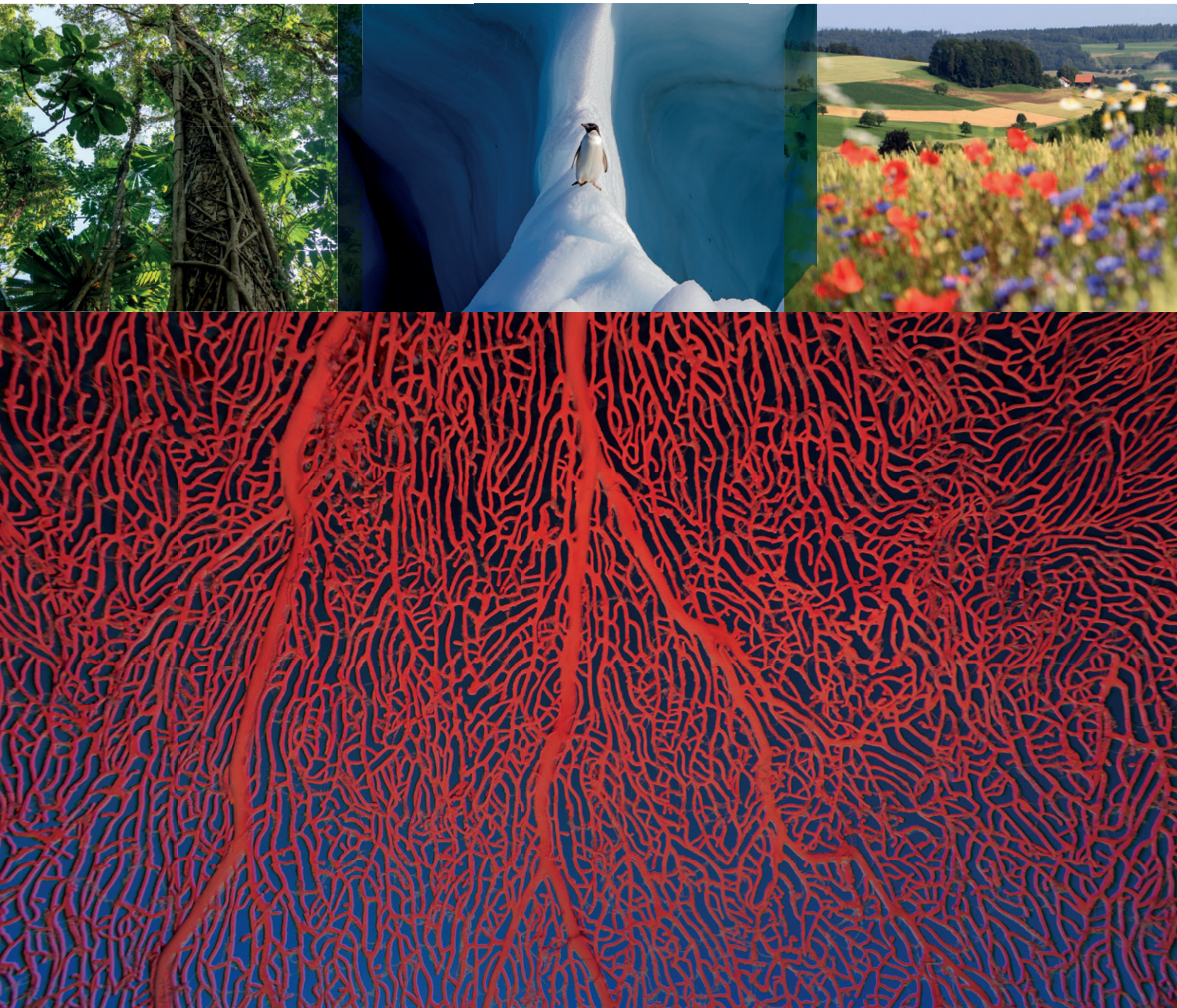
IPBES-IPCC CO-SPONSORED WORKSHOP

BIODIVERSITY AND CLIMATE CHANGE

Scientific outcome



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About this document

This “Scientific Outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change”, was prepared by participants in the workshop in support of the “Workshop Report”. It includes a set of seven sections, a list of references, a glossary and a list of acronyms. It was prepared according to the process described in the introduction to the Workshop Report, and peer reviewed. This document is currently being edited, and a final version will replace this one shortly.


SE

CTION 1

Climate and biodiversity are inextricably connected with each other and with human futures

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Climate and biodiversity are inextricably connected with each other and with human futures

1.1 CLIMATE AND BIODIVERSITY ARE INTERDEPENDENT

A well-functioning natural system and a habitable climate are the foundations of people's good quality of life **(Figure 1.1)**. Protecting biodiversity, avoiding dangerous climate change and promoting an acceptable and equitable quality of life for all is the mandate of several global initiatives, particularly the Strategic Plan for Biodiversity 2011-2020 of the Convention on Biological Diversity (CBD), the Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC) and the UN Sustainable Development Goals (SDGs). While each of these initiatives has specific goals, they also clearly state that the challenges of biodiversity decline, climate change and human well-being are closely connected, and a failure to jointly address the dual crises of climate change and biodiversity decline can compromise people's good quality of life (IPBES, 2019). This co-sponsored IPBES-IPCC workshop report examines the fundamental intertwining of biodiversity and climate and its impacts on people's quality of life **(Figure 1.2)** and makes a case for why climate policy and biodiversity policy must be considered jointly to meet the challenge of achieving a good quality of life (GQL) for all.

The very existence of life on Earth is dependent upon a climate that has varied within relatively narrow bounds over hundreds of millions of years (Haywood *et al.*, 2019; Westerhold *et al.*, 2020). Climatic variability in the distant past has played a role in shaping contemporary biodiversity, through climate-induced species redistributions, extinctions, and originations (Mathes *et al.*, 2021; Norberg *et al.*, 2012; Theodoridis *et al.*, 2020). Global biodiversity has increased over geological time despite climate changes, albeit

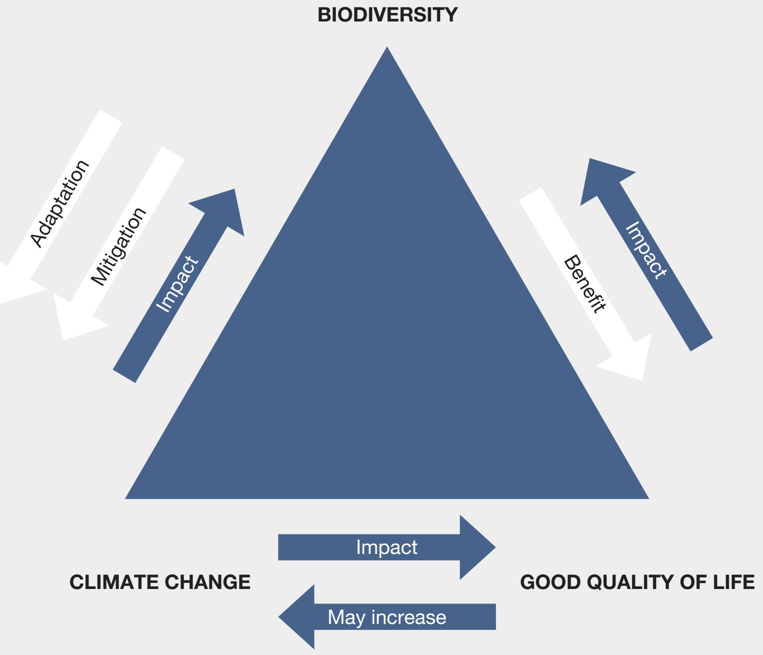


Figure ① ① **Relationships between climate change, biodiversity and good quality of life.**

Blue arrows represent interactions that are predominantly threats, white arrows predominantly opportunities.
Modified from Korn *et al.* (2019).

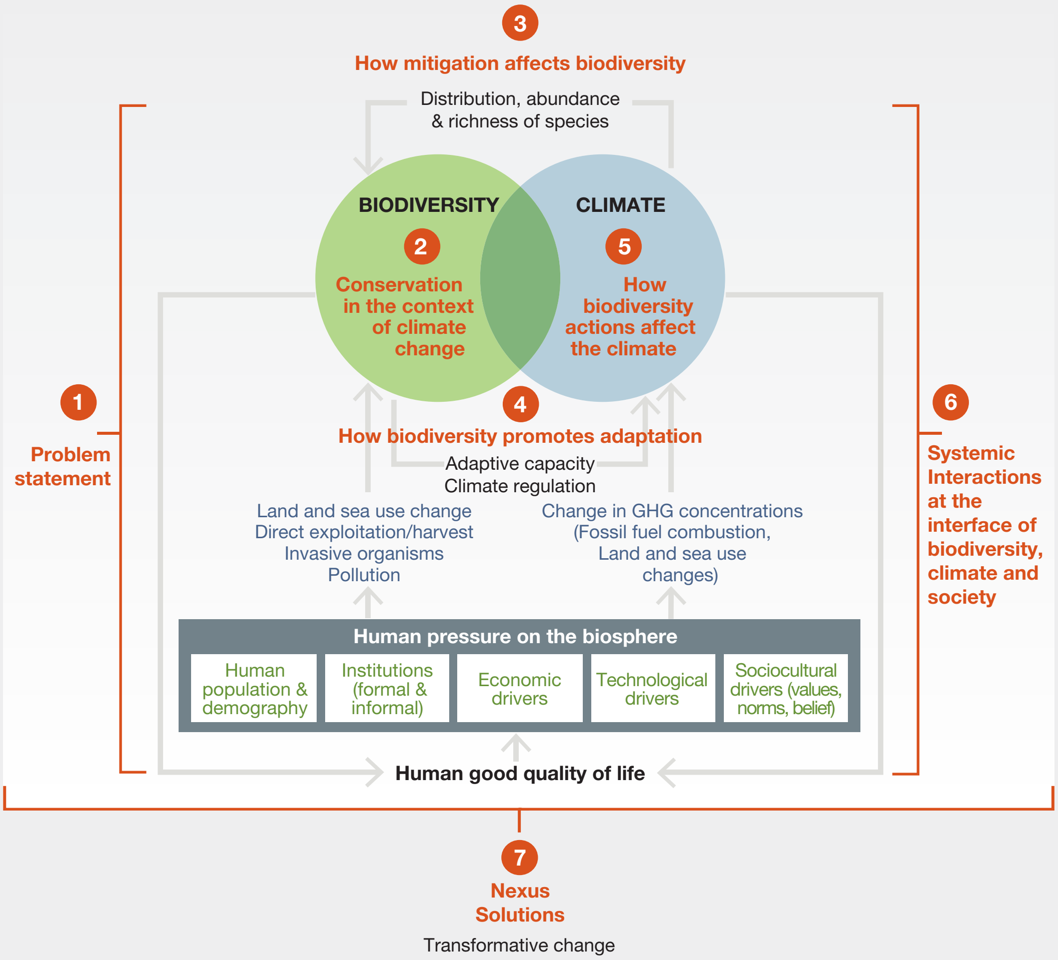


Figure ① ② **Schematic of the overall structure and scope of this report, highlighting the interconnections between biodiversity and climate, and their joint relationship with human activities and well-being.**

The various sections of the report are depicted as numbered red circles. Human activities such as land/sea use change and fossil fuel combustion (direct drivers of biodiversity loss and climate change; text highlighted in blue) have transformed the Earth's land surface and oceans and altered atmospheric chemistry, resulting in widespread loss of biodiversity and climate change. However, both climate change and biodiversity loss are ultimately driven by, and share, multiple indirect drivers (highlighted in green) that are underpinned by societal values. Strategies to conserve biodiversity must be formulated in the context of climate change (Section 2), and reciprocally, strategies to mitigate climate change should acknowledge and consider biodiversity impacts if it is to avoid unintended negative consequences (Section 3). Natural processes, dependent on particular forms and levels of biodiversity, influence the capacity and limits of socio-ecological systems to adapt to climate change (Section 4), and actions to halt biodiversity loss generally benefit the climate (Section 5). Simultaneously addressing the dual crises of biodiversity loss and climate change, while enabling a good quality of life requires navigating a complex, interconnected system, identifying synergies and trade-offs (Section 6). Implementing successful and transformative solutions has particular implications for their joint governance (Section 7).

punctuated by mass extinctions frequently associated with large or rapid climate changes (Alroy *et al.*, 2008; Bond and Grasby, 2017; Close *et al.*, 2020; Payne and Clapham, 2012). Ancient global catastrophes had the potential to trigger evolutionary and ecological novelty, for example the assembly of modern Neotropical rainforests after the end-Cretaceous mass extinction (Carvalho *et al.*, 2021).

In the last 12,000 years global mean temperatures (GMT) have ranged between +0.7 and -1°C relative to the late 19th century baseline (Kaufman *et al.*, 2020; Snyder, 2016; Stocker *et al.*, 2013). This stability was probably a precondition for the establishment and expansion of human civilizations across the planet (Rockström *et al.*, 2009). However, GMT is currently approaching the upper limits of that experienced within the last 1.2 million years, and is beyond the range experienced by humankind since the invention of agriculture (Fordham *et al.*, 2020; Steffen *et al.*, 2018). Reciprocally, living organisms are a crucial part of the Earth system that keeps the local, regional and global climate sufficiently stable and suitable for life (Planavsky *et al.*, 2021). Living organisms control the climate system by regulating the reflectivity of the land surface, altering the concentration of greenhouse gases in the atmosphere **(Box 1.1)**; (Boscolo-Galazzo *et al.*, 2021; Crowther *et al.*, 2019; Pan *et al.*, 2011) and by influencing the formation of clouds and atmospheric dust (Wang *et al.*, 2018; Zhao *et al.*, 2017). Living organisms are the main actors in the global carbon cycle and play a central role in the dynamics of all the major greenhouse gases. However, it is not only the abundance of living organisms, but also their variety that matters. For example, diatom species richness in the ocean is intimately linked to the efficacy with which carbon from the atmosphere is sequestered in seafloor sediments (Tréguer *et al.*, 2018). On land and in the ocean, the variety and specific types of soil and sediment biota influence biogeochemical cycling of nutrients and carbon (Averill *et al.*, 2014; Crowther *et al.*, 2019), while the composition, variety and abundance of both plants and animals impact carbon storage and the carbon cycle (Chen *et al.*, 2018; Huang *et al.*, 2018; Lange *et al.*, 2015; Poorter *et al.*, 2015; Sobral *et al.*, 2017; Xu *et al.*, 2020).

Throughout our existence as a species, humans have manipulated and transformed nature and natural resources to produce materials needed to adapt to, and benefit from, the variable environmental conditions on Earth. Technological advances have allowed us to achieve better living standards on average – but with strong social and economic inequalities – and have contributed to growing human populations worldwide, but at the cost of increasing energy and material consumption (Messerli *et al.*, 2019). Human use and transformation of terrestrial, freshwater and ocean ecosystems, exploitation of organisms, pollution and the introduction of invasive species have resulted in the rapid and widespread decline of biodiversity and the degradation of ecosystems worldwide (Ceballos *et al.*, 2020; Crist *et al.*, 2017; IPBES, 2018, 2019; Diaz *et al.*, 2019; Sage, 2020) **(Figure 1.3)**. Simultaneously, increases in greenhouse gas emissions, now exceeding 55 $GtCO_2e\,yr^{-1}$, associated with fossil fuel combustion (84%) and land-use changes (16%) have altered atmospheric composition (Friedlingstein *et al.*, 2020), and in turn the global climate system, influencing global temperatures, precipitation and the intensity and frequency of extreme weather events (IPCC, 2014). Such climatic changes can act to exacerbate biodiversity decline, which can in turn, feedback to further impact climate **(Figure 1.3)**.

Currently, less than a quarter (23%) of the Earth's terrestrial area (excluding Antarctica) and 13% of the ocean remains free from substantial human impacts (Allan *et al.*, 2017; Jones *et al.*, 2018; Watson *et al.*, 2018) and approximately half the area of coral reefs and over 85% of global wetland area have been lost (IPBES, 2019). Humans and livestock currently account for ~96% of the total mammal biomass on Earth, while the biomass of domestic poultry is nearly threefold higher than that of wild birds (Bar-On *et al.*, 2018). Human activities over millennia have resulted in an estimated 83% reduction in wild mammal biomass (both terrestrial and marine), and ~50% reduction in the biomass of plants, relative to pre-human times (Bar-On *et al.*, 2018). Over the last few centuries, terrestrial vertebrates have gone extinct at rates that are up to 100 times higher than previous (background) levels (Ceballos *et al.*, 2015), and species are now more threatened with extinction than ever before in human history (Diaz *et al.*, 2019; IPBES, 2019). Although empirical evidence for current climate change-driven extinctions is still meagre (Cahill *et al.*, 2013), there is evidence to indicate that ongoing climate change is driving geographic range shifts in species, altering phenology and migration patterns and the availability of suitable habitat for species and disrupting key ecological interactions in communities (Lenoir *et al.*, 2020; Lenoir and Svenning, 2015; Pecl *et al.*, 2017; Poloczanska *et al.*, 2013). All of these effects have implications for the way ecological communities and ecosystems function, and thus their capacity to deliver nature's contributions to people (NCP).

The rapid decline of biodiversity and changes in climate are tightly intertwined: they share underlying direct and indirect drivers (see Glossary), they interact, and can have cascading and complex effects that impact people's good quality of life and compromise societal goals (Diaz *et al.*, 2019; IPBES, 2019, **Figures 1.2-1.3**).

Direct drivers of climate change include greenhouse gas emissions from fossil fuel combustion and land-use change (e.g., deforestation, agricultural practices) (IPCC, 2019a, 2019b; IPCC, 2014). Direct drivers of biodiversity decline include land/sea use intensity and change, direct exploitation of organisms, pollution, climate change and invasive species (IPBES, 2019, chap. 2.2). Some direct anthropogenic drivers such as deforestation, land-use changes associated with agriculture, and pollution can strongly drive both climate change and biodiversity decline, whereas others primarily impact one or the other (e.g., invasive species or direct exploitation of organisms have effects only on biodiversity decline).

Indirect drivers are the more distant causes of biodiversity decline and climate change. They are underpinned by societal values and can be external to the system in question. Climate change and biodiversity decline share the same indirect drivers, which are the ultimate forces that underlie and shape the extent, severity and combination of anthropogenic direct drivers that operate in a given place (Barger *et al.*, 2018; IPBES, 2019). Indirect drivers of climate change and biodiversity decline include key institutional and governance structures in addition to social, economic and cultural contexts that drive human behavioural patterns including consumption and energy use. Indirect

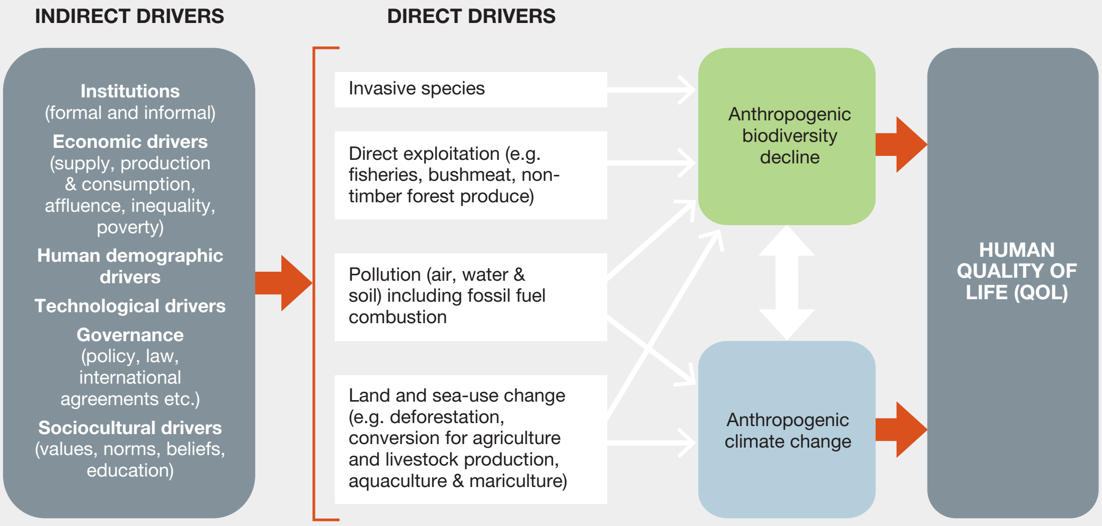


Figure 1 3 **Indirect and direct drivers of biodiversity loss and climate change due to human activities.**

Climate change and biodiversity loss share common underlying drivers, and both impact (mostly in negative ways) people's quality of life.

drivers almost always interact across multiple scales and varying degrees of proximity to the location in question, from the global (international markets, commodity prices, consumption patterns), to national and regional (national policies, governance, domestic markets, demographic change, migration, technological change) and local scales (culture, poverty, economic opportunities) (Barger *et al.*, 2018; IPBES, 2019).

Climate change and biodiversity decline are largely driven by the rapid rise in the consumption of materials and energy, thus far predominantly in highly industrialized countries (Steffen *et al.*, 2015). Both climate change and biodiversity loss have implications for people's good quality of life, locally and globally, and impact on economies (Crist *et al.*, 2017; IPBES, 2019). Degradation of the Earth's land surface negatively impacts the good quality of life of at least 3.2 billion people worldwide (IPBES, 2018). Biodiversity decline can have major consequences for public health, and can exacerbate existing inequalities, including access to healthy diets (IPBES, 2019). Climate change similarly poses significant risks for good quality of life. It can impact food production and food security, including food access, utilization and price stability (IPCC, 2019a; Ojea *et al.*, 2020; Ortiz *et al.*, 2021). Climate extremes disrupt food production and water supply, damage crops, infrastructure and transport networks, and reduce air quality with consequences for human health and good quality of life. The negative effects are disproportionately felt by people who are marginalized socially, politically, economically, or culturally (Diaz *et al.*, 2019; IPBES, 2019, 2018; IPCC, 2014).

The COVID-19 pandemic has made the fundamental interconnections among human health, biodiversity and climate change a stark reality. Disruption, degradation and fragmentation of natural ecosystems alongside growing wild animal trade has brought wildlife, such as bats, which carry viruses that can cross species boundaries, into close proximity with domestic animals and humans (Lorentzen *et al.*, 2020). Climate change has engendered habitat loss that contributes to this proximity and has also amplified (through floods, heat waves, wildfires and food insecurity) the suffering of humans during the COVID-19 pandemic (McNeely, 2021).

Safeguarding nature and ensuring a stable climate are thus vital to support people's good quality of life. Failure to recognize and address the intertwining of the direct and indirect drivers of climate change and biodiversity decline and their underlying causes will lead to less-than-optimal solutions in tackling either problem. For example, climate mitigation measures that do not acknowledge and consider biodiversity consequences, such as dense monocultural tree planting in grasslands and savannas as a carbon sequestration measure, can have severe unintended consequences in terms of loss of native and endemic species diversity (Bond, 2016; Griffith *et al.*, 2017; Seddon *et al.*, 2021; Veldman *et al.*, 2015, 2019) (see also Sections 2 and 3). Similarly, conservation measures that explicitly consider future climate scenarios and impacts are more likely to be successful at conserving biodiversity in the long-term (Hannah *et al.*, 2020) and to mitigate climate change (Sections 2 and 5).

1.2 INTERLINKAGES IN UNDERLYING DRIVERS, FEEDBACKS BETWEEN SYSTEMS, AND IMPACTS

Anthropogenic climate change has emerged as a dominant threat to ecosystems over the last few decades (Arneth *et al.*, 2020; IPBES, 2019; Maclean and Wilson, 2011; Thomas *et al.*, 2004; Urban, 2015), impacting Earth's biodiversity by altering species ranges and abundances, reshuffling biological communities and restructuring food webs, altering ecosystem functions, and generating negative feedbacks to people's good quality of life (see also Sections 1.1, 2 and 4). Species living close to their upper thermal limits are particularly at risk, as are ecosystems such as coral reefs (Hoegh-Guldberg and Bruno, 2010; Hughes *et al.*, 2019), lakes (Woolway *et al.*, 2021) and wetlands (Xi *et al.*, 2020). Under present conditions (1°C warming), warm-water coral reefs are at high risk; kelp forests and seagrasses reach high risk under modest future warming (RCP 2.6) while most other shallow ocean ecosystems experience moderate risk. Under high future warming (RCP 8.5) all ocean ecosystems, including those in the deep sea are at high or very high risk (Bindoff *et al.*, 2019).

Many terrestrial and aquatic species are already responding to climatic changes by elevational, depth (for ocean) and especially latitudinal shifts in their distribution ranges, tracking shifting isotherms (Brito-Morales *et al.*, 2020; Lenoir *et al.*, 2020; Pecl *et al.*, 2017; Pinsky *et al.*, 2013; Steinbauer *et al.*, 2018). Species redistributions due to climate change are leading to reduced marine species richness in equatorial latitudes (Chaudhary *et al.*, 2021; Yasuhara *et al.*, 2020). Moreover, barriers to dispersal, differences in the ability of species to track climate and tolerate extreme climatic events (e.g., droughts, floods, heat waves, mega-fires and cyclones), and temporal lags in species responses are triggering compositional shifts, decreasing taxonomic, functional and phylogenetic diversity and are reorganizing local communities, with such reorganization likely to continue in the future creating potentially "novel" communities (Aguirre-Gutiérrez *et al.*, 2020; Arneth *et al.*, 2020; Batllori *et al.*, 2020; Bjorkman *et al.*, 2018; Bowler *et al.*, 2020; Davidson *et al.*, 2020; França *et al.*, 2020; Fuchs *et al.*, 2020; Leadley *et al.*, 2014; Pecl *et al.*, 2017).

Although only a few recent species extinctions have as yet been formally and rigorously attributed to current climate change (Cahill *et al.*, 2013; IPCC, 2014), the fossil record tells us that rapid climate change can be a key driver of mass extinctions, capable of eliminating up to 90% of all species (Benton, 2018; Bond and Grasby, 2017; Dunhill *et al.*, 2018; Foster *et al.*, 2018), raising concerns about the adaptive potential of extant species to ongoing and future climate change (Radchuk *et al.*, 2019; Storch *et al.*, 2014). Under a global warming scenario of 1.5°C warming above the pre-modern GMT, 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range. For global warming of 2°C, the comparable fractions are 18% of insects, 16% of plants and 8% of vertebrates (IPCC, 2018; Warren *et al.*, 2018). Future warming of 3.2°C above pre-industrial levels is projected to lead to loss of more than half of the historical geographic range in 49% of insects, 44% of plants, and 26% of vertebrates (Warren *et al.*, 2018). Under warming scenarios associated with little successful climate mitigation (RCP 8.5), abrupt disruption of ecological structure, function and services is expected in tropical marine systems by 2030, followed by tropical rain forests and higher latitude systems by 2050 (Trisos *et al.*, 2020).

The impacts of climate change and other anthropogenic drivers of biodiversity loss vary geographically and between habitats and taxa (Blowes *et al.*, 2019; Bowler *et al.*, 2020). In general, marine and freshwater ectothermic organisms appear to be more vulnerable to warming than terrestrial organisms (Morgan *et al.*, 2020; Pinsky *et al.*, 2019) and biodiversity decline over the last few decades appears to be stronger, but more variable, in the ocean when compared to terrestrial systems (Blowes *et al.*, 2019). However, the magnitude and even the direction of change (loss versus gain) can be strongly scale-dependent. For example, species richness for some taxa has declined locally but increased regionally (as in the case of North American birds) or has remained unchanged locally but declined at larger spatial scales for some (e.g., Central American corals) (Chase *et al.*, 2019). Even where environmental changes have largely neutral effects on species richness at local scales, they can cause the taxonomic and functional homogenization of biological communities across large scales (Dornelas *et al.*, 2014; Guerra *et al.*, 2021), which in turn can impair ecosystem functioning, decrease the resilience of communities to environmental disturbances, and increase susceptibility to future invasions and pathogen outbreaks (Olden *et al.*, 2004).

Although patterns vary geographically, anthropogenic drivers of biodiversity change tend to act together and spatially overlap to a greater degree more often in terrestrial systems than in the marine realm (Bowler *et al.*, 2020). Direct human impacts are the dominant drivers of species decline in areas of high human densities and impact (e.g., close to human settlements, land suitable for agriculture) (Bowler *et al.*, 2020; Venter *et al.*, 2016). Climate change, on the other hand, appears to be the dominant driver of biodiversity loss in terrestrial areas that have been less impacted by humans, such as deserts, tundra and boreal forests (Bowler *et al.*, 2020). Both climate change and other anthropogenic drivers act together to drive biodiversity loss in other systems such as the oceans of the Indo-Pacific that are characterized by both high fishing and high climate change (Bowler *et al.*, 2020; Pinsky *et al.*, 2019).

Drivers of climate change and biodiversity loss interact in complex ways to produce outcomes that may be synergistic (i.e. the outcome is greater than would be expected when acting alone), antagonistic, gradual or abrupt (Berdugo *et al.*, 2020) (see Section 6 for further exploration of these concepts). When multiple drivers act together, their impacts on biodiversity and ecosystem functioning can be more pronounced, but also more variable. This means the outcome is not readily predictable based on our previous understanding of the consequences of single environmental change drivers (Thakur *et al.*, 2018; Rillig *et al.*, 2019) and thus prone to "ecological surprises" (see Section 6 for further exploration of critical thresholds and tipping points). Multiple drivers acting synergistically might result in new emergent socio-ecological conditions (e.g., as a result of change in human behaviour and consumption patterns) leading to "socio-ecological surprises", posing challenges for biodiversity conservation and climate mitigation. Climate change can also potentially cause abrupt and irreversible (or difficult to reverse) shifts from one state to another, when ecosystems are forced across critical thresholds (Barnosky *et al.*, 2012; Berdugo *et al.*, 2020). Some examples include the decline of snowfield and glacier sizes leading to a reduction in late-summer streamflow with nonlinear impacts on biodiversity (Jacobsen *et al.*, 2012), ocean warming and acidification reducing the fitness of tropical corals and the subsequent degradation of tropical coral reef ecosystems (Pandolfi *et al.*, 2011), or the synergistic interactions between deforestation and droughts that can promote fire, leading to the replacement of forests by savanna-type vegetation or fire-prone secondary forests (Leadley *et al.*, 2014). However such critical thresholds or "tipping points" (Lenton *et al.*, 2008) are often hard to predict (Dudney and Suding, 2020; Hillebrand *et al.*, 2020), and therefore difficult to prepare for.

