing and agriculture; mechanical engineering, like robotics and also nanotechnology. They should be considered as essential part of the way forward when designing transformative pathways towards sustainability.

As human pressures on the biosphere increase, so does the hope that rapid advances in AI (including automated decision making, data mining and predictive analytics) in combination with rapid progresses in sensor technology and robotics, will be able to increase society's capacities to detect, adapt and respond to climate and environmental change without creating new vulnerabilities (Joppa 2017).

Such technologies are already now being applied in a number of research fields related to the environment and climate change including environmental monitoring, conservation and "green" urban planning (Reichstein et al. 2019, Hino et al. 2018, Wearn et al. 2019, Ilieva and McPhearson 2018). A recent synthesis also points at possible applications related to the Sustainable Development Goals (Vinuesa et al. 2020). While nascent in terms of both scale and impact, such early applications should be viewed as examples of technological "niche-innovations" with the potential to rapidly upscale and shape ecosystems and institutions in multiple geographies (Geels et al. 2017). Such innovations have been claimed to be central for a "digital revolution for sustainable development" (Sachs et al. 2019).

Applications of these technologies are likely to have effects that span beyond climate and environmental research and monitoring, and more efficient natural resource use and extraction. AI-supported recommender systems as an example, influence consumer choices already today (André et al. 2018). Targeted attacks in social media by social bots, applications of computer algorithms that automatically produce content and interact with humans on social media, "trying to emulate and possibly alter their behavior" (Ferrara et al. 2016, Grinberg et al. 2019), also influence conversations in social media about climate and environmental issues (Garcia et al. 2019) and affect institutions for deliberative democracy (Dryzek et al. 2019).

So far, the technological changes to our social systems have not come about with the purpose of promoting global sustainability (van der Leeuw 2019). This remains true of recent and emerging technologies, such as online social media and information technology, causing changes that are increasingly far-reaching, ambiguous, and largely unregulated (Del Vicario et al. 2016, Bak-Coleman et al. in review). For example, online social networks are highly dynamic systems that change as a result of numerous feedbacks between people and machines. Algorithms suggest connections and people respond, and the algorithms, trained to optimize user experience, adapt to the responses. Together, these interactions and processes alter what information people see and how they view the world (Bergstrom and Bak-Coleman 2019).

Hence, applications of novel technologies stemming from advancements in AI could at best be benevolent, and lead to improved stewardship of landscapes, seascapes, water or climate dynamics, through improved monitoring and interventions, as well as more effective resource use. Negative impacts of social media on vulnerable groups (Barocas et al. 2017) are also pertinent because these technologies diffuse rapidly into society and in sectors with clear impacts on land and ocean ecosystems and the climate system. This issue needs to be taken seriously as technological changes influence decisions with very long-term climatic and biosphere consequences (Galaz 2019, Cave and Óhéigeartaigh 2019).

## Social media and social change

It is well known that dire warnings can lead to disconnect of the audience if it is not accompanied by a feasible perspective for action. Social media provides and changes our perception of the world, by promoting a sense of crisis and unfairness, but also facilitating social self-organization in novel ways, providing a powerful drive for social change.

On the worrying side, isolationism stimulated by social-media-boosted discontent may hamper global cooperation needed to curb global warming, biodiversity loss, wealth concentration, and other trends. On the other hand, social media has powered movements such as school strikes, extinction rebellion, voluntary simplicity, bartering, flight-shame, the eat-local movement and veganism to promote a steadily rising global awareness of pressing issues, that may ultimately shift social norms (Nyborg et al. 2016, Barrett et al. 2020), trigger reforms towards sustainability (Otto et al. 2020) and perhaps also wealth equalization at all institutional levels (Scheffer et al. 2017).

The combination of discontent and self-organization promotes rebellion against the old way of doing things, as in street protests, populist votes, radicalization and terrorism, but also catalyses the search for alternative ways, as in bartering and sharing platforms, or voluntary simplicity and other lifestyle movements (Carpenter et al. 2019).

The rise of social media and technologies such as bots and profiling has been explosive, and the mere rate of change has made it difficult for society to keep pace. Crowd-sourced fact checking may be combined with computer assisted analyses and judgements from professionals (Hassan et al. 2009), and labelling quality of media sources ranging from internet fora to newspapers and television stations may alert users to the risk of disinformation and heavy political bias (Pennycook and Rand 2019). With time, such approaches together with legislation, best-practice agreements, and individual skills of judging the quality of sources may catch up to control some of the negative side-effects.

The emerging picture is that social media have become a global catalyst for social change by facilitating shifts on scales ranging from individual attitudes to broad social norms and institutions. It remains unclear, however, whether this new ‘invisible hand’ will move the world on more sustainable and just pathways. Can the global, fast moving capacity for information sharing and knowledge generation through social media help lead us towards a just world where future generations thrive within the limits of our planet’s capacity (Scheffer 2020)?

## Social innovation and transformation

According to *Our Common Journey: Transitions toward sustainability* (1999) “the primary goals of a transition toward sustainability over the next two generations should be to meet the needs of a much larger but stabilizing human population, to sustain the life support systems of the planet, and to substantially reduce hunger and poverty.” The metaphors of journey and navigation used in the report reflect the view shared here that the pathways of a transition to sustainability cannot be charted fully in advance but will be a collective, uncertain and ongoing adaptive endeavour involving social learning in response to dynamic change (Clark et al. 2001, Folke et al. 2005, Pahl-Wostl et al. 2007, Chaffin and Gunderson 2016).

However, there is consensus arising that transitions toward sustainability in the Anthropocene will not be achieved by adaptation alone, and certainly not by incremental change only, but rather that more fundamental systemic transformations will be needed (Walker et al. 2009b, Biermann et al. 2012b, Hackmann and St. Clair 2012, Kates et al. 2012, Leach et al. 2012, O'Brien 2012, Olsson et al. 2017, Diaz et al. 2019, Elmqvist et al. 2019).

Transformation implies fundamentally rewiring the system, its structure, functions, feedbacks, and properties (Reyers et al. 2018). But, despite such changes, there is hope for smooth profound systemic transformations, with dignity, respect and in democratic fashions (Feola 2015), instead of large-scale disruptive or revolutionary societal transformations like those of earlier civilizations (Tainter 1988, Redman 1999, Diamond 2005, van der Leeuw 2019). It will require trust building, cooperation, collective action and solid institutions.

A characteristic feature of transformations is that change across different system states (trajectories or pathways) is not predetermined, but rather emerges through diverse interactions across scales and among diverse actors (Westley et al. 2011, Longhurst and Chilvers 2019). Therefore, the literature on transformations towards sustainability emphasize framing and navigating transformations rather than controlling those (Leach et al. 2010). Work on socio-technical sustainability transitions, social-ecological transformations, and social innovation provide insights into these dynamics (Geels and Schot 2007, Olsson et al. 2014, Patterson et al. 2017, Westley et al. 2017).

These literatures have illustrated the importance of connectivity and cross-level interactions for understanding the role of technological and social innovation and transformative systemic change (Westley et al. 2011, Loorbach et al. 2017). The work emphasizes the importance of fostering diverse forms of novelty and innovations at the micro-level, supported by the creation of 'transformative spaces', shielded from the forces of dominant system structures. These allow for experimentation with new mental models, ideas, and practices that could help shift societies onto more desirable pathways (Loorbach 2010, Pereira et al. 2018). The examples of the Seeds of a Good Anthropocene project reflect ongoing local experiments that, under the right conditions, could accelerate the adoption of pathways to transformative change (Bennett et al. 2016).

It has been shown that real world transformations come about through the alignment of mutually reinforcing processes within and between multiple levels. For example, the alignment of 'niche innovations' or 'shadow networks' (which differ radically from the dominant existing system but have been able to gain a foothold in particular market niches or geographical areas) with change at broader levels and scales can create rapid change. Both slow moving trends (e.g., demographics, ideologies, accumulation of GHG) and sudden shocks (e.g., elections, economic crises, pandemics, extreme events) can start to weaken or disturb the existing institutional system and create windows-of-opportunity for niche innovations - new practices, governance systems, value orientations - to become rapidly dominant (Olsson et al. 2004, 2008, Smith et al. 2005, Chaffin and Gunderson 2016, Geels et al. 2017) (Figure 10).

Hence, turbulent times may unlock gridlocks and traps and open up space for new things to happen, for innovation and novelty (Gunderson and Holling 2002). Key individuals, often referred to as policy, institutional or moral entrepreneurs, mobilize and combine social networks in new ways, preparing the system for change (Olsson et al. 2004, 2008, Moore and Westley 2011, Westley et al. 2013, O'Brien 2015, Antadze and McGowan 2017). Bridging organisations tend to emerge, within or with new institutions, connecting governance levels and spatial and temporal scales (Cash et al. 2006, Hahn et al. 2006, Brondizio et al. 2009, Rathwell and Peterson 2012). In several cases, the broader social contexts provide an enabling environment for such emergence, for example through various incentive structures or legal frameworks. When a window opens, there is skilful navigation of change past thresholds or tipping points, and thereafter a focus on building the resilience of the transformed system (Chapin et al. 2010, Gelcich et al. 2010, Moore et al. 2014, Schultz et al. 2015).

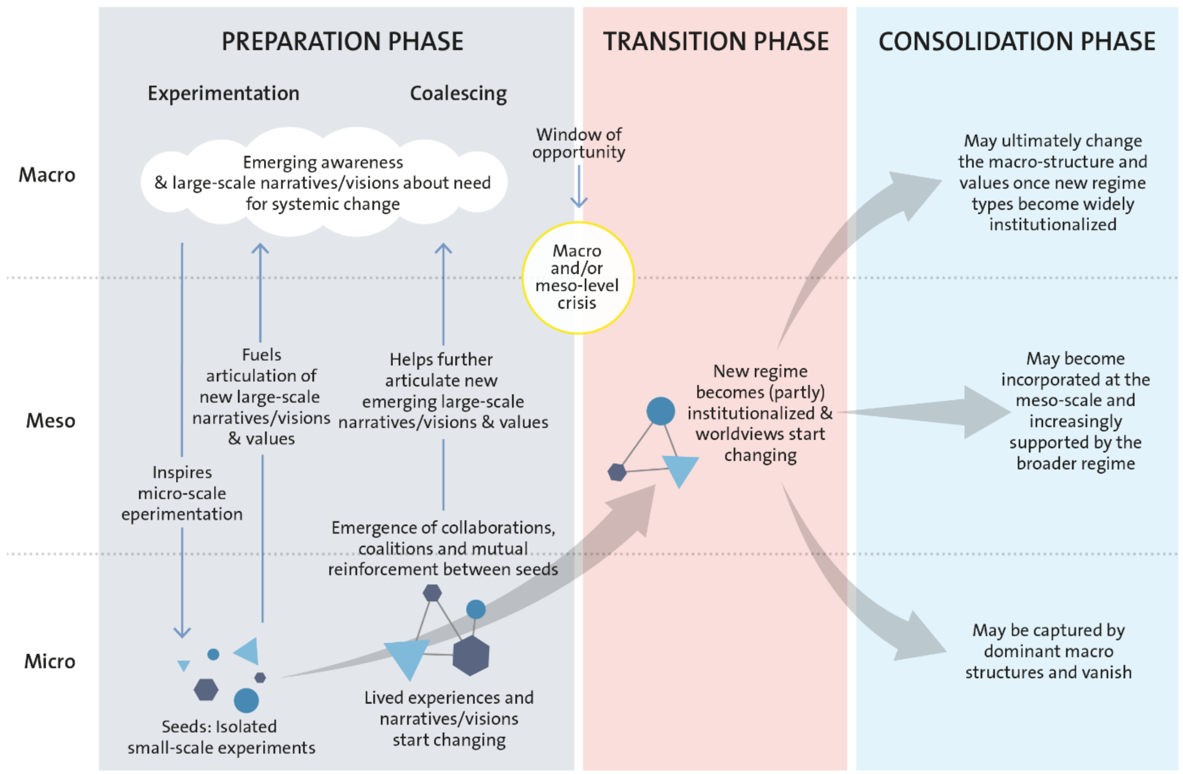

Figure 10. The transformation process. A social innovation matures to the extent that the initiative becomes *prepared for change*. And when change happens, when the *window-of-opportunity* unlocks at broader levels of governance, often in relation to disturbance, the new initiative can be skilfully *navigated through the window and transitioned* into a new development pathway, making it possible to transform the governance system and start *building resilience of the new situation* and taking it to scale (based on Olsson et al. 2004, Geels et al. 2017, Herrfahrdt-Pähle et al. 2020).

Generally, the resulting transformation goes beyond the adoption of a new technology or a local social innovation alone. Instead it includes a portfolio of actions like investment in new infrastructures, establishment of new markets, development of new social preferences, or adjustment of user practices. Furthermore, transformations gain momentum when multiple innovations are linked together, improving the functionality of each and acting in combination to reconfigure systems (Arthur 2009, Geels et al. 2017, Westley et al. 2017).

Successful social innovations are recognized by their capacity to radically shift broad social institutions (economies, political philosophies, laws, practices and cultural beliefs) that provide structure to social life (Westley at al. 2016, 2017). In addition, social innovations seldom unfold in a deterministic manner, but with a kind of punctuated equilibrium, first languishing and then accelerating at times of opportunity or crisis. There is also the need for awareness of the shadow side of all innovation, the consequences of intervention in a complex system (Holling and Meffe 1996). This is unavoidable but manageable if caught early, but needs attention, particularly in times of rapid change (Westley et al. 2017).

Social innovation is currently underway in many domains linked to climate change, like renewable energy (Geels et al. 2017) or agriculture (Pigford et al. 2018) and highlight the importance of innovations not only in science and technology, but also in institutions, politics, and social goals for sustainability. However, for these to have transformative impact, cultural shifts similar to those that accelerated the anti-smoking movement and the gay marriage movement need to occur (Marshall et al. 2012, Nyborg et al. 2016, Moore et al. 2015).

There are suggestions for social tipping interventions to activate large-scale systemic shifts through e.g. rapidly spreading of technologies, shifts in social norms and behaviors, or structural reorganization of sectors, corporations and societies (Geels et al. 2017, Folke et al. 2019, Otto et al. 2020). There are signs that such shifts are underway in western cultures, a desire for fundamental change towards a more sustainable way of life (Wibeck et al. 2019) aided by social movements such as that led by Greta Thunberg and the youth-led Extinction Rebellion, as well as a strong move to more healthy and sustainable diets (Carpenter et al. 2019, Grisby 2004, Willet et al. 2019). Again, all these changes can only unfold against a backdrop of cultural transformation, the slow variable that needs attention as urgently as the decarbonization of our economy (Fogarty et al. 2015, Creanza et al. 2017).

## Narratives of action for the future

Narratives are ways of presenting or understanding a situation or series of events that reflects and promotes a particular point of view or set of values. Narratives can serve as meaning-making devices, provide actors with confidence to act and coordinate action. They are of significance in shaping and anchoring worldviews, identities, and social interactions (van der Leeuw 2019b).

Narratives of hope have proven essential for social resilience (Markus and Nurios 1986, Eggerman and Bricks 2010, Lamont 2019). Social resilience refers to the capacity of individuals, groups, communities and nations to secure favourable outcomes (material, symbolic, emotional) under new circumstances and when necessary by new means, even when this entails significant modifications to behaviour or to the social frameworks that structure and give meaning to behaviour (Hall and Lamont 2012).

Transforming towards sustainable futures will require broadening cultural membership by promoting new narratives that resonate, inspire, and provide hope centred on a plurality of criteria of worth and social inclusion. Here, we are concerned with the challenge of motivating a collective recognition of our interdependence with the biosphere and economic and political action based on that recognition.

Collective conceptions of the future have many aspects. They include: 1) whether the future is conceived as near or far and is understood in terms of long, medium and short-term rewards; 2) what is likely and possible and how contingent these outcomes are; 3) whether the future will be good or bad; 4) how much agency individuals have on various aspects of their individual and collective future (concerning for instance, politics, societal orientation, personal and professional life; 5) who can influence the collective future (e.g., the role of the state policies and various societal forces in shaping them); 6) whether the future is conceived as a cyclical or as a linear progression; 7) how stable our conceptions of the future is and how they are influenced by events (terrorist attacks, recessions, pandemics); and 8) whether aspirations are concealed or made public.

Behind these various issues one finds other basic conceptions about agency (are individuals master of their fate), the impact of networks (how much is fate influenced by peers, family and others), the impact of social structure (what is the impact of class, race, gender, place of origin) on where we end up, and how much does our environment (segregation, resource availability, environmental conditions) influence our opportunities. Therefore, it is important to remember that, although individuals play essential roles in narratives of hope, such images of the future are seldom creations of individuals alone, but shaped by many cultural intermediaries working in the media, in education, in politics, in social movements and in other institutions that feed our societal and cultural scripts and cultural repertoires.[7]

Narratives of hope as cultural scripts are more likely to become widely shared if they offer possible course of action, something that reasonable people can aspire to. This sharing bolsters people’s sense of agency, the perception that they can have an impact on the world and on their own lives, that they can actually achieve what is offered to them. In contrast to doomsday or climate-denying narratives (Oreskes and Conway 2010), these scripts feed a sense of active agency. Such ‘fictional expectations’, anchored in narratives that are continually adapted, are at the core of market dynamics confronted with an uncertain future affecting money and credit, investment, innovation, and consumption (Beckert 2016).

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[7] Cultural scripts represent commonly held assumptions about social interaction, and serve as a kind of interpretive background against which individuals position their own acts and those of others. Cultural repertoires refer to available schemas, frames, narratives, scripts and boundaries that actors draw on in social situations (Lamont et al. 2017).

Narratives of hope represent ideas about ‘imagined futures’ or alternative ways of visualizing and conceptualizing what has yet to happen and motivate action towards new development pathways (Mische 2009, Jasanoff and Kim 2015, Milkoreit 2017). As they circulate and become more widely shared, such imagined futures have the potential to foster predictable behaviours. These in turn can stimulate new laws, regulations, and investments in research and development of new technologies that fit the aspirations of the imagined futures. Therefore, decisions under uncertainty are not simply technical problems easily dealt with by rational calculation, but are also a function of the creative elements of decision-making (Beckert and Bronk 2018).

There is a rich literature on scenarios for sustainable futures, narratives articulating multiple alternative futures in relation to critical uncertainties, increasingly emphasizing new forms of governance, technology as a bridge between people and the deep reconnection of humanity to the biosphere, and engaging diverse stakeholder in participatory processes as part of the scenario work (Peterson et al. 2003, Swart et al. 2004, Carpenter et al. 2006, Hamann et al. 2020).

Research has convincingly demonstrated that heterogeneity, nonlinearities, and innovation characterize the Anthropocene with development pathways that cannot be fully predicted in advance. Causes, at times simple, are always multiple (Gunderson and Holling 2002). The implication of inherent unpredictability is that transformations towards sustainable and just futures can realistically be pursued only through strategies that not only attend to the dynamics of the system, but also nurture our collective capacity to guide development pathways in a dynamic, adaptive, and reflexive manner (Clark and Harley 2020, Freeman et al. 2020). Rather than striving to attain some particular future it calls for a system of guided self-organization (Propenko 2009). It involves anticipating and imagining futures and behaving and acting on those in a manner that does not lead to loss of opportunities to live with changing circumstances, or even better enhances those opportunities, i.e. builds resilience for complexity and change (Berkes et al. 2003, Folke 2006).

In order to better understand the complex dynamics of the Anthropocene and uncertain futures, work is now emerging on human behaviour as part of complex adaptive systems (Levin et al. 2013), like anticipatory behaviour (using the future in actual decision processes), or capturing behaviour as both ‘enculturated’ and ‘enearthed’ and co-evolving with socio-cultural and biophysical contexts (Boyd et al. 2015, Waring et al. 2015, Hoff and Stiglitz 2016, Poli 2017, Haider and van Oudenhoven 2018, Mercon et al. 2019, Schill et al. 2019, Schlüter et al. 2019), illustrating that cultural transmission and evolution can be both continuous and abrupt (Kolodny et al. 2016, Creanza et al. 2017).

Narratives of hope for transformations towards sustainable futures are in demand. Clearly, technological change plays a central role in any societal transformation. Technological change has been instrumental in globalisation and will be instrumental for global sustainability. No doubt, the new era of technological breakthroughs will radically change the structure and operation of societies and cultures. But, as has been made clear here, the recipe for sustainable futures also concerns cultural transformations that guide technological change in support of a resilient biosphere, that reconnect development to the biosphere foundation.

## Biosphere stewardship for prosperity

Transformation towards sustainability in the Anthropocene has at least three systemic dimensions. First, it involves a shift in human behaviour away from degrading the life-support foundation of societal development. Second, it requires management and governance of human actions as intertwined and embedded within the biosphere and the broader Earth system. Third, it involves enhancing the capacity to live and develop with change, in the face of complexity and true uncertainty, that is, resilience-building strategies to persist, adapt, or transform.

Biosphere stewardship incorporates economic, social, and cultural dimensions with the purpose of shaping and safeguarding the resilience of the biosphere for human well-being and fostering the sustainability of a rapidly changing planet (Chapin et al. 2010). Stewardship is an active shaping of social-ecological change that integrates reducing vulnerability to expected changes, fostering resilience to sustain desirable conditions in the face of the unknown and unexpected, and transforming from undesirable pathways of development when opportunities emerge (Chapin et al. 2010, Mathevet et al. 2018). It involves caring for, looking after and cultivating a sense of belonging in the biosphere, ranging from local people and environments to the planet as a whole (Heise 2008, Enqvist et al. 2018, Plummer et al. 2020).

Such stewardship is not a top-down approach forced on people, nor solely a bottom-up approach. It is a learning-based process with a clear direction, engaging people to collaborate and innovate across levels and scales as integral parts of the systems they govern (Cash et al. 2003, Tengö et al. 2014, Clark et al. 2016, Folke et al. 2016, Matson et al. 2016, Norström et al. 2020).

Here, we focus on biosphere stewardship in relation to climate change, biodiversity and transformations for sustainable futures.

### From emission reductions alone to biosphere stewardship

Global sustainability involves shifting excessive, wasteful and imbalanced consumption founded on a fossil-fuel-driven economy into a renewable energy-based economy of low waste and greater circularity within a broader value foundation. Market-driven progress combined with technological change certainly plays an important role in dematerialization (Schmidheiny 1992, McAfee 2019), but do not automatically redirect the economy towards sustainable futures. Public awareness, responsible governments and international collaborations are needed for viable economic developments, acknowledging that people, nations and the global economy are intertwined with the biosphere and a global force in shaping its dynamics.

Since climate change is not an isolated phenomenon but a consequence of the recent accelerating expansion of human activities on Earth, the needed changes concern social organization and dynamics influencing the emissions of greenhouse gases from burning fossil fuels, technologies and policies for reducing such emissions, various approaches for carbon capture and storage, as well as governance of critical biosphere processes linked to climate change, such as in agriculture, forestry, and the oceans (Nielsen et al. 2020). In addition, guarding and enhancing biodiversity will help us address climate change, by helping both to mitigate climate change by storing and sequestering carbon in ecosystems, and by building resilience and capacity to adapt to the inevitable effects of unavoidable climate change (Dasgupta 2020).

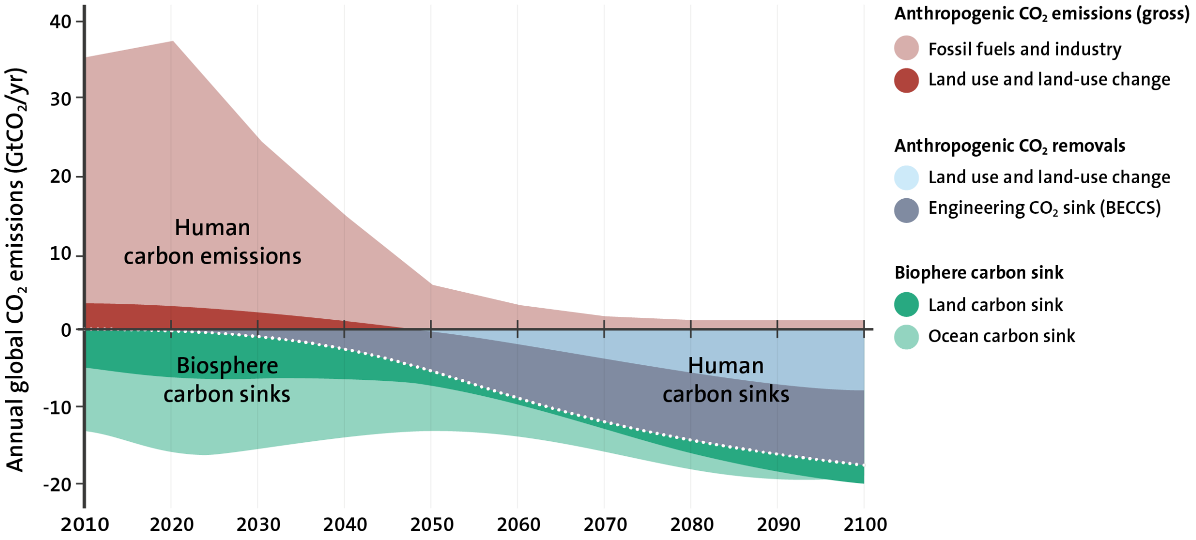

Figure 11. A Roadmap for Rapid Decarbonization – without deep emissions cuts the world takes a high risk strategy (currently the default strategy) of over-reliance on risky negative emissions technologies in the near future. Avoiding this trap means cutting emissions by half every decade – the Carbon Law trajectory. Meeting the Paris Agreement goals will require bending the global curve of $CO_2$ emissions by 2020 and reaching net-zero emissions by 2050. It furthermore depends on rising anthropogenic carbon sinks, by transitioning world agriculture from a major carbon source (red) to become a major carbon sink (green) by the 2nd half of this century, carbon sinks from bioenergy and other forms of carbon capture and storage (BECCS), engineering (grey) and land use (light blue), as well as sustained biosphere carbon sinks, to stabilize global temperatures (modified from Rockström et al. 2017).

The global pandemic caused a sharp fall in CO2 emissions in 2020. The fall was not caused by a long-term structural economic shift so it is unlikely to persist without strong government intervention. Political action to regulate carbon emission is emerging, like the new Green Deal in Europe which includes a European-wide climate law on net-zero GHG emissions at the latest in 2050. Shifts towards renewable energy are taking place in diverse sectors (Rockström et al. 2017, Jacobson et al. 2019). Carbon pricing through taxes, tariffs, tradeable permits, as well as removal of fossil-fuel subsidies and incentives for renewable energy and carbon sequestration (e.g. CCS techniques) are on the table and increasingly implemented (Sterner et al. 2019). There are substantial material and emission gains to be made from altered consumption patterns, infrastructure changes and shifts towards a circular economy. Voluntary climate action among large corporations is emerging (Vanderbergh and Gilligan

2017, Folke et al. 2019). There is general agreement that the pace of these changes must rapidly increase in order to meet the Paris climate target (Figure 11).

In addition, active biosphere stewardship of critical tipping elements and carbon sinks, as in forests, agricultural land, savannas, wetlands, and marine ecosystems is crucial to avoid the risk of runaway climate change (Steffen et al. 2018). It involves protecting, sustaining, restoring and enhancing such sinks. Recently, the existence of connections between finance actors and capital markets and the tipping elements of tropical and boreal forests (Lenton et al. 2008) have gained attention (Galaz et al. 2018), but so far this critical issue has not been addressed sufficiently by decision-makers.

Furthermore, ecosystem restoration has the potential to sequester large amounts of carbon dioxide from the atmosphere. The amount of carbon dioxide in the atmosphere derived from destroyed and degraded lands is roughly equal to the carbon that remains in ecosystems on land (about 450 billion tons of carbon) (Erb et al. 2018). The amount of degraded lands in the world is vast, and restoring their productivity, biodiversity, and ecosystem services could help keep global temperature increases within 1.5°C (Lovejoy and Hannah 2018, 2019).

It has been estimated that nature-based solutions on land (from agriculture to reforestation and afforestation) have the potential to provide over 30% of the emission reductions needed by 2050 to keep global temperature increases to 1.5 and not more than 2 degrees Celsius (Griscom et al. 2017, Roe et al. 2019). There is scope for new policies and practices for nature-based solutions (Kremen and Merenlender 2018, Diaz et al. 2019). These solutions will require shifts in governances towards active stewardship of water and ecosystem dynamics and processes across landscapes, precipitationsheds, and seascapes (Dietz et al. 2003, Folke et al. 2005, Olsson et al. 2008, Ostrom 2010, Chaffin et al. 2016, Keys et al. 2017, Österblom et al. 2017, Duarte et al. 2020, Plummer et al. 2020).

Also, social tipping interventions towards biosphere stewardship have been proposed. Such interventions can activate contagious processes of rapidly spreading technologies, behaviors, social norms, and structural reorganization, where current patterns can be disrupted and lead to fast reduction in anthropogenic greenhouse gas emissions (Nyborg et al. 2016, Geels et al. 2017, Otto et al. 2020). The window of opportunity for such shifts may emerge in times of turbulence and social discontent with the status quo (Biggs et al. 2010, Carpenter et al. 2019, Schlüter et al. 2020). Creating conditions for processes of deliberate democracy may guide transformative change (Dryzek et al. 2019).

## Resilience and biosphere stewardship

It will also be necessary to strengthen biosphere capacity for dealing with extreme events, both climate driven and as a consequence of a tightly coupled and complex globalised world in deep interplay with the rest of the biosphere (Helbing 2013, Reyers et al. 2018). For example, the challenge of policy and practice in satisfying demands for food, water and other critical ecosystem services will most likely be set by the potential consequences of the emergent risk panorama and its consequences, rather than hard upper limits to production per se (Cottrell et al. 2019, Nyström et al. 2019, Xu et al. 2020).

In this sense, a resilience approach to biosphere stewardship becomes significant. Such an approach is very different from those who understand resilience as return to the status quo, to recover to business-as-usual. Resilience in relation to stewardship of complex adaptive systems concerns capacities to live with changing circumstances, slow or abrupt, predictable or surprising. It becomes especially relevant for dealing with the uncertain and unknown and is in stark contrast to strategies that support efficiency and effectiveness for short term gain at the expense of redundancy and diversity. Such strategies may work under relatively stable and predictable conditions, but as stressed here, will create vulnerability in periods of rapid change, during turbulent times, and are ill suited to confront the unknown (Carpenter et al. 2009, Walker et al. 2009b). Financial crises and pandemics serve as real world examples of such vulnerabilities and make explicit the tension between connectivity and modularity in complex adaptive systems (Levin 1998).

In contrast, intertwined systems of people and nature characterized by resilience will have the capacity, whether through strategies like portfolio management, polycentric institutions, or building trust and nurturing diversity (Costanza et al. 2000, Ostrom 2010, Biggs et al. 2012, Carpenter et al. 2012), to confront turbulent times and the unknown. Resilience provides capacities for novelty and innovation in times of change, to turn crises into opportunities for not only adapting, but also transforming into sustainable futures (Folke et al. 2010, Westley et al 2011).

The immediate future will require capacities to confront challenges that we know little about (Kates and Clark 1996, Keys et al. 2019). Given the global connectivity of environmental, social, and economic systems, there is no scale at which resource pooling or trade can be used to hedge against all fluctuations at smaller scales. This begs the question of what types of investments may lead to a generalized capacity to develop with a wide range of potential and unknown events (Polasky et al. 2011). One strategy is to invest in general infrastructure, common to all systems, e.g. education, capacity to learn and collaborate across sectors, multi-scale governance structures that enable systems to better detect changes and nimbly address problems by reconfiguring themselves through transformative change (Levin et al. 2020).

Such strategies, often referred to as building ‘general resilience’, easily erode if not actively supported (Biggs et al. 2012, Carpenter et al. 2012, Quinlan et al. 2015). The importance of general resilience in intertwined systems of people and planet has been downplayed during the rapid development of contemporary society. Even though general resilience is critical for keeping options alive to face an uncertain turbulent world (Walker et al. 2009b), it has been viewed as inefficient from a short-term perspective because there is a cost to maintaining it. There has been a focus on short-term patchwork fixes within the short-time frames encouraged by social media, election cycles, and stock market reports, rather than addressing longer-term goals, values, vulnerabilities, and opportunities for people and nature to flourish (Nyström et al. 2019, Chapin 2020).

## Collaborating with the Biosphere

Clearly, a shift in perspective and action is needed, a shift not only within economies, societies and cultures, but a shift that also redirects the human-nature relationship (Figure 12). This includes extending management and governance from the dominant focus on producing food, fibre, and timber in simplified ecosystems to rebuilding and strengthening resilience through investing in portfolios of ecosystem services for human wellbeing in diversity-rich social-ecological systems (Reyers et al. 2013, Bennett et al. 2015, Isbell et al. 2017, Diaz et al. 2018).

Numerous activities protecting, restoring and enhancing diversity are taking place in this direction ranging from traditional societies, local stewards of wildlife habitats, marine space, and urban areas, to numerous NGOs, companies and enterprises, and various levels of government, to international collaborations, agreements, and conventions (Barthel et al. 2005, Forbes et al. 2009, Raymond et al. 2010, Andersson et al. 2014, Barrett 2007, 2016, Brondizio and Le Tourneau 2016, Österblom et al. 2017, Barbier et al. 2018, Bennett et al. 2018, Johnson et al. 2019).

Examples include widespread use of marine protected areas from local places to marine spatial planning to proposals for protecting the open ocean, enhancing marine biodiversity, rebuilding fisheries and mitigating climate change (Worm et al. 2009, Sumaila et al. 2015, Lubchenco and Grorud-Colvert 2015, Lubchenco et al. 2016, Sala et al. 2016, Gaines et al. 2018, Tittensor et al. 2019, Cinner et al. 2020, Duarte et al. 2020). There are major restoration programmes of forests, wetlands and abandoned and degraded lands and even revival of wildlife and rewilding of nature (Perino et al. 2019). Other efforts include 'working-lands conservation' like agroforestry, silvopasture, diversified farming, and ecosystem-based forest management, enhancing livelihoods and food security (Kremen and Merenlender 2018).

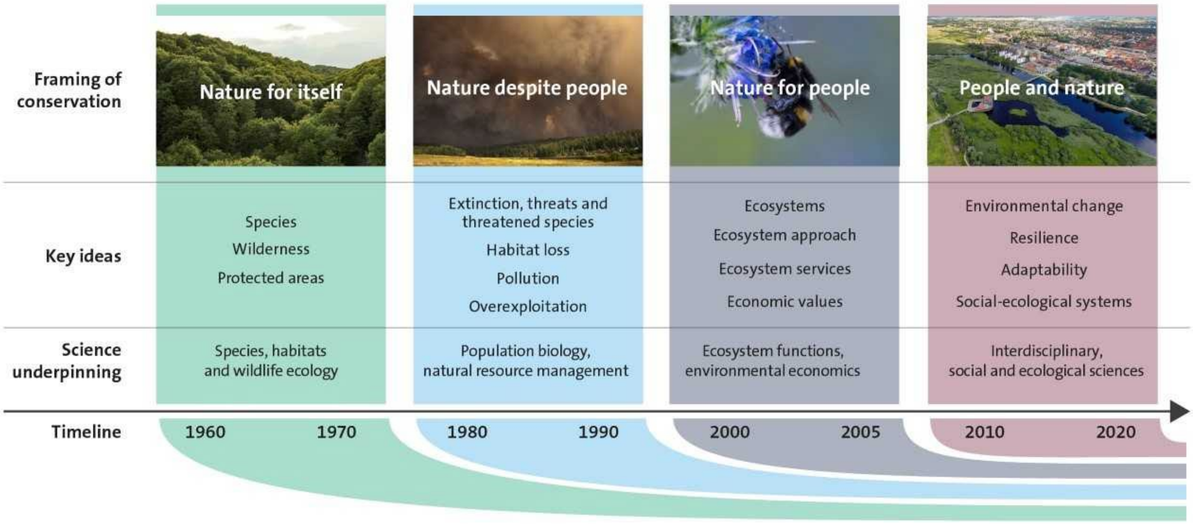

Figure 12. Shifts in perspective on the human-nature relationship (modified from Mace 2014).

The world's ecosystems can be seen as capital assets, if well-managed, their lands, waters, and biodiversity yield a flow of vital life-support services (Daily et al. 2009). Investing in natural capital has become a core strategy of agencies and major nations, like China, for wellbeing and sustainability, providing greater resilience to climate change (Guerry et al. 2015, Ouyang et al. 2016). It involves combining science, technology, and partnerships to develop nature-based solutions and enable informed decisions for people and nature to thrive and invest in green growth (Mandle et al. 2019).