Changes in species composition and the reorganization of local and regional biological communities have consequences for biophysical and biochemical processes, with implications for climate and regional energy, nutrient and water cycles (Arneth *et al.*, 2020). For example, the current northward shift of coniferous trees in the Arctic due to increased temperature reduces the reflection of sunlight from the Earth's surface (the surface albedo), amplifying global warming (Pearson *et al.*, 2013, 2013; Vowles and Björk, 2018). At the same time, biodiversity can help people to better adapt to adverse climatic changes, including extreme weather events (Chausson *et al.*, 2020; Cohen-Shacham *et al.*, 2019; Duffy *et al.*, 2016, also see Section 4), and also act as a buffer to mitigate the consequences of climate change (Cardinale *et al.*, 2012; Hautier *et al.*, 2015; Hooper *et al.*, 2012; Isbell *et al.*, 2015, 2011). Species diversity can potentially act as an insurance against declines in ecosystem functioning because when there is a greater variety of species there is a higher likelihood that some will maintain functioning, even if others fail (Eisenhauer *et al.*, 2011; Kiessling, 2005; Naeem and Li, 1997; Yachi and Loreau, 1999). Communities with a greater diversity of species and functional types, both terrestrial and marine, have often been shown, on average, to respond less to and recover sooner from, climate variability and extremes (Anderegg *et al.*, 2018; Isbell *et al.*, 2015; Rastelli *et al.*, 2020). This diversity-stability relationship also applies to entire ecosystems. Ecosystem integrity, the capacity of an ecosystem to maintain structure and functions, is facilitated by greater biodiversity (Timpane-Padgham *et al.*, 2017). However, there are limits to the adaptive capacity of biological communities, with thresholds that are system-specific and under-explored (Baert *et al.*, 2018). Conserving biodiversity in all its facets and mitigating climate change is thus crucial to ensure the longer-term stability of ecosystem functions and the continued provisioning of nature's contributions to people (Craven *et al.*, 2018; Isbell *et al.*, 2017; Oliver *et al.*, 2015).

Biophysical environmental impacts can occur across vast distances (Glantz *et al.*, 1991; Liu *et al.*, 2013). Human and natural systems around the world are also now increasingly connected with the result that the impacts of human actions in one part of the globe can be felt at distances far removed from their source (Friis *et al.*, 2016). Local actions and decisions can cascade to affect the regional availability and distribution of nature's contributions to people; impacts that might be more immediately felt by those who directly depend on nature for their livelihood, particularly in non-industrialized nations (Ojea *et al.*, 2020; Pecl *et al.*, 2017). Teleconnections are facilitated by global travel and trade but also through exchanges between distant actors through flows of capital, energy, services and information through telecommunication advances such as the internet (Carrasco *et al.*, 2017). Such linkages are stronger than ever before, with the speed and spatial scope of economic and biophysical processes previously confined to discrete governance scales now occurring at geographical distances far removed from their source (Adger *et al.*, 2009; Carrasco *et al.*, 2017). Telecoupling also provides opportunities for both biodiversity conservation and climate change mitigation and adaptation, with the causes and impacts of telecoupled drivers originating from 'distant supermarkets, corporation boardrooms, stock markets and the internet' at an unprecedented speed and intensity (Carrasco *et al.*, 2017). Telecoupling thus requires integrated and globally coordinated governance efforts to tackle the dual challenges of biodiversity decline and climate change (Sections 1.3, 6, 7).

1.3 TOWARDS A JUST AND SUSTAINABLE FUTURE

Several global initiatives, established over the past three decades, have a mandate to address the three components of biodiversity conservation, climate action and equitable sustainable development. The Strategic Plan for Biodiversity 2011-2020 of the Convention on Biological Diversity (CBD) aimed to safeguard biodiversity on land and sea through the adoption of the Aichi Biodiversity Targets. More recently such goals have been translated to the post-2020 global biodiversity framework. The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC) aims to strengthen the global response to climate change by limiting global temperature rise well below 2°C above pre-industrial levels and to ensure an adequate adaptation response in the context of the temperature goal. The United Nations Sustainable Development Goals (SDGs) aim to address global challenges, such as poverty and inequality, through the achievement of 17 goals.

Even though the goals of these initiatives are clear, as well as the message that different components need to be addressed concurrently for a peaceful and prosperous future for the planet and people, understanding of how this can be achieved through national or local actions or policies is not always straightforward. Actions or policies targeting one component can be co-detrimental and co-beneficial, respectively) (Fuso Nerini *et al.*, 2019; Kroll *et al.*, 2019; Zeng *et al.*, 2020). Therefore, it is crucial to be aware of the impacts that actions and policies targeting one component may have on others and of the synergies and trade-offs across the three components that such actions may lead to.

Currently, global strategies to halt the decline of biodiversity and mitigate climate change are usually formulated independently and often without considering their social implications (Arneth *et al.*, 2020; Díaz *et al.*, 2020; Dinerstein *et al.*, 2020). This presents a high risk because narrowly-conceived actions to combat climate change can unintentionally harm biodiversity, while measures to protect biodiversity can unintentionally impair climate mitigation or human adaptation processes, both with potential negative implications for people's good quality of life (Díaz *et al.*, 2020). For example, addressing climate change issues may become counterproductive if policies initiated to reduce greenhouse gas emissions aggravate biodiversity decline (Diaz *et al.*, 2019; Griffith *et al.*, 2017; Veldman *et al.*, 2019). The recent IPCC and IPBES reports acknowledge that transitioning to a low carbon future and curbing biodiversity loss will require rapid, far-reaching and unprecedented transformative changes (IPCC, 2014; IPBES, 2019; IPCC, 2019b, see Section 7), which will, in turn, affect the lives and livelihoods of people both in positive and negative ways.

Developing appropriate policies to simultaneously address the multiple challenges of climate change, biodiversity loss and people's good quality of life is necessary but not easy, particularly as interactions of the climate-biodiversity-society nexus operate at different temporal and spatial scales and involve actors with different perspectives. The short-term impacts of climate change and biodiversity decline are more pronounced in areas where people directly depend on nature for their livelihoods and are felt most strongly by people in situations of vulnerability with less adaptation options at hand (Diaz *et al.*, 2019; IPBES, 2019; Thomas, 2020) (see Section 4). Where ecological threats overlap with social vulnerability, climate change and biodiversity loss can further exacerbate inequalities in ensuring a good quality of life for all (Human Development Report, 2020).

Despite growing awareness of the linkages between biodiversity loss and climate change, we still lack a full understanding of how social issues, particularly inter- and intra-generational equity, are affected by interventions to mitigate climate change or to conserve biodiversity (Halpern and Fujita, 2013; Zafra-Calvo *et al.*, 2019). The linkages between biodiversity, climate and social issues can have significant implications for the effectiveness of policies designed to address them, with outcomes that can be co-detrimental, display strong or weak trade-offs, or even deliver co-benefits (see Section 6). Co-benefits may result from climate or biodiversity solutions that also bring social benefits at the local level. For example, the implementation of the REDD+ initiative (Reducing Emissions from Deforestation and Degradation, see discussions in Section 4) provides an opportunity to improve forest governance and support rural livelihoods in host countries, in addition to its main goal to mitigate climate change impacts (Garibaldi and Pérez-Méndez, 2019) (see Box 6.1 in Section 6).

However, such mitigation policies can impact social equity (Palomo *et al.*, 2019; Robiou du Pont *et al.*, 2017). They might also lead to societal trade-offs in terms of who bears the costs and who receives the benefits of biodiversity and climate change interventions (Markkanen and Anger-Kraavi, 2019; Schleicher *et al.*, 2019). For example, 'green' investments, e.g., biofuels, solar, wind, hydropower and geothermal facilities, can have negative impacts on local livelihoods, particularly if they prioritize private profits over social and environmental concerns (Corbera *et al.*, 2019; Del Bene *et al.*, 2018). Acknowledging and understanding the societal trade-offs derived from policies oriented to address the climate and biodiversity challenges is critical for the design of policies that create the enabling conditions for the transition towards a just and equitable future. Enabling conditions, or factors that can contribute to the success of such policies, include economic incentives, governance factors (i.e., policy coherence and partnership), capacity building, engagement processes for knowledge co-production, or adaptive monitoring and accountability (IPCC, 2019c; Stafford-Smith *et al.*, 2017).

Climate and biodiversity policies also need to account for the multi-level and multi-scale coupling of human-natural systems (Cheung *et al.*, 2016). Changes in biophysical drivers linked to climate, habitat loss, or removal of organisms through overexploitation will each affect biodiversity at different levels of organization, further altering human actions and behaviours, and generating cascading effects (Gregr *et al.*, 2020), which propagate across different components of coupled human-natural systems and across spatial and temporal scales. Such cascading responses to changing climate and biodiversity drivers can iteratively feedback to affect people's quality of life (Dietze *et al.*, 2018). Additionally, the uneven distribution of biodiversity and spaces for mitigation action across regions leads to numerous exchanges of resources across large distances, resulting in telecoupling (Liu *et al.*, 2013). Telecouplings can reinforce inequality because they spatially separate the drivers and consequences of a process. For example, policies implemented to promote biodiversity conservation and climate change mitigation and adaptation strategies involving transnational land deals in developing countries can initially bolster local economies. However, in the long-term these same policies can lead to social inequities and land degradation through processes of land grabbing and concentration (Hunsberger *et al.*, 2017).

A sustainable global future for people and nature remains possible but requires rapid, radical and transformative societal change including adopting a way of thinking that integrates (rather than keeps separate) the technical, governance (including participation), financial and societal aspects of the solutions to be implemented (Section 7). The window to limit damage from biodiversity loss and climate impacts is rapidly closing, so solutions need to be deployed rapidly. Several potentially useful approaches to bridge climate and biodiversity actions (and their potential social impact) are being proposed. These include nature-based solutions (NbS, defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits", see glossary and discussion in Sections 3 and 4) (Seddon *et al.*, 2020), but also solutions that create technological-ecological synergies, or an integrated systems-approach that recognizes the potential co-benefits that exist in combining technological and nature-based solutions (Hernandez *et al.*, 2019) (Section 7).

New governance models are needed that are designed to integrate multi-actor and multi-scalar governance and which measure human progress through new systems of environmental accounting and natural and social capital (Section 7.4). For example, while the UN processes recognize nations as the main actors in delivering policy actions, they often overlook the potential roles and responsibilities of other actors (e.g., local and subnational levels of government, indigenous peoples and local communities, corporations and industries, philanthropic foundations and non-governmental organisations). This not only hampers participation, but also dilutes responsibilities. Thus, despite the growing role of multinational corporations in driving the interconnected challenges of biodiversity loss and climate change, holding them accountable at the international scale is difficult as the international law system has state-actors at its core. Multi-actor governance would enlarge the participatory space and make all actors more accountable.

Delivering solutions that target the climate-biodiversity-society nexus as a whole requires moving from a sector-by-sector approach to one including high-level coordination and the balancing of social and environmental goals. Enabling transformative change towards a just and sustainable future requires new ways to evaluate and adaptively manage trade-offs between maintaining desirable aspects of current social-ecological systems and adapting to major biophysical changes to those systems.

That said, it is critical that attention is paid to achieving just transitions in the shift towards transformative change. In particular, it is important that system-wide change does not have a disproportionate impact on those who are already disadvantaged (Ciplet and Harrison, 2020; Kashwan *et al.*, 2020). As such, efforts towards transformative governance need to address existing injustices while being cognisant of complexity, feedbacks and trade-offs across social-ecological systems.

The COVID-19 pandemic provides both a time-limited learning opportunity and a chance for promoting solutions that help mitigate both the climate and biodiversity crises and advance UN Sustainable Development Goals (SDGs). On the one hand, many have suggested the COVID-related lockdowns mandated around the world in 2020 have served as biodiversity conservation (Bates *et al.*, 2020) or emissions reduction experiments (Le Quéré *et al.*, 2020) from which we can learn. But the pandemic has also taught us how easy it is to divert attention and funding away from tackling urgent biodiversity and climate challenges (McNeely, 2021). Major international plans for policy progress on biodiversity (CBD COP 15) and climate change (UNFCCC COP 26) and efforts to focus these jointly on the oceans (UN Oceans Conference) have been delayed by the pandemic for at least a year. On the other hand, funding released to alleviate the consequences of the pandemic also present an opportunity if post-COVID recovery packages are oriented to deliver a "green" and "blue" restart of the economy, mainstreaming climate and biodiversity into economic priorities (Hepburn *et al.*, 2020; McElwee *et al.*, 2020).

Box 1 1 Biodiversity and Climate are connected through carbon.

Life on Earth is based on carbon. Plant and animal tissues are made from carbon. Carbon is the critical element in carbon dioxide, methane and soot (black C), all of which trap heat when they occur in excess in the atmosphere. Carbon dioxide is the raw material for photosynthesis, which is carried out by plants and algae (and bacteria) – providing the energetic currency for life, and sequestering carbon above and below ground. Changes in temperature and carbon dioxide alter rates of photosynthesis and fates of carbon within primary producers. Plants on land and algae and some animals in the ocean (e.g., corals, sponges, bivalves) create habitat structure, modify environments and provide food that supports biodiversity. Plants, algae and microplankton degrade after death, but some are buried for millennia to eventually form coal, oil and gas. The removal and burning of plants and of fossil fuel release excess CO_2 into the atmosphere, with the latter responsible for the majority of global warming. Loss of forest cover reduces the natural photosynthetic removal of CO_2 although some plants benefit from excess CO_2 in the atmosphere. Both elevated CO_2 emissions and declining CO_2 removal contribute to warming the land and ocean, which then feeds back to affect the people's quality of life. Thus, human land use involving deforestation, agriculture, or even energy farms (large-scale installations of wind turbines or solar panels) can affect biodiversity directly or through changing climate.

Other aspects of climate change influence both the habitability of land and oceans, and their biodiversity, with direct damage to humans. Drought, rainfall, temperature, loss of sea ice, sea-level rise, changes in ocean physicochemistry (pH, CO_2 and O_2), storms and flooding, affect biodiversity directly and nature's contributions to people (food security, livelihoods, health). Plants and animals (including people) have basic physiological tolerance limits and must move or adapt when these thresholds are surpassed, or otherwise die. Movements are underway; potential for both evolutionary adaptation and plastic phenotypic change appear to be limited (but not fully known). Understanding and managing biodiversity responses are made more complex by the dispersive life stages of plants (e.g., seeds) and animals (larvae, reproductive migrations) introducing distinct habitat requirements and climate vulnerabilities for different phases; these create connections across land-sea, air-water and water-seafloor interfaces that challenge current social constructs and management capabilities.

SE

CTION 2

Biodiversity conservation in light of a changing climate

SECTION 2

Biodiversity conservation in light of a changing climate

This section focuses on how anthropogenic climate change has impacted on biodiversity and is changing the goalposts for successful conservation into the future. A broader scope for conservation is envisioned, from species and protected area focus in intact spaces to integrating people in multifunctional land, freshwater and seascapes that facilitate and enable adaptation. Such efforts would fully integrate climate and biodiversity actions and support multiple objectives under global policy processes for biodiversity, climate and sustainable development.

2.1 HOW CLIMATE CHANGE IMPACTS BIODIVERSITY

2.1.1 Evidence of impacts

Impacts of anthropogenic climate change have been documented in plants and animals across marine, terrestrial and freshwater realms. They span all principal biomes, from rainforests and deserts to wetlands, and from coastal marine to the deep ocean (Doney *et al.*, 2020; Ripley *et al.*, 2020; Scheffers *et al.*, 2016; Rogers *et al.*, 2020). Climate change impacts on species occur at a range of scales (from genes and individuals to populations), and at habitat and ecosystem scales, they may occur through changes in interspecies interactions (e.g., competition, predation or disease), community composition (Scheffers *et al.*, 2016), ecosystem function and ecosystem structure (IPBES, 2019; Chapter 2.2). Historically, loss in biodiversity has been attributed (IPBE, 2019) primarily to changes in the intensity by which the land and sea are used (34% contribution to losses over the past century) and direct exploitation of species (23%), followed by climate change and pollution (14% each). The impact of climate change is projected to surpass other threats during the 21st century (Arneth *et al.*, 2020), both through direct effects and intensifying interactions with other drivers.

Observed climate change impacts on biodiversity include direct alteration of abiotic conditions, such as shifts in climatic features (e.g., temperatures, seasonality, extreme weather), the physical environment (e.g., sea level, glacial extent, fire frequency, oxygen concentration) and atmospheric greenhouse gas concentrations (e.g., CO_2). Climate threats interact with one another and their impacts accumulate; for example, ocean temperature, acidification and hypoxia interact to produce complex biotic responses (Pörtner *et al.*, 2014). Climate change interacts with and often exacerbates non-climate threats, for example by degrading habitats, increasing disease susceptibility, changing movement patterns of non-native invasive species and increasing reliance of people on extractive resources. Human responses to climate change, with the aim of climate mitigation (see Section 3) or to assist humans to adapt to climate change (see Section 4), also affect biodiversity, either negatively or positively (Araújo *et al.*, 2017; Correa *et al.*, 2021; Foden *et al.*, 2018; Stafford *et al.*, 2019) resulting in complex patterns of change and responses (Rillig *et al.*, 2019). Since terrestrial, freshwater and marine systems are controlled by different biophysical properties and differ in their spatial structure, biodiversity responses may be fundamentally different in these different domains (Klink *et al.*, 2020).

At the individual organism level, climate change impacts may appear, for example, as changes in growth rate, reproductive success, behaviour timing, disease susceptibility or traits such as body size. At population level, this may scale up to changes in population size, age structure, sex ratio or gene flow between subpopulations. Such impacts may translate to species-level changes in abundance, range size and location, level of range fragmentation or changes in genetic diversity. These changes may increase or decrease the species' extinction risk or have varying effects in different parts of the species range. Resulting impacts on inter-species interactions include shifts in interactions between competitors, predators and prey, and those relying on pollination, biotic pollination, parasitism, and symbioses.

Cascading effects at community and ecosystem level may include changing composition, function, and interactions with disturbance effects (e.g., fire). Ecosystem shifts (e.g., savanna to woodland), loss and novel recombinations may result. As a result of these complexities, impacts on ecosystem functioning (and thus their capacity to deliver NCP) are hard to attribute to specific causes, and this has impeded actions aimed at addressing negative impacts. The strength of attribution of impacts to climate change decreases in roughly this order: changes in species abundances and ranges, certain traits such as length of fish, sustainability of exploited stocks, Net Primary Productivity (NPP) and changes in particularly vulnerable ecosystems, such as coral reefs.

Climate impacts may differ among the subregions of large or continent/ocean scale areas. The spatial patterning of subregional to local climates and ecosystems, and natural corridors for migration of species, affect how effectively they will be able to track shifting climates. Biodiversity hotspots and isolated ecosystems such as islands, mountains, lakes, enclosed seas and seamounts are particularly challenged, as they may have few or no corridors facilitating migration of species, and they are spatially limited along latitudinal or altitudinal gradients (Leclerc *et al.*, 2020).

'Climate velocity trajectories' (CVT) show the speed and direction that a species must migrate to keep pace with its current climate envelope (Brito-Morales *et al.*, 2018; Burrows *et al.*, 2014). From this perspective, climate refugia are places where the velocity of climatic parameters (e.g., temperature, precipitation) is slow, resulting in longer climatic residence times (Loarie *et al.*, 2009). Climate refugia have been associated with larger protected areas (PAs) and topographically complex (mountainous) terrain (Ackerly *et al.*, 2010; Chen *et al.*, 2011; Mora *et al.*, 2013), and often have high levels of endemism (Sandel *et al.*, 2011; Roberts & Hamann, 2016). For temperature in particular, climate trajectories are polewards at large scales, and towards complex topography, moving up slope. There is, however, significant variability especially at local scales resulting from increased topographic variability, interactions with other climate factors (e.g., precipitation and aspect on land), and degree of anthropogenic disturbances.

This variation is illustrated by combining established surface temperature warming and biodiversity intactness analyses **(Figure 2.1)**. CVT distance increases from 1 to 2 degrees of

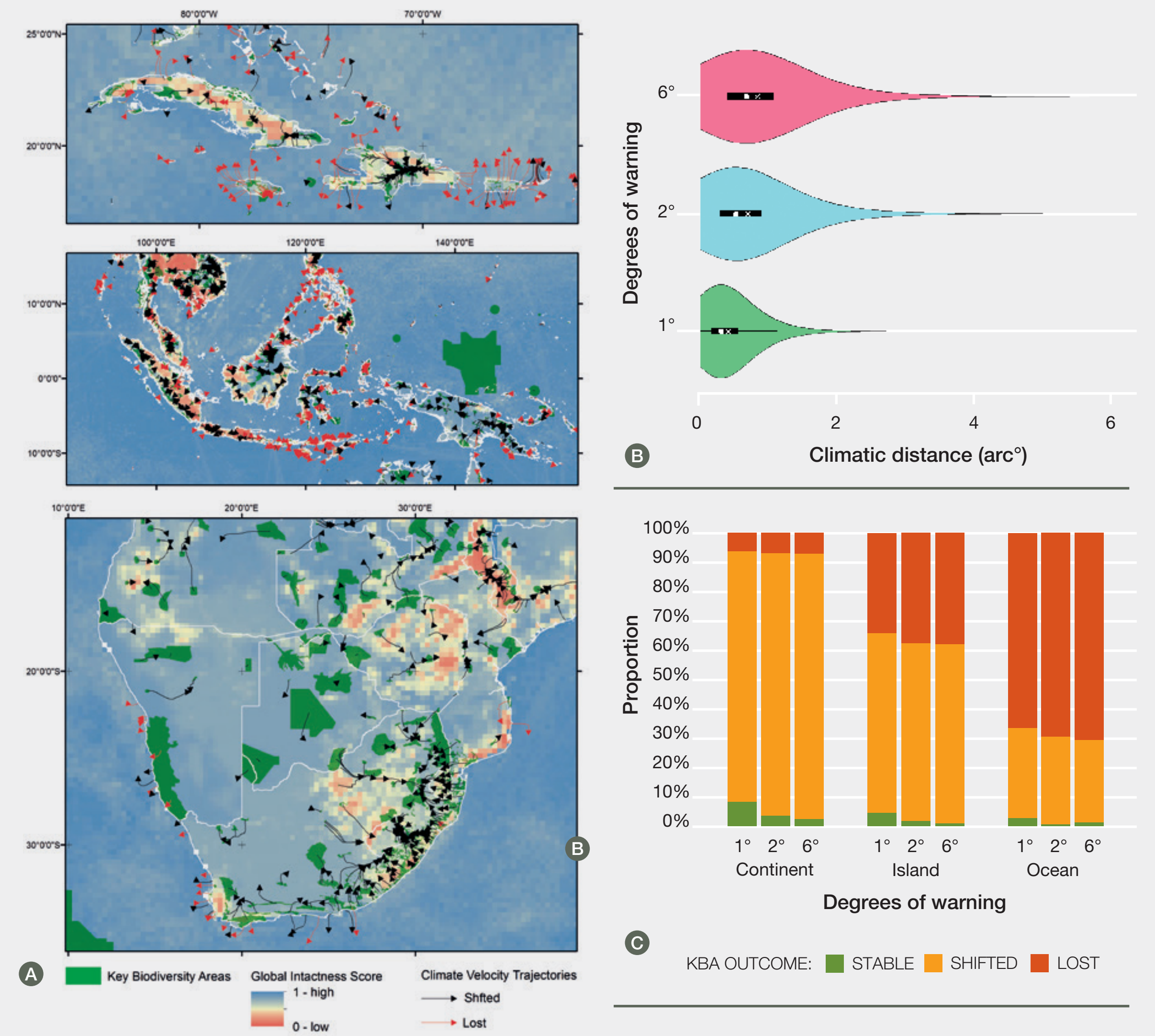


Figure ② ① **Climate velocity trajectory (CVT) patterns based on land and sea surface temperatures: for Key Biodiversity Areas (KBAs) globally under scenarios of 1, 2 and 6 degrees of warming (assuming spatially homogenized change in temperature over time, see Burrows *et al.* 2011 and 2014).**

Figure ② ①

Ⓐ Map panels for selected regions illustrate CVT at 6 degrees of warming of surface temperature above baseline (2000s decade), obtained from MEERAclim (Vega et al. 2018). From top to bottom: small islands (Northern Caribbean), large islands and oceanic systems (Southeast Asia/West Pacific) and a continental land mass (Southern Africa). Colour coding in the basemap shows global intactness (based on the Biodiversity Intactness Index, Ocean Health Index, and fraction of anthromes on land) for terrestrial and ocean surfaces. Arrows show predicted CVT for each KBA anchored at its centroid. The absence of an arrow indicates the predicted CVT remains within the KBA, i.e., the KBA is climatically stable. Black arrows indicate terrestrial and marine KBAs for which the climate envelope moves outside the KBA but remains on land or sea respectively (shifted); red arrows indicate KBAs for which the climatic envelope is 'lost', as the CVT crosses a coastline, or shifts off the top of a mountain. The right panel illustrates CVT results for all 16,310 KBAs globally (Birdlife International 2020): Ⓑ violin plot of the proportion of KBAs shifted by CVT distance (x axis) for 1, 2 and 6 degrees of warming (grouped on the y axis); Ⓒ the proportion of KBAs on continents, islands and ocean for which the climatic shift is stable, shifted or lost.

warming (above a baseline in the decade 2000-2010), with a lesser increase from 2 to 6 degrees of warming **(Figure 2.1b)**. CVT shift varies significantly spatially, illustrated at varied scales in the maps **(Figure 2.1a)** and at the broadest scale for Key Biodiversity Areas (KBAs) on continents, islands, and oceans **(Figure 2.1c).** At 1 degree of warming only 8.7, 4.8 and 3.0% of KBAs on continents, islands, and oceans have a stable climate, respectively **(Figure 2.1c)**. This decreases to only 1-3% across all three groups at 6 degrees of warming. 34-38% of island KBAs lose their climate completely (see Section 2.1.2), compared to only 6-7% for KBAs on continental land masses (6-7%). The high loss for marine KBAs may relate to blocked trajectories of coastal KBAs in biodiversity hotspots. Such potential high losses of climate envelopes from insular and coastal biodiversity hotspots may imply disproportionate losses to global biodiversity levels (e.g., Manes *et al.* 2021).

Estimated velocity of poleward range shifts for marine species average 5.92 ± 0.94 km yr^{-1}, six times faster than the average for terrestrial species (Lenoir *et al.*, 2020). This may be due to a combination of greater sensitivity to temperature increases and lower dispersal and colonization constraints for tropical marine species together with greater sensitivity to climate change at higher latitudes due to interactions with anthropogenic activities such as fishing pressure and pollution (e.g., North Sea) (Poloczanska *et al.*, 2013; Lenoir *et al.*, 2020). By contrast, the slower average velocity range shifts among terrestrial species (1.11 ± 0.96 km yr^{-1}) means that they frequently lag behind the faster-moving climate envelopes (Lenoir *et al.*, 2020). This slower tracking of climate envelopes on land has been attributed to wider thermal safety margins, impediments to dispersal across landscapes by habitat destruction and fragmentation, topo-climatic heterogeneity in mountainous regions (Scherrer and Körner 2009), and increased importance of biotic interactions within tropical regions (Graae *et al.*, 2018). Where species and assemblages are able to 'keep up' with shifting climate conditions, multiple possible endpoints in community composition and structure are nevertheless possible, such as in rapid tropicalization of temperate marine ecosystems (Vergés *et al.*, 2019). By contrast, inability to keep up with shifting climate conditions leads species and assemblages to become separated from their climate envelopes, which is inferred to result in decreased population viability and may eventually result in local extinction.

2.1.2 What might we lose?

Species range shifts in response to climate changes are a primary multigenerational adaptation response to climate change. The consequences of this locally may be extirpation of species in some parts of a species range and addition of species at another, on aggregate leading to changing patterns of species richness (Hannah *et al.*, 2020). Habitat fragmentation, such as through land-use conversion (Hu *et al.*, 2020) may turn hotspots or protected areas into islands and accelerate climate-related biodiversity loss within them (Warren *et al.*, 2018). Isolated ecosystems – such as mountains and islands – may become 'evolutionary traps', where the migration of climate zones off the top of mountains or off of islands makes it impossible for species to migrate to new locations with suitable climatic conditions (Leclerc *et al.*, 2020). Native species (especially endemics) show higher vulnerability to climate change (Pacifici *et al.*, 2015), while impacts may be neutral to positive for invasive species within terrestrial and marine systems.

Insular biodiversity hotspots are a key component of global biodiversity, with islands estimated to host close to one fifth of extant terrestrial species (Wetzel *et al.*, 2013). However, insular species are innately vulnerable, accounting for close to half of all the terrestrial species presently considered at risk of extinction (Spatz *et al.*, 2017). Insular endemics are exposed to limited resources and tend to be characterised by poor adaptation, defensive and dispersal capacities, which when combined with climate change and associated impacts such as extreme events and sea level rise, further increases their risk of extinction. Due to high endemicity levels, insular extinctions are likely to disproportionately contribute to global biodiversity loss (Pouteau & Birnbaum, 2016; Manes *et al.*, 2021). However, despite progressively improving resolutions of Regional Climate Models (RCMs), integration of robust climate projections into conservation planning in insular hotspots (especially small islands) remains impeded (Maharaj & New, 2013). This is due to RCM data from the most recent suite of models (especially Shared Socioeconomic Pathways SSPs): (i) being not yet available to the primary modelling communities of developing nations within most insular regions and (ii) requiring further (dynamical) downscaling to sub-island resolutions in order to simulate the climatic heterogeneity of complex insular topography and coastlines (e.g., Climate Studies Group Mona (Eds.), 2020). In marine systems highest concentrations of climate vulnerable species are in tropical regions (Pacifici *et al.*, 2015; Trisos *et al.*, 2020), already resulting in a decline in diversity in equatorial regions (Chaudhary *et al.*, 2021). However specific taxonomic groups may differ from this pattern, such as for marine mammals where species in northern seas and regions (e.g., N. Pacific, Greenland Sea) are most vulnerable and have long histories of overexploitation (Albouy *et al.*, 2020).

Changing climatic conditions and resulting shifts in species ranges may alter ecosystem functions and the integrity of ecosystems (De Leo and Levin 1997, Newmark 2008). Loss of ecosystem integrity can exacerbate species loss as well as the provisioning of benefits, and particularly important for this report is the potential loss and instability of carbon storage capacity for mitigating climate change (Thompson *et al.* 2012).

2.1.3 Interactions between climate change and other pressures on biodiversity

Other anthropogenic pressures and direct drivers (including land/sea-use change, direct exploitation of organisms, pollution and invasive alien species) may interact with climate change, resulting in complex and nonlinear responses in biodiversity (IPBES, 2019, 2.1.16). Increasing habitat fragmentation due to expanding infrastructural development is a key risk, including the development of mining, cities, roads and railways, transformation of coastlines into ports, coastal protection, etc. (Bugnot *et al.*, 2020), aquaculture, and energy facilities (including solar and wind farms), amongst others. In coastal zones increasing nutrient and chemical inputs to coastal waters combined with climate drivers such as increasing temperature and hypoxia result in expanding coastal dead zones and compounding stress and mortality to e.g., coral reefs (Altieri *et al.*, 2017).

Interactions between climate change and invasive and disease species are a particular concern (IPCC, 2014), both exacerbated by global trade. Invasive species are projected to benefit from climate change as it accelerates rates of colonization through adaptive migration, and weakens the integrity of *in situ* biotic assemblages, thus raising the likelihood of colonizing species being able to thrive in new locations and in novel climates. If the invading species is a pathogen, the potential for emergence of new diseases may increase (Val & Val, 2020). Changing climatic conditions also lead to shifts in disease vectors (e.g., malaria mosquitoes and ticks) and their potential release from natural controls.

2.1.4 Biodiversity declines and Good Quality of Life

Material, non-material and regulating contributions from nature to people (NCP) sustain billions of people worldwide (IPBES, 2019). The ‘co-production’ of NCP, based on the use of anthropogenic assets, is ultimately determined by the perceived values of NCP, and governance systems including those that impinge on access and control over different components of biodiversity. NCP is defined to have both ecological and social determinants, and the distribution of NCP in society is an important factor (Díaz *et al.*, 2018; Pascual *et al.*, 2017) (see Sections 6 and 7). In the context of the Sustainable Development Goals the provision of benefits is to meet the needs ‘of all people’, or ‘leave no one behind’ (IPBES, 2019). This equity-based notion is also encapsulated in objectives 2 and 3 of the Convention on Biological Diversity and the ‘common but differentiated responsibilities’ of the UNFCCC.

2.2 CONSERVING NATURE IN A CHANGING CLIMATE

2.2.1 Conservation’s changing objectives

For most of the last century, nature conservation has focused on preserving the perceived historical state of nature, with the aim of maintaining and restoring nature to its state ‘prior to human interference’. This approach effectively regarded humans as external to and detrimental to nature, and paid little concern to sustainable use regimes, nor to notions of equity and social justice – especially towards indigenous peoples impacted by conservation (IPBES, 2019). On aggregate, conservation actions to date have been too limited in relation to the scale of threats to slow the global decline in biodiversity. Currently, less than 25% of terrestrial and 3% of marine areas are considered unimpacted by people (IPBES, 2019). Nevertheless, much more biodiversity would have been lost without efforts to date (V. M. Adams *et al.*, 2019; Hoffmann *et al.*, 2015), emphasizing the need for increasing ambition, and building on (and learning from) both successes and failures (see section 2.3).

According to the Marine Protection Atlas, approximately 16,495 protected areas have been designated, covering 25,033,869 km^2 area equivalent to 7% of the global oceans by 2020. Of which 2.7% (1014 zones) of the global oceans are fully and highly protected, 3.7% (13,078 zones) are less protected, and <1% (2,403 zones) are yet to be implemented. In addition, 1.4% of additional MPAs covering 5,022,168 km^2 (232 zones) have been proposed or committed (Marine Conservation Institute, 2021). National waters, i.e., areas within declared Exclusive Economic Zones, account for 39% of the global ocean area, in 215 countries and territories. Among them 187 countries have some level of marine protection in their national waters with 52 countries protecting >10% of their marine areas. On average, 5.7% of national waters are in fully/highly protected zones, 8.7% are in implemented but less protected zones, 1.6% are in designated but unimplemented zones, and <1% are in proposed/committed zones. However, many fully protected areas are not adequately enforced, and may not be optimally located for either biodiversity protection or managing uses (O'Leary *et al.* 2018, Jones and DeSanto 2016). In an additional example, some no take MPAs may be deliberately placed in areas undesirable to fishing – and, as a result, don't really protect vulnerable populations (Jantke *et al.*, 2018).

Acknowledging and respecting different ways by which people relate to nature (Díaz *et al.*, 2015), and the importance of co-management of territory and resources for the benefit of people and biodiversity (Ancrenaz *et al.*, 2007; Lele *et al.*, 2010; UNESCO, 2017, 2017) are increasingly dominating conservation policy and practice. This follows strong pressure for change from indigenous peoples and local communities (IPLCs) and others, as well as scientific evidence of its effectiveness (Adams & Hutton, 2007; Siurua, 2006). For example, UNESCO Biosphere Reserves and World Heritage Cultural Landscapes explicitly provide for cultural and social needs, regulated use for sustainable development, as well as strictly no-go areas for biodiversity conservation (Price, 2002) and vary in scale from small sites to extensive landscapes of several thousand square kilometres (Ishwaran *et al.*, 2008). The effectiveness of small community-managed marine conservation areas is increasingly being demonstrated (Chirico *et al.*, 2017; Gilchrist *et al.*, 2020), with potential for scaling in regional networks (Newell *et al.*, 2019; Rocliffe *et al.*, 2014). While this shift is challenging to implement in both developing and developed countries, success stories indicate that it also represents an appropriate conservation model for climate mitigation and adaptation (Baird *et al.*, 2018; Doyon & Sabinot, 2014; Reed, 2016; UNESCO, 2017).

As areas of intact nature have fragmented across a mosaic of altered land- and seascapes, the importance of connectivity and migration corridors has increased, as has integration of protected zones within their broader spatial context (Pulsford *et al.*, 2015). Corridors are critical in maintaining species populations, habitats and ecological functions in a fragmented and changing world. They may extend from local to planetary scales and relate to different and critical life stages for species. Building on the functionality of corridors, conservation actions are increasingly turning towards spatial planning frameworks both on land and sea (Ehler & Douvere, 2009; McIntosh *et al.*, 2017) to minimize incompatible activities within and between adjacent areas.

Climate change alters historical disturbance regimes at a range of scales, with potentially catastrophic effects. Recent examples include the 2019-20 Australian megafires (Wintle *et al.*, 2020), forest fires in Mediterranean climates (Batllori *et al.*, 2013) and heat waves causing mass mortality of corals (Hughes *et al.*, 2018). Managing changes in the disturbance regimes to the extent possible is a critical conservation tool and may be particularly effective at the smaller scales of flooding, fires and similar events, but less effective for regional scale phenomena such as heatwaves, cyclones and other extreme events.

To make conservation actions more 'climate smart' (Stein *et al.*, 2014), climate change vulnerability assessments of species, ecosystems and protected areas (e.g., Queirós *et al.*, 2016; Bates *et al.*, 2019; Bruno *et al.*, 2019), and more societally inclusive and adaptive processes (Colloff *et al.*, 2017), are being increasingly applied. However, real-world evaluations of their effectiveness are scarce, partly because they are very recent. Climate change makes preservation-orientated objectives near-impossible, and even maladaptive. Instead, conservation practitioners are faced with the challenge of facilitating biodiversity changes that promote adaptation, and recognizing that this is inextricably linked to human and societal adaptation (Whitney *et al.*, 2017).

2.2.2 Reducing non-climatic stressors

'Doing everything else better' – to maximize the opportunity for wild organisms and ecosystems to adapt to and survive climate change, non-climate stressors such as habitat loss, invasive species, pollution, disease and over-exploitation must be minimized (Field *et al.*, 2014; IPBES, 2019; Samways *et al.*, 2020; Wanger *et al.*, 2020). Climate change interacts with and often exacerbates these stressors, for example by degrading habitats, increasing disease susceptibility, changing movement patterns of damage-causing species and increasing reliance on extractive resources. Minimising the negative impacts of non-climatic stressors has been a dominant focus of biodiversity conservation to date, and growing evidence on the effectiveness of interventions is leading to rapid and ongoing improvements in conservation practice (Sutherland *et al.*, 2016). Further, reducing these stressors improves the ability of wild organisms and ecosystems to adapt to and survive climate change (Field *et al.*, 2014; Räsänen *et al.*, 2016). Given climate change's multiplier effect on non-climatic stressors, measures to address non-climatic stressors must be upscaled and integrated into climate change focused conservation policies and practice; with a view to achieving multiple benefits.

2.2.3 Area-based conservation

Climate change involves changes in time and space of key climate variables, thus posing an existential risk to immobile, site-based conservation actions such as protected areas (Elsen *et al.*, 2020), particularly as until only recently, protected areas were not designated with climate change as a selection criterion or design factor (Hindell *et al.*, 2020). Whether the current complement of species and habitats of a protected area remains within its boundaries, shifts outside of it, or into another protected area, and the identity of species or habitats that may replace them, are highly uncertain. Further, as species respond to changes and shift their distributions individually, or with some linkages in the case of strong associations such as parasitism or symbioses, it is uncertain what assemblage or habitat may result from climate-induced migrations. Although much work is being undertaken in this regard, a robust predictive capacity is still some distance into the future.

Area-based conservation prioritisation has typically focused on 'hotspots' of overlapping biodiversity richness and species threat (e.g., Myers *et al.*, 2000), yet both factors are shifting due to climate change. A large proportion of those species most vulnerable to climate change are not considered threatened by non-climatic threats (Foden *et al.*, 2013) and, hence, are not historically considered in 'hotspot' prioritisation. This has led to exploration of the adequacy of existing protected area networks for accommodating species range shifts with climate and, thus, for most effectively protecting biodiversity (Hannah *et al.*, 2020). Where protected areas contain carbon-rich ecosystems, they play a critical role in avoiding emissions through deforestation and degradation, as well as in ongoing sequestration (Funk *et al.* 2019, Barber *et al.* 2014). However their longevity may be threatened through their downgrading, downsizing and degazettement resulting from conflicting priorities (Golden Kroner *et al.*, 2019; Mascia & Pailler, 2011).

Habitat corridors may be critical for facilitating species range shifts under climate change, leading to their widespread inclusion in climate adaptation strategies (Keeley *et al.*, 2018; Littlefield *et al.*, 2019). However, protecting and restoring habitat connectivity through on-the-ground action has been slow, despite the existence of many such plans (Keeley *et al.*, 2018), implying that the climate change benefits of connectivity conservation remains poorly known.

Recent work has shown that most countries are projected to maintain less than 10% of their current terrestrial climate representations, while in all countries protected areas are projected to retain less than half the range of climatic conditions currently within them (Elsen *et al.*, 2020). Isolated protected areas are particularly vulnerable to this effect due to their limited size and connectivity to broader landscapes or seascapes. Continued PA expansion merely based on current climatic conditions and other traditional PA criteria, and which fail to take shifting climate into account, will be unable to retain current climatic conditions, increasing the vulnerabilities of biodiversity within PAs. Conversely, establishment of PAs within underrepresented portions of climate space is likely to increase the retention of current climate conditions under protection, and this may be particularly beneficial to tropical species, the ranges of which appear more strongly structured by climatic conditions than species within temperate regions (Elsen *et al.*, 2020). Climate refugia often occur in areas with complex, high elevation topography and steep elevational gradients (e.g., mountainous, alpine landscapes), while lower climate change velocities have been detected inside terrestrial and freshwater biodiversity hotspots (Brito-Morales *et al.*, 2018; Sandel *et al.*, 2011).

Analysis of climate velocity trajectories can be a key strategy towards the development and planning of climate-smart conservation area networks (e.g., placement of mechanisms to increase connectivity such as migration corridors, and see **Figure 2.1**) (Arafeh-Dalmau *et al.*, 2020). The establishment of PA networks (together with restoration of habitats) across hotspots – strategically allocated to target underrepresented climate spaces, elevational gaps (mountainous landscapes) and potential climate refugia could provide an opportunity to significantly enhance biodiversity conservation at a global level. This could in part be achieved by strategic PA establishment (including OECMs and PAs with lower IUCN designations (Categories V-V1)) to even out protection disparities across elevational and climatic gradients. However, the omni-directional nature of climate velocity trajectories at the small island scale together with limited area may imply that protected area expansions (including mobile PAs), even if possible, may prove inadequate. Alternative, context-specific, flexible, climate-smart conservation strategies with heavy integration of human responses across a patchwork of protected and human-impacted landscapes and ecosystems may be required (e.g., incorporation of climate refugia and ridge-to-reef management (Carlson *et al.*, 2019).

In prioritizing areas for connectivity conservation, approaches should include focusing on connecting areas of low climate velocity, refugia, climate analogs, or linking current to future suitable habitats (Keeley *et al.*, 2018). For example, riparian corridors should be considered in connectivity plans because of their importance as natural movement corridors and refugia (Keeley *et al.*, 2018). Successful connectivity conservation should include community and stakeholder involvement, habitat priority-setting, native habitat restoration, and environmental services payments that satisfy tenets of climate-smart conservation, thus improving the resilience of human and ecological communities (Littlefield *et al.*, 2019). Improving connectivity will, however, have differential effects on species with different traits, favouring those that are generalist, more mobile, invasive and/or pathogenic (Donaldson *et al.*, 2017), and compensatory actions may be needed to redress these. Mobile protected areas and a range of Other Effective area-based Conservation Measures (OECMs) need to be considered to track new and changing priorities, on land and in the sea, and thereby ensure future relevance.

Climate change may impact on operational aspects of conservation measures, such as on the financial resilience of protected areas and other tourism and area-based measures. For example, the intensity of wildfires in the South African Garden Route in 2017-2018, exacerbated by conversion of natural fynbos to pine plantation (Kraaij *et al.*, 2018), had a high impact on lives and infrastructure, and impairment of conservation measures (Forsyth *et al.*, 2019). Climate change may impact multiple operational aspects of conservation, including disaster risk reduction strategies and costs, tourist behaviour (such as choosing to travel shorter distances to lower carbon emissions, or to avoid extreme heat (Coldrey & Turpie, 2020)), the loss or gain of a charismatic feature (e.g., a glacier, or charismatic species), or on costs of addressing interacting non-climatic stressors (e.g., habitat degradation, invasive species, overexploitation, human-wildlife conflict and disease). Impacts on operational and financial aspects of conservation measures may also arise from other major shocks, as has been recently demonstrated by the COVID-19 pandemic (Northrop *et al.*, 2020).

2.2.4 Dynamic species-focused conservation

Given the need for successful dispersal and establishment of species in newer bioclimatic niches, there has been a strong emphasis on habitat connectivity, both on land and in water, to facilitate this process (Costanza *et al.*, 2020; Doerr *et al.*, 2011; Jaeger *et al.*, 2014; Krosby *et al.*, 2010; Littlefield *et al.*, 2019; Magris *et al.*, 2014). Assisted migration or relocation of species is increasingly presented as an inevitable conservation tool, given the need for more rapid migration than in past times and increasing habitat fragmentation (Hoegh-Guldberg *et al.*, 2008; Lunt *et al.*, 2013; Williams & Dumroese, 2013). Varied tools such as using species distribution models (Hällfors *et al.*, 2016), creating plant seed banks (Vitt *et al.*, 2010), careful choice of species based on their functional importance in an ecosystem (Lunt *et al.*, 2013), and following reintroduction guidelines especially of animal species (IUCN/SSC, 2013) may all be needed. Planting trees in anticipation of their potential dispersal to suitable future bioclimatic space has been suggested to facilitate the shift of the original ecosystem (Hof *et al.*, 2017; Koralewski *et al.*, 2015; Smith *et al.*, 1996), with experimental studies with tree seedlings suggesting an altitudinal range shift of less than 500m improves chances of success (Gómez-Ruiz *et al.*, 2020). For freshwater animals, it has been recommended that relocations occur within the historical range of the species and the same major river basin (Olden *et al.*, 2011).

Assisted migration of species also comes with several risks such as invasions, genetic swamping, transfer of pests and diseases, disruption of ecosystem function, mismatch between anticipated and realized climate, and ill-conceived or hasty translocations outside their historical range (Ricciardi & Simberloff, 2009; Seddon *et al.*, 2009). A study of invasion risks from intracontinental species in the USA concluded that the risks of assisted migration were small overall, but that a successful invasion could make major impacts on the colonized community, and that fishes and crustaceans posed the highest risks of such invasions and impacts (Mueller & Hellmann, 2008). It has been suggested that assisted migration should initially be limited to species with little risk of invasion, attempted at small scales, and a robust monitoring mechanism put in place to ensure timely response to any adverse situation as well as to garner public and political support (Butt *et al.*, 2020). Legal and policy frameworks are also needed to guide the process of assisted colonization or migration (Camacho, 2010; Sansilvestri *et al.*, 2015). Multi-tool approaches to restoring species populations, where different techniques may be considered based on their strengths and weaknesses, and local contexts, will increasingly be needed (Rinkevich, 2019).

2.2.5 Conserving genetic diversity

Measures that protect genetic diversity are critical for maintaining and achieving diversity in species, ecosystems and sustaining multiple benefits to people (Des Roches *et al.*, 2021), including in agricultural systems. It is important to note here that adaptation to climate change is often one of a range of multiple benefits associated with conserving genetic diversity. Conservation of genetic biodiversity (also discussed in Section 3, in the context of mitigation), particularly in managed ecosystems, has a clear role to play, with important benefits from maintaining genetic diversity in both wild and domesticated species (Díaz *et al.*, 2020; Hoban *et al.*, 2020). Effectively, genetic diversity enables populations to adapt to changing environments (whether as a result of climate change, or other external stressors), and rebuilding genetic heterogeneity within a species can be an important strategy in translocation and restoration of depleted populations (Crow *et al.*, 2021) and in adaptation of agriculture to new climatic conditions.

Strategies to protect genetic diversity in agriculture can include *in situ* and *ex situ* techniques, measures to reduce monoculture cropping, including the reintroduction of heritage breeds, and the utilization of genetic diversity in plant breeding to preserve heritage traits (for example, Ebert & Waqainabete, 2018; Mastretta-Yanes *et al.*, 2018). In livestock and aquaculture, measures can be taken to maintain animal genetic resources, including the reintroduction of heritage breeds that have had typically higher genetic diversity and better adaptation to changing environments (Eusebi *et al.*, 2019; Gicquel *et al.*, 2020; Hall, 2019) and enhancing productivity and diversity of cultured species to meet growing global food demand (Houston *et al.*, 2020). However, a key trade-off is often between high yield versus resilience, and a more balanced economic model (see Section 4) may be needed to align incentives of production with climate and biodiversity objectives. While advances in genomic research are very rapid, the capacity to undertake this research and to access and use genetic data is inequitably distributed among countries, as well as being concentrated in corporate entities, highlighting an urgent need to build capacity, promote inclusive innovation and increase access to affordable technologies (Blasiak *et al.*, 2018, 2020; Österblom *et al.*, 2015).

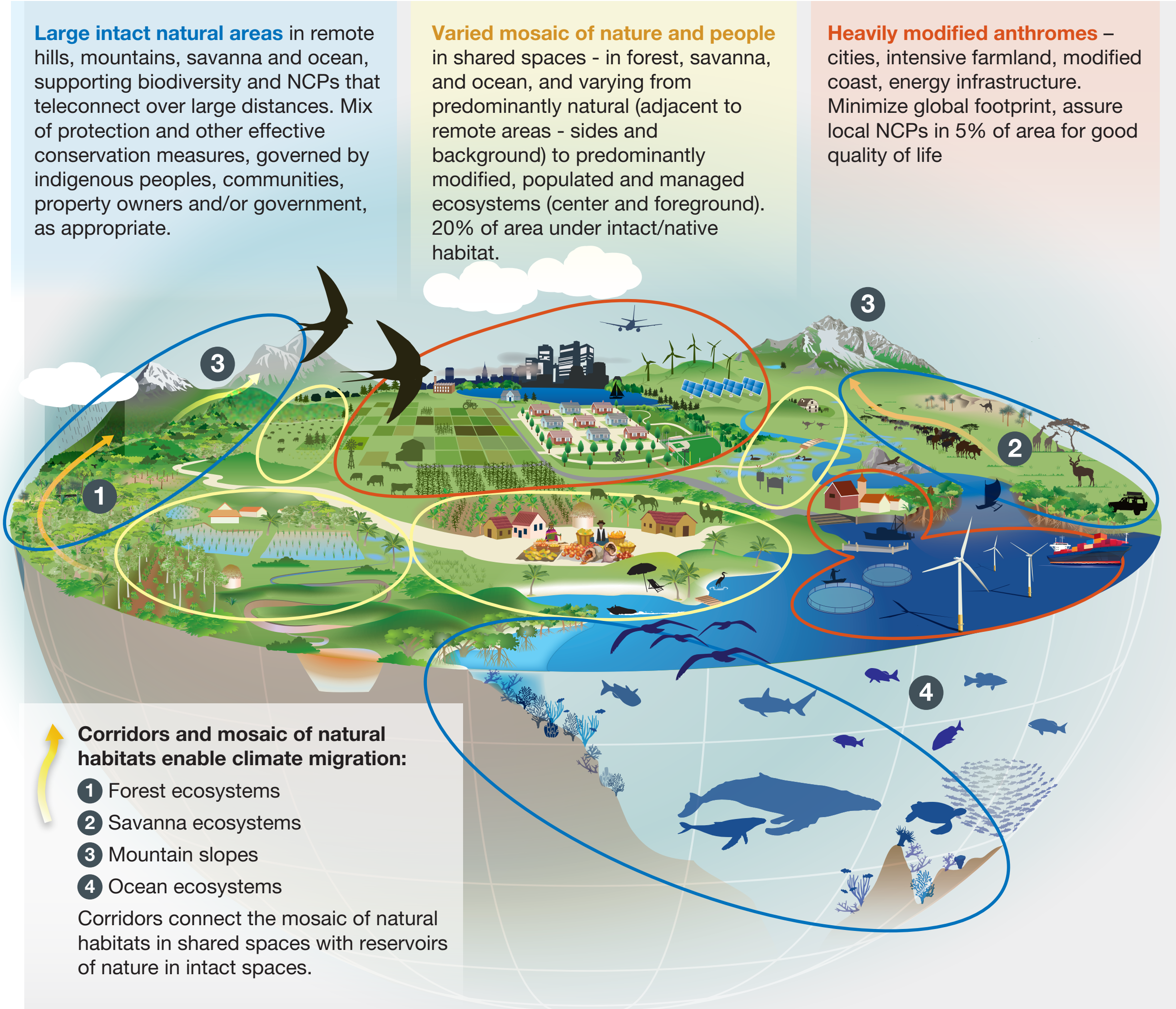
2.2.6 Multifunctional land- and seascapes: ‘scapes

Increasingly, biodiversity conservation actions are being considered across the gradient of state of nature from intact to completely altered. At one end ‘wild’, ‘intact’ or minimally impacted ecosystems (that comprise about 25% of land and 3% of the ocean) are variously termed, ‘Large Wild Areas’ (Locke *et al.* 2019) or intact nature or wilderness (IPBES, 2019). At the other extreme completely transformed spaces (about 21% of land, 1% of ocean (Bugnot *et al.*, 2020) are dominated by human infrastructure and supplying human needs, described variously as “Cities and Farms” (Locke *et al.*, 2019) or anthropogenically altered biomes or ‘anthromes’ (Ellis *et al.*, 2010; IPBES, 2019). In between, natural ecosystems persist along a gradient of change, comprising about 55% of land and likely >95% of ocean, and termed ‘shared lands’ (Locke *et al.*, 2019), ‘working landscapes’ (Garibaldi *et al.*, 2021), or ‘managed ecosystems’ (Díaz *et al.*, 2020). People use and benefit from nature across all of these states, with varied and multifunctional uses in intact and shared spaces, but only a limited set of benefits are possible from nature in anthromes. Examples of shared spaces that emphasize sustainability and integration of people with nature include Cultural Landscapes under the World Heritage Convention, Globally Important Agricultural Heritage Systems (GIAHS) recognized by the FAO and Satoyama Initiative societies living in harmony with nature.

In anthromes, nature is highly transformed by people in order to maximize particular functions and benefits. Examples are for food production in agricultural systems (20% of global land area) and shelter or infrastructure in urban and semi-urban systems (1% of land area) (IPBES, 2019). The original natural system is hardly present, and the multiple other benefits needed by people are subsidized by natural or artificial means from beyond the immediate area – such as for freshwater provisioning (from mountains and forest ‘water towers’) and filtering (wetlands), for protein from hunting and fishing in natural but often impacted biomes, or for sequestering carbon released in the anthromes, in e.g., natural forests and seagrass beds. Within anthromes the value of non-material and regulating contributions from nature provide for a good quality of life, with standards being set for green spaces in cities (Dorst *et al.*, 2019; Maryanti *et al.*, 2016). With economic development and population growth, the spatial extent of anthromes and their extension into adjacent increasingly degraded shared spaces has increased, while shared spaces encroach into wild or intact spaces. Interactions at a distance, for instance driven by global trade, result in ‘telecoupling’ of use and impact chains at increasingly larger scales (IPBES, 2019).

A multifunctional ‘scape approach (‘scape being shorthand for land-, freshwater- and seascapes) incorporates spatial planning concepts in conservation, enabling consideration of biodiversity at different levels of integrity in wild spaces, in shared spaces such as community and extensive use land- and seascapes with pockets of intact nature, and in anthromes **(Figure 2.2)**. The historic dichotomy between ‘human’ and ‘natural’ spaces breaks down across this gradient, providing opportunities for spatial planning across multifunctional ‘scapes to optimize the integrity of nature, provisioning for people, and good quality of life across all states of nature. The multifunctional ‘scape approach also incorporates concepts of land ‘sparing’ and ‘sharing’ in relation to reducing the footprint of food production (Balmford *et al.*, 2018, and see Section 5.1.2.5).

In anthromes there are limited options for large or high-biodiversity areas, but significant options for parcels of nature to provide a range of contributions to people. In ‘shared’ spaces, land and seascape-based approaches which incorporate sustainable use, community-managed and privately-owned mechanisms may be explored to achieve broader goals (Scriven *et al.*, 2019). Approximately 20% coverage by native habitat has been recommended to sustain local NCP provisioning (Garibaldi *et al.*, 2021). Wild and intact spaces provide scope for large-scale conservation



Large intact natural areas in remote hills, mountains, savanna and ocean, supporting biodiversity and NCPs that teleconnect over large distances. Mix of protection and other effective conservation measures, governed by indigenous peoples, communities, property owners and/or government, as appropriate.

Varied mosaic of nature and people in shared spaces - in forest, savanna, and ocean, and varying from predominantly natural (adjacent to remote areas - sides and background) to predominantly modified, populated and managed ecosystems (center and foreground). 20% of area under intact/native habitat.

Heavily modified anthromes – cities, intensive farmland, modified coast, energy infrastructure. Minimize global footprint, assure local NCPs in 5% of area for good quality of life

Corridors and mosaic of natural habitats enable climate migration:

1. Forest ecosystems
2. Savanna ecosystems
3. Mountain slopes
4. Ocean ecosystems

Corridors connect the mosaic of natural habitats in shared spaces with reservoirs of nature in intact spaces.

Figure 2.2 **A multifunctional 'scape across land, freshwater and marine biomes, including large, intact wilderness spaces (blue circles), shared spaces (yellow circles) and anthromes (red circles).**

In shared spaces the mosaic of intact natural habitat provides critical contributions from nature to people. Corridors of natural habitat (yellow arrows) are illustrated facilitating climate migration of species up elevational gradients. This multifunctional 'scape concept can assist integrating global and large-scale targets within local geographies.

actions, managed under appropriate governance regimes, to provide the multiple contributions and benefits needed for global-scale stability of biodiversity and human societies (Dinerstein *et al.*, 2019; Sala *et al.*, 2021).

The multifunctional 'scapes framework **(Figure 2.2)** allows conservation to link to broader spatial aspects of land and sea dynamics. At a broader scale, multifunctional 'scapes are embedded in ecosystem and regional scale processes, such as, for example, larger watersheds (Wang *et al.*, 2016) and oceanic current systems (Akiwumi & Melvasalo, 1998; Sherman & Duda, 1999), which at this scale often require transboundary approaches to conservation. Corridors of natural habitat that link across multiple scales allow for climate migration **(Figure 2.1)**. The concept is also compatible with emerging recognition that some cultural landscapes have higher biodiversity than fully natural ones, due to long term interactions and stewardship actions by people (Taylor *et al.*, 2017; IPBES, 2019).

Using multifunctional 'scapes as a basis for future conservation will need investment in research to understand how varying intensities and types of uses, and local context dependencies, affect achieving multiple objectives, here with a focus on a habitable climate, self-sustaining biodiversity, and a good quality of life for all. For example, increased atmospheric CO_2 promotes transformation of southern and eastern African mixed savannas and grasslands to woodland (Midgley & Bond, 2015). This transition is moderated by grazing; intact herbivore populations, appropriate livestock grazing, and controlled wood harvesting can prevent the transition, with benefits for native biodiversity and for human uses including livestock rearing and meat production, wood use and tourism. Insufficient grazing results in loss of grasslands, whether in cattle-grazing rangeland (shared spaces) or in protected areas (wild spaces) that lack the right balance of herbivores. Another example is of wetland responses to sea level rise (Spencer *et al.*, 2016). Under natural conditions, wetlands would retreat inland, but in anthromes this is prevented and their varied functions (carbon sequestration, shoreline protection, nursery habitat for fisheries, nutrient removal etc.) are lost.

2.2.7 Nature-based Solutions (NbS)

Nature-based solutions are active strategies to rebuild or increase measures of intact nature that enhance provision of one or more benefits to people (see Glossary). Reflecting the broad scope and multifunctionality of NbS, multiple definitions have emerged for varied purposes, such as of carbon sequestration to address climate change, disaster risk reduction in relation to natural hazards, and provisioning of benefits by green spaces in cities (Dorst *et al.*, 2019), among others. A major concern about NbS developed for single purposes has been the growing evidence of the potential for perverse or negative impacts (N. Seddon *et al.*, 2020). For example, plantation forests may be efficient for carbon sequestration, but harm biodiversity; afforestation of natural savannas and peatlands has been shown to result in degradation of ecosystem and community structure and function and the loss of distinctive species, including endemics (Abreu *et al.*, 2017; J. D. Wilson *et al.*, 2014). In order to avoid this kind of unintended consequence, in the context of the biodiversity-climate nexus, NbS for climate mitigation or adaptation (see Sections 3, 4 and 5) must also be positive (or at least neutral) in terms of biodiversity benefits. In many cases additional nature's contributions to people might be generated by the action, adding to the total value of NbS for biodiversity, climate and people.

NbS may become a key strategy in multifunctional 'scapes given their dual roles in delivering positive outcomes for biodiversity and peoples' well-being. For this, it is important that the proportion of nature in shared spaces be fractal in nature (Garibaldi *et al.*, 2021). That is, while the large parcels of land or sea that meet a conservation area target may be important for human and natural systems that telecouple over long distances (e.g., carbon emission and sequestration, global food supply chains), also important are parcels of nature down to a square kilometre scale, in meeting other needs, such as for food and medicinal products provided by forest patches in rural areas, habitat for pollinators in hedgerows, or for recreation and mental health provided by green spaces in cities. While there are ecological and biological (nutritional) benefits of this scaling, there are also equity considerations in ensuring actions and targets meet both nature and human needs.

2.2.8 Restoration

Restoration for species and/or natural habitats is particularly critical where natural systems are so damaged that spontaneous recovery is unlikely, too slow, or to achieve certain outcomes such as mitigation or adaptation to climatic disruption (IPCC, 2000; Munasinghe & Swart, 2005). The term "rehabilitation" may be more appropriate in the context of climate change, where re-establishing the pre-existing conditions may not be possible, but an enhanced state and functions appropriate to shifting conditions, such as in relation to mangroves (López-Portillo *et al.*, 2017) and coral reefs (Kleypas *et al.*, 2021) is feasible. Restoration provides an opportunity to incorporate adaptation measures to future climate, such as in trait selection for higher temperatures, accommodating species range shifts and securing benefits to people under future conditions. As with NbS, restoration may achieve multiple objectives (Martin, 2017), including for people, biodiversity and climate, such as food provisioning and economic benefits, rebuilding carbon stocks, and reduced exposure to climate-related hazards.

In the context of climate change it is important, however, that restoration targets are appropriate to future conditions (Harris *et al.*, 2006), as a result of combinations of factors such as shifts in environmental conditions or species ranges (see Sections 2.1.1 and 2.2.3 on climate velocity), or exceedance of ultimate tolerance limits of species in low latitudes, such as reef-building corals (Hughes *et al.*, 2018). In some cases, such as the deep ocean, restoration may not be feasible unless under specialized circumstances (Da Ros *et al.*, 2019). Increasingly, restoration is being viewed from a perspective of restoring functions and societal benefits of natural habitat (Duarte *et al.*, 2020), and under climate change, for carbon sequestration.