There are several examples of adaptive management and adaptive governance systems that have transformed social-ecological dynamics of landscapes and seascapes into biosphere stewardship (Chaffin et al. 2014, Schultz et al. 2015, Walker 2019, Plummer et al. 2020). Stewardship of diversity as a critical feature in resilience building is about reducing vulnerability to change and multiplying the portfolio of options for sustainable development in times of change, it shifts focus from commodity to redundancy to response diversity for dealing with change (Elmqvist et al. 2003, Grêt-Regamey et al. 2019, Dasgupta 2020).

Clearly, the economic contributions of biodiversity are highly significant as reflected in many efforts to expose and capture economic values of biodiversity and ecosystem services (Daily et al. 2000, Sukhdev et al. 2010, Kinzig et al. 2011, Costanza et al. 2014, Naeem et al. 2015, Barbier et al. 2018, Dasgupta 2020).

Also, the role of the cultural context is fundamental in clarifying the significance of diversity and resilience in nature's contribution to people (Diaz et al. 2018). A focus on biocultural diversity and coevolution of people and nature is gaining ground as a means to understand dynamically changing social-ecological relations (Barthel et al. 2013, Mercon et al. 2019, Haider et al. 2019).

Broad coalitions among citizens, businesses, nonprofits, and government agencies have the power to transform how we view and act on biosphere stewardship and build Earth resilience. Science has an important new role to play here as an honest broker, engaging in evidence-informed action and coproduction of knowledge in collaboration with practice, policy and business (Reyers et al. 2015, Wyborn et al. 2019, Norström et al. 2020*).* Such actions range from direct engagements between scientists and local communities (Tengö et al. 2014) or transnational corporations (Österblom et al. 2017), or through the delivery of scientific knowledge and method into multi-stakeholder arenas, such as boundary or bridging organisations (Crona and Parker 2012, Cash et al. 2003, Hahn et al. 2006, Kristjanson et al. 2009) where it can provide a basis for learning and be translated into international negotiations (Bäckstrand 2003, Biermann et al. 2008, Tengö et al. 2017, Galaz et al. 2016) or government practice (Crona and Parker 2011).

In this context, work identifying leverage points for anticipated and deliberate transformational change towards sustainability is gaining ground, focusing on less obvious but potentially far more powerful areas of intervention and centred on reconnecting people to nature, restructuring institutions, and rethinking how knowledge is created and used in pursuit of sustainability (Abson et al. 2017, Fischer and Riechers 2019). This includes efforts to accelerate positive transformations by identifying powerful actors, like financial investors or transnational corporations, and articulating key domains with which these actors need to engage in order to enable biosphere stewardship (Österblom et al. 2017, Galaz et al. 2018, Folke et al. 2019, Jouffray et al. 2019). Such efforts serve an increasingly important space for scientists to engage in, helping hold corporations accountable, stimulating them to take on responsibility for the planet and develop leadership in sustainability. Such science-business engagement will become increasingly important to ensure that companies' sustainability agendas are framed by science rather than the private sector alone (Österblom et al. 2015, Barbier et al. 2018, Blasiak et al. 2018, Galaz et al. 2018, Folke et al. 2019, Jouffray et al. 2019).

The International science-policy platform for biodiversity and ecosystem services (IPBES), an international body for biodiversity similar to the IPCC for the climate, has proposed key features for enabling transformational change (Figure 13)

The rapid acceleration of current earth-system changes provides new motivations for action. Climate change is no longer a vague threat to some distant future generation but an environmental, economic, and social disruption that today's youth, communities, corporations, and governments are increasingly experiencing. This provides both ethical and selfish motivations for individuals and institutions to launch transformative actions that shape their futures rather than simply reacting to crises as they emerge.

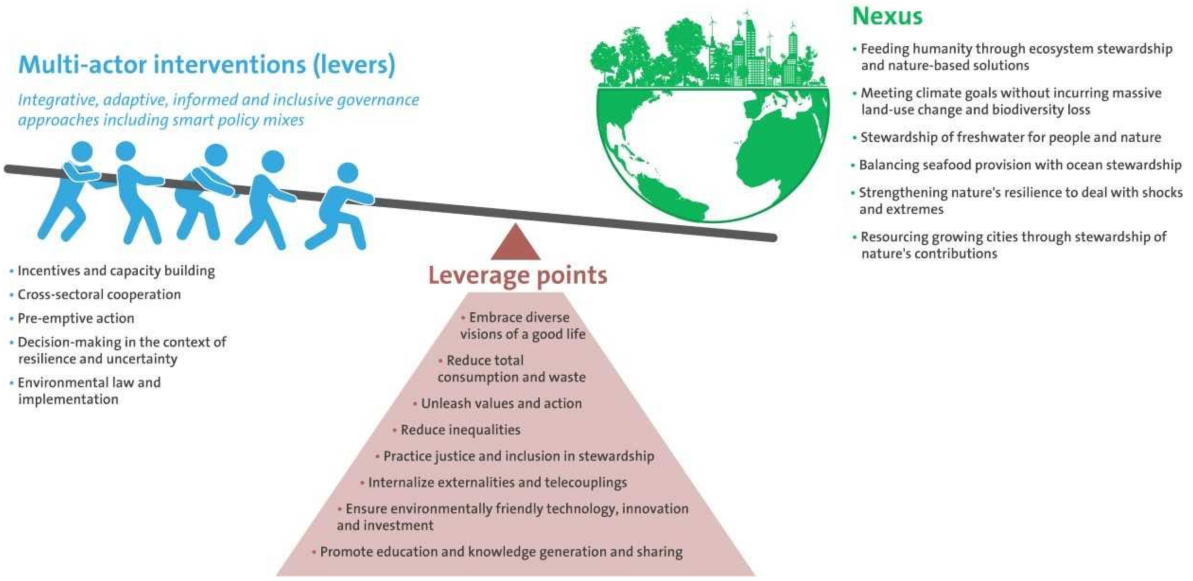

Figure 13. Collaborative implementation of priority interventions (levers) targeting key points of intervention (leverage points representing major indirect drivers) could enable transformative change from current trends toward more sustainable ones. Effectively addressing these levers and leverage points requires innovative governance approaches and organizing the process around nexuses, representing closely interdependent and complementary goals (modified from Diaz et al. 2019).

Given the urgency of the situation and the challenge of stabilising the Earth System in Holocene-like conditions, the pace of current actions have to rapidly increase and expand to support a transformation towards active stewardship of human actions in concert with the biosphere foundation. It will require reform of critical social, economic, political, and cultural dimensions (Tallis et al. 2018, Diaz et al. 2019, Barrett et al. 2020).

## Concluding remarks

The success of social organisation into civilizations and more recently into a globalized world has been impressive and highly efficient. It has been supported by a resilient biosphere, and a hospitable climate. Now, in the Anthropocene, a continuous expansion mimicking the development pathways of the past century is not a viable option for shifting towards sustainable futures.

Humanity is embedded within, intertwined with and dependent upon the living biosphere. Humanity has become a global force shaping the operation and future of the biosphere and the broader Earth system. Climate change and loss of biodiversity are symptoms of the situation. The accelerating expansion has eroded biosphere and Earth system resilience and is now challenging human wellbeing, prosperity and possibly even the persistence of societies and civilisations.

The expansion has led to hyper-connectivity, homogenisation, and vulnerability in times of change, in contrast to modularity, redundancy and resilience to be able to live with changing circumstances. In the Anthropocene, humanity is confronted with turbulent times and with new intertwined dynamics of people and planet where fast and slow change interplay in unexperienced and unpredictable ways. This is becoming the new normal.

Our future on our planet will be determined by our ability to keep global warming well-below 2°C and foster the resilience of the living biosphere. A pervasive thread in science is that building resilient societies, ecosystems, and ultimately the health of the entire Earth system hinges on supporting, restoring and regenerating diversity in intertwined social and ecological dimensions. Diversity builds insurance and keeps systems resilient to changing circumstances. Clearly, nurturing resilience is of great significance in transformations towards sustainability and requires collective action on multiple fronts, action that is already being tested by increasing turbulence incurred by seemingly unrelated shocks.

Equality holds communities together, and enables nations and regions to evolve along sustainable development trajectories. Inequality, in terms of both social and natural capitals, are on the rise in the world, and need to be addressed as an integral part of our future on Earth.

We are facing a rapid and significant repositioning of sustainability as the lens through which innovation, technology and development is driven and achieved. What only a few years ago was seen as a sacrifice is today creating new purposes and meanings, shaping values and culture, and is increasingly seen as a pathway to novelty, competitiveness and progress.

This is a time when science is needed more than ever. Science provides informed consensus on the facts and trade-offs in times of misinformation and polemics. The planetary challenges that confront humanity need governance that mobilizes the best that science has to offer with shared visions for sustainable futures and political will and competence to implement choices that will sustain humanity and the rest of the living world for the next millennium and beyond.

There is scope for changing the course of history into sustainable pathways. There is urgent need for people, economies, societies and cultures to actively start governing nature’s contributions to wellbeing and building a resilient biosphere for future generations. It is high time to reconnect development to the Earth system foundation through active stewardship of human actions into prosperous futures within planetary boundaries.

# References

Abson, D.J. J. Fischer, J. Leventon, J. Newig, T. Schomerus, et al. 2017. Leverage points for sustainability transformation. Ambio 46: 30-39.

Adger, W.N., J.M. Pulhin, J. Barnett, G.D. Dabelko, G.K. Hovelsrud, et al. 2014. Human security. In: Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, et al. (eds.). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of IPCC. Cambridge University Press, Cambridge, UK.

Adger, W. N., H. Eakin, and A. Winkels. 2009. Nested and teleconnected vulnerabilities to environmental change. *Frontiers in Ecology and the Environment* 7: 150-157.

Allen, C.R., D.G. Angeler, G. Cumming, C. Folke, D. Twidwell, and D.R. Uden. 2016. Quantifying spatial resilience. *Journal of Applied Eco*logy 53: 625-635.

Althor, G., J.E.M. Watson, and R.A. Fuller. 2016. Global mismatch between greenhouse gas emissions and the burden of climate change. *Science Reports* 6: 20281.

Alvaredo, F., L. Chancel, T. Piketty, E. Saez, and G. Zucman (eds.). 2018. *World Inequality Report*. The Belknap Press of Harvard University Press, Boston, MA, USA.

Anand, R. 2017. *International Environmental Justice: A North-South Perspective*. London: Routledge.

André, Q., Z. Carmon, K. Wertenbroch, A. Crum, D. Frank, et al. 2018. Consumer choice and autonomy in the age of artificial intelligence and big data. *Customer Needs and Solutions* 5: 28-37.

Anderies, J.M., S.R. Carpenter, W. Steffen, and J. Rockström. 2013. The topology of non-linear global carbon dynamics: from tipping points to planetary boundaries. *Environmental Research Letters* 8: 044048. doi: 10.1088/1748-9326/8/4/044048

Andersson, E., S. Barthel, S. Borgström, J. Colding, T. Elmqvist, C. Folke, and Å. Gren. 2014. Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services. *Ambio* 43: 445-453.

Antadze, N., and K.A. McGowan. 2017. Moral entrepreneurship: thinking and acting at the landscape level to foster sustainability transitions. *Environmental Innovation and Societal Transitions* 25: 1-13.

Anthony, K.W., T. Schneider von Deimling, I. Nitze, S. Frolking, A. Emond, et al. 2018. 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. *Nature Communications* 9: 3262. doi:10.1038/s41467-018-05738-9

Arneth, A., F. Denton, F. Agus, A. Elbehri, K. Erb, et al. 2019. Framing and Context. In: Climate Change and Land. An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems (IPCC, 2019).

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, et al. 1995. Economic growth, carrying capacity, and the environment. *Science* 268: 520-521.

Arthur, W.B. 2009. *The Nature of Technology: What it is and How it Evolves*. Free Press, New York, USA.

AWG. 2019. The Anthropocene Working Group http://quaternary.stratigraphy.org/working-groups/anthropocene/

Bäckstrand, K. 2003. Civic science for sustainability: reframing the role of experts, policy-makers and citizens in environmental governance. *Global Environmental Politics* 3: 24-41.

Bai, X., S. van der Leeuw, K. O'Brien, F. Berkhout, F. Biermann, et al. 2016. Plausible and desirable futures in the Anthropocene: a new research agenda. *Global Environmental Change* 39: 351-362. doi.org/10.1016/j.gloenvcha.2015.09.017

Bak-Coleman et al. in review PNAS

Barberá, P., A. Casas, J. Nagler, P. Egan, R. Bonneau, J. Jost, and J. Tucker. 2019. Who leads? who follows? measuring issue attention and agenda setting by legislators and the mass public using social media data. *American Political Science Review* 113: 883-901.

Barbier, E.B. 2005. *Natural Resources and Economic Development*. Cambridge University Press, Cambridge, UK.

Barbier, E.B., J.C. Burgess, and T.J. Dean. 2018. How to pay for saving biodiversity. *Science* 360: 486-488.

Barnett, J., and J. Campbell. 2010. *Climate Change and Small Island States: Power, Knowledge, and the South Pacific*. Earthscan Ltd., London, UK.

Barnosky, A.D., E.A. Hadly, J. Bascompte, E.L. Berlow, J.H. Brown, et al. 2012. Approaching a state shift in Earth's biosphere. *Nature* 486: 52-58.

Barocas, S., K. Crawford, A. Shapiro, and H. Wallach. 2017. The problem with bias: from allocative to representational harms in machine learning. Special Interest Group for Computing, Information and Society (SIGCIS).

Bar-On, Y.M., R. Phillips, and R. Milo. 2018. The biomass distribution on Earth. *Proceedings of the National Academy of Sciences, USA.* 115: 6506-6511.

Barrett, C.B., and L.E.M. Bevis. 2015. The self-reinforcing feedback between low soil fertility and chronic poverty. *Nature Geoscience* 8: 907-912.

Barrett, S. 2007. *Why Corporate?* Oxfrod University Press, Oxford, UK.

Barrett, S. 2016. Coordination vs. voluntarism and enforcement in sustaining international environmental cooperation. *Proceedings of the National Academy of Sciences, USA* 113: 14515-14522.

Barrett, S., A. Dasgupta, P. Dasgupta, W.N. Adger, J. Anderies, et al. 2020. Fertility behavior and consumption patterns in the Anthropocene. *Proceedings of the National Academy of Sciences, USA* 117: 6300-6307. doi.org/10.1073/pnas.1909857117

Barthel, S., J. Colding, T. Elmqvist and C. Folke. 2005. History and local management of a biodiversity rich, urban, cultural landscape. *Ecology and Society* 10(2): 10. www.ecologyandsociety.org/vol10/iss2/art10/

Barthel, S., C. Crumley, and U. Svedin. 2013. Bio-cultural refugia: safeguarding diversity of practices for food security and biodiversity. *Global Environmental Change* 23: 1142-1152.

Bartomeus, I., M.G. Park, J. Gibbs, B.N. Danforth, A.N. Lakso, and R. Winfree. 2013. Biodiversity ensures plant-pollinator phenological synchrony against climate change. *Ecology Letters* 16: 1331–1338. doi: 10.1111/ele.12170

Beckert, J. 2016. *Imagined Futures: Fictional Expectations and Capitalist Dynamics*. Harvard University Press, Cambridge, MA, USA.

Beckert, J., and R. Bronk (eds.). 2018. *Uncertain Futures: Imaginaries, Narratives, and Calculation of the Economy.* Oxford University Press, Oxford, UK.

Bellwood, D., T. Hughes, C. Folke, and M. Nyström. 2004. Confronting the coral reef crisis. *Nature* 429: 827-833.

Bengtsson, J., P. Angelstam, T. Elmqvist, U. Emanuelsson, C. Folke, M. Ihse, F. Moberg and M. Nyström. 2003. Reserves, resilience, and dynamic landscapes. *Ambio* 32: 389-396.

Bennett, E.M., S.R. Carpenter, L.J. Gordon, N. Ramankutty, P. Balvanera, et al. 2014. Toward a more resilient agriculture. *Solutions* 5(5): 65-75.

Bennett, E.M., W. Cramer, A. Begossi, G. Cundill, S. Diaz, et al. 2015. Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. *Current Opinion in Environmental Sustainability* 14:76–85.

Bennett, E.M., M. Solan, R. Biggs, T. McPhearson, A.V. Norström, et al. 2016. Bright spots: seeds of a good Anthropocene. *Frontiers in Ecology and the Environment* 14: 441-448. doi:10.1002/fee.1309

Bennett, N.J., A.M. Cisneros-Montemayor, J. Blythe, J.J. Silver, G. Singh, et al. 2019. Towards a sustainable and equitable blue economy. *Nature Sustainability* 2: 991-993. doi.org/10.1038/s41893-019-0404-1

Bennett, N.J., T.S. Whitty, E. Finkbeiner, J. Pittman, H. Bassett, S. Gelcich, and E.H. Allison. 2018. Environmental stewardship: a conceptual review and analytical framework. *Environmental Management* 61: 597-614.

Bergstrom, C.T., and J.B. Bak-Coleman. 2019. Gerrymandering in social networks. *Nature* 573: 40-41.

Berkes, F., and C. Folke (eds.). 1998. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press, Cambridge UK.

Berkes, F., J. Colding and C. Folke (eds.). 2003. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge University Press, Cambridge UK.

Biermann, F., K. Abbott, S. Andresen, K. Bäckstrand, S. Bernstein, et al. 2012. Transforming governance and institutions for global sustainability: key Insights from the Earth System Governance project. *Current Opinion in Environmental Sustainability* 4: 51-60 doi10.1016/j.cosust.2012.01.014

Biermann, F., K. Abbott, S. Andresen, K. Bäckstrand, S. Bernstein, M.M. Betsill, H. Bulkeley, B. Cashore, J. Clapp, C. Folke, A. Gupta, J. Gupta, P.M. Haas, A. Jordan, N. Kanie, T. Kluvánková-Oravská, L. Lebel, D. Liverman, J. Meadowcroft, R.B. Mitchell, P. Newell, S. Oberthür, L. Olsson, P. Pattberg, R. Sánchez-Rodríguez, H. Schroeder, A. Underdal, S. Camargo Vieira, C. Vogel, O.R. Young., A. Brock, and R. Zondervan. 2012. Navigating the Anthropocene: improving Earth System governance. *Science* 335: 1306-1307.

Biermann, F., and P. Pattberg. 2008. Global Environmental Governance: Taking Stock, Moving Forward. *Annual Review of Environment and Resources* 33: 277-294.

Biggs, D., R. Biggs, V. Dakos, R. J. Scholes, and M. Schoon. 2011. Are we entering an era of concatenated global crises? *Ecology and Society* 16(2):27. www.ecologyandsociety.org/vol16/iss2/art27/

Biggs, R., S.R. Carpenter, and W.A. Brock. 2009. Turning back from the brink: detecting and impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences, USA* 106: 826-831.

Biggs, R., F.R. Westley, and S.R. Carpenter. 2010. Navigating the back loop: fostering social innovation and transformation in ecosystem management. *Ecology and Society* 15(2): 9. www.ecologyandsociety.org/vol15/iss2/art9/

Biggs, R., M. Schlüter, D. Biggs, E. L. Bohensky, S. BurnSilver, et al. 2012. Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources* 37: 421-448. doi.org/10.1146/annurev-environ-051211-123836.

Bjorkman, A.D., I.H. Myers-Smith, S.C. Elmendorf, S. Normand, N. Rüger, et al. 2018. Plant functional trait change across a warming tundra biome. *Nature* 562: 57-62. doi.org/10.1038/s41586-018-0563-7.

Blasiak, R., J.-B. Jouffray, C.C.C. Wabnitz, E. Sundström, and H. Österblom. 2018. Corporate control and global governance of marine genetic resources. *Sciences Advances* 4: eaar5237.

Blasiak, R., J. Spijkers, K. Tokunaga, J. Pittman, N. Yagi, and H. Österblom. 2017. Climate change and marine fisheries: least developed countries top global index of vulnerability. *PLoS One* 12: e0179632.

Bodin, Ö. 2017. Collaborative environmental governance: achieving collective action in social-ecological systems. *Science* 357: eaan1114.

Bongaarts, J. and B.C. O'Neill. 2018. Global warming policy: is population left out in the cold? population policies offer options to lessen climate risks. *Science* 361: 650-652.

Bottom, D.L., K.K. Jones, C.A. Simenstad, and C.L. Smith. 2009. Reconnecting social and ecological resilience in salmon ecosystems. *Ecology and Society* 14(1): 5. www.ecologyandsociety.org/vol14/iss1/art5/

Bourguignon, F. 2015. Revisiting the debate on inequality and economic development. *Revue d'Économie Politique* 125: 633-663.

Bowles, S., S.N. Durlauf, and K. Hoff. 2006. *Poverty Traps*. Princeton University Press, Princeton, NJ, USA.

Boyd, E., B. Nykvist, S. Borgström, and I.A. Stacewicz. 2015. Anticipatory governance for social-ecological resilience. *Ambio* 44: S149–S161 doi10.1007/s13280-014-0604-x

Breitburg, D., L.A. Levin, A. Oschlies, M. Grégoire, F.P. Chavez, et al. 2018. Declining oxygen in the global ocean and coastal waters. *Science* 359: 6371, eaam7240. doi:10.1126/science.aam7240.

Brienen, R., O.L. Phillips, T.R. Feldpausch, E. Gloor, T.R. Baker, et al. 2015. Long-term decline of the Amazon carbon sink. *Nature* 519: 344-348.

Brock, W. and Hansen, L.P. 2017. Wrestling with uncertainty in climate economic models. Working paper, Environment Policy Institute, University of Chicago, Chicago, USA. https://epic.uchicago.edu/research/wrestling-with-uncertainty-in-climate-economic-models/

Brondizio, E.S., E. Ostrom, and O.R. Young. 2009. Connectivity and the governance of multilevel social-ecological systems: the role of social capital. *Annual Review of Environment and Resources* 34: 253-278.

Brondizio, E.S., K. O'Brien, X. Bai, F. Biermann, W. Steffen, et al. 2016. Re-conceptualizing the Anthropocene: a call for collaboration. *Global Environmental Change* 39: 318-327.

Brondizio, E.S., and F.-M. Le Tourneau. 2016. Environmental governance for all. *Science* 352: 1272-1273. doi:10.1126/science.aaf5122

Brown, K. 2016. *Resilience, Development and Global Change*. Routledge, London, UK.

Brown, K., and E. Westaway. 2011. Agency, capacity, and resilience to environmental change: lessons from human development, well-being, and disasters. *Annual Review of Environment and Resources* 36: 321-342.

Brown, K., W.N. Adger, P. Devine-Wright, J.M. Anderies, S. Barr, et al. 2019. Empathy, place and identity interactions for sustainability. *Global Environmental Change* 56: 11-17. doi.org/10.1016/j.gloenvcha.2019.03.003

Buchmann, S.L., and G.P. Nabhan. 1996. *The Forgotten Pollinators*. Island Press, Washington DC, USA.

Burke, K.D., J.W. Williams, M.A. Chandler, A.M. Haywood, D.J. Lunt, and B.L. Otto-Bliesner. 2018. Pliocene and Eocene provide best analogs for near-future climates. *Proceedings of the National Academy of Sciences, USA* 115: 13288–13293.

Carpenter, S.R., and E.M. Bennett. 2011. Reconsideration of the planetary boundary for phosphorus. *Environmental Research Letters* 6: 014009. doi: 10.1088/1748-9326/6/1/014009

Carpenter, S.R., B.H. Walker, J.M. Anderies, and N. Abel. 2001. From metaphor to measurement: resilience of what to what? *Ecosystems* 4: 765-781.

Carpenter, S.R., E.M. Bennett, and G.D. Peterson. 2006. Scenarios for ecosystem services: an overview. *Ecology and Society* 11(1):29.

Carpenter, S.R., C. Folke, M. Scheffer, and F. Westley. 2009. Resilience: accounting for the non-computable. *Ecology and Society* 14(1): 13.

Carpenter, S.R., W. Brock, C. Folke, E. van der Nees, and M. Scheffer. 2015. Allowing variance may enlarge the safe operating space for exploited ecosystems. *Proceedings of the National Academy of Sciences, USA* 112: 14384-14389.

Carpenter, S.R., C. Folke, M. Scheffer, and F.R. Westley. 2019. Dancing on the volcano: social exploration in times of discontent. *Ecology and Society* 24(1):23.

Carpenter, S.R., K.J. Arrow, S. Barrett, R. Biggs, W.A. Brock, et al. 2012. General resilience to cope with extreme events. *Sustainability* 4: 3248-3259.

Carpenter, S.R., E.H. Stanley, and M.J. Vander Zanden. 2011. State of the World's freshwater ecosystems: physical, chemical, and biological changes. *Annual Review of Environment and Resources* 36: 75-99.

Carter, M.E., P.D. Little, T. Mogues, and W. Negatu. 2008. Poverty traps and natural disasters in Ethiopia and Honduras. In: Barrientos A., and D. Hulme (eds). *Social Protection for the Poor and Poorest*. Palgrave Macmillan, London, UK.

Cash, D.W., W.C. Clark, F. Alcock, N. Dickson, N. Eckley, et al. 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences, USA*. 100: 8086-8091.

Cash, D.W., W. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young. 2006. Scale and cross-scale dynamics: governance and information in a multilevel world. Ecology and Society 11(2):8.

Cave, S., and S.S. Óhéigeartaigh. 2019. Bridging near- and long-term concerns about AI. *Nature Machine Intelligence* 1: 5–6.

Centeno, M.A., M. Nag, T.S. Patterson, A. Shaver, and A.J. Windawi. 2015. The emergence of global systemic risk. *Annual Review of Sociology* 41: 65-85.

Chaffin, B.C., H. Gosnell, and B.A. Cosens. 2014. A decade of adaptive governance scholarship: synthesis and future directions. *Ecology and Society* 19(3): 56.

Chaffin, B.C., A.S. Garmestani, L.H. Gunderson, M.H. Benson, D.G. Angeler, et al. 2016. Transformative environmental governance. *Annual Review of Environment and Resources* 41: 399-423.

Chaffin, B.C., and L.H. Gunderson. 2016. Emergence, institutionalization, and renewal: rhythms of adaptive governance in complex social-ecological systems. *Journal of Environmental Management* 165: 81-87.

Challinor, A.J., W.N. Adger, and T.G. Benton. 2017. Climate risks across borders and scales. *Nature Climate Change* 7: 622-623.

Chapin III, F.S., B.H. Walker, R.J. Hobbs, D.U. Hooper, J.H. Lawton, O.E. Sala, and D. Tilman. 1997. Biotic control over the functioning of ecosystems. *Science* 277: 500-504.

Chapin III, F.S., S.R. Carpenter, G.P. Kofinas, C. Folke, N. Abel, et al. 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in Ecology and Evolution* 25:241-249.

Chapin, F.S., III. 2020. *Grassroots Stewardship: Sustainability within Our Reach*. Oxford University Press, New York, USA.

Chaplin-Kramer, R., R.P. Sharp, C. Weil, E.M. Bennett, U. Pascual et al. 2019. Global modelling of nature's contributions to people. *Science* 366: 255-258. doi:10.1126/science.aaw3372

Cheng, L., J. Abraham, J. Zhu, K.E. Trenberth, J. Fasullo, at al. 2020. Record-setting ocean warmth continued in 2019. *Advances in Atmospheric Sciences* 37: 137-142.

Chillo, V., M. Anand, and R.A. Ojeda. 2011. Assessing the use of functional diversity as a measure of ecological resilience in arid rangelands. *Ecosystems* 14: 1168-1177. doi:10.1007/s10021-011-9475-1

Ciais, P., C. Sabine, B. Govindasamy, L. Bopp, V. Brovkin, et al. 2013. Chapter 6: Carbon and Other Biogeochemical Cycles. In: Stocker, T., D. Qin, and G.-K. Platner (eds.). *Climate Change 2013, The Physical Science Basis*. Cambridge University Press, Cambridge, UK.

Cinner, J.E., W.N. Adger, E.H. Allison, M.L. Barnes, K. Brown, P.J. Cohen, et al. 2018. Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change* 8: 117-123.

Cinner, J.E., J. Zamborain-Mason, G.G. Gurney, N.A.J. Graham, M.A. MacNeil, et al. 2020. Meeting fisheries, ecosystem function, and biodiversity goals in a human-dominated world. *Science* 368: 307-311. doi:10.1126/science.aax9412

Clark, W.C., and A.G. Harley. 2020. Sustainability science: towards a synthesis. *Annual Review of Environment and Resources* 45: in press.

Clark, W.C., and R.E. Munn (eds). 1986. *Sustainable Development of the Biosphere*. Cambridge University Press, Cambridge, UK.

Clark, W.C., J. Jäger, J. van Eijndhoven, and N.M. Dickson (eds.). 2001. *Learning to Manage Global Environmental Risks: A Functional Analysis of Social Responses to Climate Change, Ozone Depletion, and Acid Rain*. MIT Press, Cambridge, USA.

Clark, W.C., L. van Kerkhoff, L. Lebel, and G. Gallopi. 2016. Crafting usable knowledge for sustainable development. *Proceedings of the National Academy of Sciences, USA* 113: 4570-4578.

Coe, N.M., M. Hess, H.W.-C. Yeung, P. Dicken, and J. Henderson. 2004. 'Globalizing' regional development: a global production networks perspective. *Transactions of the Institute of British Geographers* 29: 468-484.

Cohen, J., K. Pfeiffer, and J.A. Francis. 2018. Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications* 9: 869. doi:10.1038/s41467-018-02992-9

Collier, P., and A. Hoeffler. 2004. Greed and grievance in civil war. *Oxford Economic Papers* 56: 563–595. doi.org/10.1093/oep/gpf064

Conselice, C.J., A. Wilkinson, K. Duncan, and A. Mortlock. 2016. The Evolution of Galaxy number density at Z < 8 and its implications. *The Astrophysical Journal* 830: 83.

Conway, D., R.J. Nicholls, S. Brown, M.G.L. Tebboth, W.N. Adger, et al. 2019. The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. *Nature Climate Change* 9: 503-511.

Costanza, R. (ed.). 1991. *Ecological Economics: The Science and Management of Sustainability*. Columbia University Press, New York, USA.

Costanza, R., and H.E. Daly. 1992. Natural capital and sustainable development. *Conservation Biology* 6: 37-46.

Costanza, R., H. Daly, C. Folke, P. Hawken, C.S. Holling, T. McMichael, D. Pimentel, and D. Rapport. 2000. Managing our environmental portfolio. *BioScience* 50: 149-155.

Costanza, R., R. de Groot, P. Sutton, S. vad der Ploeg, S.J. Anderson, et al. 2014. Changes in the global value of ecosystem services. *Global Environmental Change* 26: 152-158.

Cottrell, R.S., K.L. Nash, B.S. Halpern, T.A. Remeny, S.P. Corney et al. 2019. Food production shocks across land and sea. *Nature Sustainability* 2: 130–137.

Coumou, D., and S. Rahmstorf. 2012. A decade of weather extremes. *Nature Climate Change* 2: 491-496.

Coumou, D., G. Di Capua, S. Vavrus, L. Wang, and S. Wang. 2018. The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications* 9: 2959. doi:10.1038/s41467-018-05256-8

Creanza, N., O. Kolodny, and M.W. Feldman. 2017. Cultural evolutionary theory: how culture evolves and why it matters. *Proceedings of the National Academy of Sciences, USA*, 114:7782-7789.

Crona, B.I., and Ö. Bodin. 2010. Power asymmetries in small-scale fisheries: a barrier to governance transformability? *Ecology and Society* 15(4): 32. www.ecologyandsociety.org/vol15/iss4/art32/

Crona, B.I, and J.N. Parker. 2011. Network determinants of knowledge utilization: preliminary lessons from a boundary organization. *Science Communication* 33: 448-471.

Crona, B.I, and J.N. Parker. 2012. Learning in support of governance: theories, methods, and a framework to assess how bridging organizations contribute to adaptive resource governance. *Ecology and Society* 17(1): 32.

Crona, B.I., T. Van Holt, M. Petersson, T.M. Daw, and E. Buchary. 2015. Using social-ecological syndromes to understand impacts of international seafood trade on small-scale fisheries. *Global Environmental Change* 35: 162–175.

Crona, B.I., T. Daw, W. Swartz, A. Norström, M. Nyström, et al. 2016. Masked, diluted, and drowned out: global seafood trade weakens signals from marine ecosystems. *Fish and Fisheries* 17: 1175-1182. doi:10.1111/faf.12109

Crutzen, P.J., and E.F. Stoermer. 2000. The Anthropocene. *Global Change Newsletter 41:* 17-18.

Cumming, G.S., A. Buerkert, E.M. Hoffmann, E. Schlecht, S. von Cramon-Taubadel, and T. Tscharntke. 2014. Implications of agricultural transitions and urbanization for ecosystem services. *Nature* 515: 50-57. doi:10.1038/nature13945

Cumming, G.S., and G.D. Peterson. 2017. Unifying research on social-ecological resilience and collapse. *Trends in Ecology & Evolution* 32: 695-713.

Cutter, S.L. and C. Finch. 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences, USA* 105: 2301–2306. doi/10.1073/pnas.0710375105

Daily, G.C. (eds.). 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington DC, USA.

Daily, G., T. Söderqvist, S. Aniyar, K. Arrow, P. Dasgupta, et al. 2000. The value of nature and the nature of value? Science 289: 395-396.

Daily, G.C., S. Polasky, J. Goldstein, P. Kareiva, H.A. Mooney et al. 2009. Ecosystem services in decision making: time to deliver. *Frontiers in Ecology and the Environment* 7: 21-28.

Dainese, M., E.A. Martin, M.A. Aizen, M. Albrecht, I. Bartomeus, et al. 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances* 5: eaax0121. DOI:10.1126/sciadv.aax0121

Dannenberg, A., and S. Barrett. 2018. Cooperating to avoid catastrophe. *Nature Human Behaviour* 2: 435-437. doi.org/10.1038/s41562-018-0374-8

Dasgupta, P., K.-G. Mäler. 2000. Net national product, wealth and social well-being. *Environment and Development Economics* 5: 69-93.

Dasgupta, P. 1995. *An Inquiry into Well-being and Destitution*. Oxford University Press, Oxford, UK.

Dasgupta, P. 1995b. Population, poverty and the local environment. *Scientific American* 272: 40-45.

Dasgupta, P. 2014. Measuring the wealth of nations. *Annual Review of Resource Economics* 6: 17-31.

Dasgupta, P. 2020. The Dasgupta Review – Independent Review on the Economics of Biodiversity. Interim Report, April 2020. www.gov.uk/official-documents

Dasgupta, P., and V. Ramanathan. 2014. Pursuit of the common good. *Science* 345: 1457-145. doi:10.1126/science.1259406

de Bello, F., S. Lavorel, S. Dıaz, R. Harrington, J.H.C. Cornelissen et al. 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. *Biodiversity Conservation* 19: 2873–2893. doi 10.1007/s10531-010-9850-9

Dearing, J.A., R. Wang, K. Zhang, J.G. Dyke, H. Haberl, et al. 2014. Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change* 28: 227–238. doi:10.1016/j.gloenvcha.2014.06.012

De Fries, R., E.C. Ellis, F.S. Chapin, P.A. Matson, B.L. Turner et al. 2012. Planetary opportunities: a social contract for global change science to contribute to a sustainable future. *BioScience* 62: 603-606.

De Groot, R.S. 1992. *Functions of Nature*. Wolters-Noordhoff BV, Groningen, The Netherlands.

de Vries, W., J. Kros, C. Kroeze, and S.P. Seitzinger. 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Current Opinion in Environmental Sustainability* 5: 392–402. doi: 10.1016/j.cosust.2013.07.004

Del Vicario, M., A. Bessi, F. Zollo, F. Petroni, A. Scala, et al. 2016. The spreading of misinformation online. *Proceedings of the National Academy of Sciences, USA* 113: 554-559.

Delson, E. 2019. An early modern human outside Africa. *Nature* 571: 487-488.

Diamond, J. 2005. *Collapse: How Societies Choose to Fail or Succeed*. Viking Penguin/Allen Lane, New York, USA.

Diaz, S., U. Pascual, M. Stenseke, B. Martín-López, R.T. Watson, et al. 2018. Assessing nature's contributions to people: recognizing culture, and diverse sources of knowledge, can improve assessments. *Science* 359: 270-272.