2.3 STRENGTHENING POLICY BY RAISING AMBITION AND DIVERSIFYING ACTIONS

2.3.1 Revisiting global targets

The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets specified global targets of 17%

of land and 10% of ocean to be under strict protection. These targets were approached but not met for land and marine systems, at 15 and 7.5% respectively (GBO5 2020), though they fell dramatically short in terms of representativity (42% of terrestrial ecoregions met their target, and 46% of marine ecoregions; only 29% of amphibians, birds and land mammals have their overall distribution adequately represented by protected areas), effective management (<10% of terrestrial PAs have been assessed for effectiveness, and <8% are adequately resourced), and equity of management and governance (Oldekop *et al.*, 2016; Zafra-Calvo *et al.*, 2019).

For 2030, a new area-based protection target (Target 2) as high as 30% of nature has been suggested, along with stricter requirements for representativity, effectiveness and equity (CBD, 2020). Estimates of the proportion of intact habitat needed to avert biodiversity losses range from 30-50% of global land areas (Wilson, 2016; Dinerstein *et al.*, 2019, 2017; Watson *et al.*, 2020). Identifying which locations will achieve new goals with optimal biodiversity and benefits outcomes will require multifactorial analysis considering biodiversity components (Girardello *et al.*, 2019), multiple risks (e.g., extinction threat) and benefits (e.g., carbon sequestration) for both land (Dinerstein *et al.*, 2019) and ocean (Sala *et al.*, 2021).

2.3.2 From global targets to local realities

Global targets for the proportion of nature that needs to be protected may not scale down to local levels, may not apply uniformly across all biomes, and some biomes may already be significantly impacted beyond these levels (e.g., temperate and tropical grasslands; (IPBES, 2019)), requiring restoration to meet the targets. The global target may also be too small to maintain functions of local or national importance. Equity between people and between countries, based on the current levels of intactness of their biota, historic patterns of damage and present and future development needs for their populations are also important, and recognized in the notion of 'common but differentiated responsibilities' under convention frameworks (Jones *et al.*, 2019).

For some countries, even the current targets of 17% land and 10% ocean protection may not be possible to attain, or may be inappropriate due to socioeconomic, development and regional contextual limitations. For example, on many oceanic islands, there is often less potential for significant expansion of terrestrial protected areas, due to intense needs for agriculture, settlement and development as human populations rise. In the Amazon Basin, despite low human population densities, some functions may require more than 30% protection to avoid a regime shift from forest to savanna. Estimates ranging from 60% (Lapola *et al.*, 2014) to 80% have been reported, taking into account interactive effects between deforestation, climate change mitigation and adaptation, and widespread use of fire (Lovejoy & Nobre, 2018).

Meeting these higher protection targets will require consideration of intact and restored habitat fragments in shared spaces, consolidating and building the current protected area estate (e.g., Golden Kroner *et al.*, 2019), and including the temporal dynamics of recovery to appropriate functional levels. It will also require consideration of disparities among countries' conservation capacities for actions and distribution of future allocations (Woodley *et al.*, 2019), and consideration of equity in meeting peoples' needs e.g., of food (Mehrabi *et al.*, 2018; Schleicher *et al.*, 2019). Suitable indicators for such targets across multiple facets of nature and contributions to people will be needed to assess progress (Díaz *et al.*, 2020) complementary to those already developed for e.g., the Paris Agreement, and in relation to other planetary systems (Rockström *et al.*, 2021).

The need to embrace species and assemblage range shifts offers policy and legislative challenges (van Kerkhoff *et al.*, 2019; McDonald *et al.*, 2019), including transboundary collaboration where shifts cross national and administrative boundaries. Current definitions of 'alien' (outside a historic baseline range) and 'invasive' (proliferating outside this range) species were set prior to concerns of climate change. As a result, species successfully undergoing adaptive range shifts may be considered alien and their migration prevented, and conservation actions such as assisted migration may be prohibited. Review of relevant conventions and legislation is essential to promote and assist biodiversity responses under climate change. Further, as range shifting species may have positive and/or negative implications for livelihoods and biodiversity, well-informed bilateral and/or multilateral discussions will be needed to coordinate management and conservation action.

2.3.3 Setting biodiversity and climate targets jointly

Climate change makes some current conservation goals impossible to achieve. Spatial conservation planning will have to adapt goal-setting approaches to ones that accommodate change, that reach and integrate across scales and among biomes and systems, that consider linked biological and social outcomes, and that are fully integrated in the economic and social sectors that drive the pressures on climate and biodiversity. In the coming decades, biodiversity and climate targets will be mutually dependent on one another to be achievable. They must also be dynamic and adaptable to accommodate synergies and uncertainties (Arneth *et al.*, 2020). The persistence of biodiversity under changing climates is essential for the success of NbS for climate mitigation and adaptation, so inclusion of strategies to promote biodiversity adaptation to assure longevity of solutions is essential in NbS codes of practice (Section 3).

Targets to adequately support joint objectives need to be appropriately worded and mutually supportive. In addition to increasing the contributions of NbS they could also reflect a growing number of approaches for reducing climate change threats to biodiversity. The field of 'climate smart' conservation (Stein *et al.*, 2014) guides and promotes biodiversity-focused climate change adaptation practices, including practices that maximize nature contributions to people provisioning under climate change. The multifunctional 'scapes approach (Section 2.2.6, **Figure 2.2**) integrates native, restored, and modified (perhaps novel) habitats within shared spaces and anthromes to support biodiversity and multiple benefits to people. A working target of 20% of such habitats in shared spaces has been proposed (Garibaldi *et al.*, 2021).

2.3.4 Conservation inside and outside of protected areas

There are strong calls for raising effectiveness of protection to the standard required (Dinerstein *et al.*, 2019; Jones *et al.*, 2020; Watson *et al.*, 2020; Woodley *et al.*, 2019). Given the challenges of multiple threats to biodiversity, and growing needs of local to global society, trade-offs in achieving both are many (Schleicher *et al.*, 2019; Mehrabi *et al.*, 2018). Conservation actions other than protected areas are also essential, currently addressed under the term Other Effective area-based Conservation Measures or OECMs (IUCN WCPA Task Force on OECMs, 2019), as well as assessment processes that inform planning and approval of any activities and addressing a full scope of pressures and enabling factors for success. To halt and reverse the impacts of climate change on biodiversity, practices that qualify as 'climate-smart' or sustainable in all economic sectors will be essential.

The multifunctional 'scapes approach may contribute significantly to minimizing and reversing climate and other impacts on nature, through its focus on people and contributions from nature, and planning for conservation action across all states of nature (Locke *et al.*, 2019). Large intact, wilderness and critical habitats, such as the Amazon rainforest and the open ocean, play an essential role for global biodiversity, climate and other functions. Ecosystem-based approaches, nature-based solutions and ecological restoration, guided by clear objectives for biodiversity conservation, climate adaptation and/or mitigation and meeting peoples' needs will be essential in shared spaces. Importantly, success at all scales will incentivize the stewardship, investment, and engagement of people with nature.


SE

CTION 3

The effects of climate mitigation actions on biodiversity

SECTION 3

The effects of climate mitigation actions on biodiversity

Presently more than 50% of annual anthropogenic CO_2 emissions get (physically and biologically) absorbed in land and oceans (Friedlingstein *et al.*, 2020). Maintaining or enhancing these sinks and ensuring long-term carbon storage in biomass, soils or sediments is an important aspect of climate change mitigation, and in avoiding exacerbating climate change (Ciais *et al.*, 2013). Many different climate change mitigation measures exist (considering not only CO_2 emission and uptake, but also CH_4 and N_2O emissions) that target the use of terrestrial, freshwater and marine ecosystem processes or space. They differ considerably in terms of their mitigation potential (see **Table 3.1** for selected examples), and the degree to which they have positive or negative impacts on human societies' adaptive capacity or on biodiversity, as well as in their scalability and cost-effectiveness. The mitigation approaches are anticipated to vary regionally both in terms of meeting mitigation targets and the consequences they have for biodiversity and human societies. In particular, negative emission technologies that claim a cumulative potential CO_2 uptake over the next century of hundreds of Gt have been criticised as being ecologically unrealistic, likely to impact negatively on local people's well-being, and leading to a false sense of security, which encourages the adoption of risky (delayed) emissions-reduction pathways (Dooley & Kartha, 2018; Girardin *et al.*, 2021; Arneth *et al.*, 2019; Smith *et al.*, 2020). Some of these mitigation options are also vulnerable to climate change itself (e.g., net carbon fluxes into marine and land ecosystems can be reversed in a hotter, drier climate) and thus contribute to positive climate feedbacks (Ciais *et al.*, 2013). Here we consider a range of specific mitigation approaches, selecting some important example measures in order to highlight potential challenges for biodiversity and adaptation. The most robust path to progress in limiting climate change while safeguarding biodiversity depends not just on the identification of the strongest win-win solutions to pursue by region, but also to eliminate demonstrably inadequate – or worse, lose-lose – 'solutions'. This should preferably take place before counterproductive societal or environmental outcomes become 'locked-in'. Nature based solutions have been underutilised, could help in long term global cooling, but they must be designed for longevity and avoid too much focus on rapid sequestration as a lone measure of value (Girardin *et al.*, 2021). While ecosystems can contribute sustainably to mitigation over time, the bulk of mitigation efforts needs to come from rapid, ambitious emissions reductions in fossil fuel emissions to meet the Paris Agreement target of keeping climate change well below 2°C (Girardin *et al.*, 2021; Hoegh-Guldberg *et al.*, 2019).

3.1 CLIMATE CHANGE MITIGATION ACTIONS HARMFUL TO BIODIVERSITY OUTCOMES

3.1.1 Challenges arising from competition for land

3.1.1.1 Planting trees over large areas

Reforestation and afforestation are considered relatively cost-effective climate change mitigation options (Fuss *et al.*, 2018). Besides the carbon removal from the atmosphere and its storage in biomass during tree growth, which is a once-off benefit, there is potential (estimated as 10-700 Tg (million tonnes) of carbon, cf 0.04-2.6 $GtCO_2e$) for substituting emissions-intensive materials such as concrete and steel using timber-based materials. This carbon then becomes stored in buildings (Churkina *et al.*, 2020), and the forests can be regrown and repeatedly harvested.

Recent claims of a potential to reforest massive areas (up to 9 Mkm^2; (Bastin *et al.*, 2019)) have been criticized for having serious methodological flaws and ignoring fundamental ecological and societal processes (Friedlingstein *et al.*, 2019; Grainger *et al.*, 2019; Lewis *et al.*, 2019; Skidmore *et al.*, 2019; Veldman *et al.*, 2019). Existing international activities such as the "Bonn Challenge", which aims to restore 3.5 Mkm^2 of forested landscapes by 2030, could, if successful in the long-term, deliver substantial mitigation benefits, and may do so with co-benefits to biodiversity in some situations – such as helping to rehabilitate degraded lands, or restore forests that have been cleared (Lewis *et al.*, 2019). But if implemented poorly, they may also promote the usage of the planted forests as sources of bioenergy, be detrimental to existing ecosystems' carbon storage, water balance, biodiversity, and even reduce food security (Abreu *et* *al.*, 2017; Fuss *et al.*, 2018; Holl & Brancalion, 2020; Veldman *et al.*, 2015). Large expansion of land committed to forest or to bioenergy crops (3.1.1.2) competes for land used for food production, either within a region or in the form of indirect land-use change even large distances away, such that the land uses they replace are simply moved to other areas (Fuss *et al.*, 2018; Holl & Brancalion, 2020). Replacement of sparse seasonal vegetation by evergreen, high leaf area, rapidly transpiring forests or tree crops reduces freshwater availability in rivers (Cao *et al.*, 2016; Zheng *et al.*, 2016). Large-scale afforestation or other mitigation-oriented land uses may dispossess local people of access to land (Dooley & Kartha, 2018; Holl & Brancalion, 2020). Monocultural plantations have little or no positive impact on biodiversity, and can be detrimental if the planted species becomes invasive and outcompetes the native species (Brundu & Richardson, 2016). Relying on tree biomass for long-term carbon sequestration is risky, particularly in monocultures with high vulnerability to storms, fire or pest outbreak (Anderegg *et al.*, 2020).

Mitigating climate change by devoting vast land areas globally to reforestation and afforestation, an assumption still integral to many climate change mitigation scenarios used in IPCC assessments (Rogelj *et al.*, 2018), should be considered unsustainable (Arneth *et al.*, 2019; Smith *et al.*, 2020; Fuss *et al.*, 2018). By contrast, more modest reforestation projects that are adapted to the local socioecological context and consider local as well as distant trade-offs, can be an important component of climate change mitigation, biodiversity protection and contributions to a good quality of life (see subsection 3.3, and Sections 4.4.1 and 5.1.1).

3.1.1.2 Large areas of bioenergy crops

Besides large-scale forest area expansion, most global climate change mitigation pathways in the IPCC SR1.5 report (IPCC, 2018) rely heavily on the deployment of biomass for bioenergy, often used in conjunction with carbon capture and storage (BECCS) (range ca: 40 to >300 EJ a–1, primary energy, in 2050; (Rogelj *et al.*, 2018)); rates at the upper end of these scenarios are equivalent to >50% of today's total global primary energy production of approximately 580 EJ a^{-1}). In some scenarios that allow for continued high fossil-fuel emissions over the coming decades, while still aiming to limit warming to 1.5°C or 2°C, BECCS is expected to support the decarbonization of the energy system with annual removal rates >10 $GtCO_2$ a^{-1} in 2050 (IPCC, 2018; Rogelj *et al.*, 2018; Popp *et al.*, 2016). In these scenarios, the required land area to grow bioenergy crops may be up to, or exceed, 500 Mha[1] (today's cropland area is ca. 1600 Mha; the land area of India approximately 330 Mha), with significant consequences for biodiversity and ecosystem services (Arneth *et al.*, 2019; Smith *et al.*, 2020; Popp *et al.*, 2016; Rogelj *et al.*, 2018). BECCS CO_2 uptake rates of 10-15 Gt CO_2 a^{-1} would be equivalent to approximately doubling the total carbon sink on land estimated for the last decade (Friedlingstein *et al.*, 2020), which raises severe doubt about their environmental and societal realism, given today's already extensive use of the total ice-free land area. Even more moderate scenarios, which project potential of BECCS around 5 $GtCO_2$ a^{-1} would still aim to enhance today's total land carbon sink by 50%. In addition to jeopardizing SDG 15 (life on land), attempting to use millions of hectare of land for bioenergy (Rogelj *et al.*, 2018) rather than food production would seriously undermine the fight against hunger (SDG 2) (Dooley & Kartha, 2018), if these modelled scenarios were to be realized.

But when planted at smaller scales, woody or perennial grass bioenergy crops in principle can support restoration of severely degraded areas, and biodiversity can benefit from perennial bioenergy crops in agricultural landscapes previously dominated by monocultural crops (Rowe *et al.*, 2013; Landis *et al.*, 2018). That way, bioenergy crops enhance the portfolio of ecosystem services, and increase landscape heterogeneity and hence habitat diversity (3.2.3.1). By contrast large areas of monoculture bioenergy crops that displace other land covers or uses (especially natural or near-natural ecosystems) will have negative biodiversity implications either in the same region or elsewhere (Hof *et al.*, 2018; Humpenöder *et al.*, 2018; Newbold *et al.*, 2016). In addition, nitrogen fertilizer and pesticide use on the bioenergy crop, could affect biodiversity negatively in adjacent land, freshwater and marine ecosystems (Maxwell *et al.*, 2016). Large-scale bioenergy crop production can affect freshwater ecosystems through changes in the magnitude of runoff or its water quality (Cibin *et al.*, 2016), and by increasing agricultural water withdrawals for irrigation of dedicated bioenergy crops (Bonsch *et al.*, 2016; Hejazi *et al.*, 2014). Nitrogen fertilization can lead to freshwater and coastal eutrophication, harmful algal blooms and dead zones which are exacerbated by ocean warming. Harvesting high proportions of agricultural and forest residues for bioenergy can have negative implications on soil fertility, erosion risk, and soil carbon (Liska *et al.*, 2014).

A global 2nd generation bioenergy potential of 88 EJ a^{-1} has been estimated in a study that applied EU renewable energy sustainability criteria everywhere, with the authors cautioning that this may reduce to 50 EJ a^{-1} when uncertainties related to future crop yields have been considered (Schueler *et al.*, 2016). A potential of around 60 EJ a^{-1} (for illustration, around 10% of today's primary energy production) have also been suggested as a conservative estimate, based on studies that restrict bioenergy crops to 'marginal' land and exclude expansion into currently protected areas (Fuss *et al.*, 2018). Applying a conversion factor of 0.02-0.05 Gt CO_2/EJ (Rogelj *et al.*, 2018) 50 EJ a^{-1} implies a mitigation potential of 1-2.5 Gt CO_2 a^{-1}.

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[1] Mha is million hectares.

3.1.1.3 Fuel switching

Fuel switching has been a much-promoted component of decarbonizing strategies and is well underway in the transport sector, where for example fossil-fuel derived liquid fuels have been replaced by bioethanol, electricity and hydrogen. The same concerns related to the competition for land arise as in other land-area based mitigation strategies (Bordonal *et al.*, 2018). One critical aspect is also whether the substantial N_2O emissions associated with current biofuel production practices would substantially reduce the climate change mitigation potential (Yang *et al.*, 2021). Amongst the most publicized impacts of fuel switching measures has been increased intrusion into protected areas and remaining wilderness, as a result of growing biofuel crops or mining for raw materials to build renewable energy infrastructure (Sonter *et al.*, 2020; Levin *et al.*, 2020; see also 3.1.3). For instance, an attempt to reduce coal reliance in the steel industry in Brazil saw considerable expansion of plantation forests for charcoal production, aimed as being carbon neutral within CDM (Clean Development Mechanism) projects (Sonter *et al.*, 2015). However, the authors found that although coal demand declined from 2000 to 2007, annual CO_2 emissions from steel production doubled to >0.18 $GtCO_2$ over a seven-year period, caused by increased native deforestation outside CDM-sourced charcoal. The environmental footprint can be influenced e.g., as a result of fuel switching from a centralised to distributed form, altering infrastructural requirements and spreading impact. This could be seen as a benefit in some places.

3.1.2 Regional climate trade-offs and synergies arising from biophysical processes

In addition to their climate effects through altering the atmospheric concentrations of CO_2 and other greenhouse gases, land-based mitigation measures can affect climate through biophysical mechanisms. While being most pronounced locally, these biophysical processes can even have climate impacts thousands of kilometres away, although these 'teleconnections' are still poorly understood (Jia *et al.*, 2019). Many of these effects are not included in UNFCCC mitigation project guidelines, compromising the full quantification of mitigation effectiveness (Duveiller *et al.*, 2020). 'Biophysical' processes are mostly related to changes in the surface energy balance through alteration of reflectance (albedo) and evapotranspiration (Perugini *et al.*, 2017). Although the net climate impact from biophysical processes arising from land cover changes (including for climate change mitigation) is considered globally to be small, these processes can result in local or regional cooling or warming, as well as impacting precipitation (Jia *et al.*, 2019; Perugini *et al.*, 2017). For instance, forest restoration in tropical regions causes local cooling as a climate co-benefit, due to the forests' large evapotranspiration rates (Alkama & Cescatti, 2016; Perugini *et al.*, 2017). By contrast, reforestation in the boreal region can result in increased surface warming, especially in winter and spring when dark, evergreen conifer foliage absorbs solar radiation that would otherwise have been reflected by a snowy background. The additional cooling due to the formation of secondary organic aerosols in boreal forests, which may offset part of this warming so far is difficult to quantify (Alkama & Cescatti, 2016; Carslaw *et al.*, 2013; Perugini *et al.*, 2017).

Bioenergy plantations with large biogenic volatile organic carbon (BVOC) emissions (in particular the compound isoprene) may – depending on the overall atmospheric chemical environment – lead to increased tropospheric ozone formation and thus ozone-related radiative forcing, and furthermore being detrimental to human and crop health (Ashworth *et al.*, 2013; Rosenkranz *et al.*, 2015). BVOC emissions contribute to the formation of secondary organic aerosols (with direct radiative properties, and effects on cloud formation) (Carslaw *et al.*, 2013; Jia *et al.*, 2019). In marine ecosystems, climate change feedbacks due to altered emissions of dimethyl sulphate are often discussed (Wang *et al.*, 2018; Woodhouse *et al.*, 2018), but there is not yet any evidence that proposed ocean-based mitigation measures will contribute to aerosol or other biophysical-related regional climate impacts.

3.1.3 Impacts on biodiversity arising from technological mitigation measures

Multiple technological-focussed mitigation measures are in place or under development on land and in the oceans. Many of these are less (land) area demanding and/or are considered to have high mitigation potential. For instance, solar radiation and wind are discussed as being amongst the most promising renewable energy sources. At present ca, 402 GW of solar energy and ca. 650 GW of wind energy are realized (https://gwec.net/global-wind-report-2019/) (Dhar *et al.*, 2020), magnitudes lower than their theoretical upper limit. Likewise, hydropower supplies ca. 16% of the world's total electricity (Wanger, 2011) (Gernaat *et al.*, 2017) (with an estimated potential of ca. 13 PWh a^{-1} and a remaining potential of close to 10 PWh a^{-1} (Gernaat *et al.*, 2017). These numbers highlight the large scope for climate change mitigation by promoting these renewables further. Nevertheless, all these mitigation measures could potentially harm the environment, including biodiversity and good quality of life, through the required inputs in terms of materials and resources or through toxic waste products (Dhar *et al.*, 2020). An important aspect therefore is to develop the necessary additional mining activity with strong environmental and social sustainability criteria in mind, and to emphasise the importance of a circular economy.

3.1.3.1 Mining in the ocean and on land

Reducing greenhouse gas (GHGs) emissions through the development of renewable energies in the transport and energy sector are important options for mitigating climate change (IPCC, 2019; Shahsavari & Akbari, 2018) with the co-benefit of reducing pollutants that have deleterious effects on human health and the environment (Akhmat *et al.*, 2014). However, their implementation requires specific minerals, and mining for those minerals has potential for large detrimental environmental and societal impacts. The total lifecycle material resources required for lithium batteries, for instance, can exceed the weight of the battery itself by nearly 200 times (Kosai *et al.*, 2020). Demand for lithium may surpass supply already by the mid-2020s (Anwani *et al.*, 2020; Wanger, 2011). Most environmental considerations of electric batteries to date has been of performance during operation but production can be carbon costly, for example a 1kWh Li-ion battery may cost more than 400 kWh (75kg CO_2, the equivalent of 35L of petrol) to manufacture (Larcher & Tarascon, 2015). Enhanced evaporative lithium extraction is associated with water pollution and occurs in areas that provide unique biodiversity habitat (Wanger, 2011; Sonter *et al.*, 2020).

With increasing demand for rare and critical metals, deep-ocean mining of sulphide deposits, ocean-floor polymetallic nodules or cobalt crusts have raised concerns regarding impacts on biodiversity and ecosystem functioning, in an ecosystem that is as yet largely under-researched (Jones *et al.*, 2018; Orcutt *et al.*, 2020). For example, Simon-Lledo *et al.* (2019) found far reaching biodiversity and ecosystem functioning consequences of simulating deep sea mining (Simon-Lledó *et al.*, 2019). Polymetallic nodules are the resource likely to be targeted earliest, followed by sulphides and cobalt crusts. The large environmental and social impacts of land and seafloor mining underpin the need for developing alternative batteries, long-lived products, an efficient recycling system for resources, together with mining approaches with strong considerations for environmental as well as social sustainability (Blay *et al.*, 2020; Borah *et al.*, 2020; Larcher & Tarascon, 2015). Several promising options exist, but with large uncertainties regarding their technical realization (Blay *et al.*, 2020; Borah *et al.*, 2020; Larcher & Tarascon, 2015). Policy measures that foster recycling and/or production quota will support the development of such options (Henckens & Worrell, 2020).

3.1.3.2 Biodiversity impacts of wind power

Reducing GHGs emissions through wind energy development can have several positive impacts, aside from climate change mitigation, such as reducing air pollution, combating desertification, and land degradation (IPCC, 2019). However, wind turbines can interfere with e.g., migratory or soaring birds as well as bats, with mortality rates that can be in some locations of similar magnitude to those caused by other human infrastructures (industry, cars) (Agha *et al.*, 2020; Dai *et al.*, 2015; Kaldellis *et al.*, 2016). Whether or not mortality biased towards predator species might have knock-on effects on communities remains an open question (Agha *et al.*, 2020). Mortality is much lower now than in the last century and can be mitigated by turbine design, placement and operation (Dai *et al.*, 2015). Offshore turbines have been found to affect also benthic flora and fauna, such as changing fish distribution or creating artificial reefs, with both beneficial and mildly negative impacts on biodiversity (Soukissian *et al.*, 2017). Acoustic impacts of wind turbines on marine mammals seem minor during operation but can be important during construction (Madsen *et al.*, 2006). Some impacts of offshore wind have been little investigated, such as the effects of the electric fields around cables connecting them to land. These may be minor, but to date are little known. However, placement of considerable hard substrate ‘islands’ on sediment plains of continental shelf could influence recruitment of jellyfish – although hard substrata surrounded by muds tend to promote hotspots of both ecosystem carbon storage and biodiversity (Barnes & Sands, 2017; Popescu *et al.*, 2020). Popescu *et al.* (Popescu *et al.*, 2020) approached energy source comparisons by specifically considering trade-offs between GHG emissions, energy costs and biodiversity priorities (at both regional and larger scales). They found the clearest benefits were from wind turbines regarding emissions, electricity generated and biodiversity costs, at least in British Columbia, Canada.

3.1.3.3 Biodiversity impacts of solar power

Large-scale solar plants require land area, which involves clearing or conversion of otherwise managed land. Impacts can thus range from directly destroying natural habitat, affecting movement of wildlife species, increasing pressure of agricultural intensification (if solar is competing for crop area, while food production has to be maintained) or indirect land-use change (i.e., displacement effects) (Dhar *et al.*, 2020; Hernandez *et al.*, 2014). Nonetheless, area and resources required over the life cycle of fossil-fuel power plants are estimated to be notably larger than solar plants (Dhar *et al.*, 2020). Moreover, integrated solar-cropping (or grazing) systems can create double-use of land, and positive spillover effects into neighbouring fields have been observed if underneath solar panels habitat for pollinators is created (Dhar *et al.*, 2020) (3.2.4.3). Solar power generation is deemed also much more efficient on an area basis than for example growth of bioenergy crops and could thus contribute to reducing land competition in the climate change-mitigation – food production – conservation debate (Searchinger *et al.*, 2017).

3.1.3.4 Biodiversity impacts of hydropower

Of rivers longer than 1000 km, only 37% remain free-flowing over their entire length, often in very remote regions (Grill *et al.*, 2019). The building of dams for freshwater storage and hydropower creation alters habitats for all freshwater organisms and blocks fish migration, leading to range contraction and population decline (though this does not apply to run-of-the-river schemes). In recent years, many newer dam projects focussed at building multiple small ones rather than one big, aiming to reduce environmental impact (Lange *et al.*, 2018). These efforts have also decentralised power supply (Lange *et al.*, 2018; Tomczyk & Wiatkowski, 2020). Such smaller dams can still cause continued habitat fragmentation and degradation, and may also result in larger transport infrastructural requirements (Popescu *et al.*, 2020). These impacts can be reduced by appropriate infrastructure (such as low-speed turbines), planning that includes basin-scale perspectives and ecological assessment methods, and integrated schemes that capture needs of riverine societies (Jager *et al.*, 2015; Lange *et al.*, 2018; Tomczyk & Wiatkowski, 2020).

3.1.3.5 Biodiversity impacts of enhanced ocean carbon uptake

Enhanced ocean uptake of CO_2 can occur through three main pathways, a) creating and restoring “blue carbon” biological sinks such as mangrove swamps and other coastal ecosystems such as seagrass beds (technical potential: <1 $GtCO_2e$ a-1; see (Froehlich *et al.*, 2019; Hoegh-Guldberg *et al.*, 2019), b) ocean fertilization, e.g., with iron, to increase surface primary production which increases the delivery of fixed CO_2 into the deep sea (technical potential: 1-3 $GtCO_2e$ a-1; (Minx *et al.*, 2018; Ryaboshapko & Revokatova, 2015)), and c) increasing the alkalinity of seawater through seeding the ocean with natural or artificial alkaline materials to sequester CO_2 as bicarbonate and carbonate ions (HCO_3-, CO_3^{2-}) in the ocean (technical potential: 0.1-10 $GtCO_2e$ a^{-1}; (Fuss *et al.*, 2018)). Additional approaches include the electrochemical splitting of water into hydrogen (H+) and hydroxide (OH-) ions, which can be used through various processes to capture CO_2 or to increase alkalinity of seawater. While options under (a) have sound footing in biological processes, actions under (b) and (c) are theoretical and the fate of the extra captured carbon is unknown, including potentially harmful disruption in the marine food web (Hoegh-Guldberg *et al.*, 2019). Another is growing macroalgae at very large scales and subsequently dumping it in the deep ocean or converting it to long-lived products such as biochar and thus sequestering CO_2 over large time scales (100s – 1000s years).

Many of these approaches are conceptually feasible or have been demonstrated in the laboratory, but their consequences for the ocean, including on its biodiversity are uncertain especially if applied at scale. For example, planting mangroves at too high a tree density can reduce rather than enhancing biodiversity (Huang *et al.*, 2010). Some approaches such as growing macroalgae may start with restoration of natural kelp forests as a blue carbon sink, which may be worth 173 TgC yr^{-1} in terms of export to deep waters and sequestration (Krause-Jensen & Duarte, 2016). However, it is important to look beyond traditional blue carbon habitats to embrace wider blue carbon potential, such as bivalve reef restoration (zu Ermgassen *et al.*, 2019). Overall creating, restoring and protecting blue carbon sinks should have positive impacts on biodiversity (Bax *et al.*, 2021; Sanderman *et al.*, 2018). However, there are significant risks to the extent of blue carbon gains and biodiversity associated with widespread ocean fertilization (Glibert *et al.*, 2008).

3.1.3.6 Biodiversity impacts of ocean-based renewable energy

Concerns about biodiversity impacts on marine renewable energy installations have included habitat loss, noise and electromagnetic fields as well as collision risk for megafauna (Inger *et al.*, 2009). However, the authors highlight that from what we know to date, benefits (such as artificial reef creation, fish aggregation and essentially acting as marine protected areas) far outweigh negative impacts. They further suggest that wave and tidal energy have been under-utilised and have significant potential to replace fossil fuels, adding to decarbonisation targets.

3.1.3.7 Biodiversity impacts of accelerated mineral weathering

Accelerated mineral weathering involves a) the mining of rocks containing minerals that naturally react with CO_2 from the atmosphere over geological timescales, b) the crushing of these rocks to increase the surface area, and c) the spreading of these crushed rocks on soils (or in the ocean) so that they absorb atmospheric CO_2 (Beerling *et al.*, 2018). Construction waste, and waste materials can also be used as a source material (Lenton, 2014; Strefler *et al.*, 2018). The biodiversity impacts are largely unquantified but raising the pH when spread on some acidic soils could enhance floral diversity (Beerling *et al.*, 2018), whereas an increase in mining operations would likely have an adverse local impact at these sites (Younger *et al.*, 2004).