Díaz, S., J. Settle, E.S. Brondízio, H.T Ngo, J. Agard, et al. 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* 366: eaax3100.

Diaz, S., S. Lavorel, F. de Bello, F. Quetier, K. Grigulis, M. Robson. 2007. Incorporating plant functional diversity effects in ecosystem service assessments. *Proceedings of the National Academy of Sciences, USA* 104: 20684–20689.

Dietz, T., E. Ostrom, and P.C. Stern. 2003. The struggle to govern the commons. *Science* 302: 1907-1912.

Downing, A.S., A. Bhowmik, D. Collste, S.E. Cornell, J. Donges, et al. 2019. Matching scope, purpose and uses of planetary boundaries science. *Environmental Research Letters* 14: 073005. doi:10.1088/1748-9326/ab22c9

Dryzek, J.S., A. Bächtiger, S. Chambers, J. Cohen, J.N. Druckman, et al. 2019. The crisis of democracy and the science of deliberation. *Science* 363: 1144-1146.

Duarte, C.M., S. Agusti, E. Barbier, G.L. Britten, J.-C. Castilla, et al. 2020. Rebuilding marine life. *Nature* 580: 39-51. doi.org/10.1038/s41586-020-2146-7

Durante, F., S.T. Fiske, M.J. Gelfand, F. Crippa, C. Suttora, et al. 2017. Ambivalent stereotypes link to peace, conflict, and inequality across 38 nations. *Proceedings of the National Academy of Sciences, USA*, 114: 669-674.

Ebbesson, J. 2010. The rule of law in governance of complex socio-ecological changes. *Global Environmental Change* 20: 414-422.

Eggerman, M., and C. Bricks. 2010. Suffering, hope, and entrapment: resilience and cultural values in Afghanistan. *Social Science & Medicine* 71: 71-83.

Ehrlich, P.R., and G.C. Daily. 1993. Population extinction and saving biodiversity. *Ambio* 22: 64-68.

Ehrlich, P.R., and A.H. Ehrlich. 1992. The value of biodiversity. *Ambio* 21: 219-226.

Ellen MacArthur Foundation. 2019. Completing the Picture: How the Circular Economy Tackles Climate Change. www.ellenmacarthurfoundation.org/publications

Ellis, E.C., and N. Ramankutty. 2008. Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment* 6: 439-447. doi: 10.1890/070062

Ellis, E.C., K. Klein Goldewijk, S. Siebert, D. Lightman, and N. Ramankutty N. 2010. Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecological Biogeography* 19: 589-606.

Ellis, E.C., 2015. Ecology in an anthropogenic biosphere. *Ecological Monographs* 85: 287-331.

Elmqvist, T, N. Frantzeskaki, E. Andersson, T. McPhearson, C. Folke, et al. 2019. Sustainability, resilience and transformation in the urban century. *Nature Sustainability* 2: 267-273. doi.org/10.1038/s41893-019-0250-1

Elmqvist, T., C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker and J. Norberg. 2003. Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 1: 488-494.

Enqvist, J.P., S. West, V.A. Masterson, L.J. Haider, U. Svedin, and M. Tengö. 2018. Stewardship as a boundary object for sustainability research: linking care, knowledge and agency. *Landscape and Urban Planning* 179: 17-37.

Erb, K.H., T. Kastner, C. Plutzar, A.L.S. Bais, N. Carvalhais, et al. 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* 553: 73-76.

Estes, J.A., J. Terborgh, J.S. Brashares, M.E. Power, J. Berger et al. 2011. Trophic downgrading of Planet Earth. *Science* 333: 301-306.

Falkenmark, M. 2017. Water and human livelihood resilience: a regional-to-global outlook. *International Journal of Water Resources Development* 33: 181-197.

Falkenmark, M., L. Wang-Erlandsson, and J. Rockström. 2019. Understanding of water resilience in the Anthropocene. *Journal of Hydrology X* 2:100009.

Felipe-Lucia, M.R., B., Martín-López, S. Lavorel, L. Berraquero-Díaz, J. Escalera-Reyes, and F.A. Comín. 2015. Ecosystem services flows: why stakeholders' power relationships matter. *PLoS One* 10, e0132232.

Feola, G. 2015. Societal transformation in response to global environmental change: a review of emerging concepts. *Ambio* 44: 376-390.

Ferrara, E., O. Varol, C. Davis, F. Menczer, and A. Flammini. 2016. The rise of social bots. *Communications of the ACM* 59: 96-104. doi.org/10.1145/2818717

Fischer, J., T.A. Gardner, E.B. Bennett, P. Balvanera, R. Biggs, et al. 2015. Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environmental Sustainability* 14: 144-149.

Fischer, J., and M. Riechers. 2019. A leverage points perspective on sustainability. *People and Nature* 2019 1: 115-120. doi:10.1002/pan3.13

Fogarty, L., N. Creanza, and M.W. Feldman. 2015. Cultural evolutionary perspectives on creativity and human innovation. *Trends in Ecology & Evolution* 30:736-754.

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, et al. 2005. Global consequences of land use. *Science* 309: 570-574.

Folke, C. 1991. Socio-economic dependence on the life-supporting environment. In: Folke, C. and T. Kåberger (eds.). *Linking the Natural Environment and the Economy: Essays from the Eco-Eco Group*. Kluwer Academic Publishers. pp. 77-94.

Folke, C., R. Biggs, A.V. Norström, B. Reyers, and J. Rockström. 2016. Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society* 21(3):41.

Folke, C., T. Hahn, P. Olsson and J. Norberg. 2005. Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources* 30:441-473.

Folke, C., S.R. Carpenter, B.H. Walker, M. Scheffer, F.S. Chapin III, and J. Rockström. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society* 15(4): 20.

Folke, C., H. Österblom, J.-B. Jouffray, E. Lambin, M. Scheffer, et al. 2019. Transnational corporations and the challenge of biosphere stewardship. *Nature Ecology & Evolution* 3: 1396-1403. doi 10.1038/s41559-019-0978-z

Folke, C. 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. *Global Environmental Change* 16: 253-267.

Folke, C., Å. Jansson, J. Rockström, P. Olsson, S.R. Carpenter, et al. 2011. Reconnecting to the Biosphere. *Ambio* 40: 719-738. doi 10.1007/s13280-011-0184-y

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution and Systematics* 35: 557-581.

Folke, C., Å. Jansson, J. Larsson and R. Costanza. 1997. Ecosystem appropriation by cities. *Ambio* 26:167-172.

Forbes, B.C., F. Stammler, T. Kumpula, N. Meschtyb, A. Pajunen, and E. Kaarlejarvi. 2009. High resilience in the Yamal-Nenets social-ecological system, West Siberian Arctic, Russia. *Proceedings of the National Academy of Sciences, USA* 106: 22041-22048.

Fortnam, M., K. Brown, T. Chaigneau, B. Crona, T.M. Daw, et al. 2019. The gendered nature of ecosystem services. *Ecological Economics* 159: 312–325.

Frank, A.B., M.G. Collins, S.A. Levin, A.W. Lo, J. Ramo, et al. 2014. Dealing with femtorisks in international relations. *Proceedings of the National Academy of Sciences, USA* 111: 17356-17362. doi.org/10.1073/pnas.1400229111

Frank, R.H. 1985. *Choosing the Right Pond: Human Behavior and the Quest for Status*. Oxford University Press, Oxford, UK.

Free, C.M., J.T. Thorson, M-L- Pinsky, K.L. Oken, J. Wiedenmann, and O.P. Jensen. 2019. Impacts of historical warming on marine fisheries production. *Science* 363: 979-983.

Freeman, J., J.A. Baggio, and T.R. Coyle. 2020. Social and general intelligence improves collective action in a common pool resource systems. *Proceedings of the National Academy of Sciences, USA* 117: 7712-7718. doi/10.1073/pnas.1915824117

Friedlingstein, P., M.W. Jones, M. O'Sullivan, R.M. Andrew, J. Hauck et al. 2019. Global carbon budget 2019. *Earth Systems Science Data* 11: 1783–1838. doi.org/10.5194/essd-11-1783-2019

Gaines, S.D., C. Costello, B. Owashi, T. Mangin, J. Bone, et al. 2018. Improved fisheries management could offset many negative effects of climate change. *Science Advances*, *4*(8), p.eaao1378.

Galaz, V. 2014. *Global Environmental Governance, Technology and Politics: The Anthropocene Gap*. Edward Elgar Publishing, Cheltenham, UK.

Galaz, V. (ed.). 2019. *Global Challenges, Governance, and Complexity*. Edward Elgar Publishing, Cheltenham, UK.

Galaz, V., B. Crona, A. Dauriach, B. Scholtens, and W. Steffen. 2018. Finance and the Earth system: exploring the links between financial actors and non-linear changes in the climate system. *Global Environmental Change* 53: 296-302.

Galaz, V., F. Moberg, E.-K. Olsson, E. Paglia, and C. Parker. 2011. Institutional and political leadership dimensions of cascading ecological crises. *Public Administration* 89: 361-380.

Galaz, V., B. Crona, H. Österblom, P. Olsson, and C. Folke. 2012. Polycentric Systems and interacting planetary boundaries: emerging governance of climate change - ocean acidification - marine biodiversity. *Ecological Economics* 81:21-32.

Galaz, V., H. Österblom, Ö. Bodin, and B. Crona. 2016. Global networks and global change-induced tipping points. *International Environmental Agreements: Politics, Law and Economics* 16: 189-221.

Galaz, V., J. Tallberg, A. Boin, C. Ituarte-Lima, E. Hey et al. 2017. Global governance dimensions of globally networked risks: the state of the art in social science research. *Risk, Hazards, & Crisis in Public Policy* 8: 4-27. doi.org/10.1002/rhc3.12108

Gamfeldt, L., T. Snäll, R. Bagchi, M. Jonsson, L. Gustafsson, et al. 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications* 4: 1340. doi:10.1038/ncomms2328.

Gaupp, F., J. Hall, S. Hochrainer-Stigler, and S. Dadson. 2020. Changing risks of simultaneous global breadbasket failure. *Nature Climate Change* 10: 54–57. doi.org/10.1038/s41558-019-0600-z

Geels, F.W., and J. Schot. 2007. Typology of sociotechnical transition pathways. *Research Policy* 36: 399-417. doi.org/10.1016/j.respol.2007.01.003

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell. 2017. Sociotechnical transitions for deep decarbonisation. *Science* 357: 1242-1244.

Gelcich, S., T.P. Hughes, P. Olsson, C. Folke, O. Defeo, et al. 2010. Navigating transformations in governance of Chilean marine coastal resources. *Proceedings of the National Academy of Sciences, USA* 107: 16794-16799.

Gleeson, T., L. Wang-Erlandsson, M. Porkka, S.C. Zipper, F. Jaramillo et al. 2020. Illuminating water cycle modifications and Earth System resilience in the Anthropocene. *Water Resources Research*. doi.org/10.1029/2019WR024957

Gleeson, T., L. Wang-Erlandsson, S.C. Zipper, M. Porkka, F. Jaramillo, et al. 2020b. The water planetary boundary: interrogation and revision. *One Earth* 2: 223-234. doi.org/10.1016/j.oneear.2020.02.009

Gordon, L.J., G.D. Peterson, and E.M. Bennett. 2008. Agricultural modifications of hydrological flows create ecological surprises. *Trends in Ecology and Evolution* 23: 211-219.

Gordon, L.J., V. Bignet, B. Crona, P. Henriksson, T. van Holt, et al. 2017. Rewiring food systems to enhance human health and biosphere stewardship. *Environmental Research Letters* 12, 100201

Green, J.F., and B. Rudyk. 2020. Closing the high seas to fishing: a club approach. *Marine Policy* (forthcoming). doi.org/10.2139/ssrn.3531845

Grêt-Regamey, A., S.H. Huber, and R. Huber. 2019. Actors' diversity and the resilience of social-ecological systems to global change. *Nature Sustainability* 2: 290-297.

Grigsby, M. 2004. *Buying Time and Getting By: The Voluntary Simplicity Movement*. State University of New York Press, Albany, NY, USA.

Grimm, N.B., S.H. Faeth, N.E. Golubiewski, C.L. Redman, J. Wu, X. Bai, and J.M. Briggs. 2008. Gloal change and the ecology of cities. *Science* 319: 756-760.

Grinberg, N., K. Joseph, L. Friedland, B. Swire-Thompson, D. Lazer. 2019. Fake news on Twitter during the 2016 U.S. presidential election. *Science* 363: 374-378. doi:10.1126/science.aau2706

Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, et al. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences, USA* 114: 11645-11650.

Gruber, N., D. Clement, B.R. Carter, R.A. Feely, S. van Heuven, et al. 2019. The oceanic sink for anthropogenic $CO_2$ from 1994 to 2007. *Science* 363: 1193-1199.

Guerry, A.D, S. Polasky, J. Lubchenco, R. Chaplin-Kramer, G.C. Daily, et al. 2015. Natural capital informing decisions: from promise to practice. *Proceedings of the National Academy of Sciences, USA.* 112: 7348-7355. doi/10.1073/pnas.1503751112

Gunderson, L.H., and C.S. Holling (eds.). 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington DC, USA.

Gunderson, L.H., and L. Pritchard Jr (eds.). 2002. *Resilience and the Behavior of Large-Scale Systems*. Island Press, Washington DC, USA.

Hackmann, H. and A.L. St.clair. 2012. Transformative cornerstones of Social Science research for Global change. Report of the international Social Science Council. Paris.

Hahn, T., P. Olsson, C. Folke, and K. Johansson. 2006. Trust building, knowledge generation and organizational innovations: the role of a bridging organization for adaptive co-management of a wetland landscape around Kristianstad, Sweden. *Human Ecology* 34: 573–592.

Haider, L.J., and F.J.W. van Oudenhoven. 2018. Food as a daily art: ideas for its use as a method in development practice. *Ecology and Society* 23(3):14. doi.org/10.5751/ES-10274-230314

Haider, L.J., W.J. Boonstra, A. Akobirshoeva, and M. Schlüter. 2019. Effects of development interventions on biocultural diversity: a case study from the Pamir Mountains. *Agriculture and Human Values.* doi.org/10.1007/s10460-019-10005-8

Hallegatte, S., M. Bangalore, L. Bonzanigo, M. Fay, T. Kane, et al. 2016. *Shock Waves: Managing the Impacts of Climate Change on Poverty*. World Bank, Washington, DC, USA.

Halpern, B.S., S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, et al. 2008. A global map of human impact on marine ecosystems. *Science* 319: 948-952.

Hall, P. A., and M. Lamont, editors. 2013. *Social Resilience in the Neoliberal Era*. Cambridge University Press, Cambridge, UK.

Hamann, M., R. Biggs, and B. Reyers. 2015. Mapping social-ecological systems: identifying 'green-loop' and 'red-loop' dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change* 34: 218-226.

Hamann, M., K. Berry, T. Chaigneau, T. Curry, R. Heilmayr et al. 2018. Inequality and the biosphere. *Annual Review of Environment and Resources* 43: 61–83

Hamann, M., R. Biggs, L. Pereira, R. Preiser, T. Hichert, et.al. 2020. Scenarios of good Anthropocenes in southern Africa. *Futures* 118, 102526. doi:10.1016/j.futures.2020.102526

Harper, A.B., T. Powell, P.M. Cox, J. House, C. Huntingford et al. 2018. Land-use emissions play a critical role in landbased mitigation for Paris climate targets. *Nature Communications* 9: 2938. doi:10.1038/s41467-018-05340-z.

Harper, S., D. Zeller, M. Hauzer, D. Pauly, and U.R. Sumaila. 2013. Women and fisheries: contribution to food security and local economies. *Marine Policy* 39: 56-63.

Hassan, N., M. Yousuf, M.A. Mahfuzul Haque, J. Suarez Rivas, and M. Khadimul Islam. 2019. Examining the roles of automation, crowds and professionals towards sustainable fact-checking. *Companion Proceedings of The 2019 World Wide Web Conference*, pp 1001-1006.

Häyhä, T., P.L. Lucas, D.P. van Vuuren, S.E. Corell, and H. Hoff. 2016. From Planetary Boundaries to national fair shares of the global safe operating space: how can the scales be bridged? *Global Environmental change* 40:60-72.

Heal, G., B. Walker, S. Levin, K. Arrow, P. Dasgupta, G. Daily, P. Ehrlich, K-G. Mäler, N. Kautsky, J. Lubchenco, S. Schneider, and D. Starret. 2004. Genetic diversity and interdependent crop choices in agriculture. *Resource and Energy Economics* 26: 175-184.

Heise, U.K. (ed.) 2008. *Sense of Place and Sense of Planet: The Environmental Imagination of the Global.* Oxford University Press, Oxford, UK.

Helbing, D. 2013. Globally networked risks and how to respond. *Nature* 497: 51-59.

Herrfahrdt-Pähle, E., M. Schlüter, P. Olsson, C. Folke, S. Gelcich, and C. Pahl-Wostl. 2020. Sustainability transformations: socio-political shocks as opportunities for governance transitions. *Global Environmental Change* 63:102097. https://doi.org/10.1016/j.gloenvcha.2020.102097

Hicks, C., A. Levine, A. Agrawal, X. Basurto, S. J. Breslow, et al. 2016. Engage key social concepts for sustainability: social indicators, both mature and emerging, are underused. *Science* 352: 38-40.

Hicks, C.C., P.J. Cohen, N.A.J. Graham, K.L. Nash, E.H. Allison, C. D'Lima, et al. 2019. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* 574: 95-98. doi.org/10.1038/s41586-019-1592-6

Hino, M., E. Benami, and N. Brooks. 2018. Machine learning for environmental monitoring. *Nature Sustainability* 1: 583-588. doi.org/10.1038/s41893-018-0142-9

Hirota, M., M. Holmgren, E.H. van Nes, and M. Scheffer. 2011. Global resilience of tropical forest and savanna to critical transitions. *Science* 334: 232-235.

Hisano, M., H.Y.H. Chen, E.B. Searle, and P.B. Reich. 2019. Species-rich boreal forests grew more and suffered less mortality than species-poor forests under the environmental change of the past half-century. *Ecological Letters* 22: 999-1008.

Hoff, K. and J.E. Stiglitz. 2016. Striving for balance in economics: towards a theory of the social determination of behavior. *Journal of Economic Behavior and Organisation* 126: 25-57.

Holling, C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4: 1-23.