3.1.3.8 Biodiversity impacts of producing biochar

Biochar is produced by pyrolysis of biomass with the resulting product applied to soils (technical potential: 0.03-6 $GtCO_2e$ a^{-1}; (Smith *et al.*, 2020). Impacts of addition to soil are unlikely to have biodiversity consequences, but the production of feedstock for pyrolysis required to provide CO_2 removal on several $GtCO¬_2e$ a^{-1} scale was assessed by (McElwee *et al.*, 2020) to have potential negative impacts on biodiversity.

Table ③ ① Effects on biodiversity of selected (example) global climate mitigation and adaptation practices based on land and ocean management.

Ordered by maximum mitigation potentials. Practices often overlap, so are not additive (modified from Smith *et al.*, 2020; Roe *et al.*, 2019; Hoegh-Guldberg *et al.*, 2019; Barnes *et al.*, 2018). See these sources for further references, uncertainties and confidence levels. Estimates for measures in coastal and marine ecosystems are given for 2050 (Hoegh-Guldberg *et al.*, 2019) – estimates for 2030 can also be found in (Hoegh-Guldberg *et al.*, 2019); estimates for land ecosystems are for ca. 2030-2050 (Smith *et al.,* 2020).Biodiversity impact: based on (McElwee *et al.*, 2020; Girardin *et al.*, 2021), together with judgement by authors, and Section 5. Under 'Synopsis', Adaptation is added with a question mark in cases for which no global estimates exist, but authors judge that an action would indeed contribute to societies' adaptation to climate change.

See footnotes for additional explanations.

Practice	Summary/synopsis of overall expected impact	Mitigation potential	Adaptation potential (estimated number of people more resilient to climate change from intervention)	Biodiversity impact (positive unless otherwise stated)
Ⓐ Land				
Increased food productivity		>13 GtCO$_2$e a^{-1}	>163 million people	High[1] or Low[2]
Bioenergy and BECCS	🌐 ⚠	0.4-11.3 GtCO$_2$e a^{-1}	Potentially large negative consequences from competition for arable land and water.	Negative/low positive[3]
Reforestation and forest restoration	🌐 🔄 🐊	1.5-10.1 Gt CO$_2$e a^{-1}	> 25 million people	High
Afforestation	🌐 ⚠	See —Reforestation	Unclear	Negative/low positive[3]
Increased soil organic carbon content	🌐 🔄 🐊	0.4-8.6 GtCO$_2$e a^{-1}	Up to 3200 million people	Medium
Fire management	🌐 🔄	0.48-8.1 GtCO$_2$e a^{-1}	> 5.8 million people affected by wildfire; max. 0.5 million deaths per year by smoke	Low
Biochar addition to soil	🌐 🔄	0.03-6.6 GtCO$_2$e a^{-1}	Up to 3200 million people; but potential negative (unquantified) impacts if arable land used for feedstock production	Low[4]
Reduced deforestation and degradation	🌐 🔄 🐊	0.4-5.8 Gt CO$_2$e a^{-1}	1-25 million people	High
Agroforestry	🌐 🔄 🐊	0.1-5.7 Gt CO$_2$e a^{-1}	2300 million people	High
Enhanced weathering of minerals	🌐	0.5-4 GtCO$_2$e a^{-1}	No global estimates	Insufficient data to make judgement
Restoration and reduced conversion of coastal wetlands	🌐 🔄 🐊	0.3-3.1 GtCO$_2$e a^{-1}	up to 93-310 million people	High
Improved livestock management	🌐 🔄 🐊	0.2-2.4 GtCO$_2$e a^{-1}	1-25 million people	Medium
Improved cropland management	🌐 🔄 🐊	1.4-2.3 GtCO$_2$e a^{-1}	>25 million people	Medium
Improved and sustainable forest management	🌐 🔄 🐊	0.4-2.1 Gt CO$_2$e a^{-1}	> 25 million people	High
Restoration and reduced conversion of peatlands	🌐 ? 🐊	0.6-2 GtCO$_2$e a^{-1}	No global estimates	High
Improved grazing land management	🌐 🔄 🐊	1.4-1.8 GtCO$_2$e a^{-1}	1-25 million people	Medium
Integrated water management	🌐 🔄 🐊	0.1-0.72 Gt CO$_2$e a^{-1}	250 million people	Medium

Table ③ ①

Practice	Summary/synopsis of overall expected impact	Mitigation potential	Adaptation potential (estimated number of people more resilient to climate change from intervention)	Biodiversity impact (positive unless otherwise stated)
Reduced grassland conversion to cropland	🌐 ? 🦎	0.03-0.7 Gt CO$_2$e a^{-1}	No global estimates	High[5]
Reduced soil erosion	🔄	Source of 1.36-3.67 to sink of 0.44-3.67 Gt CO$_2$e a^{-1}	Up to 3200 million people	Low
Biodiversity conservation	🌐 🔄 🦎	0.9 GtCO$_2$-e-e a^{-1}	Likely many millions	High
Agricultural diversification	🔄 🦎	> 0	>25 million people	High
Management of invasive species / encroachment	🔄 🦎	No global estimates	No global estimates	High
On-shore wind	🌐	Depends on substitution effect	No global estimates	Low
Solar panels on land	🌐	Depends on substitution effect[6]	No global estimates	Low
Ⓑ Demand changes (related to land)				
Dietary change	🌐 🦎	0.7 to 8 GtCO$_2$e a^{-1} (land)	No global estimates	High[7]
Reduced post-harvest losses	🌐 🔄 🦎	4.5 GtCO$_2$e a^{-1}	320-400 million people	Medium/High
Reduced food waste (consumer or retailer)	🌐 🔄 🦎	0.8 to 4.5 GtCO$_2$e a^{-1}	No global estimates	Medium/High
Management of supply chains	🔄 🦎	No global estimates	>100 million	Medium[8]
Enhanced urban food systems	🦎	No global estimates	No global estimates	Medium
Ⓒ Ocean				
Ocean-based renewable energy	🌐	0.76–5.4 GtCO$_2$e a^{-1}	No global estimates	Low
Carbon storage in seabed	🌐	0.5–2.0 GtCO$_2$e a^{-1}	No global estimates	Low
Fisheries, aquaculture and dietary shifts	🌐 ? 🦎	0.48–1.24 GtCO$_2$e a^{-1}	No global estimates	Medium/high
Costal and marine ecosystems	🌐 ? 🦎	0.5–1.38 GtCO$_2$e a^{-1}	No global estimates	Medium/High

🌐 Mitigation potential 🔄 Adaptation potential ? Possible adaptation potential ⚠ Negative impacts on biodiversity 🦎 Positive impacts on biodiversity

1. If achieved through sustainable intensification;
2. If achieved through increased agricultural inputs;
3. If small spatial scale and (for bioenergy) second generation bioenergy crops;
4. Low if biochar is sourced from forest ecosystems, application can be beneficial to soils locally;
5. If conversion takes place in (semi-)natural grassland;
6. See Creutzig *et al.* (2017) for a recent summary of energy potentials;
7. Due to land sparing;
8. Related to increased eco-labelling, which drives consumer purchases towards more ecosystem-friendly foods.

3.2 ACTIONS THAT BENEFIT BOTH CLIMATE AND BIODIVERSITY

Protection and restoration of carbon rich ecosystems is the top priority from a joint climate change mitigation and biodiversity protection perspective. Girardin *et al.* (2021) point out that to maximize climate-mitigation targeting nature-based solutions (NbS) it is important to assess actions for longevity; it can be counterproductive if sole emphasis is placed on rapid sequestration. They prioritise protection of intact ecosystems, managing working lands and restoring native cover. Such activities score high on mitigation, biodiversity and adaptation co-benefits **(Table 3.1)** and can be cost effective and scalable. However, even when existing direct human pressures (such as conversion and over-extraction) are removed, climate change poses severe threats to many of these ecosystems (e.g., through permafrost thaw, increasing risk of wildfire and insect outbreak, mangrove or kelp-forest dieback) that cannot be alleviated without halting warming. The ambition to retain, restore and protect natural ecosystems (Arneth *et al.*, 2020; Watson *et al.*, 2020) will be difficult, if not impossible, to achieve, unless climate change is simultaneously mitigated through ambitious fossil fuel emissions.

3.2.1 Protect

3.2.1.1 Reduction of emissions from deforestation and forest degradation

Measures that prioritise avoided deforestation combined with restoration of existing but degraded forests have large climate mitigation potential and large biodiversity co-benefits. Reducing the loss of forests has the single largest potential for reducing carbon emissions in the AFOLU sector, with estimates ranging from 0.4–5.8 $GtCO_2e\ a^{-1}$ (IPCC, 2019). Considering the loss of additional sink capacity associated with deforestation (estimated as 3.3 $GtCO_2\ a^{-1}$ (0.9 $GtC\ a^{-1}$) for years 2009-2018, (Friedlingstein *et al.*, 2020) provides an additional large mitigation incentive. Globally, less than 30% of the world's forests are considered to be still intact (Arneth *et al.*, 2019), and less than 40% of forest area has been estimated to contain forest older than 140 years (Pugh *et al.*, 2019). Reducing forest degradation can thus contribute an estimated 1-2.2 $GtCO_2e\ a^{-1}$ in avoided GHG emissions. At least for neo-tropical forests, the area of degraded forests could well equal or even exceed the area of deforestation in many regions (Bullock *et al.*, 2020; Matricardi *et al.*, 2020); associated above-ground carbon losses have been estimated to increase estimates of gross deforestation losses by ca. 25% up to >600% (Maxwell *et al.*, 2019), with possibly additional, unknown carbon lost from soils. A successful Reduction of Emissions from Deforestation and forest Degradation (REDD+) or equivalent financed at 25 US$/tonne CO_2 could reduce projected species extinctions by 84%-93% (Strassburg *et al.*, 2012). Degradation can double the biodiversity loss arising from deforestation (Barlow *et al.*, 2016). Regarding societal co-benefits, a model experiment showed that an equitable allocation of REDD+ funds among eligible countries lead to a larger number of countries benefiting, without significantly compromising the carbon efficiency and biodiversity outcomes (Section 6). Nevertheless, for a variety of broadly governance-related issues REDD+ so far has not yet achieved the hoped-for tangible results (Angelsen *et al.*, 2017) (Section 6).

3.2.1.2 Conservation of non-forest carbon-rich ecosystems on land and sea

Non-forest ecosystems on land, including freshwater systems and sea, including coastal areas, have also an important role to play. The total amount of carbon stored in wetlands and peatlands has been estimated at ca. 1500 GtC, around 30-40% of the global terrestrial carbon stock (Kayranli *et al.*, 2010; Page & Baird, 2016). Despite the importance of protecting these systems for climate change mitigation and human well-being (flood and pollution control), an estimated 87% of the world's wetlands were lost in the last 300 years, 35% since 1970 (Darrah *et al.*, 2019). Prominent examples include the Rwenzori-Virunga montane moorlands of Rwanda, and the Andean Páramo in Venezuela, Colombia and Ecuador (Soto-Navarro *et al.*, 2020). Likewise, grasslands and savannas are estimated to store around 15% of the total terrestrial C (Lehman & Parr, 2016; McSherry & Ritchie, 2013). Yet, for instance, tropical grassy biomes have even a substantially lower proportion of protected areas than tropical forest. About 50% of Brazilian Cerrado has been transformed for use in agriculture and pastures, while African savannas are also under large land-use change pressure (Aleman *et al.*, 2016; Lehman & Parr, 2016). Formerly occupying ~8% of the land surface, natural temperate grasslands are now considered one of the most endangered biomes in the world (Carbutt *et al.*, 2017; van Oijen *et al.*, 2018). Less than 5% of global temperate grasslands are currently protected (Carbutt *et al.*, 2017). In this context, the conservation of carbon and biodiversity rich ecosystems to reach 30% in both terrestrial and marine ecosystems, as promoted by CBD, can have important effects in reducing biodiversity decline and enhancing climate change mitigation (Hannah *et al.*, 2020).

Mangroves, seagrass meadows, salt marshes and kelp forests are key marine and coastal ecosystems for carbon capture and storage. The former two accumulate their carbon *in situ* (though with some export, see Li *et al.*, 2018), kelp does so by export, and salt marsh through both *in situ* and export. Stores of carbon in marine life are called 'blue carbon'. Mangroves have particularly powerful potential and can sequester four times more than rainforest per unit area (Donato *et al.*, 2011). However, mangroves (and other coastal marine vegetation) occupy narrow coastal niches and thus a small global area, so they have considerably less carbon standing stock and total climate mitigation potential than forest. Nevertheless, despite occupying <1% of global area, mangroves held more than 6 GtC (22 $GtCO_2e$) in 2000 (Sanderman *et al.*, 2018). There can be strong interdependence of adjacent environments, for example mangroves, seagrasses and coral reefs each conveying benefits to others in terms of functioning (e.g., in nutrient release, nursery grounds and hindering erosion) thereby enhancing collective societal benefits such as carbon storage. "Blue carbon environments" can also be disproportionally biodiversity rich (per area, see Morrison *et al.*, 2017) and host completely different suites of species (as well as providing fish nursery grounds, coastal storm and erosion protection). Up to 2000 species can be present in mangroves in a single region (Saenger *et al.*, 1983) so climate mitigation schemes preventing their deforestation could safeguard these as well as prevent 0.1-0.4Gt CO_2e soil carbon lost (as has been in the last 15 years (Sanderman *et al.*, 2018)). Conservation of non-forest carbon rich land and coastal ecosystems have important climate benefits with co-benefits for biodiversity.

3.2.2 Restore

3.2.2.1 Restoration of degraded ecosystems

Ecosystem restoration can provide major contributions to climate change mitigation. In forests alone, estimates of annual net carbon removal from forest area expansion range from 1.5–10.1 $GtCO_2e\ a^{-1}$. (Smith *et al.*, 2020; Roe *et al.*, 2019). However, current scenarios used by the IPCC do not differentiate between natural forest regrowth, reforestation with plantations, and afforestation of land not previously tree-covered, which makes assessment of biodiversity impacts difficult (Chazdon & Brancalion, 2019; Temperton *et al.*, 2019). Peatland restoration (and avoided conversion) could remove 0.2–2 $GtCO_2e\ a^{-1}$ and coastal wetlands restoration has a sequestration potential of 0.20–0.84 $GtCO_2e\ a^{-1}$ (IPCC, 2019; Smith *et al.*, 2020). Ecosystem restoration provides opportunities for co-benefits for climate change mitigation and biodiversity conservation, which are maximized if restoration occurs in priority areas for both goals. For instance, restoring 30% of converted lands in priority areas for climate change mitigation and biodiversity conservation can simultaneously sequester 465 ± 59 $GtCO_2$ and avoid 71±4% of current extinction debt (Strassburg *et al.*, 2020). These are long-term estimates, but tropical forests, where most global priorities are located, can recover half of their reference carbon stocks in the first 20 years after restoration, and 90% in 60-70 years (Poorter *et al.*, 2016). Natural forest regeneration can generate substantial global CO_2 removal and is a key component of cost-effective large-scale restoration strategies (Strassburg *et al.*, 2018). Related to the 'Bonn Challenge', encouraging natural forest regrowth may be >40 times more effective (in terms of storing carbon in biomass in 2100) compared to monoculture plantations (Lewis *et al.*, 2019). The large historic loss of soil carbon (about 20% to over 60% (Olsson *et al.*, 2019)) implies that agricultural soils, appropriately managed, have a significant future capacity to take up CO_2 from the atmosphere (e.g., 0.4-8.6 Gt $CO_2\ a^{-1}$ (Smith *et al.*, 2020)) and to store it in the form of soil carbon, potentially with a wide range of co-benefits in addition to climate change mitigation (Bossio *et al.*, 2020). There have also been a wide variety of blue carbon habitat restoration projects, but to date small-scale projects using the voluntary carbon market or alternative financing tend to be among the more successful outcomes (e.g., in mangrove swamps and seagrass meadows, see Wylie *et al.*, 2016).

Restoring already degraded wetlands can sequester carbon on a century scale, albeit at a very slow pace and possibly at the expense of increased CH_4 emissions (which will diminish but not necessarily eliminate their climate change mitigation potential), but with large potential to improve conditions for biodiversity (Hemes *et al.*, 2019; Meli *et al.*, 2014; Strassburg *et al.*, 2020). Ecosystem restoration also provides multiple nature´s contribution to people, such as the regulation of water quality, regulation of the hydrological cycle, decrease the frequency and severity of floods and droughts and pollination services (Chazdon & Brancalion, 2019; IPBES, 2018). Ecosystem restoration can also provide multiple social benefits, such as creation of jobs and income, but in order to avoid negative social outcomes, its implementation must follow proper culturally inclusive decision-making and implementation, in particular when affecting indigenous peoples' and local community lands (Reyes-Garcia *et al.*, 2019).

3.2.3 Manage

3.2.3.1 Climate- and biodiversity-friendly agricultural practices

Globally, the food system is responsible for a quarter of anthropogenic GHG emissions (IPCC, 2019), even up to one third if emissions arising from e.g., food processing, transport or storage are included (IPCC, 2019; Crippa *et al.*, 2021). There is potential to reduce emissions both on the supply-side and the demand-side (see below). Supply-side measures include improved cropland management (technical potential: 1.4-2.3 $GtCO_2e\ a^{-1}$; (Smith *et al.*, 2020)), grazing land management (technical potential: 1.4-1.8 $GtCO_2e\ a^{-1}$; (Smith *et al.*, 2020)), and livestock management (technical potential: 0.2-2.4 $GtCO_2e\ a^{-1}$; (Smith *et al.*, 2020)) which together reduce methane emissions from enteric fermentation, livestock manure, rice production and biomass burning, reduce nitrous oxide emissions from fertiliser production and application and livestock manure, and also create soil carbon sinks (Smith *et al.*, 2020). The impacts of these interventions on biodiversity are assessed to be neutral to (mostly) medium positive at various scales (Smith *et al.*, 2018; McElwee *et al.*, 2020). Another mitigation option is sustainable intensification (briefly defined as obtaining more yield from the same land area, while keeping the off-site environmental and social impacts low) with a technical potential >13 $GtCO_2e\ a^{-1}$; (Smith *et al.*, 2020)). Intensification can free land for biodiversity conservation, by sustainably increasing productivity per unit of agricultural area (Pretty *et al.*, 2018). Whist bioenergy has a large mitigation potential (technical potential: 0.4-11.3 $GtCO_2e\ ^{a-1}$; (Smith *et al.*, 2020)), the widespread cultivation of energy crops to provide CO_2 removal on several $GtCO_2e\ a^{-1}$ scale was assessed by Heck *et al.*, 2018 and McElwee *et al.*, 2020 to have negative impacts on biodiversity. However, at smaller scales, and when integrated into sustainably managed agricultural landscapes, the impact of energy crops on biodiversity could be neutral to (low) positive (McElwee *et al.*, 2020; Smith *et al.*, 2020).

3.2.3.2 Climate- and biodiversity-friendly forestry practices

Forestry has historically focused on optimizing the efficiency of commodity production, mostly of wood for timber, pulp, and fuel, and -like intensive agriculture or fisheries- has been criticised for negative environmental impacts such as depleting ecosystem carbon stocks (Olsson *et al.*, 2019; Puettmann *et al.*, 2015). Through species selection, and different management options during tree growth and harvest, foresters have the option to guard the carbon stock in biomass, dead organic matter, and soil – with additional large co-benefits if long-lived wood-based products support emissions reductions in other sectors through material substitution (Campioli *et al.*, 2015; Churkina *et al.*, 2020; Erb *et al.*, 2018; Luyssaert *et al.*, 2018; Nabuurs *et al.*, 2017; Wäldchen *et al.*, 2013). If adopted widely, preserving and enhancing carbon stocks in forests via locally adjusted sustainable management practices has the potential to mitigate 0.4–2.1 $GtCO_2$-eq a^{-1} (IPCC, 2019). These numbers may in some studies include -and in others not- estimates of mitigation potential from reducing forest degradation (see 3.2.1 and 3.2.2). Intensification of forest management schemes and associated fertilization may enhance productivity but would increase N_2O emissions and possibly have negative impacts on overall forest and aquatic biodiversity.

In some regions, climate change can provide net benefits to forests through lengthening the growing season (especially at high latitudes but see Housett *et al.* 2015) and CO_2 fertilization. However, climate change can also drastically reduce the mitigation potential of forests, due to an increase in extreme events like fires, insects and pathogens (Anderegg *et al.*, 2020; Seidl *et al.*, 2014). Adoption of measures such as reduced-impact logging or fire-control measures, together with (in formal mitigation projects) including carbon “buffer pools” to account for unintended carbon loss can help to address permanence risks (Anderegg *et al.*, 2020; Sasaki *et al.*, 2016). If planned carefully, forest management for climate change mitigation can be associated with a number of co-benefits for biodiversity conservation as well as regeneration (Mori *et al.*, 2017; Triviño *et al.*, 2017). In general, mixed-species forests should be maintained as they are likely to provide a wider range of benefits to society within the forest and for adjacent land uses. However, there are trade-offs between different benefits depending on the tree mixture and stand type involved (Brockerhoff *et al.*, 2017; IPCC, 2019).

3.2.3.3 Biodiversity-friendly fishing and aquaculture practices

The growth and increasing wealth of human populations forecasts a considerable need to produce more food from the ocean, but fishing is the main current driver of marine biodiversity decline (IPBES, 2019). Bottom trawling is particularly destructive, especially in deep water, from which biodiversity recovery may take decades (Clark *et al.*, 2016, 2019). Fishing driven reduction of ecosystem functionality can reduce blue carbon storage on the seabed but also re-expose buried blue carbon – both reducing climate mitigation potential (see Rogers *et al.*, 2020; Bax *et al.*, 2021). In addition, elimination of illegal, unregulated and unreported (IUU) fishing is critical to moving the fisheries sector to sustainability. Reducing overfishing and bycatch, as well as focusing new aquaculture activities on low trophic level species (e.g., plankton feeders such as bivalve molluscs) and broadening the range of species cultivated could both increase global seafood production and reduce impact to the environment and biodiversity (see also **Table 4.3 & 5.1.3**). Expanded cultivation of seaweed also offers biodiversity friendly possibilities for sequestering CO_2 and producing food.

3.3.3.4 Localisation of supply chains

The expansion of global trade has brought about an increase from 22 billion tonnes in 1970 to 70 billion tonnes in 2010 in global material extraction (including fossil fuels, biomass, metal ores, and non-metallic minerals) (UNEP *et al.*, 2016). Extraction rates are considered to be accelerating beyond sustainable levels (Bringezu, 2015). In 2011, carbon emissions embodied in trade accounted for 21%

of global emissions (OECD, 2019). Many of the industries in this global trade generate large amounts of GHG such as agriculture and mining with direct and indirect (such as deforestation) impacts on biodiversity and ecosystem integrity. Between 1990 and 2010, an average of 32.8 Mt CO_2e emissions were embodied in meat (beef, pork and chicken) traded internationally (Caro *et al.*, 2014), which brought important environmental and biodiversity costs to the country providing the goods (Galloway *et al.*, 2007). The same is true for agricultural trade (Balogh & Jámbor, 2020). About 30% of global species threats are associated with the international trade of commodities (Lenzen *et al.*, 2012). There are important opportunities for reducing emission in global trade, by moving into less carbon intense and more biodiversity-friendly practices (e.g., (Griscom *et al.*, 2017; Smith *et al.*, 2018). In particular, modifying the trade itself by providing incentives for the localization of supply chains and through the stipulation of higher environmental standards in the production of commodities to be traded among countries under free trade agreements (e.g., (Kehoe *et al.*, 2020)). Internationally adopted standards help to reduce the risk of generating countries that behave as “pollution heavens” with low level of environmental regulations and enforcements and specialized in the production of carbon intensive goods later exported to the rest of the world (OECD, 2019). Reconsidering supply chains is a key tool to help achieve global temperature rise limits (e.g., 1.5-2°C). Localizing food supply chains is important, mainly by reducing the GHG emissions caused by transportation and by building resilience to large scale disasters (Clark *et al.*, 2020). However, practices such as just-in-time inventory can lead to frequent transport and more GHG emission (Ugarte *et al.*, 2016).

3.2.3.5 Changes in consumption

Meat and dairy are responsible for 58% of GHG emissions from the global food system (IPCC, 2019) and half of these emissions are due to cattle and sheep alone (Poore & Nemecek, 2018). One third of all cereals grown in the world are used to feed livestock rather than humans (Mottet *et al.*, 2017). Animal agriculture is a major driver of deforestation and biodiversity decline (Crist *et al.*, 2017). Ruminant meat has 10-100 times the climate impact of plant-based foods (Clark & Tilman, 2017; Poore & Nemecek, 2018) with a similarly greater adverse impact on land, water and energy use, and indicators of air and water quality. A third of all the food produced globally is lost or wasted (Alexander *et al.*, 2017). Demand-side measures encouraging reduced food loss and waste (technical potential: 0.8-4.5 $GtCO_2e\ a^{-1}$ (Smith *et al.*, 2020); and dietary shifts, toward diets including more plant-based foods and less meat and dairy (technical potential: 0.7-8 $GtCO_2e\ a^{-1}$; (Smith *et al.*, 2020)), have significant potential for climate change mitigation, as well as reducing the pressure on land that drives biodiversity loss (Roe *et al.*, 2019). Large environmental and human well-being co-benefits arise, if dietary shifts have a strong focus on achieving globally larger equity in health (Clark & Tilman, 2017), leading to a redistribution in consumption that reduces undernutrition as well as wasteful consumption, overweightness and obesity. The land freed by reducing the need to produce animal feed globally greatly enhances the potential to use it for nature-based solutions that benefit climate change and biodiversity alike (Seddon *et al.*, 2020).

3.2.4 Create

3.2.4.1 Urban greening and biodiversity support

Cities play a role in the conservation of global biodiversity, particularly through the planning and management of urban green spaces (UGS) (Aronson *et al.*, 2017). UGS and biodiversity protection increase carbon uptake (De la Sota *et al.*, 2019) and deliver cooling effects that indirectly lead to reduced energy consumption (Alves *et al.*, 2019). They also reduce air pollution, maintain health, reduce flooding, sand and dust, and assist in adapting to climate change (Capotorti *et al.*, 2019; Carrus *et al.*, 2015). Although UGS research is recent (Aronson *et al.*, 2017), urban greening has played a key role in most adaptation strategies (Butt *et al.*, 2018) (see Section 4.4). In densely populated cities planting of trees has a larger potential to reduce heat impacts than green roofs, because of shade provisioning (Zolch *et al.*, 2016). Carbon sequestration and storage in urban trees and gardens varies considerably between cities and location. UGS can contribute in a meaningful way to mitigating cities’ GHG emissions, provide a local cooling effect or be co-beneficial to a cities’ population food supply (Bellezoni *et al.*, 2021). It is thus both possible and necessary to rationally design and manage UGS and biodiversity in combination with adaptation and/or mitigation measures (Butt *et al.*, 2018; Sharifi, 2021) (see Sections 4.4, 5.1.2).

3.2.4.2 Trophic rewilding

Trophic rewilding, the reintroduction of herbivores and carnivores to systems where they have been lost, is foremost discussed as a measure to enhance biodiversity (see Section 5.1.2.6) and can also contribute to ecosystem restoration (3.2.2). Some recent analysis have discussed the impact of rewilding on ecosystem carbon cycling and hence climate change mitigation, given the effects animals and trophic cascades have on biomass consumption, carbon turnover, or methane emissions (Schmitz *et al.*, 2018; Tanentzap & Coomes, 2012). Reindeer grazing could, for instance, reduce shrub encroachment into tundra ecosystems, help to maintain high snow albedo and to reduce otherwise positive climate feedbacks in boreal regions (Schmitz *et al.*, 2018). Likewise in tropical forest, disturbance through "ecosystem engineers" such as elephants has been found in model simulations to result in changes to the forest canopy that led to increased aboveground carbon storage (Berzaghi *et al.*, 2019). In other regions, however, trophic rewilding could also diminish carbon storage (Schmitz *et al.*, 2018). The existing body of literature indicates that climate change mitigation considerations (supporting or reducing mitigation potential) be brought into rewilding initiatives, and -in some regions- provide additional positive stimulus to biodiversity conservation (Section 5.1.1).

3.2.4.3 Combined technology and nature-based mitigation options

Because of the many challenges related to climate change mitigation measures demanding large land areas (see 3.2.1, 3.2.2), the concept of technological-ecological synergies (TES) has begun to emerge as an integrated systems-approach that recognizes the potential co-benefits that exist in combining technological and nature-based solutions (Hernandez *et al.*, 2019). So far it has been applied mostly in the solar-energy sector (Hernandez *et al.*, 2019; Liu *et al.*, 2020; Schindele *et al.*, 2020). Example strategies include, for instance, to preferentially employ solar panels on contaminated lands that would otherwise be extremely costly to restore, to utilize transpiration of vegetation underneath solar panels to cool the panels, or -combined with appropriate grazing regimes- to enhance soil carbon stocks under solar panels (Hernandez *et al.*, 2019). For the US, the planned placement of solar developments >= 1 MW could benefit 3500 km^2 of nearby cropland if vegetation underneath the solar panels can provide pollinator habitat (Walston *et al.*, 2018). Floatovoltaics, solar photovoltaic cells supported on the surface of water bodies, have been demonstrated to reduce evaporation from the water bodies and are being discussed as promising options especially when applied to hydroelectric reservoirs in arid regions. Little is understood of the impacts of floatovoltaics on the hosting water body's physical, chemical and biological properties (Armstrong *et al.*, 2020).

3.2.4.4 Mitigation opportunities on newly emerging habitats

Ice and snow retreat at high latitudes and altitudes changes the surface albedo to darker, more heat absorbing levels. In addition, permafrost thawing can release substantial volumes of methane. These processes have a large potential to amplify climate change. However, there are potentially new habitats emerging from the snow and ice that can yield both mitigation and biodiversity benefits, if appropriately managed. The biodiversity benefits of new habitat creation have been widely seen at small spatial scales, either through anthropogenic structures (e.g., artificial reefs) or in naturally emerging volcanic islands. The potential climate mitigation benefits of novel habitats have only recently been explored. Snow and ice retreat in the subarctic (and subantarctic), exposing tundra and taiga, not only increased heat absorption, but also enhanced growth and carbon capture and storage (Housset *et al.*, 2015). This terrestrial negative feedback to the climate is dwarfed by the adjacent marine ice losses (less extent in time and space of the seasonal sea surface freezing), which effectively creates new polar continental shelf habitat across millions of km^2, doubling seabed carbon stocks in 25 years (Barnes *et al.*, 2018). Hundreds of fjords have become exposed by glacier retreat, and massive coastal embayments are emerging as a result of giant iceberg breakout from ice shelves. New and intense phytoplankton blooms have established in these new habitats (Peck *et al.*, 2010) followed by colonization of the seabed (Fillinger *et al.*, 2013). The climate mitigation potential of these new habitats is driving urgent calls for their protection, for instance from fishing (Bax *et al.*, 2021) and see Section 5). The considerable associated biodiversity benefits clearly go hand-in-hand, especially considering the very high endemism and richness. Marine ice loss in the Arctic has many consequences in addition to these. The net outcome of changes in primary production in open Arctic waters, loss of benthic production from under-ice algae, loss of pagophilic (ice-dependent) species and lower albedo is as yet unclear so we cannot yet reach any clear conclusions on Arctic mitigation potential (Rogers *et al.*, 2020).

3.3 THE PARIS AGREEMENT AND THE CBD POST-2020 GLOBAL BIODIVERSITY FRAMEWORK

3.3.1 Acknowledging the trade-offs

By 2050, in 1.5°C pathways, renewable energies (including bioenergy, hydro, wind, and solar) are expected to supply 52–67% (interquartile range) of primary energy. As food demand is projected to increase substantially and with the land area already today under large exploitation-pressures, conversion of areas equivalent to about one third of today's food crop area or 10-15% of today's forest area for mitigation purposes (Rogelj *et al.*, 2018) would potentially jeopardise existing land- or marine-area related biodiversity conservation measures (Fuss *et al.*, 2018; Hof *et al.*, 2018; Veldkamp *et al.*, 2020). It would also further aggravate hunger and the loss of nature's contributions to people contributing to the delivery of SDGs (IPCC, 2019; Fuss *et al.*, 2018; IPBES, 2019). These results are particularly pertinent in the light of studies that have raised doubts on whether the projected cumulative carbon uptake on land at the massive scales proposed could, in fact, be achieved (Harper *et al.*, 2018). The expected large mitigation contributions by various renewable energy sources and/or land and marine management highlight the profound challenges for sustainable management of demands on land and in the ocean (IPCC, 2019).

Both land- and ocean-based mitigation activities can contribute to limiting warming to 1.5°C or 2°C, including 'traditional' nature-based solutions but also by providing space for technical infrastructure (and the combination of the two). As seen in the previous sections, trade-offs and compromises are inevitable and require management for carbon uptake as well as energy mixes that minimize net environmental damage associated with addressing mitigation-related biodiversity and adaptation impacts (Rehbein *et al.*, 2020) (Sections 4, 5). Given the current over-exploitation of land and marine ecosystems, there is a clear need for transformative change in the land and ocean management, and food and energy production sectors to achieve these mitigation potentials and capitalise on their climate change adaptation and biodiversity conservation co-benefits.

3.3.2 Combinations of measures that are locally adjusted and societally accepted

Better alignment and fulfilment of the Paris Agreement commitments with CBD post-2020 global biodiversity framework goals and targets and UN SDGs is essential to bring about social and economic transformations in order to achieve quality of life in parallel with nature (see Section 6.1.4., 7.2). Approaches that are multi-pronged and emphasize decarbonization of economies and the energy sector in the short term, as well as implementing nature-based solutions that have strong capacity to sequester carbon as well as bringing benefits for local communities, have a better chance of success (Seddon *et al.*, 2020). Though these options are time limited for mitigation because biological sinks saturate (see **Box in Section 1**), nature-based solutions can provide significant mitigation potential this century (see **Table 3.1**) if accompanied by the essential reductions in fossil fuel emissions. In published global assessments of mitigation potential, the fundamental context-specific interactions, opportunities and limits arising from a specific location (such as ecosystem type, local governance or the mix of decision-making actors) thus far have not be accounted for but are important when implementing mitigation measures "on the ground" (Smith *et al.*, 2020; Griscom *et al.*, 2017).

On land, five options with large mitigation potential (>3 Gt CO_2eq a^{-1}) and five with moderate potential (0.3-3 Gt CO_2eq a^{-1}) have been identified in the IPCC SRCCL, with no or only little adverse impacts on other land challenges such as food security or adaptation (McElwee *et al.*, 2020; Roe *et al.*, 2019; Smith *et al.*, 2020) (see **Table 3.1**). These options combine the carbon uptake potential from avoided conversion of natural land, restoration, enhancing yields through sustainably managing agricultural and forest lands, as well as reducing post-harvest losses. From a yield-biodiversity-carbon uptake co-benefit perspective, agroforestry practices are often considered an important win:win:win measure (Nunez *et al.*, 2019). Likewise, by 2050 carbon taken up and stored in coastal and marine ecosystems and seabeds could contribute an additional >3 Gt CO_2e a^{-1}, while 5.4 Gt CO_2e a^{-1} are estimated to be supplied from different ocean-based renewable energy such as offshore wind or tidal energy (Hoegh-Guldberg *et al.*, 2019).

Positive synergies are possible when combining measures that act on the supply as well as demand side, for instance adjusting diets towards an overall healthy and equitable animal protein intake, reducing food waste, and measures to reduce expansion or over-intensification in agriculture and fisheries. One particular challenge when assessing the sustainable land and marine mitigation potentials is that potentials for individual practices cannot be simply summed to a global total, since response options implemented at local or at regional scales likely lead to different outcomes and because of how different measures interact with each other either in same locations or through displacement effects (Smith *et al.*, 2020; Griscom *et al.*, 2017). There is also increasing recognition that restoration and management of restored ecosystems will need to be dynamically adapted in response to ongoing and unavoidable changes (Arneth *et al.*, 2020; Seddon *et al.*, 2020; Donatti *et al.*, 2019; Morecroft *et al.*, 2019) (Section 4). In face of climate change, restoration will be much about managing change, a return to a historical state of many indicators will be hard or impossible to achieve.

3.3.3 Social issues and the 'securitizing' of climate change

NbS by definition provide co-benefits to biodiversity as well as for local communities, promoting improvements in quality of life and governance through changes that are locally adjusted and socially accepted, especially in urban environments (Frantzeskaki *et al.*, 2019; Tozer *et al.*, 2020; UNDP, 2020). Realizing the full potential of NbS, including their social co-benefits, requires fast action towards abating emissions and limiting warming, since warming itself affects the effectiveness of NbS in the mid-term (Seddon *et al.*, 2020). Strong incentives, such as an attractive carbon price and the unlocking of Article 6 of the Paris Agreement to create international carbon markets based on additionality and increased ambition, are key to achieving this fast transformation. But to make such actions sustainable will require changes in the way we relate to ourselves and the rest of nature (e.g., Callicott, 2013; Haraway, 2016; UNDP, 2020). Building what has been dubbed a “Nature-based human development” (UNDP, 2020) can be supported by aligning the best natural science with the best social science, arts, humanities, and diplomacy (Section 6).

There is an increasing realization that climate change is a global security issue with potential to lead to social unrest, forced migration, and displacement of populations especially of less developed countries (Hoffmann *et al.*, 2020; UNDP, 2020). This can be an important driver for international multilateralism and cooperation and an increased ambition in the framing of measures such as the NDCs (Nationally Determined Contributions) to reduce emissions and adapt to impacts of climate change; https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs. This ‘securitization’ of climate change, however, can backfire and lead to negative consequences, such as leading to fatalism, scepticism and inaction (Warner & Boas, 2019), disincentivising international cooperation and the adoption of nature-based solutions, especially if this securitization goes along with a communication strategy that tries to increase the sense of urgency appealing to fear, guilt, or shame (Moser, 2007; De Witt & Hedlund, 2017). To adequately communicate what science knows about climate change, its impacts on biodiversity and the earth system, and to catalyse urgent actions in people and governments without overwhelming and paralyzing them is a complex issue (Moser, 2010). Among other considerations it is critical that statements regarding impacts of climate change capture uncertainty in projections (Bradshaw & Borchers, 2000), thus leading to actionable futures instead of inaction and fatalism. Recognising that a broad set of people’s values regarding material and non-material benefits from nature underpin motivation to change (Sections 6, 7). A good example is by granting access rights to local populations exploiting common pool resources, such as small scale fisheries (Wilen *et al.*, 2012) as with granting access to ancestral lands for indigenous groups. These social changes can increase sustainable management, improve biodiversity and the carbon capture and storage capacity of ecosystems (e.g., Herrmann, 2006; Díaz *et al.*, 2018; Köhler *et al.*, 2019; Gelcich *et al.*, 2019; Fa *et al.*, 2020). They do so by reinforcing the sense of and the relationship with place, wherein lies the foundation for cultural practices through which environmental change is experienced, understood, resisted, and responded to (Ford *et al.*, 2020).

3.3.4 Good environment stewardship practices are dynamic

The outcomes of coupled climate-biodiversity-human systems are hard to predict. Even in a relatively simple system, such as the Southern Ocean with short food chains and few direct anthropogenic stressors, best environmental practice can be difficult to discern (Rogers *et al.*, 2020). Species have widely varying levels of thermal sensitivity but many at high latitude or altitude are stenothermal, so they must shift range to maintain temperature envelopes. However, zones of marine management or protection usually have fixed geographic or bathymetric boundaries. Thus, effectiveness of stewardship practices (see Section 2) will see changing climate mitigation and biodiversity yields unless management boundaries can flex with temperature. The West Antarctic Peninsula (WAP) may be an early warning sign of this. Less than 1°C of surface water warming there has sustained strong marine ice losses, both increasing and decreasing carbon capture in places and range shifting some species but not others (Montes-Hugo *et al.*, 2009; Rogers *et al.*, 2020). Such moderate (1°C) surface water warming can increase growth amongst polar benthos; life on WAP seabed now sequestrates 4 $GtCO_2e$ a^{-1} (Barnes, 2017) but in contrast there have been decrease in carbon stored in life on the Weddell seabed (Pineda-Metz *et al.*, 2020). There is evidence that more severe warming is complicated and has unpredictable effects on species (Ashton *et al.*, 2017).

Both at sea and on land, adopting dynamic approaches to conservation, rather than static goals, will allow flexible responses and leverage biodiversity’s capacity to contribute to climate-change mitigation and adaptation. In face of climate change, conservation will be about managing the change, since a return to the historical state will be impossible to achieve (Arneth *et al.*, 2020) (see also Sections 4-7).

SE

CTION 4

Biodiversity and adaptation to climate change

SECTION 4

Biodiversity and adaptation to climate change

4.1 OVERVIEW

The aims of Section 4 are to highlight the capacity and limits of socioecological systems to adapt to climate change, examine the role of biodiversity in contributing to adaptation and evaluate the impacts of a wide range of climate change adaptation measures on biodiversity. This section specifically addresses ecological adaptation that occurs without human intervention, human-led adaptation in natural systems where interventions are intended to enhance ecological adaptive capacity and adaptation in human-dominated systems including urban systems (see **Box 4.1**).

Global temperatures have already risen by about 1°C since the beginning of the 20th century and are almost certain to rise another 0.5 to 1.0°C by 2050, even under extremely ambitious climate mitigation scenarios (IPCC, 2019a). Biological and human systems often have substantial capacity to adapt to changing climate, but the speed and magnitude of contemporary climate change may greatly exceed these capacities and thereby create high risks for nature and people, especially under moderate to high greenhouse gas emissions scenarios (Arneth *et al.*, 2020; IPBES, 2019; IPCC, 2019a; Morecroft *et al.*, 2019). It is therefore crucial that adaptation to climate change is not seen as a substitute for strong climate mitigation. Exceeding the adaptive capacity of ecosystems imperils their ability to contribute to attenuating climate change, leading to even greater climate change (IPCC, 2019a; Morecroft *et al.*, 2019).

Dealing with inevitable climate change requires an understanding of the objectives of adaptation measures, capacities and limits to adaptation, and interventions that are intended to enhance adaptive capacity (IPCC, 2019a, **Figure 4.1**; IPBES, 2019). The objectives of climate adaption can range from maintaining the system as is, to allowing for autonomous adaptation, to facilitating transformation **(Figure 4.1)**. The choice of objectives, and the measures that are implemented to achieve them, depends on the interactions between underlying values as well as the levers and barriers to adaptation (Secretariat of the Convention on Biological Diversity, 2009, **Figure 4.1**; Colloff *et al.*, 2017; van Valkengoed & Steg, 2019, **Figure 4.1**). Adaptation measures can range from narrowly defined interventions that focus on addressing the impacts exclusively associated with climate change, to reducing non-climatic stressors that make ecosystems and people vulnerable to much broader actions designed to build robust systems for problem solving (McGray *et al.*, 2007; Klein, 2011). The primary focus of Section 4 is on adaptation measures that directly address climate change impacts, with an emphasis on measures that are intended to avoid the degradation of regulating and material nature's contributions to people (NCP) sensu (Díaz *et al.*, 2018) (also known as regulating and provisioning ecosystem services). Non-material NCP and cultural contexts (sensu Díaz *et al.*, 2018, equivalent to cultural services and intrinsic values of nature in earlier terminology) are also treated, but less extensively.

Interventions to enhance climate adaptation may focus on nature-based solutions (NbS), technical and technological solutions, or social and institutional solutions alone or in combination (**Figure 4.1**, **Box 4.1**, Secretariat of the Convention on Biological Diversity, 2009; Berry *et al.*, 2014; Sharifi, 2021). This section emphasizes the differences in these measures because they reflect distinct socioecological and sociotechnical perspectives and often have radically different impacts on biodiversity (Secretariat of the Convention on Biological Diversity, 2009; Berry *et al.*, 2014). In most cases, there are choices between multiple measures to achieve similar adaptation goals (Berry *et al.*, 2014; Morris *et al.*, 2020; Seddon *et al.*, 2020). These measures may be synergistic or conflicting; for example, nature-based solutions such as stabilizing dunes with vegetation and hard structures such as seawalls to adapt to sea-level rise can be complementary but are often seen as conflicting due in part to overreliance on engineered ('hard') structures (Morris *et al.*, 2020, Section 4.4.2).

The distinction between adaptation and mitigation measures is not always clear cut (Berry *et al.*, 2014; IPCC, 2019a; Sharifi, 2021; Smale *et al.*, 2019; Smith *et al.*, 2019). In some cases, measures that improve adaptive capacity can also contribute to climate mitigation and vice versa. For example, soil conservation practices can increase soil carbon sequestration and make soils more resilient to climate change (see Section 4.4.1). In other cases, mitigation and adaptation strategies may be in conflict. The interactions between climate mitigation and adaptation creates some overlap between Sections 3 and

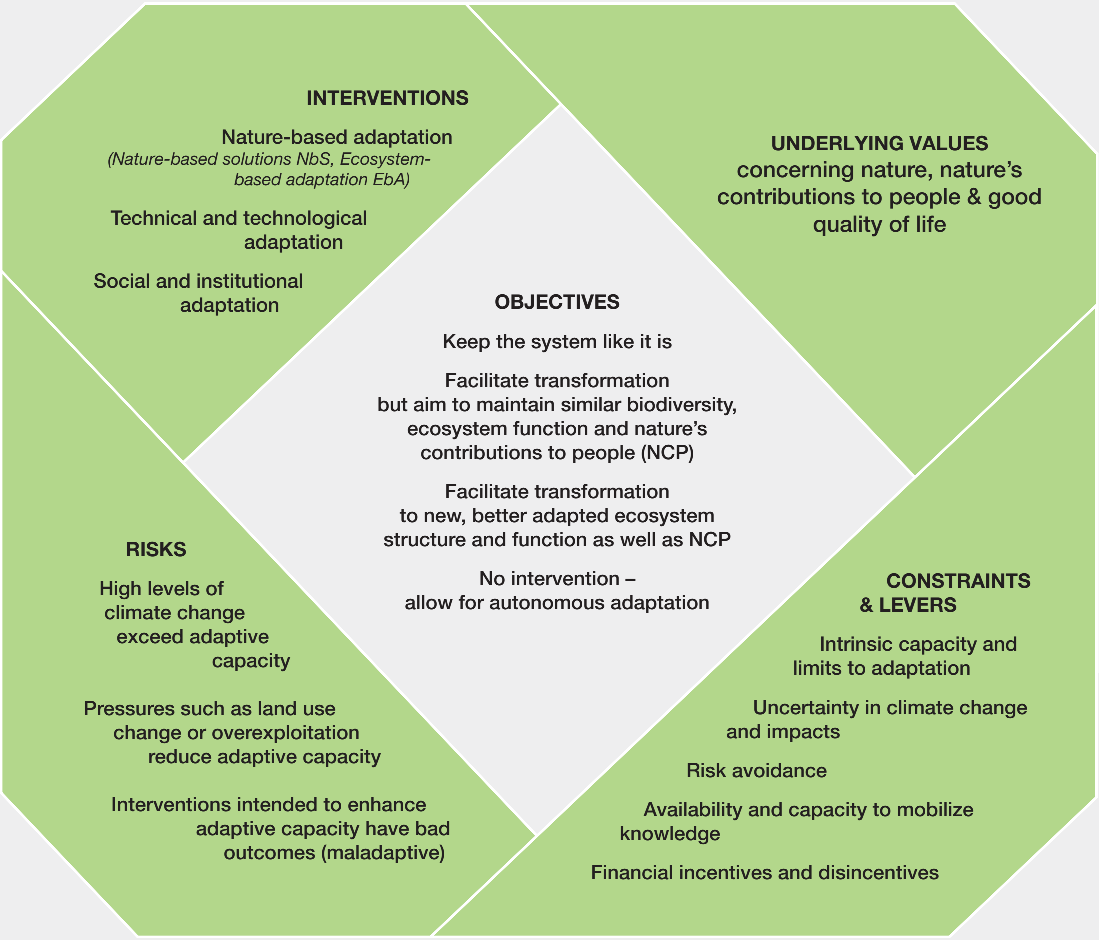

Figure 4 1 **Elements that play a role in setting objectives and types of interventions for climate adaptation, as well as evaluation of the associated risks.**

4: this section focuses on adaptation aspects. The need to better integrate climate mitigation, climate adaptation and biodiversity protection and restoration measures are discussed in greater detail in Sections 6 and 7.

Adaptation measures can lead to maladaptation – even when seemingly well-conceived (Gaitán-Espitia & Hobday, 2021; IPCC, 2019a; Morecroft *et al.*, 2019). Climate change and its impacts on ecosystems and society have high uncertainty, with some aspects that have much higher uncertainty than others; for example, regional precipitation projections have much more uncertainty than projections of global temperature rise (IPCC, 2014a). Adaptive measures that do not account for these uncertainties may turn out to be maladaptive; for example, planting drought resistant trees to anticipate increased water stress can be counterproductive if projected changes in water stress turn out to be wrong or if drought resistant trees have unintended side effects on nature and nature's contributions to people (Morecroft *et al.*, 2019, Section 4.4.1).

High uncertainty in climate change, climate change impacts and effects of adaptation measures requires a greater focus on risk management and adaptive management than is currently implemented in many climate adaptation strategies (Kundzewicz *et al.*, 2018; Sharifi, 2021; Stafford-Smith *et al.*, 2011). This means implementing management strategies that leave options open to change strategies as conditions and understanding evolves over time (Arneth *et al.*, 2020; Kundzewicz *et al.*, 2018; Terando *et al.*, 2020). Risk management to cope with uncertainty in future climates can greatly benefit biodiversity and vice versa (Seddon *et al.*, 2020). Spreading risk, for example through a diversification of crop rotations, genetic variety of crops, or variety of tree species, can make social-ecological systems more resilient to climate change and increase species and habitat diversity (see Section 4.4.1). Current economic incentives, for example in agriculture and forestry, frequently do not promote such diversification and fail to reflect the multiple facets of nature that contribute to good quality of life (see Section 4.4.1).

Box ④ ① Definitions of adaptation.

"Adaptation" has well-developed and widely accepted definitions, reflecting its many facets. The IPBES and IPCC definitions are similar:

- IPBES[1] defines adaptation as *"Adjustment in natural or human systems to a new or changing environment, whether through genetic or behavioural change."*
- The IPCC[2] AR5 glossary defines adaptation as *"The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects."*

This report generally refers to the narrower definition of IPCC focusing on adaptation to climate, but also uses the IPBES definition when referring to adaptation to other pressures. For this report we have adopted the IPBES and IPCC distinctions between adaptation in human and natural systems, as well as between ecological adaptation and human-led adaptation in natural systems.

Ecological adaptation is unplanned and unmanaged change in natural systems that improves resilience and maintains functioning in the face of changing pressures. At species-level, this includes behavioural change, physiological adaptation, range shifts, and evolutionary change (Whitney et al., 2017). At the level of ecological communities, this manifests as changes in relative abundance species, for example changes in the abundance of cool and warm-affinity species in response to climate change. Such changes have consequences for nature's contributions to people.

Human-led adaptation is human intervention that protects natural systems and changes managed systems to improve their own resilience and the services they deliver. One way to achieve such adaptation is to develop nature-based solutions (NbS)[3] "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits".

Adaptation actions with biodiversity consequences result from adjustment to climate change in human systems that have impacts on biodiversity. This kind of adaptation is generally associated with human actions designed to adapt to climate-related changes in physical conditions, such as coastal defence construction to counter sea-level rise, or irrigation schemes to respond to precipitation change.

NOTES:

1. IPBES https://ipbes.net/glossary
2. IPCC AR5 WGII Glossary https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_Annexes.pdf
3. IUCN https://www.iucn.org/theme/nature-based-solutions/resources/iucn-global-standard-nbs

4.2 HUMAN AND SOCIAL DIMENSIONS

Culture results from the interplay and continuous adaptation of human populations and natural resources, expressing people's attitudes towards and beliefs in other forms of life. At a fundamental level, biological and cultural diversities are closely interdependent and have developed over time through co-evolutionary processes. Human populations adapt to challenges imposed by climate change on ecosystems in particularly different ways by different cultures rooted in a time and place (Adger *et al.*, 2017; Martins & Gasalla, 2020). Culture also plays an important role in mediating human responses to environmental change (Heyd & Brooks, 2009). In general terms, contemporary adaptation measures, especially nature-based options, can contribute to sustainable development goals, racial, gender and environmental justice, pandemics prevention and recovery. The implementation of adaptive measures creates winners and losers in society and therefore issues of social justice and power relationships are at play.

Climate justice recognizes responsibility for the impacts on the poorest and most vulnerable people by critically addressing inequality and promoting transformative approaches to address the root causes of climate change (Jafry, 2018). Human rights issues, threatening livelihoods, development and security are part of the urgent and critical considerations to adapt to climate change. This includes furthering the discourse on safeguarding the rights of the most vulnerable people and on ensuring equitable and fair sharing of the burdens and benefits of climate change and its impacts. The role of community-led solutions, knowledge sharing and empowerment for local action are proved to be essential.

Over the past few years, a range of pathways that examine how global society, demographics and economics might change over the next century have been described by interdisciplinary teams of scientists tasked with developing global socioeconomic scenarios of change. The so-called Shared Socioeconomic Pathways (SSP) consider five different situations to explore how societal choices will affect greenhouse gas emissions and, therefore, the degree and pathway by which climate goals could be met (Riahi *et al.*, 2017). It is clear that adaptation would be most challenging under the SSP3 (Regional Rivalry) and SSP4 (Inequality) scenarios. The risks of maladaptation seem to be inequitably distributed geographically across all scenarios (Chaplin-Kramer *et al.*, 2019). People in Africa, South Asia and the Americas are most at risk from diminishing NCP. The number of people at risk is reduced 3 to 10-fold under scenarios more closely aligned to Sustainable Development Goals.

As COVID-19 ravages the global economy, some parallels can be made with climate adaptation. Firstly, it brings to the fore the exacerbated vulnerabilities to the lives and livelihoods of the already marginalized. Secondly, climate change affects the social and environmental determinants of health through essential requirements like clean air, safe drinking water, sufficient food and secure shelter. Between 2030 and 2050, climate change is expected to cause approximately 250 000 additional deaths per year, from malnutrition, malaria, dengue (and other vector-borne diseases), diarrhoea and heat stress. The direct damage costs to health (i.e., excluding costs in health- determining sectors such as agriculture and water and sanitation), is estimated to be between USD 2-4 billion/year by 2030. Areas with weak health infrastructure – mostly in developing countries – will be the least able to cope without assistance to prepare and respond. The key role of adaptation in addressing these pressing issues should be further explored. Climate-induced deaths should be avoided by all available means.

The willingness of different actors to implement adaptive measures depends on many factors such as knowledge on risks, evaluation of risks, costs of adaptive measures, institutional support, and social organization. Social, institutional and technological lock-ins can slow or prevent adaptation, while some aspects of transformational change could facilitate adaptation. Adaptive activities often consist of a combination of 'top-down' policies and 'bottom-up' or community-led solutions.

Climate-driven shifts in species ranges may interfere with human adaptation strategies, e.g., returning from monoculture plantations to natural ecosystems may need different species than were present previously. The acceptability of many adaptive measures is contested among scientists, decision makers and the society at large. Examples include allowing for ecosystem change (the emergence of "novel ecosystems") versus trying to maintain historical ecosystem structure and function; assisted migration of species; allowing for colonization by non-local species (including invasive alien species); and abandoning conservation of species especially "doomed" by climate change.

Ethical behaviour with respect to nature ("geoethics") is at the core of several discussions regarding adaptation. The values which underpin appropriate behaviours and practices wherever human activities interact with the Earth system play an important role in the awareness of society regarding problems with biodiversity and NCP. Ethical, social, and cultural implications of both scientific knowledge and humankind's role as an active geological force on the planet and the ethical responsibility that this implies need to be addressed in every plan of action (Bobrowsky *et al.*, 2017). This includes equity issues linked to biodiversity-related interventions. These are often not distributionally neutral and have equity implications both within and between generations.

Considering community-led solutions, several factors seem to increase adaptive capacity, and management that maintains and builds resilience of natural systems. Adaptive capacity depends upon the availability of natural, human, social, physical, financial and institutional resources, as can be measured as the ability people have to convert these resources into useful adaptation strategies (Brooks & Adger, 2005; Folke *et al.*, 2005; Smit & Wandel, 2006). The flexibility component (personal, occupational, and institutional) adds to the measure of the potential of people and institutions to overcome their present situation and deal with future conditions (Marshall, 2010). Overall, community self-organization, leadership, partnership with research and diversification are major drivers reducing vulnerability and increasing the adaptive capacity (Martins & Gasalla, 2020).

Successful adaptation policies tend to emphasize:

- Incentives to empowering communities to adapt, including the protection of indigenous cultural values
- Education efforts and improved equity in access to knowledge
- Policy-oriented plans of action (adaptation plans) at the different local scales

The limits of human adaptation, both in absolute and in rate terms, is dependent on the degree to which we are able to maintain resilient ecosystems. Unless sufficient climate mitigation is achieved to allow us to stay within an adaptive range, then those limits will be breached. The adaptive space shrinks if we fail to protect biodiversity. Thus, human adaptation is partly constrained by the evolutionary adaptation limits of species and ecosystems.

4.3 CONSTRAINTS AND LIMITS TO ADAPTATION OF SPECIES AND ECOSYSTEMS

Species can respond to climate change through physiological, behavioural and genetic adaptation or by moving to remain in favourable climates (Arneth *et al.*, 2020; Bellard *et al.*, 2012). Most species that have been studied have moved in response to 20th century warming, in some cases more than 100 km over the last few decades (IPCC, 2014a; Lenoir *et al.*, 2020). However, many species ranges have failed to move fast enough to track favourable climates, in part because rates of climate change exceed the capacity of many species to move and in part due to human created impediments to movement such as habitat fragmentation (Lenoir *et al.*, 2020; Settele *et al.*, 2014). In cases where they cannot track favourable climates, species will go locally or globally extinct unless they adapt (Arneth *et al.*, 2020). Based on modelling studies there is considerable concern that even climate change of 2°C will greatly increase the risk of global extinction for many species because they cannot move fast enough or because there will be little or no remaining areas with favourable climates (IPBES, 2019; IPCC, 2018). The vast majority of these models do not, however, account for important mechanisms of adaptation (Razgour *et al.*, 2019; Settele *et al.*, 2014). Substantial capacity for physiological, behavioural and genetic adaptation has been demonstrated for a few species, especially species with rapid life cycles (Gaitán-Espitia & Hobday, 2021), but the capacities and limits to adaptation for the vast majority of species are not well known due to lack of sufficient data (Urban *et al.*, 2016; IPBES, 2019; Razgour *et al.*, 2019).

People can help species and ecosystems to adapt to climate change in a variety of ways. Most importantly, adaptation can be substantially improved by slowing the rate, as well as the ultimate degree of climate change (Arneth *et al.*, 2020; Lenton *et al.*, 2019). Adaptation can also be greatly facilitated by reducing non-climate stressors. Actions like reducing pollution, making sure that exploitation is at levels that allow for resistance and resilience and managing invasive alien species can make substantial contributions to adaptive capacity of species and ecosystems (IPBES, 2019; IPCC, 2014a). Nature-based approaches to climate adaptation have been promoted for most types of ecosystems and focus on risk spreading and promotion of ecological adaptation processes (Gaitán-Espitia & Hobday, 2021). Other specific actions that are common across many species and ecosystems include assisted migration, where people help species to track favourable climates (Thomas, 2020); selection of genotypes that are adapted to projected future climates for use in intensively managed ecosystems like in agriculture, aquaculture and some forests (see Section 4.4.1) and by restoring and re-creating habitats, possibly in the direction of species movement (P. Berry *et al.*, 2013). These actions are not without risks since there is high uncertainty in future climate projections and because the introduction of novel species or genotypes (especially genetically modified organisms) may have unforeseen negative effects on other species or ecosystem dynamics (Gaitán-Espitia & Hobday, 2021; Librán-Embid *et al.*, 2020; Morecroft *et al.*, 2019).

Ecosystem adaptation is much less well defined than adaptation at the species level. This is partly because ecosystems are always in a state of flux in terms of structure (for example, the identity of species present and their abundance) and function (for example, water, nutrient and carbon fluxes). The result is a wide range of perspectives on adaptation objectives and the most suitable interventions to enhance ecosystem adaptation to climate change (Morecroft *et al.*, 2019). At one extreme, the objective of interventions can be to maintain ecosystem structure, function and services close to the current state. Many consider this an unrealistic goal given the observed and projected changes in all ecosystems due to rising atmospheric CO_2 concentrations and climate change (Arneth *et al.*, 2020). At the other extreme is the perspective that substantial ecosystem change is inevitable and therefore aggressive adaptation measures should focus on anticipating and facilitating these changes (Morecroft *et al.*, 2019; Thomas, 2020). Another perspective is to avoid “regime shifts” that result in major changes in ecosystem structure or degradation of ecosystem function and nature’s contributions to people (IPBES, 2019; Morecroft *et al.*, 2019; Staal *et al.*, 2020). Two examples illustrate the differences in these perspectives. Forest management in the face of climate change can focus on measures to preserve current plant communities, especially tree species, versus replacing vulnerable species with climate change tolerant tree species, versus converting forests to other types of ecosystems such as short rotation coppice (see Section 4.4.1). Likewise, coral reef management in the face of climate change can focus on efforts to maintain current hard coral species communities, versus introducing new heat tolerant hard coral species, versus managing for a shift to non-hard coral dominated communities (see Section 4.4.3). These approaches to enhancing adaptation can be contradictory but are not always mutually exclusive (Morecroft *et al.*, 2019).

Actions to enhance adaptive capacity can be reinforced by improved monitoring and detection and risk assessment. To be effective in a context of change and uncertainty, actions have themselves to be adaptive. The appropriate governance is based on the implementation of dynamic adaptation plans (Arneth *et al.*, 2020). This may include new arrangements for cooperation, improving innovation and coordination across sectors and governance scales, improving communication and reinforcing international cooperation.