Holling, C.S., and G.K. Meffe. 1996. Command and control and the pathology of natural resource management. *Conservation Biology* 10: 328-337

Homer-Dixon, T., B. Walker, R. Biggs, A.-S. Crepin, C. Folke, E.F. Lambin, G.D. Peterson, J. Rockström, M. Scheffer, W. Steffen, and M. Troell. 2015. Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society* 20(3):6.

Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, et al. 2012. The geological record of ocean acidification. *Science* 335: 1058-1063. doi:10.1126/science.1208277

Hooper, D.U., F.S. Chapin III, J.J. Ewel, A. Hector, P. Inchausti, et al. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs* 75: 3-35.

Houghton, R.A. 2007. Balancing the global carbon budget. *Annual Review of Earth and Planetary Sciences* 35: 313-347.

Hughes, T.P., M.J. Rodrigues, D.R. Bellwood, D. Ceccarelli, O. Hoegh-Guldberg, et al. 2007. Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Current Biology* 17: 1-6. doi:10.1016/j.cub.2006.12.049

Hughes, T.P., K.D. Anderson, S.R. Connolly, S.F. Heron, J.T. Kerry, et al. 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* 359*:* 80-83.

Hughes, T.P., S.R. Carpenter, J. Rockström, M. Scheffer, and B.H. Walker. 2013. Multiscale regime shifts and planetary boundaries. *Trends in Ecology & Evolution* 28: 389-395. doi:10.1016/j.tree.2013.05.019;

Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, et al. 2017. Estimating economic damage from climate change in the United States. *Science* 56: 1362-69.

Ide, T., M. Brzoska, J.F. Donges, and C.-F. Schleussner. 2020. Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change* 62: 102063. https://doi.org/10.1016/j.gloenvcha.2020.102063

Ilieva, R.T., and T. McPhearson. 2018. Social-media data for urban sustainability. *Nature Sustainability* 1: 553–565.

IPBES (2016). The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on pollinators, pollination and food production. S.G. Potts, V. L. Imperatriz-Fonseca, and H. T. Ngo (eds). Secretariat of IPBES, Bonn, Germany. 552 pages.

IPCC. 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland, 151 pp.

IPCC. 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, et al. (eds.). In press.

Isbell, F., A. Gonzalez, M. Loreau, J. Cowles, S. Diaz et al. 2017. Linking the influence and dependence of people on biodiversity across scales. *Nature* 546: 65-72.

Islam, S.N., and J. Winkel. 2017. Climate Change and Social Inequality. *DESA Working Paper* 152. Department of Economic & Social Affairs, United Nations.

Ives, C.D., R. Freeth, and J. Fischer. 2020. Inside-out sustainability: the neglect of inner worlds. *Ambio* 49: 208-217. doi.org/10.1007/s13280-019-01187-w

Jackson. J.B., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629-638.

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, S.J. Coughlin, C.A. Hay, et al. 2019. Impacts of green new deal energy plans on grid stability, costs, jobs, health, and climate in 143 Countries. *One Earth* 1: 449-463.

Jasanoff, S., and S.-H. Kim. 2015. *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*. University of Chicago Press, Chicago, Illinois, USA.

Jejeebhoy, S. 1995. *Women's Education, Autonomy, and Reproductive Behaviour: Experience from Developing Countries*. Clarendon, Oxford, UK.

Johnson, M., D.H. Locke, E. Svendsen, L. Campbell, L.M. Westphal, M. Romolini, and J. Grove. 2019. Context matters: influence of organizational, environmental, and social factors on civic environmental stewardship group intensity. *Ecology and Society* 24(4): 1.

Jones, C.G., J.H. Lawton, and M. Shachak. 1994. Organisms as ecosystem engineers. *Oikos* 69: 373-386.

Joppa, L.N. 2017. AI for Earth. *Nature* 552: 325-328.

Jørgensen, P.S., A. Aktipis, Z. Brown, Y. Carrière, S. Downes, et al. 2018. Antibiotic and pesticide susceptibility and the Anthropocene operating space. *Nature Sustainability* 1: 632-641. doi.org/10.1038/s41893-018-0164-3.

Jørgensen, P.S., C. Folke, and S.P. Carroll. 2019. Evolution in the Anthropocene: informing governance and policy. *Annual Review of Ecology, Evolution, and Systematics* 50: 527-546. doi.org/10.1146/annurev-ecolsys-110218-024621.

Jouffray, J.-B., R. Blasiak, A.V. Norström, H. Österblom, and M. Nyström. 2020. The blue acceleration: the trajectory of human expansion into the ocean. *One Earth* 2: 43-54. doi.org/10.1016/j.oneear.2019.12.016

Jouffray, J.-B., B. Crona, E. Wassenius, J. Bebbington, and B. Scholtens. 2019. Leverage points in the financial sector for seafood sustainability. *Science Advances* 5(10): eaax3324.

Kates, R.W. and W.C. Clark. 1996. Environmental surprise: expecting the unexpected. *Environment* 38, No. 2, pp. 6-11, 28-34.

Kates, R.W., and P. Dasgupta. 2007. African poverty: a great challenge for sustainability science. *Proceedings of the National Academy of Sciences, USA* 104: 16747-16750.

Kates, R.W., W.R. Travis, and T.J. Wilbanks. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences, USA* 109: 7156–7161.

Kavanagh, P.H., B. Vilela, H.J. Haynie, T. Tuff, M. Lima-Ribeiro, R.D. Gray, C.A. Botero, and M.C. Gavin. 2018. Hindcasting global population densities reveals forces enabling the origin of agriculture. *Nature Human Behaviour* 2: 478-484.

Kebede, E., A. Goujon, and W. Lutz. 2019. Stalls in Africa's fertility decline partly result from disruptions in female education. *Proceedings of the National Academy of Sciences, USA* 116: 2891-2896.

Keeler, B.L., K.D. Derickson, H. Waters, and R. Walker. 2020. Advancing Water Equity Demands New Approaches to Sustainability Science. *One Earth* 2: 211-213. doi.org/10.1016/j.oneear.2020.03.003

Keys, P.W., L. Wang-Erlandsson, and L.J. Gordon. 2016. Revealing invisible water: moisture recycling as an ecosystem service. *PLoS ONE* 11(3): e0151993.

Keys, P.W., L. Wang-Erlandsson, L.J. Gordon, V. Galaz, and J. Ebbesson. 2017. Approaching moisture recycling governance. *Global Environmental Change* 45: 15-23.

Keys, P.W., L. Wang-Erlandsson, and L.J. Gordon. 2018. Megacity precipitationsheds reveal tele-connected water security challenges. *PLoS ONE* 13(3): e0194311. doi.org/10.1371/journal.pone.0194311

Keys, P., V. Galaz, M. Dyer, N. Matthews, C. Folke, M. Nyström, and S. Cornell. 2019. Anthropocene risk. *Nature Sustainability* 2: 667-673. doi.org/10.1038/s41893-019-0327-x

Khoury, K.C., A.D. Bjorkman, H. Dempewolf, J. Ramirez-Villegas, L. Guarino, A. Jarvis, L.H. Rieseberg, and P.C. Struik. 2014. Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences, USA* 111: 4001-4006.

King, A.D., and L.J. Harrington. 2018. The inequality of climate change from 1.5 to 2°C of global warming. *Geophysical Research Letters* 45: 5030–5033.

Kinzig, A.P., C. Perrings, F.S. Chapin III, S. Polasky, V.K. Smith, D. Tilman, and B.L. Turner. 2011. Paying for ecosystem services: promise and peril. *Science* 334: 603-604.

Kolodny, O., N. Creanza, and M.W. Feldman. 2016. Game-changing innovations: how culture can change the parameters of its own evolution and induce abrupt cultural shifts. *PLOS Computational Biology* 12:e1005302.

Kremen, C., and A.M. Merenlender. 2018. Landscapes that work for biodiversity and people. *Science* 362: eaau6020

Kristjanson, P. R.S. Reid, N. Dickson, W.C. Clark, D. Romney, et al. 2009. Linking international agricultural research knowledge with action for sustainable development. *Proceedings of the National Academy of Sciences, USA* 106: 5047-5052.

Kummu, M., P. Kinnunen, E. Lehikoinen, M. Porkka, Cibele Queiroz, et al. 2020. Interplay of trade and food system resilience: Gains on supply diversity over time at the cost of trade independency. *Global Food Security* 24: 100360. doi.org/10.1016/j.gfs.2020.100360

Lachat, C., J.E. Raneri, K. Walker Smith, P. Kolsteren, P. Van Damme, et al. 2018. Dietary species richness as a measure of food biodiversity and nutritional quality of diets. *Proceedings of the National Academy of Sciences, USA* 115: 127–132. doi.org/10.1073/pnas.1709194115

Lade, S.J., W. Steffen, W. de Vries, S.R. Carpenter, J.F. Donges, et al. 2020. Human impacts on planetary boundaries amplified by Earth system interactions. *Nature Sustainability* 3: 119-128. doi.org/10.1038/s41893-019-0454-4.

Lade, S.J., J. Norberg, J.M. Anderies, C. Beer, S.E. Cornell, et al. 2019. Potential feedbacks between loss of biosphere integrity and climate change. *Global Sustainability* 2: e21. 1-15. doi.org/10.1017/sus.2019.18

Lade, S.J., L.J. Haider, G. Engström, and M. Schlüter. 2017. Resilience offers escape from trapped thinking on poverty alleviation. *Science Advances* 3: e1603043

Lambin, E.F., and P. Meyfroidt. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences, USA* 108: 3465-3472.

Lamont, M. 2019. From 'having' to 'being': self-worth and the current crisis of American society. *The British Journal of Sociology* 70: 660-707.

Lamont, M. 2018. Addressing recognition gaps: destigmatization and the reduction of inequality. *American Sociological Review* 83: 419-444.

Lamont, M., L. Adler, B.Y. Park, and X. Xiang. 2017. Bridging cultural sociology and cognitive psychology in three contemporary research programmes. *Nature Human Behaviour* 1: 886-872.

Lazer, D.M., M.A. Baum, Y. Benkler, A.J. Berinsky, K.M. Greenhill, et al. 2018. The science of fake news. *Science* 359:1094-1096.

Leach, M., I. Scoones, and A. Stirling. 2010. *Dynamic Sustainabilities: Technology, Environment, Social Justice*. Routledge, London, UK.

Leach, M., J. Rockström, P. Raskin, I. Scoones, A.C. Stirling, A .Smith, J. Thompson, E. Millstone, A. Ely, E. Arond, C. Folke, and P. Olsson. 2012. Transforming innovation for sustainability. *Ecology and Society* 17(2):11.

Leach, M., B. Reyers, X. Bai, E.S. Brondizio, C. Cook et al. 2018. Equity and sustainability in the Anthropocene: a social-ecological systems perspective on their intertwined futures. *Global Sustainability* 1, e13, 1–13.

Lefcheck, J.S., J.E.K. Byrnes, F. Isbell, L. Gamfeldt, J.N. Griffin, et al. 2015. Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. *Nature Communications* 6:6936. doi:10.1038/ncomms7936.

Leichenco, R., and J.A. Silva. 2014. *WIREs Climate Change* 5:539–556. doi:10.1002/wcc.287

Lenton, T.M., J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, and H.J. Schellnhuber. 2019. Climate tipping points: too risky to bet against. *Nature* 575: 592-595.

Lenton, T.M. 2016. *Earth System Science*. Oxford University Press, Oxford, UK.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber. 2008. Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences, USA* 105: 1786-1793.

Levin, S.A., and J. Lubchenco. 2008. Resilience, robustness and marine ecosystem-based management. *BioScience* 58: 27-32.

Levin, S.A., J. Anderies, N. Adger, S. Barrett, E. Bennett, et al. 2020. Governance in the shadow of extreme events. *Proceedings of the National Academy of Sciences, USA,* in revision.

Levin, S.A. 1999. *Fragile Dominion: Complexity and the Commons*. Helix Books, Perseus, Cambridge, Massachusetts, USA.

Levin, S.A, T. Xepapadeas, A.-S. Crepin, J. Norberg, A. de Zeeuw, et al. 2013. Social-ecological systems as complex adaptive systems: modeling and policy implications? *Environment and Development Economics* 18:111-132.

Limburg, K.E., D. Breitburg, D.P. Swaney, and G. Jacinto. 2020. Ocean deoxygenation: a primer. *One Earth* 2: 24-29 doi.org/10.1016/j.oneear.2020.01.001

Liu, J., T. Dietz, S.R. Carpenter, M. Alberti, C. Folke, et al. 2007. Complexity of Coupled Human and Natural Systems. *Science* 317:1513-1516.

Liu, J., H. Mooney, V. Hull, S.J. Davis, J. Gaskell, et al. 2015. Systems integration for global sustainability. *Science* 347, 1258832.

Liu, J., W. Yang, and S.X. Li. 2016. Framing ecosystem services in the telecoupled Anthropocene. *Frontiers in Ecology and the Environment* 14:27-36. doi 10.1002/16-0188.1

Longhurst, N., and J. Chilvers. 2019. Mapping diverse visions of energy transitions: co-producing sociotechnical imaginaries. *Sustainability Science* 14: 973-90. doi.org/10.1007/s11625-019-00702-y.

Loorbach, D., N. Frantzeskaki, and F. Avelino. 2017. Sustainability transitions research: transforming science and practice for societal change. *Annual Review of Environment and Resources* 42: 599-626. doi.org/10.1146/annurev-environ-102014-021340.

Loorbach, D. 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance* 23: 161-183. doi:10.1111/j.1468-0491.2009.01471.x

Lotze, H.K., D.P. Tittensor, A. Bryndum-Buchholz, T.D. Eddy, W.W.L. Cheung, et al. 2019. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences, USA* 116: 12907-12912. doi.org/10.1073/pnas.1900194116

Lovejoy, T.E., and C. Nobre. 2018. Amazon tipping point. *Sciences Advances* 4: eaat2340

Lovejoy, T.E. and L. Hannah (eds.). 2019. *Biodiversity and Climate Change: Transforming the Biosphere*. Yale University Press, New Haven, USA.

Lovejoy, T.E. and L. Hannah. 2018. Avoiding the climate failsafe point. *Science Advances* 4:eaau9981.

Lubchenco, J. and S.D. Gaines. 2019. A new narrative for the ocean. *Science* 364: 911. doi:10.1126/science.aay2241

Lubchenco, J. 1998. Entering the century of the environment: a new social contract for science. *Science* 279: 491–497.

Lubchenco, J., E.B. Cerny-Chipman, J.N. Reimer, and S.A. Levin. 2016. The right incentives enable ocean sustainability successes and provide hope for the future. *Proceedings of the National Academy of Sciences, USA* 113: 14507-14514.

Lubchenco, J., and K. Grorud-Colvert. 2015. Making waves: the science and politics of ocean protection. *Science* 350: 382-383.

Luck, G.W., G.C. Daily, and P.R. Ehrlich. 2003. Population diversity and ecosystem services. *Trends in Ecology & Evolution* 18: 331–336.

Lutz, W., R. Muttarak, and E. Striessnig. 2014. Universal education is key to enhanced climate adaptation. *Science* 346: 1061-1062.

Mace, G.M. 2014. Whose conservation? *Science* 345: 1558-1560. doi:10.1126/science.1254704

Mace, G.M., B. Reyers, R. Alkemade, R. Biggs, F.S. Chapin III, et al. 2014. Approaches to defining a planetary boundary for biodiversity. *Global Environmental Change* 28: 289-297.

Mach, K.J., C.M. Kraan, W.N. Adger, H. Buhaug, M. Burke, et al. 2019. Climate as a risk factor for armed conflict. *Nature* 571: 193-197.

Maharini, C.D., M. Moelionon, G.Y. Wong, M. Brockhaus, R. Carmenta, and M. Kallio. 2019. Development and equity: a gendered inquiry in a swidden landscape. *Forest Policy and Economics* 101:120.128.

Mandle, L., J. Salzman, and G.C. Daily (eds.). 2019. *Green Growth That Works: Natural Capital Policy and Finance Mechanisms from Around the World*. Island Press, Washington DC, USA.

Markus, H., and P. Nurius, P. 1986. Possible selves. *American Psychologist* 41: 954-969.

Marshall, N.A., S.E. Park, W.N. Adger, K. Brown, and S.M. Howden. 2012. Transformational capacity and the influence of place and identity. *Environmental Research Letters* 7: 034022.

Mathevet, R., F. Bousquet, and C.M. Raymond. 2018. The concept of stewardship in sustainability science and conservation biology. *Biological Conservation* 217: 363-370.

Matson, P., W.C. Clark, and K. Andersson. 2016. *Pursuing Sustainability*. Princeton University Press, Princeton, New Jersey, USA.

Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero et al. 2019. Food Security. In: P.R. Shukla, et al. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

McAfee, A. 2019. *More from Less: The Surprising Story of How We Learned to Prosper Using Fewer Resources, and What Happens Next.* Scribner, New York, USA.

McCauley, D.J., M. Pinsky, S.R. Palumbi, J.A. Estes, F.H. Joyce, and R.R. Warner. 2015. Marine defaunation: animal loss in the global ocean. *Science* 347:1255641.

McDonald, R.I., A.V. Mansur, F. Ascensão, M. Colbert, K. Crossman, et al. 2020. Research gaps in knowledge of the impact of urban growth on biodiversity. *Nature Sustainability* 3: 16-24. doi:10.1038/s41893-019-0436-6

McNeill, J. R. 2000. *Something New under the Sun: An Environmental History of the Twentieth Century*. W.W. Norton, New York, USA.

Mendelsohn, R., A. Dinar, and L. Williams. 2006. The distributional impact of climate change on rich and poor countries. *Environment and Development Economics* 11: 159-178.

Meng, J., Z. Mi, D. Guan, J. Li, S. Tao, et al. 2018. The rise of South-South trade and its effect on global CO2 emissions. *Nature Communications* 9:1871 doi:10.1038/s41467-018-04337-y

Merçon J., S. Vetter, M. Tengö, M. Cocks, P. Balvanera, et al. 2019. From local landscapes to international policy: contributions of the biocultural paradigm to global sustainability. *Global Sustainability* 2, e7, 1–11.

Meyfroidt, P., and E.F. Lambin. 2009. Forest transition in Vietnam and displacement of deforestation abroad. *Proceedings of the National Academy of Sciences, USA* 106: 16139-16144.

Meyfroidt, P., R.R. Chowdhury, A. de Bremond, E.C. Ellis, K.H. Erb, et al. 2018. Middle-range theories of land system change. *Global Environmental Change* 53: 52-67.

Milillo, P., E. Rignot, P. Rizzoli, B. Scheuchl, J. Mouginot, J. Bueso-Bello, and P. Prats-Iraola. 2019. Heterogeneous retreat and ice melt of Thwaites Glacier, West Antarctica. *Science Advances* 5:eaau3433.

Milkoreit, M. 2017. Imaginary politics: climate change and making the future. *Elementa: Science of the Anthropocene* 5(62). doi.org/10.1525/elementa.249

Mische, A. 2009. Projects and possibilities: researching futures in action. *Sociological Forum* 24: 694-704.

Moore, M.-L., O. Tjornbo, E. Enfors, C. Knapp, J. Hodbod, et al. 2014. Studying the complexity of change: toward an analytical framework for understanding deliberate social-ecological transformations. *Ecology and Society* 19(4): 54. doi.org/10.5751/ES-06966-190454

Moore, M.-L., D. Riddell, D. and D. Vosicano. 2015. Scaling out, up and deep. *The Journal of Corporate Citizenship* 58: 67-84.

Moore, M., and F. Westley. 2011. Surmountable chasms: networks and social innovation for resilient systems. *Ecology and Society* 16(1): 5. www.ecologyandsociety.org/vol16/iss1/art5/

Mori, A.S., T. Furukawa, and T. Sasaki. 2013. Response diversity determines the resilience of ecosystems to environmental change. *Biological Reviews* 88: 349–364. doi:10.1111/brv.12004

Morton, J.F. 2007. The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences, USA* 104: 19680-19685. doi10.1073pnas.0701855104

Myers, S.S., and J.J. Patz. 2009. Emerging threats to human health from global environmental change. *Annual Review of Environment and Resources* 34: 223-252.

Mounier, A., and M.M. Lahr. 2019. Deciphering African late middle Pleistocene hominin diversity and the origin of our species. *Nature Communications* 10:3406 doi.org/10.1038/s41467-019-11213-w

Naeem, S., and S.B. Li. 1997. Biodiversity enhances ecosystem reliability. *Nature* 390: 507-509. doi:10.1038/37348

Naeem, S., J.C. Ingram, A. Varga, T. Agardy, P. Barten, et al. 2015. Get the science right when paying for nature's services. *Science* 347: 1206-1207.

Nash, K.L., N.A.J. Graham, S. Jennings, S.K. Wilson, and D.R. Bellwood. 2016. Herbivore cross-scale redundancy supports response diversity and promotes coral reef resilience. *Journal of Applied Ecology* 53: 646–655. doi:10.1111/1365-2664.12430

Neukom, R., N. Steiger, J.J. Gómez-Navarro, J. Wang, and J.P. Werner. 2019. No evidence for globally coherent warm and cold periods over the preindustrial Common Era. *Nature* 571: 550-572. doi.org/10.1038/s41586-019-1401-2.

Newbold, T., L.N. Hudson, S.L.L. Hill, S. Contu, I. Lysenko, et al. 2015. Global effects of land use on local terrestrial biodiversity. *Nature* 520: 45-50. doi:10.1038/nature14324

Newbold, T., L.N. Hudson, A.P. Arnell, S. Contu, A. De Palma, et al. 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* 353: 288-291. doi10.1126/science.aaf2201

Newbold T., L.N. Hudson, S. Contu, S.L.L. Hill, J. Beck, et al. 2018. Widespread winners and narrow-ranged losers: land use homogenizes biodiversity in local assemblages worldwide. *PLOS Biology* 16, e2006841 (2018).

Nielsen, K.S., J.M. Gilligan, T. Dietz, M.J. Figueroa, C. Folke, et al. 2020. Improving climate change mitigation analysis: a framework for examining feasibility. *One Earth* in revision

Nobre, C.A., G. Sampaio, L.S. Borma, J.C. Castilla-Rubio, J.S. Silva, and M. Cardoso. 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences, USA* 113: 10759-10768.

Norström A.V., C. Cvitanovic, M.F. Löf, S. West, C. Wyborn, et al. 2020. Principles for knowledge co-production in sustainability research. *Nature Sustainability* 3: 182-190. doi.org/10.1038/s41893-019-0448-2

Nyborg, K., J.M. Anderies, A. Dannenberg, T. Lindahl, C. Schill, et al. 2016. Social norms as solutions: policies may influence large-scale behavioral tipping. *Science* 354: 42-43.

Nyström, M. 2006. Redundancy and response diversity of functional groups: implications for the resilience of coral reefs. *Ambio* 35: 30-35.

Nyström M., J.-B. Jouffray, A. Norström, P.S. Jørgensen, V. Galaz, B.E. Crona, S.R. Carpenter, and C. Folke. 2019. Anatomy and resilience of the global production ecosystem. *Nature* 575: 98-108.

O'Brien, K. 2012. Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography* 36:667-676.

O'Brien, K. 2015. Political agency: The key to tackling climate change. *Science* 350: 1170-1171. doi:10.1126/science.aad0267

O'Brien, K., B. Hayward, and F. Berkes. 2009. Rethinking social contracts: building resilience in a changing climate. *Ecology and Society* 14(2): 12.

Odum, E.P. 1989. *Ecology and Our Endangered Life-Support Systems*. Sinauer, Sunderland, Massachusetts, USA.

Oelkers, E.H., and D.R. Cole. 2008. Carbon dioxide sequestration: a solution to the global problem. *Elements* 4: 305-310.

Oliver, T.H. M.S. Heard, N.J.B. Isaac, D.B. Roy, D. Procter, et al. 2015. Biodiversity and Resilience of Ecosystem Functions. *Trends in Ecology & Evolution* 30: 673-684. doi.org/10.1016/j.tree.2015.08.009

Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, et al. 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9:1324. doi:10.1038/s41467-018-03732-9

Olson, M. 1965. *Logic of Collective Action: Public Goods and the Theory of Groups*. Harvard University Press, Boston, USA.

Olsson, P., C. Folke, and T. Hahn. 2004. Social-ecological transformation for ecosystem management: the development of adaptive co-management of a wetland landscape in southern Sweden. *Ecology and Society* 9(4): 2.

Olsson, P., C. Folke, and T.P. Hughes. 2008. Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia. *Proceedings of the National Academy of Sciences, USA* 105: 9489-9494.

Olsson, P., V. Galaz, and W.J. Boonstra. 2014. Sustainability transformations: a resilience perspective. *Ecology and Society* 19(4): 1. http://dx.doi.org/10.5751/ES-06799-190401

Olsson, P., M.-L. Moore, F.R. Westley, and D.D.P. McCarthy. 2017. The concept of the Anthropocene as a game-changer: a new context for social innovation and transformations to sustainability. *Ecology and Society* 22(2): 31. https://doi.org/10.5751/ES-09310-220231

O'Neill, D.W., A.L. Fanning, W.F. Lamb, and J.K. Steinberger. 2018. A good life for all within planetary boundaries. *Nature Sustainability* 1:88-95.

Ordway, E.M., R.L. Naylor, R.N. Nkongho, and E.F. Lambin. 2019. Oil palm expansion and deforestation in Southwest Cameroon associated with proliferation of informal mills. *Nature Communications* 10: 114

Oreskes, N., and E.M. Conway. 2010. *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*. Bloomsbury Press, New York, USA.

Österblom, H., C.C.C. Wabnitz, D. Tladi, E.H. Allison, S. Arnaud Haond*,* et al. 2019. *Towards Ocean Equity*. World Resources Institute, Washington, D.C.

Österblom, H., , J.-B. Jouffray, C. Folke, and J. Rockström. 2017. Emergence of a global science–business initiative for ocean stewardship. *Proceedings of the National Academy of Sciences, USA* 114: 9038-9043.

Österblom, H., J.-B. Jouffray, C. Folke, B. Crona, M.Troell, A. Merrie, and J. Rockström. 2015. Transnational corporations as keystone actors in marine ecosystem. *Plos One* 10(5): e0127533. doi:10.1371/journal.pone.0127533

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge, UK. Cambridge University Press.

Ostrom, E. 2009. A general framework for analysing the sustainability of social-ecological systems. *Science* 325: 419-422. doi:10.1126/science.1172133

Ostrom, E. 2010. Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change* 20: 550-557.

Otto, I.M., J.F. Donges, R. Cremades, A. Bhowmik, R.J. Hewitt, et al. 2020. Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences, USA* 117: 2354-2365.

*Our Common Journey: A Transition Toward Sustainability*. 1999. National Research Council Policy Division Board on Sustainable Development. Natl Acad Press, Washington, DC.

Ouyang, Z., H. Zheng, Y. Xiao, S. Polasky, J. Liu et al. 2016. Improvements in ecosystem services from investments in natural capital. *Science* 352: 1455-1459.

Pace, N.R. 1997. A molecular view of microbial diversity and the biosphere. *Science* 276: 734-740. doi:10.1126/science.276.5313.73

Page, S.E., F. Siegert, J.O. Rieley, H.-D.V. Boehm, A. Jayak, and S. Limink. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420: 61–65.

Pahl-Wostl, C., M. Craps, A. Dewulf, E. Mostert, D. Tabara, and T. Taillieu. 2007. Social learning and water resources management. *Ecology and Society* 12(2): 5. www.ecologyandsociety.org/vol12/iss2/art5/

Palumbi, S.R., P.A. Sandifer, J.D. Allan, M.W. Beck, D.G. Fautin et al. 2009. Managing for ocean biodiversity to sustain marine ecosystem services. *Frontiers in Ecology and the Environment* 7: 204–211. doi:10.1890/070135

Palumbi, S.R. 2001. Humans as the world's greatest evolutionary force. *Science* 293: 1786-1790.

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37:637-669.

Patterson, J., K. Schulz, J. Vervoort, S. van der Hel, O. Widerberg, et al. 2017. Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions* 24: 1-16. doi:10.1016/j.eist.2016.09.001

Pennycook, G., and D.G. Rand. 2019. Fighting misinformation on social media using crowdsourced judgments of news source quality. *Proceedings of the National Academy of Sciences, USA* 116: 2521-2526

Pereira, L.M., T. Karpouzoglou, N. Frantzeskaki, and P. Olsson. 2018. Designing transformative spaces for sustainability in social-ecological systems. *Ecology and Society* 23(4):32. doi.org/10.5751/ES-10607-230432

Perino, A., H.M. Pereira, L.M. Navarro, N. Fernández, J.M. Bullock, et al. 2019. Rewilding complex ecosystems. *Science* 364: eaav5570. doi:10.1126/science.aav5570

Peters, D.P.C. R.A. Pielke, Sr, B.T. Bestelmeyer, C.D. Allen, S. Munson-McGee, and K.M. Havstad. 2004. Cross-scale interactions, nonlinearities, and forecasting catastrophic events. *Proceedings of the National Academy of Sciences, USA* 101: 15130–15135.

Peters, G.P., R.M. Andrew, J.G. Canadell, P. Friedlingstein, R.B. Jackson et al. 2020. Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nature Climate Change* 10**:** 3-6. https://doi.org/10.1038/s41558-019-0659-6

Peterson, G., C.R. Allen, and C.S. Holling. 1998. Ecological resilience, biodiversity, and scale. *Ecosystems* 1: 6-18. doi.org/10.1007/s100219900002

Peterson, G.D., G.S. Cumming, and S.R. Carpenter. 2003. Scenario planning: a tool for conservation in an uncertain world. *Conservation Biology* 17: 358-366.

Phillips, C.A., A. Caldas, R. Cleetus, K.A. Dahl, J. Declet-Barreto, et al. 2020. Compound climate risk in the COVID-19 pandemics. *Nature Climate Change* https://doi.org/10.1038/s41558-020-0804-2

Pickering, J., and Å. Persson. 2020. Democratising planetary boundaries: experts, social values and deliberative risk evaluation in Earth system governance. *Journal of Environmental Policy & Planning* 22:59-71. doi 10.1080/1523908X.2019.1661233

Pigford, A.A., G. Hickey, and L. Klerkx. 2018.Beyond agricultural innovation systems? exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. *Agricultural Systems* 164: 116-121.

Pihl, E., M.A. Martin, T. Blome, S. Hebden, M.P. Jarzebski, et al. 2019. 10 New Insights in Climate Science 2019. Future Earth & The Earth League, Stockholm, Sweden.

Piketty, T. 2014. *Capital in the Twenty-First Century*. Belknap Press of Harvard University Press, Cambridge, Massachusetts, USA.

Pinsky, M.L., G. Reygondeau, R. Caddell, J. Palacios-Abrantes, J. Spijkers, and W.W.L. Cheung. 2018. Preparing ocean governance for species on the move. *Science* 360: 1189-1191. doi:10.1126/science.aat2360

Plummer, R., J. Baird, S. Farhad, and S. Witkowski. 2020. How do biosphere stewards actively shape trajectories of social-ecological change? *Journal of Environmental Management* 261: 110139

Polasky, S., S.R. Carpenter, C. Folke, and B. Keeler. 2011. Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology and Evolution* 26: 398-404.

Polasky, S., B. Bryant, P. Hawthorne, J. Johnson, B. Keeler, and D. Pennington. 2015. Inclusive wealth as a metric of sustainable development. *Annual Review of Environment and Resources* 40: 445-46.

Poli, R. 2017. *Introduction to Anticipation Studies*. Springer, Berlin, Germany.

Poore, J. and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360: 987-992.

Prokopenko, M. 2009. Guided self-organization. *HFSP Journal* 3: 287-289.

Quinlan, A.E., M. Berbés-Blázquez, L.J. Haider, and G.D. Peterson. 2015. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology* 23:677-687. doi.org/10.1111/1365-2664.12550

Rader, R., J. Reilly, I. Bartomeus, and R. Winfree. 2013. Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops. *Global Change Biology* 19: 3103-3110. doi: 10.1111/gcb.12264

Rathwell, K.J., and G.D. Peterson. 2012. Connecting social networks with ecosystem services for watershed governance: a social-ecological network perspective highlights the critical role of bridging organizations. *Ecology and Society* 17(2): 24.

Raymond, C.M., I. Fazey, M.S. Reed, L.C. Stringer, G.M. Robinson, and A.C .Evely. 2010. Integrating local and scientific knowledge for environmental management. *Journal of Environmental Management* 91: 1766-1777.

Raworth, K. 2012. A safe and just space for humanity: can we live within the doughnut? Oxfam Discussion Papers, February 2012.

Reardon, T., E. Ruben, J. Berdegué, B. Minten, S. Liverpool-Tasie, et al. 2019. Rapid transformation of food systems in developing regions: highlighting the role of agricultural research & innovations. *Agricultural Systems* 172: 47-59.

Redman, C. 1999. *Human Impact on Ancient Environments*. The University of Arizona Press, Tuscon, Arizona, USA.

Reich, P.R., D. Tilman, F. Isbell, K. Mueller, S.E. Hobbie, D.F.B. Flynn,, and N. Eisenhauer. 2012. Impacts of biodiversity loss escalate through time as redundancy fades. *Science* 336: 589-592. doi:10.1126/science.1217909

Reichstein, M., G. Camps-Valls, B. Stevens, M. Jung, J. Denzler, et al. 2019. Deep learning and process understanding for data-driven Earth system science. *Nature* 566: 195-204. doi.org/10.1038/s41586-019-0912-1

Renard, D., and D. Tilman. 2019. National food production stabilized by crop diversity. *Nature* 571: 257-260.

Reyers, B., J.L. Nel, P.J. O'Farrell, N. Sitas, and D.C. Nel. 2015. Navigating complexity through knowledge coproduction: mainstreaming ecosystem services into disaster risk reduction. *Proceedings of the National Academy of Sciences, USA* 112:7362-7368.

Reyers, B., R. Biggs, G.S. Cumming, T. Elmqvist, A.P. Hejnowicz, and S. Polasky. 2013. Getting the measure of ecosystem services: a social-ecological approach. *Frontiers in Ecology and Evolution* 11: 268–273.

Reyers, B., C. Folke, M.-L. Moore, R. Biggs, and V. Galaz. 2018. Social-ecological systems resilience for navigating the dynamics of the Anthropocene. *Annual Review of Environment and Resources* 43: 267–289.

Rocha, J. C., G. D. Peterson, and R. O. Biggs. 2015. Regime shifts in the Anthropocene: drivers, risks, and resilience. *PLoS ONE* 10 (8):e0134639.

Rocha, J.C., G. Peterson, Ö. Bodin, and S. Levin. 2018. Cascading regime shifts within and across scales. *Science* 362: 1379-1383.

Rockström, J., O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, and H.J. Schellnhuber. 2017. A roadmap for rapid decarbonization: emissions inevitably approach zero with a "carbon law". *Science* 355**:** 1269-1271. doi:10.1126/science.aah3443

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin III, et al. 2009. A safe operating space for humanity. *Nature* 461: 472-475.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin III, et al. 2009b. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14(2): 32.

Roe, S., C. Streck, M. Obersteiner, S. Frank, B. Griscom et al. 2019. Contribution of the land sector to a 1.5°C world. *Nature Climate Change* 9: 817-828.

Rosling, H. 2015. Gapminder: a fact-based worldview. Gapminder, Stockholm, Sweden. [online] URL: http://www.gapminder.org/Gapminder. 2019. Number of people by income. https://www.gapminder.org/tools/#$chart-type=mountain

Sachs, J.D., G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, and J. Rockström. 2019. Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability* 2: 805-814. doi.org/10.1038/s41893-019-0352-9

Saez, E., and G. Zucman. 2016. Wealth inequality in the United States since 1913: evidence from capitalized income tax data. *Quarterly Journal of Economics* 131: 519-578.

Sakschewski, B., W. von Bloh, A. Boit, L. Poorter, Ma. Peña-Claros, J. Heinke, J. Joshi, and K. Thonicke. 2016. Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change* 6: 1032-1036. doi.org/10.1038/nclimate3109

Sala, E., and N. Knowlton. 2006. Global marine biodiversity trends*. Annual Review of Environment and Resources* 31: 93-122.

Sala, E.,C. Costello, J.D. Parme, M. Fiorese, G. Heal, et al. 2016. Fish banks: an economic model to scale marine conservation. *Marine Policy* 73: 154-161.