4.4 KEY SYSTEMS AND SECTORS

4.4.1 Terrestrial

4.4.1.1 Forests and forestry

Biome models and Dynamic Global Vegetation Models (DGVMs) project fundamental, large-scale shifts in the global distribution of forest types during the 21st century, as a consequence of climate change. For temperature-limited forests, poleward and upward (in elevation) shifts are consistently predicted across models and scenarios (Settele *et al.*, 2014). Such shifts might be beneficial for nature's contributions to people (NCP) delivered by the forest systems that gain new habitat, but they endanger species and NCP that depend on non-forested mountain or tundra habitats (Settele *et al.*, 2014). In the mid- and lower latitudes, where water availability is a more important driver, the results from different models diverge more, which implies large uncertainty (Settele *et al.*, 2014; Martens *et al.*, 2020).

Heat and drought-induced tree mortality has been increasing in many forest areas across the world (Settele *et al.*, 2014; Martens *et al.*, 2020), for example, the western U.S. (van Mantgem *et al.*, 2013; Anderegg *et al.*, 2015), Europe (Senf *et al.*, 2018) and old-growth Amazon rainforest (Hubau *et al.*, 2020). In some cases, drought has triggered large-scale forest dieback, in particular through insect outbreaks (Anderegg *et al.*, 2015; Schuldt *et al.*, 2020). Under a high greenhouse gas emission scenario, the Amazon rainforest might face a tipping point with massive forest loss (Lyra *et al.*, 2016). Here, climate-driven forest die-back might be reinforced by a negative feedback from anthropogenic deforestation on precipitation (Lovejoy & Nobre, 2018). Rising atmospheric CO_2 concentrations might ameliorate drought effects to some extent since it increases water use efficiency, but strong effects on tree vigour and mortality under extreme drought are unlikely (Allen *et al.*, 2015; Walker *et al.*, 2021).

It will be a major challenge for the forestry sector to adapt to the impacts of climate change. Observations increasingly show that current forestry practices cannot maintain the societal benefits historically provided by forests (e.g., Schuldt *et al.*, 2020). Projections of future climate change impacts on forestry are mostly negative. For Europe, e.g., economic losses of up to several hundred billion Euros until the end of the century have been predicted based on climate-driven species distribution models (Hanewinkel *et al.*, 2013). Negative impacts of climate change are even expected for cold boreal regions in Northern North America, where warmer temperatures and longer growing seasons have increased vegetation productivity (Zhu *et al.*, 2016) and positive impacts on timber production and the forestry industry might be expected. However, in large parts of Canada, the warming trend has been accompanied by increasing drought stress, fire disturbances and insect damages, leading to increasing mortality in particular of late-successional economically important tree species. Therefore, it is expected that climate change will have negative economic impacts on forestry in Canada (Brecka *et al.*, 2018).

Extreme fires, i.e., fires that are of larger extent or greater intensity than were the expectation in the past, are also an important threat to forest ecosystems. Even though the total global burned area might have decreased during recent decades (Andela *et al.*, 2017), increases in extreme fires have been observed in several regions, such as the western U.S. (Bowman *et al.*, 2017) and Australia, where fires during the 2019/2020 fire season were the largest recorded in temperate Australian forests since European settlement (Nolan *et al.*, 2020). Future weather-driven fire risk is expected to increase (Bowman *et al.*, 2017; Lange *et al.*, 2020), but large uncertainties in the representation of human impacts on wildfire in DGVMS (Teckentrup *et al.*, 2019) are a challenge for future predictions of the burned area (Lange *et al.*, 2020). Both fire ignitions and effects on society will also be strongly influenced by future urbanization dynamics (Knorr *et al.*, 2016).

A large number of potential adaptive strategies exist for managing forests in order to maximize resilience and NCP (see **Table 4.1** for examples). Many of these have positive effects on biodiversity but some have negative or poorly known impacts on biodiversity and are hampered by large uncertainties. Promoting genetic and species diversity in order to spread risks appears to be crucial in most forest systems. Field and modelling studies have confirmed the common notion that tree species or functional diversity often positively affect forest productivity and carbon storage (Hulvey *et al.*, 2013; Huang *et al.*, 2018), resilience to climate change (Sakschewski *et al.*, 2016; Hutchison *et al.*, 2018), and multiple NCP (Gamfeldt *et al.*, 2013; van der Plas *et al.*, 2016), even though, under certain conditions, such as small environmental changes, monocultures can produce the highest timber yields and short-term economic revenues. Furthermore, communities in developing countries that depend on forests for subsistence, tend to use many different species for, e.g., their edible fruits, fuelwood supply and medical purposes (Roberts *et al.*, 2009; Heubach *et al.*, 2011). Thus, they rely on a higher tree diversity than commercial forestry operations and face different adaptation challenges (Roberts *et al.*, 2009). As a more technological measure, genetic engineering of trees has increasing potential to improve productivity, wood quality and resistance to biotic and abiotic stresses, which in many areas will be of increasing importance under climate change. However, due to the anticipated risks, limited societal acceptance and regulatory hurdles, field research and commercial applications have been limited so far (Chang *et al.*, 2018).

Table ④ ① **Examples of major adaptation measures in the forestry sector.**

Note that local conditions might differ from the generalisations made here.

Adaptive strategy	Comment	Impact on biodiversity
Persistence of current forest types	Trees are locally adapted and acclimatized and often have high phenotypic plasticity and, thus, capacity to adapt (Bussotti *et al.*, 2015).	Positive if current forest types are viable under climate change, negative if climate-driven forest dieback leads to habitat loss.
Local adaptation through natural regeneration	Intraspecific (genetic and phenotypic) variability at a given site is often higher than the variability among sites. Therefore, natural regeneration can lead to local adaptation and high functional diversity. (Bussotti *et al.*, 2015).	Positive as natural regeneration processes often lead to high tree species and vegetation structural diversity.
Promoting mixed stands instead of monocultures	Mixed forests appear to be more resistant, at least, to small-scale natural disturbances (Jactel *et al.*, 2017). Diversity in terms of hydraulic strategies increases ecosystem resilience during drought (Anderegg *et al.*, 2018).	Positive as forest resilience increases and mixed stands provide more different habitats.
Assisted migration[1]	Can contribute to forest resilience (Bussotti *et al.*, 2015), but appropriate choices of source regions differ between climate scenarios, implying large uncertainties (Broadmeadow *et al.*, 2005; Williams & Dumroese, 2013).	Positive or negative, depending on specific circumstances.
Introduction of non-native species[2]	Larger choice of appropriate species and provenances than with assisted migration, but similar challenges and potentially higher risk to introduce new forest pests (Liebhold *et al.*, 2012; Lovett *et al.*, 2016).	Mostly negative as fewer species are adapted to non-native tree species far away from the planting region (Ennos *et al.*, 2019; Pötzelsberger *et al.*, 2020).
Fire management	Reducing fuel loads with regular prescribed burning or increased thinning can reduce fire severity, but effects are system-specific and debated (Bowman *et al.*, 2021).	Positive if mimicking natural fire regimes and catastrophic fires can be prevented.
Shorter rotation periods	Can lower risk from windstorms and increasingly novel climates. Can compensate for accelerated stand development in regions with temperature-limited tree growth. (Kolström *et al.*, 2011).	Mostly negative as older trees provide valuable habitats. Also reduces the forest carbon stock.
Reducing stem density and water demand	Can mitigate drought effects (Kolström et al., 2011; Cabon *et al.*, 2018; McDowell & Allen, 2015), but changes in stand integrity can also have adverse effects on trees (Kolström *et al.*, 2011).	Positive if forest persistence under climate change is promoted.
Reducing non-climate stressors	Reducing forest exposure to stressors like ozone and high nitrogen deposition can enhance forest resilience to climate change. In some areas, a reduction of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions, which result in soil acidification, can also enhance forest resilience.	Positive

1. Defined as movement of species and populations to facilitate natural range expansion in direct management response to climate change (Vitt *et al.*, 2010). The implication is that these are nearby species who cannot reach the area of preferred climate because they are two slow to disperse or are blocked by habitat fragmentation.
2. Defined as the introduction of tree species from distant locations e.g., from other continents, that would not reach the target area without being brought there by people.

The long lifespan of trees makes adaptation in the forestry sector particularly challenging. Forests planted or regenerated today should be viable under the present climate and, at least, decades of future climate, whereby future changes in precipitation and drought stress are extremely uncertain in most areas (IPCC, 2019a). Even adaptation to warmer temperatures alone might be challenged by the occasional occurrence of cold winters, which sets a limit for assisting migration of species from the south (Bussotti *et al.*, 2015). Furthermore, sudden large-scale tree mortality through forest pests (Weed *et al.*, 2013; Anderegg *et al.*, 2015) is very difficult to predict with current forest or vegetation models. This applies in particular to the effects of potentially invasive forest pests (Hurley *et al.*, 2016; Seidl *et al.*, 2018). Finally, it is difficult to predict the market for timber products decades in the future. The large uncertainty in future climate projections and the impacts on forestry have been a major obstacle to adaptation. For example, without confidence in certain potential adaptation measures, forest owners in Central Europe are often inclined to continue with business as usual (Brunette *et al.*, 2020).

Nature-based solutions and promoting natural adaptation processes are central for climate adaptation in forest ecosystems. The large uncertainties in future climate projections imply that risk spreading (e.g., planting different tree species and provenances, avoiding large even-aged stands) and promoting the capacity of forest ecosystems to adapt (e.g., through natural regeneration) are options with high priority. Such a diversification of our forest landscapes would have strong co-benefits for biodiversity and many NCP.

Assisted migration and the introduction of non-native species and provenances can contribute to risk spreading and forest resilience but are subject to large uncertainties. Monocultures of non-native species have mostly negative effects on biodiversity, in particular when diverse tropical or subtropical forests are replaced with single species (e.g., Cazetta & Zenni, 2020; Valduga *et al.*, 2016) often with a very narrow genetic base, such as a particular cultivar or a hybrid clone. It has even been argued that non-native trees should generally be avoided in native woodlands where the protection of biodiversity or recreation are important goals (e.g., Brundu *et al.*, 2020).

The promotion of risk-spreading in forest management practices implies a fundamental paradigm shift, as the maintenance of forest ecosystems becomes more important than maximizing shorter-term economic gains, which are often higher from large-scale monocultures. Current economic incentives primarily reward the production of timber and other biomass-based products and do not reflect the multitude of NCP that forests provide, such as soil protection, water purification as well as microclimate and global climate regulation. Economic incentives and regulations might need to be re-designed to achieve efficient adaptation with co-benefits to biodiversity. This also implies that it is crucial to embrace indigenous and local knowledge in adaptation planning (IPBES, 2019).

4.4.1.2 Agriculture

Agriculture is extremely climate-sensitive; thus adaptation is essential, but will take a variety of forms across regions and types of agriculture (IPCC, 2014a, 2019a). Negative impacts of climate change are generally related to increased drought, heat stress, other climate extremes (e.g., late frost, hailstorms, etc.) and pressure from climate change effects on pathogens and insect pests. Positive effects arise from rising CO_2 concentrations and more favourable climates in areas where production was previously limited, especially by low temperatures. This explains why crops, livestock and grasslands are generally projected to be negatively affected in tropical regions and positively affected in high latitude systems over the coming decades (IPCC, 2019a). Towards the end of the 21st century at moderate to high levels of greenhouse gas emissions, negative impacts are projected to become more widespread and affect a large proportion of areas that currently provide most of the world's food (IPCC, 2014a, 2018, 2019a, 2020).

Projections of climate change impacts on agriculture remain highly uncertain, especially in relation to changes in precipitation and the effects that climate change has on the frequency and magnitude of extreme events (Ben-Ari *et al.*, 2018; IPCC, 2014b). As such, it is important to distinguish adaptive responses that focus on adaptation to commonly anticipated changes in climate such as increasing water and heat stress, versus adaptation focusing on enhancing resilience to unpredictable and highly variable climate (i.e., "bet hedging"). Adaptive responses based on projected changes in climate, especially when relying on a single scenario or average projections, run a substantial risk of being maladaptive, in part because of the unpredictable nature of future climate and its impacts (Beillouin *et al.*, 2020), whereas resilience-oriented adaptations are less likely to be maladaptive, but often involve production trade-offs.

There is already a tremendous amount of thought about climate change adaptation in agriculture (IPCC, 2014a, 2019a; FAO, 2019a, 2019b). There are also many programs already in place to encourage the adoption of practices that would increase adaptive capacity in agriculture including livestock husbandry. Initiatives around "climate-smart" agriculture are a good example of this (World Bank Group, 2015; FAO, 2019a, 2019b; but see limitations to this approach in Taylor *et al.*, 2017). "Climate-smart" approaches can contribute to enhancing biodiversity in agricultural landscapes, climate mitigation, and reduction of overall environmental impacts of agriculture, and so are frequently presented as win-win solutions (FAO, 2019a). These adaptive responses can occur at many levels ranging from the farm and field level, to landscape levels, to global scales, with important interactions between these scales. For example, adaptive responses that reduce agricultural productivity per unit area in one part of the world may have indirect effects on biodiversity by increasing the area used for agricultural production in other parts of the world. In addition, global trade in agricultural commodities is a major determinant of agricultural practices at local and national levels.

Much of the scientific literature and actions on climate adaptation in agriculture focuses on management responses at the farm and field scales (Aguilera *et al.*, 2020; FAO, 2019a, 2019b; IPCC, 2014a; Smith *et al.*, 2019; Stringer *et al.*, 2020; van Wijk *et al.*, 2020; Wiederkehr *et al.*, 2018; World Bank Group, 2015). At the level of farmers this often emphasizes managing real and perceived short- and long-term risk and the costs of implementation of adaptation strategies (Acevedo *et al.*, 2020; Gardezi & Arbuckle, 2020; Ju *et al.*, 2020; Smith *et al.*, 2019; Waldman *et al.*, 2020).

Recognition that agrobiodiversity contributes to the resilience and social benefits of agricultural systems is common in many traditional farming systems (FAO, 2019c; Jackson *et al.*, 2012). Mobilizing biodiversity and natural ecological functions to replace chemical inputs, embodied in agroecological practices, is drawing increasing attention as alternatives to conventional agricultural systems that are heavily dependent on chemical inputs (Doré *et al.*, 2011; FAO, 2019c), and these practices also frequently contribute to improving climate adaptation capacity (FAO, 2019a, 2019b, 2019c). There are, however, strong economic and socio-technical barriers to the adoption of practices that favour agrobiodiversity in many contexts (Jackson *et al.*, 2012). These could be addressed by economic mechanisms such as payments for ecosystem services that overcome market failures (Narloch *et al.*, 2011) and systemic approaches to creating transformative change in agrifood systems (Caron *et al.*, 2018; Meynard *et al.*, 2017).

Table ④ ② **Measures at field to regional scales that can enhance the adaptive capacity of agricultural production systems.**

The table is divided into two parts: ❶ Biodiversity-based measures aim to increase resistance and resilience of agricultural ecosystems and reduce environmental impacts by mobilizing biodiversity to replace chemical inputs with ecological functions. These measures often increase climate adaptation capacity. ❷ Technical and technological solutions that focus more specifically on climate adaptation and are not biodiversity-based. This portion of the table also includes observed and projected societal responses in agricultural systems to climate change. Note that implementation of biodiversity-based measures often involves technical, technological and social innovation. Summarized from (FAO, 2019a, 2019c, 2019b; IPBES, 2019; IPCC, 2019a; Smith et al., 2019; Doré et al., 2011; Landis, 2017).

Adaptive strategy	Comment	Impact on biodiversity
① Biodiversity-based strategies		
Agroecological practices	Increasing crop and livestock diversity including by using varietal mixes, more complex crop rotations, intercropping, wild relatives for crop and livestock selection, on-farm crop selection, and integrated farming (combining livestock raising with crop and fodder production) have several advantages for climate adaptation especially risk spreading. They also have other advantages including reduction of susceptibility to disease and insect pest attacks.	Agroecological practices are intended to reduce environmental impacts and many practices are based on reinforcing biodiversity.
Agroforestry	Mixing trees with crops can reduce water and thermal stress for crops in many situations and provides risk spreading if trees or shrubs are used for diversifying income and livelihoods.	Enhancing biodiversity is often one of the objectives of agroforestry.
Improving soil biodiversity and health	Reducing tillage, using less pesticides and increasing organic material input enhances the abundance and diversity of soil organisms, and participates in making soils more resistant and resilient in the face of climate change. Combating desertification and soil degradation through management of grazing pressure, vegetation restoration and soil conservation practices at landscape to regional scales can enhance resilience in the face of climate change.	Soil conservation measures can have large benefits for soil and non-soil biodiversity if done wisely.
Organic agriculture	Organic agriculture is not primarily a climate adaptation strategy; however, it does typically aim to improve soil health and employ higher crop diversity which can contribute to greater adaptive capacity.	Biodiversity is generally higher in landscapes with a substantial fraction of organic agriculture. However, organic farming practices often reduce productivity per unit area that can lead to biodiversity impacts elsewhere.
Managing landscape heterogeneity	At the landscape level, agricultural productivity and socioecological resilience to climate change and other stressors can be achieved through managing the diverse landscapes such as Satoyama in Japan and Hani Terrace in China.	Managing landscape heterogeneity can be a very important component of maintaining and restoring culturally important aspects of biodiversity and NCP.
② Technical and Technological Actions and Societal Adaptations		
Improvements in irrigation efficiency	Measures to improve the amount of water used to produce crops such as precision irrigation or "Alternate Wetting Drying (AWD)" rice can support adaptation to increased water stress under climate change.	Improved irrigation efficiency can potentially be beneficial for biodiversity by reducing water abstraction from rivers, streams and lakes, although in practice it frequently does not (Grafton *et al.*, 2018).
Increasing irrigation capacity	Increasing irrigation capacity is a common strategy to enhance climate adaptive capacity, but has numerous potential drawbacks including long-term soil salinization, environmentally harmful levels of water abstraction and creating water use conflicts.	Irrigation strategies involving building dams or increased water abstraction pose considerable risks for freshwater biodiversity (see Section 4.4.2 on freshwater).

Table ④ ②

Adaptive strategy	Comment	Impact on biodiversity
Genetically Modified Crops (GM crops)	GM crops that are more heat and water stress tolerant, as well as crops that use water more efficiently are commonly proposed technological solutions to climate change adaptation.	GM crops pose a wide range of environmental risks including spread of genes to wild relatives. For example, genes from drought resistant GMO crops could spread to wild relatives, altering their competitive ability and thereby impacting biodiversity and ecosystem functioning (Liang, 2016).
Precision agriculture	Precision agriculture, such as remote sensing and/or robots to target fertilizer, pesticide and water use is often presented as playing a major role in climate adaptation as well as a means to reduce environmental impacts of agriculture.	The impacts of precision agriculture on biodiversity are rarely considered, but appropriately used can enhance biodiversity in agricultural settings (Librán-Embid *et al.*, 2020).
Mobile livestock keeping	Mobile livestock keeping, which is common in Africa and Central Asia, helps pastoralists to adapt to the climate change and weather extremes such as droughts and snowstorms.	Mobile livestock keeping can contribute to sustainably using natural resources (e.g., grass, water). However, the merits of maintaining mobility (e.g., transhumance) vs. sedentarization is still a disputed question among scientists and policymakers.
Fire management in grazing lands	Fire management strategies can help avoid excessively frequent or intense fire which are projected to become a more significant problem under climate change in many areas.	Fire is a major driver of ecosystem function and biodiversity in many grazing lands and should be accounted for in climate adaptation strategies.
Shifts in the location of agricultural activities	Shifts in the location of agricultural activities, either land abandonment due to unfavourable climate or transformation of new areas for agricultural use in areas where climate becomes favourable or is projected to be in the future(Mendelsohn & Dinar, 2009; Liu et al., 2015).	Shifts in location are likely to have very large impacts on biodiversity and society, but the likelihood of large-scale shifts and their impacts are not well understood due to the complex interplay between social, economic, technical and environmental factors underlying such major transformations.

Adaptive strategies are often most successful when approached integratively. Nature-based solutions, technical and social innovation can be highly complementary. For example, on Mount Kilimanjaro, Tanzania, agroforestry combined with diversification of agriculture and improving irrigation efficiency led to greater resilience to climate risk, spread economic risk, improved income, and enhanced several other ecosystems services (e.g., climate mitigation, watershed protection, FAO, 2019b). However, it is important not to oversell win-win aspects of integrated adaptation strategies since all adaptive solutions have drawbacks for some actors.

As a broad generality, there is an emphasis in the agri-food industry on technical solutions to climate change such as biotechnology for crops and livestock, precision agriculture, etc., versus resilience and risk spreading measures, in part because the later often rely on social and technical innovation rather than marketable technological innovations (Meynard *et al.*, 2017). There are many barriers to adoption of climate adaptation in agriculture practices, including behavioural response of farmers (especially perception of risk) and consumers, information for farmers, institutions, subsidies (Gardezi & Arbuckle, 2020). Socio-technical lock-ins in food systems often greatly constrain adaptive response and tend to favour solutions that fit into current paradigms such as increasing drought resistance of current crop types, improving or adding irrigation (Gardezi & Arbuckle, 2020).

It is necessary to consider adaptive strategies in agriculture in the broader context of the food systems which they supply. Diets with modest portions of meat and reductions in food loss can ease pressure for increasing productivity to feed a growing and more affluent human population, which generally makes implementing adaptive solutions easier (IPBES, 2019; IPCC, 2019a, 2019b). Demand from consumers and constraints in the food supply chain also drive changes in agricultural practice: this can provide incentives and disincentives for biodiversity friendly adaptive measures in agriculture. For example, shifts in emphasis to local food supply chains in some regions can have both liberating and constraining effects on adaptive response (Caron *et al.*, 2018).

4.4.1.3 Other terrestrial Systems

Table 4.3 summarizes major challenges to natural adaptation and nature-based solutions for climate adaptation in terrestrial biomes that cover large areas of the globe other than the forest and agricultural ecosystems addressed above. In most of these biomes, climate adaptation measures typically focus more on biodiversity conservation and on regulating and non-material nature's contributions to people (NCP), and focus less on material NCP than forests and agricultural systems. Likewise, human intervention in these biomes is often absent or minimal, in part due to low human population densities. For example, Arctic and mountain tundras cover 14 Mkm^2, are home to 160 million people and only 5% have been converted to agriculture (IPBES, 2019). Deserts and semideserts cover 28 Mkm^2, are home to 788 million people and only 8% has been converted to agriculture. This can be compared with tropical and subtropical forests that cover 28 Mkm^2, are home to 2.9 billion people and 22% have been converted to agriculture. The vast areas of these biomes and low levels of human intervention mean that adaptation will primarily depend on ecological adaptation. Human-led interventions to enhance adaptation may be locally important but affects small areas relative to the overall size of the biome. A notable exception to this is grasslands and savannas which often have moderate to high provisioning NCP value and moderate to strong human intervention, in particular related to livestock grazing, management of large populations of wild grazers or management of fire. See Section 4.4.2 for discussion of adaptation in grasslands used intensively or extensively for livestock grazing. In all cases, reductions in non-climate stressors such as land use change, land degradation, invasive species, pollution and resource extraction can make substantial contributions improving climate adaptation capacity.

Table ④ ③ **Adaptation challenges and measures for key terrestrial biomes.**

The first column highlights risks and constraints on ecological adaptation to climate change **(Box 4.1)**. Human-led adaptation measures in this table focus on nature-based solutions to reduce impacts on biodiversity and nature's contributions to people. Biome classification is based on IUCN (IUCN, 2020) which is very similar to the IPBES "units of analysis" (IPBES, 2019). See **Box 4.1** for the definition of nature-based solutions used in this report.

Biome	Ecological adaptation: Risks and constraints	Nature-based solutions	References
Polar – alpine: Arctic Tundra	• Very high rates of climate change in many areas • Invasion by woody vegetation • Tipping points especially related to loss of permafrost and snow cover • Limitation by non-climate factors such as daylength • Slow regeneration following disturbance • Pressures such as accumulation of pollutants	• Rewilding with large herbivores • Herding of managed species such as reindeer to maintain short stature vegetation – very limited in area compared to global extent of these biomes	(IPCC, 2014a, 2019a, 2019c; Section 6)
Polar – alpine: Mountain	• Loss of area as species move up in altitude • Tipping points related to loss of snow cover, permafrost and glaciers • Limitation by non-climate factors such as soils • Slow regeneration after disturbance	• Assisted migration • Grazing by livestock • Rewilding – limited in area compared to global extent of these biomes	(IPCC, 2014a, 2019b; Section 6)
Grasslands & Savannas (see Section 4.4.1.2 for discussion of livestock grazing)	• Pressure from habitat destruction and fragmentation • Invasion by woody vegetation due to land management and rising CO_2 • Environmental limitation by non-climate factors • Large areas of savannas close to climate tipping points (see Section 6)	• Protect remaining semi-natural areas • Maintain and restore connectivity • Active and passive restoration • Wildlife grazing management • Fire management	(IPBES, 2018), (IPCC, 2019a), (IPCC, 2014a)
Deserts & Semideserts	• Many species may already be at the edge of climate adaptation limits • Regeneration is slow following disturbance	• Wildlife grazing and fire management especially in semideserts • Active and passive restoration • Soil protection and management • Restore hydrological function – all very limited in area compared to global extent of deserts	(IPBES, 2018), (IPCC, 2019a), (IPCC, 2014a)
Shrublands & shrubby woodlands	• Pressure from land use change and fragmentation is very high in many regions	• Fire management • Passive and active restoration	IPCC, 2014a)

4.4.2 Freshwater systems

Global climate change is recognized as a threat to species survival and ecosystems health (Erwin, 2009). Aquatic ecosystem's biodiversity in particular has been declining worldwide over the last century with climate change becoming an additional pressure, especially in regions already characterized by water deficit (Lefebvre *et al.*, 2019). Climate change will therefore make future efforts to restore and manage wetlands more complex. Since the IPCC AR5 report (IPCC, 2014a), many adaptation plans and strategies have been developed to protect species, ecosystems and their benefits to people, but there is limited evidence of the extent to which adaptation is taking place and even less evaluation of its effectiveness.

4.4.2.1 Rivers and streams

Restoring riparian vegetation, streambeds and wetlands – Responses in freshwater species are strongly related to climate driven changes in the physical and hydrological environment, including increased water temperature and reduced ice cover, timing of runoff and peak flows or loss of connectivity in rivers. Catchment Adaptation Framework can enable river basin management to systematically assess the adaptation options for better decision-making (Lukasiewicz *et al.*, 2016). Apart from catchment adaptation, the use of formal decision support systems such as Bayesian belief networks (Gawne *et al.*, 2012) and multi-criteria decision analysis (Zsuffa *et al.*, 2014), which are easily iterated with updated information, may prove useful in the adaptive management of wetlands within the context of climate change. Hydrological modelling also plays an important role in facilitating strategic decision-making concerning environmental response and in developing adaptation strategies to climate change as well as policies for hazard mitigation (Ghazal *et al.*, 2019).

Riparian ecosystems are likely to play a critical role in determining the vulnerability of natural and human systems to climate change, and in influencing the capacity of these systems to adapt (Capon *et al.*, 2013). The need for planned adaptation of and for riparian ecosystems is likely to be strengthened as the importance of many riparian ecosystem functions, goods and services will grow under a changing climate (Palmer *et al.*, 2009). Riparian restoration often begins with the removal of stressors that have altered the system. Here science may or may not be needed to identify the stressor (e.g., grazing), and once identified, simply altering or removing it (i.e. passive restoration) may be all that is needed for restoration (Palmer *et al.*, 2016). One should also recognize that most stressors and drivers of wetland and riparian systems are interactive or synergistic (Patten, 2016). For example, while riparian zones can cross climate gradients, many of which are being impacted by climate change, they also create microclimates for the vegetation, reducing environmental heterogeneity (Hopley & Byrne, 2019). Species with differing distributions in these environments provide an opportunity to investigate the importance of genetic connectivity in influencing signals of adaptation over relatively short geographical distance (Wang & Bradburd, 2014). Thus, successful long-term restoration and management of wetlands ecosystems amid climate change impacts depend on how we choose to respond to the effects of climate change (Erwin, 2009).

Wetland habitat responses to climate change and the implications for restoration will be realized differently on a regional and mega-watershed level, making it important to recognize that specific restoration and management plans will require examination by habitat (Erwin, 2009). Wetlands and their riparian or floodplain forests store, distribute and hold water in ecosystems and whole landscapes (Haase, 2017). For this reason, nature-based solutions are good options for wetlands. Wetlands and riparian forests are very efficient spaces for water and matter regulation, pollutants fixation and flood water retention. Thus, particularly for dense urban areas, they represent almost perfect nature-based solutions for risk mitigation and adaptation concerning climate extremes that result in floods and droughts. Nature-based solutions (NbS) are most often used as a term to signify an approach for increasing resilience to the impacts of climate change and has been a focus in climate mitigation and adaptation projects (Ruangpan *et al.*, 2020). Today, nature-based solutions are increasingly adopted as a measure for facilitating climate change mitigation and adaptation, for reducing flood risks, and for enhancing urban ecosystems (Cohen-Shacham *et al.*, 2016; Denjean *et al.*, 2017; Debele *et al.*, 2019).

For example, in the United Kingdom, flood control has been done using NbS. The project involved working with landowners to create in-channel, riparian, field, and woodland structures aimed at attenuating high flows or increasing infiltration rates to reduce flood risk. Early results suggest that social, as well as natural, capital has been enhanced through the project (Short *et al.*, 2019). NbS can combine technical, business, finance, governance, and social innovation, bringing together established ecosystem-based approaches, such as ecosystem services, green-blue infrastructure, ecological engineering, and natural capital (Nesshöver *et al.*, 2017). In Slovenia, practitioners and policymakers have realized that grey infrastructures may not be the most suitable solution to reduce flood risk, but rather a shift from grey solutions to nature-based solutions is required (Zwierzchowska *et al.*, 2019).

Restoring environmental flows and connectivity – The deteriorating condition of riverine and wetland ecosystems and loss of freshwater biodiversity resulting from water infrastructure impacts, water extraction, and altered flow regimes has led to a need to restore environmental flows in order to protect the health of the river and its biodiversity (Andersson *et al.*, 2018). The types of interventions for restoration depend on the extent to which functionality has been lost and the desired endpoints. Interventions can range from allowing natural regeneration to much more invasive measures including physical reconstruction of riverbeds **(Figure 4.2)**. The science and practice of environmental flow management has a long history as an approach to protect and recover aquatic biodiversity, ecosystem integrity and NCP (Matthews *et al.*, 2014). An important new element of the Declaration and Action Agenda is the emphasis given to full and equal cross-cultural participation for people of all cultures, and respect for their rights, responsibilities and systems of governance in environmental water decisions (Arthington *et al.*, 2018; Jorda-Capdevila & Rodríguez-Labajos, 2017). The Global Action Agenda (2018) makes 35 actionable recommendations to guide and support implementation of environmental flows through legislation and regulation, water management programs, and research, linked by partnership arrangements involving diverse stakeholders (Arthington *et al.*, 2018).

Dam construction for water storage and flood prevention: Many densely populated cities are prone to inundation and existing infrastructure may not be resilient enough facing the increased peak flows that may occur with climate change. As such, many approaches to adaptation against floods have been proposed: The operation of water infrastructure may disrupt the natural movement of water and may change important hydrological indicators such as water level rise and fall rates, flooding extent and extreme (annual, seasonal and monthly) water levels (Dang *et al.*, 2016).