Sasaki, T., X. Lu, M. Hirota, and Y. Bai. 2019. Species asynchrony and response diversity determine multifunctional stability of natural grasslands. *Journal of Ecology* 107: 1862-1875. doi:10.1111/1365-2745.13151

Scheffer, M. 2020. Eye-opening revisited social media as a driver of discontent and transformation. *Proceedings of the National Academy of Sciences*, *USA* in review

Scheffer, M., S.R. Carpenter, T.M. Lenton, J. Bascompte, W. Brock, V. Dakos, J. van de Koppel, I.A. van de Leemput, S.A. Levin, E.H. van Nes, M. Pascual, and J. Vandermeer. 2012. Anticipating critical transitions. *Science* 338: 344-348.

Scheffer, M., S.R. Carpenter, J. Foley, C. Folke, and B.H. Walker. 2001. Catastrophic shifts in ecosystems. *Nature* 413: 591-596.

Scheffer, M., B. Bavel, I.A. van de Leemput, and E.H. van Nes. 2017. Inequality in nature and society. *Proceedings of the National Academy of Sciences*, *USA* 114: 13154-13157.

Scheffer, M., S. Barrett, S. Carpenter, C. Folke, A.J. Greene, et al. 2015. Creating a safe operating space for the world's iconic ecosystems. *Science* 347:1317-1319.

Schill, C., J.M. Anderies, T. Lindahl, C. Folke, S. Polasky, et al. 2019. A more dynamic understanding of human behaviour for the Anthropocene. *Nature Sustainability* 2: 1075-1082. doi.org/10.1038/s41893-019-0419-7

Schlüter, M., L.J. Haider, S. Lade, E. Lindkvist, R. Martin, K. Orach, N. Wijermans, and C. Folke. 2019. Capturing emergent phenomena in social-ecological systems: an analytical framework. *Ecology and Society* 24(3): 11. doi.org/10.5751/ES-11012-240311

Schmidheiny, S., with the Business Council for Sustainable Development. 1992. *Changing Course: A Global Business Perspective on Development and the Environment*. MIT Press, Cambridge, MA, USA.

Schultz, L., C. Folke, H. Österblom, and P. Olsson. 2015. Adaptive governance, ecosystem management and natural capital. *Proceedings of the National Academy of Sciences, USA* 112: 7369-7374. doi/10.1073/pnas.1406493112

Seto, K. C., A. Reenberg, C. G. Boone, M. Fragkias, D. Haase, T. Langanke, P. Marcotullio, D. K. Munroe, B. Olah, and D. Simon. 2012. Urban land teleconnections and sustainability. *Proceedings of the National Academy of Sciences, USA* 109: 7687-7692.

Seto, K., B. Guneralp, and L. Hutyra. 2012b. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences, USA* 109: 16083-16088.

Smith, A., A. Stirling, and F. Berkhout. 2005. The governance of sustainable socio-technical transitions. *Research Policy* 34: 1491-1510. doi:10.1016/j.respol.2005.07.005

Smith, T.B., M.T. Kinnison, S.Y. Strauss, T.L. Fuller, and S.P. Carroll. 2014. Prescriptive evolution to conserve and manage biodiversity. *Annual Review of Ecology, Evolution, and Systematics* 45: 1-22.

Soliveres, S., F. van der Plas, P. Manning, D. Prati, M.M. Gossner, et al. 2016. Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. *Nature* 536: 456-459. doi:10.1038/nature19092

Staver, C.A., S. Archibald, and S.A. Levin 2011. The global extent and determinants of savanna and forest as alternative biome states. *Science* 334: 230-232.

Steffen, W., Å. Persson, L. Deutsch, J. Zalasiewicz, M. Williams, et al. 2011. The Anthropocene: from global change to planetary stewardship. *Ambio* 40: 739-761.

Steffen, W., J. Rockström, K. Richardson, T.M. Lenton, C. Folke, et al. 2018. Trajectories of the Earth system in the Anthropocene. *Proceedings of the National Academy of Sciences, USA,* 115: 8252-8259.

Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, et al. 2015. Planetary boundaries: guiding human development on a changing planet. *Science* 347: 6223

Steffen, W., J. Crutzen, and J.R. McNeill. 2007. The Anthropocene: are humans now overwhelming the great forces of Nature? *Ambio* 36: 614-621.

Steffen, W., R. A. Sanderson, P. D. Tyson, J. Jäger, P. A. Matson, B. Moore III, F. Oldfield, K. Richardson, H. J. Schellnhuber, B.L. Turner, R. J. Wasson (eds.). 2004. *Global Change and the Earth System: A Planet under Pressure.* Springer, New York, New York, USA.

Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney, and C. Ludwig. 2015b. The trajectory of the Anthropocene: the great acceleration. *Anthropocene Review* 2: 81-98.

Steffen, W., K. Richardson, J. Rockström, H.J. Schellnhuber, O.P. Dube, T.M. Lenton, and J. Lubchenco. 2020. The emergence and evolution of Earth System Science. *Nature Reviews: Earth and Environment* 1: 54-63.

Steinert-Threlkeld, Z.C., D. Mocanu, A. Vespignani, and J. Fowler. 2015. *EPJ Data Science* 4: 19. doi.org/10.1140/epjds/s13688-015-0056-y

Sterk, M., G. Gort, A. Klimkowska, J. van Ruijven, A.J.A. van Teeffelen, and G.W. Wamelink. 2013. Assess ecosystem resilience: linking response and effect traits to environmental variability. *Ecological Indicators* 30: 21-27.

Sterner, T., E.B. Barbier, I. Bateman, I. van den Bijgaart, A.-S. Crépin, et al. 2019. Policy design for the Anthropocene. *Nature Sustainability* 2: 14–21.|

Stewart, A.J., M. Mosleh, M. Diakonova, A.A. Arechar, D.G. Rand, and J.B. 2019. *Nature* 573: 117-121. doi.org/10.1038/s41586-019-1507-6

Stiglitz, J. E. 2012. *The Price of Inequality*. W.W. Norton, New York, USA.

Stott, P.A., D.A. Stone, and M.R. Allen. 2004. Human contribution to the European heatwave of 2003. *Nature* 432: 610-614.

Sukhdev, P., H. Wittmer, C. Schröter-Schlaack, C. Nesshöver, J. Bishop, et al. 2010. Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB. The Economics of Ecosystems and Biodiversity (TEEB). www.teebweb.org/our-publications/teeb-study-reports/synthesis-report/

Sumaila, U.R., V.W.Y. Lam, J.D. Miller, L. Teh, R.A. Watson, et al. 2015. Winners and losers in a world where the high seas is closed to fishing. *Scientific Reports* 5: 8481.

Swart, R.J., P. Raskin, and J. Robinson. 2004. The problem of the future: sustainability science and scenario analysis. *Global Environmental Change* 14: 137-146.

Tainter, J.A. 1988. *The Collapse of Complex Societies.* Cambridge University Press, New York, USA.

Tallis H.M., P.L. Hawthorne, S. Polasky, J. Reid, M.W. Beck, et al. 2018. An attainable global vision for conservation and human well-being. *Frontiers in Ecology and the Environment* 16: 563-570.

Tamea, S., F. Laio, and L. Ridolfi. 2016. Global effects of local food production crises: a virtual water perspective. *Scientific Reports* 6:18803. doi:10.1038/srep18803.

Tengö, M., E.S. Brondizio, T. Elmqvist, P. Malmer, and M. Spierenburg. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. *Ambio* 43: 579-591.

Tengö, M., R. Hill, P. Malmer, C.M. Raymond, M. Spierenburg, F. Danielsen, T. Elmqvist, and C. Folke. 2017. Weaving knowledge systems in IPBES, CBD and beyond: lessons learned for sustainability. *Current Opinion in Environmental Sustainability* 26-27: 17-25. doi.org/10.1016/j.cosust.2016.12.005

Tilman, D., F. Isbell, and J.M. Cowles. 2014. Biodiversity and ecosystem functioning. *Annual Review of Ecology, Evolution, and Systematics* 45: 471-493.

Tittensor, D.P., M. Berger, K. Boerder, D.G. Boyce, R.D. Cavanagh, et al. 2019. Integrating climate adaptation and biodiversity conservation in the global ocean. *Science Advances* 5: eaay9969

Tu, C., S. Suweis, and P. D'Odorico. 2019. Impact of globalization on the resilience and sustainability of natural resources. *Nature Sustainability* 2: 283-289.

Turco, M., J.J. Rosa-Cánovas, J. Bedia, S. Jerez, J.P. Montávez, M.C. Llasat, and A. Provenzale. 2018. Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with nonstationary climate-fire models. *Nature Communications* 9:3821. doi: 10.1038/s41467-018-06358-z.

Turner II, B.L., W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews, and W.B. Meyer (eds.). 1990. *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the past 300 years*. Cambridge University Press, Cambridge, UK.

Turner II, B.L., P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen et al. 2003. Illustrating the coupled human-environment system for vulnerability analysis: three case studies. *Proceedings of the National Academy of Sciences, USA* 100: 8080-8085 doi.org/10.1073/pnas.1231334100

Turner, B.L., E.F. Lambin, and A. Reenberg. 2007. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences, USA* 104: 20666-20671.

Turner, M.G., W.J. Calder, G.S. Cumming, T.P. Hughes, A. Jentsch, S.L. LaDeau, et al. 2020. Climate change, ecosystems and abrupt change: science priorities. *Philosophical Transactions of the Royal Society B: Biological Sciences* 375:20190105.

UN. 2019. The 2019 Revision of World Population Prospects. The Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, United Nations, New York, USA.

UN DESA. 2018. The *2018 Revision of World Urbanization Prospects* produced by the Population Division of the UN Department of Economic and Social Affairs (UN DESA) United Nations, New York, USA.

UNDP. 2019. United Nations Development Program. 2019. World Development Report 2019. Beyond Income, Beyond Averages, Beyond Today: Inequalities in Human Development in the 21st Century. New York: United Nations.

UN-Habitat. 2016. The widening urban divide. Chapter four in Urbanisation and Development: Emerging Futures. World Cities Report 2016, United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya.

Urban, M.C. 2015. Accelerating extinction risk from climate change. *Science* 348: 571-573. doi:10.1126/science.aaa4984

USAID. 2018. Reflecting the Past, Shaping the Future: Making AI Work for International Development. USAID.

van der Leeuw, S.E. 2019. *Social Sustainability Past and Present: Undoing Unintended Consequences for the Earth's Survival*. Cambridge University Press, Cambridge, UK.

van der Leeuw, S. 2019b. The role of narratives in human-environmental relations: an essay on elaborating win-win solutions to climate change and sustainability. *Climatic Change* doi.org/10.1007/s10584-019-02403-y

van Oldenborgh, G.J., F. Krikken, S. Lewis, N.J. Leach, F. Lehner, et al. 2020. Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences* in review, https://doi.org/10.5194/nhess-2020-69

Vandenbergh, M. P. and J.M. Gilligan. 2017. *Beyond Politics: The Private Governance Response to Climate Change*. Cambridge University Press, Cambridge, UK.

Vang Rasmussen, L., B. Coolsaet, A. Martin, O. Mertz, U. Pascual, E. Corbera et al. 2018. Social-ecological outcomes of agricultural Intensification. *Nature Sustainability* 1: 275-282.

Veblen, T. 1899. *The Theory of Leisure Class: An Economic Study of Institutions*. Unwin Books, London, UK, reprinted 1994 Dover Publications, New York, USA.

Vinuesa, R., H. Azizpour, I. Leite, M. Balaam, V. Dignum, et al. 2020. The role of artificial intelligence in achieving the Sustainable Development Goals. *Nature Communications* 11: 233. doi.org/10.1038/s41467-019-14108-y

Vitali, S., J.B. Glattfelder, and S. Battiston. 2011. The network of global corporate control. *PLoS ONE* 6, e25995.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of Earth's ecosystems. *Science* 277: 494-499.

Walker, B.H. 1992. Biological diversity and ecological redundancy. *Conservation Biology* 6: 18-23.

Walker, B.H. 2019. *Finding Resilience*. CSIRO Press, Canberra, Australia.

Walker, B.H., A. Kinzig, and J. Langridge. 1999. Plant attribute diversity, resilience, and ecosystem function: the nature and significance of dominant and minor species. *Ecosystems* 2: 95–113.

Walker, B.H., S. Barrett, S. Polasky, V. Galaz, C. Folke, et al. 2009. Looming global-scale failures and missing institutions. *Science* 325: 1345-1346.

Walker, B.H., N. Abel, J.M. Anderies, and P. Ryan. 2009b. Resilience, adaptability, and transformability in the Goulburn-Broken Catchment, Australia. *Ecology and Society* 14(1): 12.

Wang-Erlandsson, L., I. Fetzer, P.W. Keys, R.J. van der Ent, H.H.G. Savenije, and L.J. Gordon. 2018. Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences 22: 4311-4328. doi:10.5194/hess-22-4311-2018*

Waring, T.M., M.A. Kline, J.S. Brooks, S.H. Goff, J. Gowdy, et al. 2015. A multilevel evolutionary framework for sustainability analysis. *Ecology and Society* 20(2): 34. doi.org/10.5751/ES-07634-200234

Waters, C. N., J. Zalasiewicz, C. Summerhayes, A. D. Barnosky, C. Poirier, et al. 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* 351: aad2622. doi:10.1126/science.aad2622

Wearn, O.R., R. Freeman, and D.M.P. Jacoby. 2019. Responsible AI for conservation. *Nature Machine Intelligence* 1: 72-73.

Westley, F., K. McGowan, and O. Tjornbo (eds.). 2017. *The Evolution of Social Innovation.* Edward Elgar Press, London, U.K.

Westley, F.R., K.A. McGowan, N. Antadze, J. Blacklock, and O. Tjornbo. 2016. How game changers catalyzed, disrupted, and incentivized social innovation: three historical cases of nature conservation, assimilation, and women's rights. *Ecology and Society* 21(4).

Westley, F.R., B. Zimmerman, and M.Q. Patton. 2006. *Getting to Maybe: How the World is Changed*. Random House Canada, Toronto, Ontario, Canada.

Westley, F., P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, et al. 2011. Tipping toward sustainability: emerging pathways of transformation. *Ambio* 40: 762-780.

Westley, F., O. Tjörnbo, L. Schultz, P. Olsson, C. Folke, B. Crona, and Ö. Bodin. 2013. A theory of transformative agency in linked social-ecological systems. *Ecology and Society* 18(3): 27.

Wibeck, V., B.-O. Linnér, M. Alves, T. Asplund, A. Bohman et al. 2019. Stories of transformation: a cross-country focus group study on sustainable development and societal change. *Sustainability* 11: 2427. doi.org/10.3390/su11082427.

Wilkinson, R., and K. Pickett. 2009. *The Spirit Level: Why Greater Equality Makes Societies Stronger*. Bloomsbury Press, London UK.

Willeit, M., A. Ganopolski, R. Calov, and V. Brovkin. 2019. Mid-Pleistocene transition in glacial cycles explained by declining CO2 and regolith removal. *Science Advances* 5: eaav7337.

Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, et al. 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet Commission* 393:447-492

Williams, H.T.P., J.R. McMurray, T. Kurz, and F.H. Lambert. 2015. Network analysis reveals open forums and echo chambers in social media discussions of climate change. *Global environmental change* 32: 126-138.

Williams, M., J. Zalasiewicz, P.K. Haff, C. Schwägerl, A.D. Barnosky, and E.C. Ellis. 2015. The Anthropocene biosphere. *Anthropocene Review* 2: 196-219.

Winfree, R., and C. Kremen. 2009. Are ecosystem services stabilized by differences among species? A test using crop pollination. *Proceedings of the Royal Society B* 276: 229-237. doi: 10.1098/rspb.2008.0709

WMO. 2019. United in Science. World Meteorological Organization under the auspices of the Science Advisory Group of the UN Climate Action Summit 2019. public.wmo.int/en/resources/united_in_science

WMO. 2020. World Meteorological Organization Statement of the State of the Climate 2019. WMO Report-1248, Geneva, Switzerland.

Wood, S.A., M.R. Smith, J. Fanzo, R. Remans, and R. DeFries. 2018. Trade and the equitability of global food nutrient distribution. *Nature Sustainability* 1: 34-37.

World Bank. 2003. World Development Report 2003. World Bank, Washington, DC, USA.

World Bank. 2019. Poverty. https://www.worldbank.org/en/topic/poverty/overview

World Inequality Report 2018. https://wir2018.wid.world, UNESCO Publ. Paris.

Worm, B., R. Hilborn, J.K. Baum, T.A. Branch, J.S. Collie, et al. 2009. Rebuilding global fisheries. *Science* 325: 578-585.

Worm, B., and R.T. Paine. 2016. Humans as a hyper-keystone species. *Trends in Ecology & Evolution* 2118: 137-193.

Worm, B., E.B. Barbier, N. Beaumont, J.E. Duffy, C. Folke, et al. 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science* 314: 787-790.

WRI. 2020. 4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors, World Resources Institute, Washington DC, USA.

Wyborn, C., A. Datta, J. Montana, M. Ryan, P. Leith, et al. 2019. Co-producing sustainability: reordering the governance of science, policy, and practice. *Annual Review of Environment and Resources* 44: 319-346.

Xu, C., T.A. Kohler, T.M. Lenton, J.-C. Svenning and M. Scheffer. 2020. Future of the human climate niche. *Proceedings of the National Academy of Sciences, USA*. https://www.pnas.org/cgi/doi/10.1073/pnas.1910114117

Yin, J., P. Gentine, S. Zhou, S.C. Sullivan, R. Wang, Y. Zhang, and S. Guo. 2018. Large increase in global storm runoff extremes driven by climate and anthropogenic changes. *Nature Communications* 9:4389. doi:10.1038/s41467-018-06765-2.

Young, O.R., F. Berkhout, G.C. Gallopin, M.A. Janssen, E. Ostrom, and S. van der Leeuw. 2006. The globalization of socio-ecological systems: an agenda for scientific research. *Global Environmental Change* 16: 304-316.

Zalasiewicz, J., M. Williams, C.N. Waters, A.D. Barnosky, J. Palmesino, et al. 2017. Scale and diversity of the physical technosphere: a geological perspective. *The Anthropocene Review* 4: 9-22.

Zemp, D.C., C.F. Schleussner, H.M.J. Barbosa, M. Hirota, V. Montade, G. Sampaio, A. Staal, L. Wang-Erlandsson, and A. Rammig. 2017. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications* 8: 1468.