Across sub-Saharan Africa for example, there is increasing dependency on wetland ecosystem services among poorer and vulnerable people in rural areas. The sustainable use of wetlands therefore requires a social-ecological catchment wide management approach that balances livelihood needs with environmental sustainability (Dixon *et al.*, 2021). Across Africa, Wetland Action's 'Functional Landscape Approach' (FLA), which has been developed over two decades of action research among wetland communities, is an important innovation for wetland management and a potential means of addressing this existential challenge of increased use of wetlands across sub-Saharan Africa.

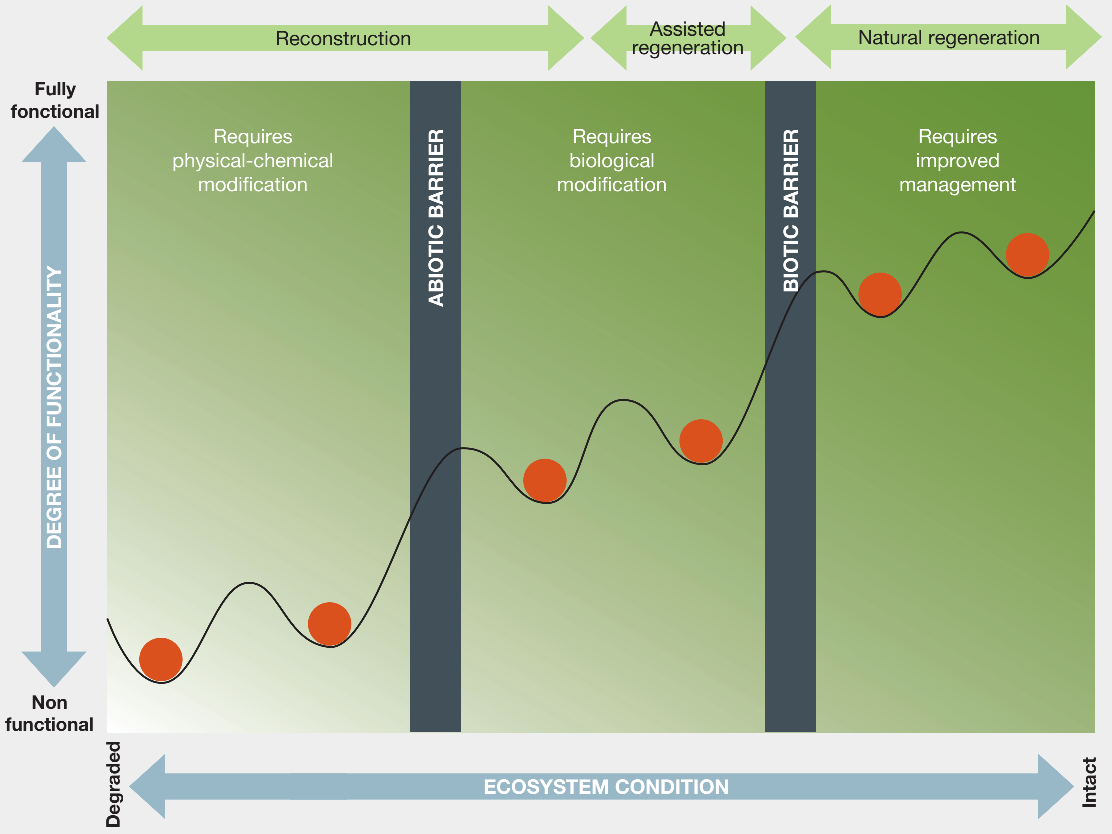

Figure ④ ② **Conceptual model of ecosystem degradation and responses to it through restoration.**

Adopted and modified from Keenleyside *et al.* 2012 with permission from Parks Canada.

The FLA essentially draws upon a holistic, social-ecological systems view of the dynamic relationship between people and the environment, in both space and time.

Changing irrigation and other types of water abstraction. An increasing number of nations are becoming aware of the pressures that ever-changing economic conditions, ever-changing technologies, population growth and ongoing climatic change are placing on their water management regimes (Young, 2014). It is estimated that urban water demand will increase by 80% by 2050, while climate change will alter the timing and distribution of water (Flörke *et al.*, 2018). Changing agricultural practices can therefore be an effective climate adaptation strategy (Davidson, 2016). Improving irrigation efficiency could effectively deal with changing global water endowments, especially if achieved via farmers adopting new behaviours and water efficient practices rather than through large-scale infrastructural interventions. Well-designed adaptation processes such as community-based adaptation can be effective depending upon context and levels of vulnerability. It is therefore appropriate to replace the existing water abstraction management regime with one that is designed specifically to enable the cost-effective management of the many challenges that increasing water scarcity brings to a region (Young, 2014).

Improved irrigation efficiency has been cited as an important way to adapt to climate change (Frisvold & Bai, 2016; Joyce *et al.*, 2011). However there exists significant regional disparities in vulnerability to climate change in the irrigation sector as experienced across Europe (Garrote *et al.*, 2015).

4.4.2.2 Lakes and ponds

Lakes and associated wetlands are inherently dynamic systems. In their native state, they are constantly adjusting to changes in sediment and water inputs by laterally migrating across the landscape and by changing the depth, width, and sinuosity of their channels (Hohensinner *et al.*, 2018).

For this reason, actions to restore or protect wetlands, floodplains, and riparian areas can help moderate or reduce stream temperatures, alleviate the flooding and scouring effects of extreme rainfall or rapid snowmelt, improve habitat quality, and enable species migrations (Shannon *et al.*, 2019). To be effective, management must be place-based focusing on local watershed scales that are most relevant to management scales. The first priority should be enhancing environmental monitoring of changes and river responses coupled with the development of local scenario-building exercises that take land use and water use into account. Protection of a greater number of rivers and wetlands corridors is essential, as is conjunctive groundwater/surface water management (Palmer *et al.*, 2009). Adaptation actions may thus occur in legal, regulatory, institutional, or decision-making processes, as well as in on-the-ground conservation activities (Meffe *et al.*, 2002).

Changing fisheries management: Fisheries managers have a long history of adapting management strategies to changing environmental and social conditions. Climate change is adding to the suite of uncertainties influencing fish populations and their response to management (Hansen *et al.*, 2015). Adaptation can thus be facilitated by forecasting future climate conditions. However, such predictions are fraught with uncertainty (Capela Lourenço *et al.*, 2015). Therefore, our capacity to manage fisheries under a changing climate relies solely on reasonably accurate future predictions of ecological conditions but, more important, it depends on our ability to manage ecosystems in a way that buffers against some of these predicted changes by using a management structure designed to adapt to rapidly changing ecological and social systems. Managing for resilient systems requires collaboration between fisheries management and a wide range of partners focused on land use, policy, and human systems.

In capture fisheries, adaptation involves adjusting fishing pressure to sustainable levels. Setting catch limits based on changes in recruitment, growth, survival and reproductive success can be done via adaptive management, monitoring and precautionary principles (Das *et al.*, 2019). For example, conceptualizing the fisheries of Lake Victoria as a complex adaptive social-ecological system (SES) is a step towards a more holistic, ecosystem-based approach to fisheries management in the basin that considers humans to be a part of "the environment." This means that reducing vulnerability and enhancing the adaptive capacity of Lake Victoria as a SES is essential for coping with future climate change. Key strategies to implement SES include: protecting and enhancing biological and occupational diversity, reducing pollution, reducing gender disparities (Whitney *et al.*, 2017), accounting for the social and environmental externalities of Nile perch exports (Johnson, 2010). This may also require changes in vessel or gear types if new fisheries opportunities become available. Other issues could include transboundary issues if populations move into other territorial waters. This will require cooperation and discussion between neighbouring countries and regions, including developing or modifying fishing agreements and collaborative management. Additionally, adaptation in fisheries and aquaculture can include a variety of policy and governance actions, specific technical support or community capacity building activities that address multiple sectors, not just capture fisheries or aquaculture farmers. Adaptation activities may be addressing short- or long-term impacts. **Table 4.4** lists adaptations to specific impacts such as reduced yields and profitability and increased risk.

Table ④ ④ **Potential adaptation measures in Fisheries and Aquaculture (based on Shelton, 2014).**

Impact	Adaptation measure
Reduced yields	• Access higher-value markets Increase fishing effort (risks overexploitation) • Shift aquaculture to non-carnivorous commodities • Selective breeding for increased resilience in aquaculture • Moving/planning siting of cage aquaculture facilities • Change aquaculture feed management: fishmeal and fish oil replacement; find more appropriate feeds • Migration as fish distribution changes (risks overexploitation) • Research and investments into predicting where fish populations will move to (risks overexploitation) • Improve water-use efficiency and sharing efficacy (e.g., with rice paddy irrigators) in aquaculture • Aquaculture infrastructure investments (e.g., nylon netting and raised dykes in flood-prone pond systems)
Increased yield variability	• Diversify livelihood portfolio (e.g., algae cultivation for biofuels or engage in non-fishery economic activity such as ecotourism) • Precautionary management • Ecosystem approach to fisheries/aquaculture and adaptive management • Shift to culture-based fisheries • Shift to propagated seed for previously wild-caught seed stocks (higher cost)
Reduced profitability	• Diversify livelihoods, markets and/or products • Exit fishery Reduce costs to increase efficiency • Change aquaculture feed management • Shift to culture-based fisheries
Increased risk	• Adjustments in insurance markets • Insurance underwriting • Weather warning systems • Improved communication networks • Improve capacity through training to teach data gathering and interpretation • Monitoring of harmful algal blooms where molluscs farmed • Improved vessel stability/safety • Compensation for impacts
Increased vulnerability for those living near rivers and lakes	• Hard defences (e.g., sea walls) (risks affecting local ecosystem processes and/or local livelihoods) • Soft defences (e.g., wetland rehabilitation or managed retreat) (risks affecting local livelihoods) • Early warning systems and education • Rehabilitation and disaster response • Infrastructure provision (e.g., harbour and landing site protection, building aquaculture facilities to withstand increased storm damage) • Post-disaster recovery • Encourage native aquaculture species to reduce impacts if fish escape damaged facility

4.4.3 Marine systems

Exploitation of biologically produced marine resources depends heavily on harvesting natural systems (fishing, harvesting of shellfish, seaweed), although the contribution of food from aquaculture now exceeds that of fishing, albeit from a much smaller area of the ocean. Ocean ecosystems contrast with those on land and in freshwater in the degree to which they are managed. A far smaller proportion of the ocean is actively managed for production of resources than is the case on land (Chen *et al.*, 2018).

Climate change impacts specific to ocean ecosystems pose particular challenges for adaptation. Reduced primary productivity in low latitudes through reduced surface nutrients and increased productivity at high latitudes due to increases in light with sea ice loss and deepening mixed layers are likely to have consequences for fisheries (IPCC, 2014a). Hypoxia in coastal oxygen minimum zones, especially in areas of increased temperature and productivity, severely impacts biodiversity and reduces tolerance of thermal extremes (Pörtner *et al.*, 2017). Marine heatwaves can result in loss of genetic variability (Gurgel *et al.*, 2020). Ocean acidification threatens calcifying organisms (Figuerola *et al.*, 2021; Mao *et al.*, 2020; Orr *et al.*, 2005). Impacts emerge for species, (including farmed shellfish), ecological communities (producing shifts from calcifying to non-calcifying algae, for example), habitats (through loss of habitat-forming species: mussel reefs, coral reefs including cold-water corals, *Lophelia*) and ecosystems (increasing primary production in macroalgae, (Kroeker *et al.*, 2013); but reducing primary production from calcareous phytoplankton, (Fox *et al.*, 2020)). Effects of extreme climatic events such as marine heatwaves, or coastal hurricanes can be especially rapid and tip ecosystems into novel states, often through loss of foundation species: coral bleaching, kelp forest loss (Wernberg *et al.*, 2013). The consequences for nature's contributions to people from oceans can be dramatic and are often well understood from responses to climate fluctuations in the past. The collapse of South Eastern Pacific fisheries such as anchovy has been linked to climatic variability (Arias Schreiber *et al.*, 2011), for example.

Loss or gain of species as cold-adapted species retreat from and warm-adapted species expand into specific locations can have unpredictable consequences for ecosystem services (Nagelkerken *et al.*, 2020). Species spreading polewards from more species-rich lower latitudes generally increases biodiversity, resulting in growing biotic homogenization of ecosystems (in exploited fishery species, (Magurran *et al.*, 2015). Such changes are reflected in fishery catch composition (see Section 4.3) with warm-adapted species generally replacing cold-adapted ones (Burrows *et al.*, 2019; Cheung *et al.*, 2013).

4.4.3.1 Ecological Adaptation in coral reefs

On coral reefs, a 1-2°C rise in temperature can result in widespread bleaching (Donner *et al.*, 2005), the most evident impact of climate change in this habitat, particularly evident during marine heatwaves (Smale *et al.*, 2019; Selig *et al.*, 2010). Replacement of sensitive genetic clades by more temperature-tolerant ones has been seen for both coral hosts and their photosynthetic symbionts (Ove Hoegh-Guldberg *et al.*, 2017). While genetic adaptation to elevated temperatures is possible, the present pace of temperature change has not been experienced for millions of years, and the lifetime of many species extends over many decades. Together, these factors make genetic adaptation to high rates or high magnitudes of climate change unlikely (Ove Hoegh-Guldberg *et al.*, 2017). Poleward expansions of ranges have been seen in both Northern (Yamano *et al.*, 2011) and Southern Hemisphere species (Baird *et al.*, 2012), balancing negative effects of heating focused in the warmest parts of the species distribution ranges (Smale *et al.*, 2019). Range expansion may be blocked by lack of suitable hard seabed habitats at cold range edges. The capacity for natural geographical spread of species and tolerant genetic clades may be limited, leading to suggested interventions to assist the processes of ecological adaptation (van Oppen *et al.*, 2015).

4.4.3.2 Conservation management of natural marine systems

Addressing the challenges posed by climate-related changes through increased protection and effective conservation will help in maintaining biodiversity, food provision and carbon storage in marine systems (Sala *et al.*, 2021). Climate-related shifts in species distributions present issues such as changes in fishery catch composition, as well as opportunities such as the expansion of coral reefs in subtropics (Price *et al.*, 2019). Adaptation strategies to anticipated shifts in distribution of foundation species (particularly those supporting NCP) under climate change include climate-smart marine protected areas., i.e., the design and location of area-based management schemes, such that they continue to fulfil their function in the presence of such shifts. (Fulton *et al.*, 2015; Hobday, 2011). Networks of spatial management units that allow for shifts in key species between areas of differing climate sensitivity can ensure that key species can be protected over long periods, despite short “climate residence time” (Ackerly *et al.*, 2010). Such networks connect metapopulations (such as those on coral islands) in a way analogous to connecting habitat patches on land (Robillard *et al.*, 2015) or creating wildlife corridors through heavily fragmented or urbanized landscapes (Lawler *et al.*, 2020). For coastal species with relatively limited mobility (seaweeds) identifying core regions of species ranges with high genetic diversity (including glacial refugia, (Assis *et al.*, 2017) helps in targeting conservation actions where most needed.

Where climate change makes new regions habitable (usually at poleward range edges) but capacity for colonization is limited, adaptation is facilitation of colonization by assisted colonization or migration. This may be a last resort to the issue of species extinction or local extirpation (Hoegh-Guldberg *et al.*, 2008), particularly useful for isolated populations or the last remnant of a species range. While facilitating distribution shifts may be an attractive solution for severely threatened systems such as coral reefs, evidence so far (Hughes *et al.*, 2017) suggests that such efforts have limited success and would be prohibitively expensive to implement at meaningful spatial scales, as well as introducing risks that introduced species become invasive. Deliberate translocation of aquaculture species (see aquaculture) involves shifting heat-tolerant strains or species to cooler areas. Direct translocation by unintentional transport via shipping and movement of materials associated with aquaculture activity enables shifts of species across biogeographical barriers including ocean basins and hemispheres. This has an adaptive effect for the species being transported in expanding its geographical range, but potentially negative for the new host community or ecosystem. Hard structures in the ocean may unintentionally provide stepping-stones for climate shifts (coastal protection structures: Airoldi *et al.*, 2015; Dong *et al.*, 2016).

4.4.3.3 Coastal protection

Nature-based solutions for coastal flood protection, such as using natural coastal habitats (vegetation or coral reefs) to provide protection from flooding during storm events, increasingly likely due to sea-level rise, is frequently preferred to engineered defences, partly because the former also provide biodiversity benefits whereas the latter may be damaging to biodiversity. The coastal wetlands that naturally provide coastal protection are moving inland and polewards, including poleward expansion of mangroves into saltmarshes, but their extent is generally declining by 0.2% – 0.4% per year because of development and land use change (Bindoff *et al.*, 2019). Development and construction of hard coastal defences produces "coastal squeeze" (Ducrotoy *et al.*, 2019; Leo *et al.*, 2019; Raw *et al.*, 2020): the restriction of area available for natural habitats (mostly vegetation such as saltmarshes or mangroves) to provide wave attenuation during storms (IPCC, 2020). Once built, sea-level rise (SLR) progressively reduces the area seaward of defence structures. Such defences (dykes, groynes) can also change patterns of transport of sediment along coastlines, increasing erosion and coastline retreat at sites with reduced sediment supply, which can be maladaptive for biodiversity. Further coastal defence works include realignment of rivers changing salinity and ecosystem structure. Adaptation strategies include sediment augmentation and restoration of shorelines to natural states to stem the loss of intertidal habitat and vegetation under sea-level rise. Managed realignment can also be effective, converting pasture to saltmarshes, albeit with a slow establishment of the novel habitat as a carbon store, (Burden *et al.*, 2013), while sediment inputs from rivers can counteract effects of sea-level rise.

4.4.3.4 Coastal marine fisheries

Adaptation has implications not only for fish stocks and their management, but also for food security and the livelihoods of the millions of people that are employed in fisheries and related industries. Adaptation to sea-level rise and extreme events that are having impacts on fishing operations and safety at sea must be planned systematically, including the effects on the physical infrastructure of coastal fishing communities, if it is to avoid destroying or severely damaging assets such as boats, landing sites, post-harvesting facilities and roads. In some coastal areas, impoverished small-scale fishing communities already subsist in precarious conditions and may face increased food insecurity in areas currently vulnerable to hunger and malnutrition. The lack of ability to anticipate and adapt to climate change tends to be greatest among the most vulnerable. Early warning systems are important adaptive responses for both industrial and small-scale fisheries.

Much can be done at the household, community and industry levels to support the resilience of the sector in a changing climate. For example, communities can receive targeted and improved weather and extreme event information, which can help ensure the safety of fishing vessels and fisheries while out fishing. The sector can also be supported to improve its monitoring and analysis of local changes and to have access to global information (Hobday *et al.*, 2016; Popova *et al.*, 2016; Martins & Gasalla, 2020). Other adaptation options include social protection and livelihood diversification, and potentially the use of improved technologies such as refrigeration to prolong use of produce in remote areas.

Methods and zones of fishing can be adapted to the change that is likely to occur and post-harvest processes can be improved to adjust to changing species and to minimize losses. The adaptive capacity of the marine ecosystems can also be improved by nature-based solutions and ecosystem approach to fisheries, using natural defences to erosion and storms and minimizing the negative impacts of harmful activities. Enabling conditions include secure tenure and access rights to the natural resources upon which they depend. Policymakers and managers can implement adaptive fisheries co-management plans, development and trade climate-smart strategies. It is also essential that the needs of the sector are included in broader national and regional adaptation plans (Johnson *et al.*, 2019).

Small-scale fisheries are highly exposed and sensitive to climate change but also possess flexibility and the capacity to adapt to future change. Ensuring the implementation of effective primary fisheries management is a fundamental action that will underpin all other adaptation efforts.

Incorporating local knowledge, capacity and governance will be key components of successful adaptation to minimize climate change vulnerability and enhance resilience of small-scale fisheries (Martins & Gasalla, 2018).

Climate-informed, ecosystem-based approaches to fisheries management that incorporate community awareness of the effects of changing climate on coastal fish stocks and habitats are required (Martins & Gasalla, 2020). Therefore, actions to use coastal fish and invertebrates sustainably in the face of a changing climate are key to minimizing vulnerability and supporting adaptation (Bell *et al.*, 2015). Most critical, however, is the need to support responsible fisheries transitions (e.g., to different species, gears, techniques) with alternative protein and income sources in some areas such as small islands that have limited options when harvest controls increase. Key lessons from successful adaptations in small islands developing states (SIDS) can help to identify the suite of options most appropriate to small islands and their fisheries, also guiding international and regional initiatives and investments to address specific needs of small-scale fisheries (Johnson *et al.*, 2019).

Community-based (bottom-up) adaptation has emerged as an important part of the response to this need and an increasing number of case studies are emerging that focus on the development of adaptation tools and the application of locally relevant data collection methods (Reid *et al.*, 2019; Johnson *et al.*, 2019). This includes examples where social learning, networking and empowerment was found to support community adaptation efforts (Butler *et al.*, 2016); community-based adaptation actions that emphasize local knowledge to complement and validate scientific data at appropriate spatial and temporal scales (Martens *et al.*, 2020); and integrated multi-sector planning efforts that seek to enhance community benefits (Wongbusarakum *et al.*, 2015). These local studies support the overall development of adaptation tools, improve the prioritization, funding, and completion of adaptation projects in small island communities, and support an understanding of how climate change impacts on small island communities and associated fisheries can be best addressed.

Supporting policies that address direct climate impacts are also a critical element of adaptation, and the climate and disaster provisions in the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries (SSF Guidelines) (FAO, 2018) are of particular interest to fisherfolk. They have engaged in influencing policies so that they incorporate more fisheries perspectives in regional climate arrangements that have been endorsed at the highest ministerial levels (McConney *et al.*, 2015). Such influence is intended to mobilize resources beyond those normally allocated to small-scale fisheries. Climate change adaptation provides the leverage required to obtain additional resources.

Climate-driven reductions in fisheries production and alterations in fish-species composition will be especially important in locations with limited adaptive capacity, as is often the case in tropical regions dominated by developing economies. Given the billions of people dependent on marine fisheries in some capacity, there is a clear need to adapt to the effects of climate change on these resources when building climate-resilient sustainable-development pathways (Lam *et al.*, 2020).

Table ④ ⑤ **Major adaptation strategies in marine fisheries.**

Adaptive strategy	Comment
Increasing regional and international awareness of and support for adaptation	While adaptation projects address complex challenges posed by climate change, there is limited current investment in adaptation to marine fisheries. There is also little agreement on the factors needed to support local-scale adaptation or guidance on how adaptation should proceed (Mcleod *et al.*, 2015).
Risk-management and insurance	The broad concept of insurance as a risk management tool and a climate change adaptation strategy in fisheries has been widely accepted by governments and their fisheries sectors. This prompted the trial of schemes designed to ensure a large pool of fishers on the one hand and to be a viable business for insurers on the other. Innovative insurance programmes can promote good management practices. Public-private partnership models such as mutual insurance can be feasible in providing insurance services to groups of small fishers, but government subsidies are needed initially.
Emerging fisheries	New fisheries are emerging because of increased abundance of previously rare species or those that were not heavily exploited, e.g., zooplankton and mesopelagic fish. New fisheries can also have negative effects on other commercially important species and result in an additional pressure for range contraction or local extirpation of those species. In some locations, developed markets need to adapt to those changes or become more volatile. Also, there are potential feedbacks to climate of new fisheries when they target significant elements of the active biological carbon pump in the ocean (e.g., mesopelagic fish).
Climate-smart fisheries management	Improving fisheries management and rebuilding overexploited or depleted fish stocks can help alleviate climate-induced decrease in potential fisheries production on actual catches. Quantitative models predict that adopting proactive and adaptive fishery management approaches today would lead to substantially higher global profits (154%), harvest (34%), and biomass (60%) in the future compared to no adaptation (Gaines *et al.*, 2018). There is also a general consensus that improving the resilience of fisheries is a key adaptation option (Free et al., 2020; Ojea *et al.*, 2020). However, the effectiveness of such adaptation measures is likely to be lower in many tropical developing countries, particularly in small-scale fisheries, where capacity for effective fisheries management is not ideal (Martins & Gasalla, 2020; Oremus *et al.*, 2020). As such, enhancing fisheries management capacity, from gathering and utilizing scientific information to fisheries governance, is an important part of the portfolio of adaptation measures (Lam *et al.*, 2020). Adaptation strategies are required in several cases, as follows.
Shifting target-species	Expected shifts need to be considered by fisheries commissions and agencies when governing the sustainable use, developing harvest strategies and allocating fishing rights to minimize the implications of fish redistribution for local economies (Lam *et al.*, 2020). Examples regarding management of highly mobile oceanic prey and predators, such as mackerel and tunas (Bell *et al.*, 2013; Hobday *et al.*, 2013) call for flexible strategies, e.g., allowing for spatial shifts in fishing effort. Another consequence of range shifts is overexploitation on the "trailing edge" of a population shifting its distribution. Also, displacement and migration of human populations from low-lying areas to less risky areas or to follow changes in fish distribution do require interventions (Viraparat, 2019).
Reallocation of fishing areas	With range shifts of the stocks, fishing fleets adapt by reallocating to new fishing grounds.

Table ④ ⑤

Adaptive strategy	Comment
Changing management measures	In addition to reducing vulnerability, fisheries management frameworks should be capable of evaluating and predicting the response of marine ecosystems to climate change and to adequately assess the threats and opportunities created by climate change (Lindegren & Brander, 2018). Flexible fisheries management practices can allow fishers to change target species, diversity of gears, improve technologies, and cope with seasonality (Ojea *et al.*, 2020). A critical feature is the ability to properly model and account for multiple sources of uncertainty and risks through Management Strategy Evaluations (MSE). MSE will be particularly useful to evaluate the consequences of a range of scenarios and management strategies under climate change (Lindegren & Brander, 2018). A fisheries reform to address current inefficiencies, to respond to changes in productivity and improve institutional performance is likely to contribute to reducing the consequences of climate change for industrial fisheries under good national governance.
Implementing adaptive management	Adaptive management is indicated to both industrial and small-scale fisheries as an adaptation option. It includes monitoring and updating catch and effort controls to shifting stock status that can avoid overexploitation and sustain livelihoods for a longer period (Ojea *et al.*, 2020).
Granting equitable fishing rights	Property rights guarantee stewardship over new resources, and stock ownership allows for spatial mobility.
Increasing adaptive capacity	Adaptive capacity is a key component to reduce vulnerability and should therefore be a priority consideration in adaptation planning and management. Adaptation among fishers is typically reactive, based on previous experience of change. One of the primary factors building adaptive capacity is awareness, yet a number of case studies present limited awareness of climate change impacts among fishermen and fishing industries. This is typically due to an individual perception of limited risk to climate change, at least compared to other greater and more immediate pressures, such as overfishing (Lindegren & Brander, 2018). In order to increase awareness of climate-related risk and support communities to adapt to change, effective science communication is therefore needed. Another key factor impairing the adaptive capacity is the reliance on a single stock, sector, or source of income. To increase the adaptive capacity and reduce risks facing individual fishers or fishing communities, more diverse and flexible livelihoods, partially including sectors and sources of income outside fishing is often suggested (Lindegren & Brander, 2018; Martins & Gasalla, 2020).
Reducing other non-climate stressors (e.g., eutrophication, plastic pollution, noise pollution).	Local management (e.g., integrated coastal zone management and marine protected areas) can play an important role to improve ocean health. Also, the situation in the high-seas and areas beyond national jurisdiction (ABNJ) require Regional fisheries management organisations (RFMO) to promote solutions to ocean pollution that amplifies climate change impacts as part of the Ecosystem Approach to Fisheries implementation. Lack of power for artificial light and refrigeration can be considered as an additional stressor for some fishing communities.
Negotiating new agreements	Adaptation for the new fisheries that cross jurisdictional boundaries within and between countries and/or in international waters is required.

Many of the world's exclusive economic zones (EEZs) are likely to receive one to five new, climate-driven transboundary stocks by the end of the century. Up to ten new stocks were projected for some EEZs in East Asia, a region where new transboundary stocks could exacerbate maritime relations already complicated by disputed territories, overlapping EEZ claims, and illegal fishing (Pinsky *et al.*, 2018). Previous examples such as range shifts in Pacific salmon which caused a severe and long-lasting conflict regarding quota allocations between Canada and the United States, showed that adaptation is difficult when fish stocks are exploited by many competing users, especially in the light of incomplete information regarding stock structure and dynamics (Miller *et al.*, 2010). The need for accurate scientific assessments combined with flexible institutional arrangements to maintain cooperation should enable adaptation (Lindegren & Brander, 2018).

Thus, climate-driven shifts in distributions of fish species across political boundaries require higher levels of collaboration to avoid disputes that can impair the sustainability of co-managed fisheries. Effective management of transboundary fish stocks in the face of climate change will depend on identifying all self-replenishing populations within the geographical range of the species, modelling the response of each population to climate change and identifying the stakeholders for each current and redistributed population. New combinations of stakeholders require the development of cooperative sustainable harvest strategies informed by changing ocean conditions (Lam *et al.*, 2020).

Effective management of the large transboundary stocks that underpin several industrial fisheries also requires improved monitoring, modelling and decision-support frameworks. Built-environment options, such as improved climate-forecasting and advanced-warning systems, not only for the extreme events that affect fishing vessel and crew safety at sea but also for geographical shifts in biomass of target fish species, will also facilitate sustained operation of industrial fisheries, and the equitable sharing of economic benefits derived from them, as the climate continues to change (Lam *et al.*, 2020).

Regional Fishery Management Organization (RMFOs) should cooperate on the potential for future shared stocks, interacting with other regional and sectoral regulators (Pinsky *et al.*, 2018). This is currently a concern since there are limited signals of action. Concerns also remain over the limited application of ecosystem-based management principles by RFMOs, including limited consideration of impacts on non-focal species. Data-sharing with other bodies is also vital. An exception seems to be the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) which has established collaborative arrangements with neighbouring RFMOs to monitor the movement of stocks across regulatory frontiers. Crucially, CCAMLR has forged similar arrangements with other sectoral regulators to consider the prospective ecological footprint of a moving fishing industry. However, taking effective account of climate change impacts in both target species and related predators seems to be still limited.

In tropical regions, some cooperative fisheries-management arrangements seem to be flexible enough to respond reasonably effectively to transboundary redistribution of biomass (Lam *et al.*, 2020). With adaptable agreements between states, ocean fisheries can continue to provide the myriad nutritional, livelihood, and economic opportunities relied upon by billions of people around the world (Pinsky *et al.*, 2018).

Lastly, the effects of climate-driven changes in the distribution, catch composition and catch potential of small pelagic fish on aquaculture operations (for fishmeal) have been documented. Salmon aquaculture in Norway, Chile, the UK and Canada provides over 85% of global farmed salmon production and, with the exception of Chile, these countries depend heavily on imported fishmeal, including that derived from Peruvian anchoveta. The pronounced effects of El Niño–Southern Oscillation (ENSO)-mediated climatic variability on annual harvests of Peruvian anchoveta led telecoupled aquaculture industries to develop mechanisms to cope with dramatic variations in the supply of anchoveta. In particular, the wild-fish component in aquaculture feed is being replaced with soybean meal, rendered terrestrial animal products and seafood or aquaculture processing wastes. These innovations might enable the consumption of farmed fish to increase by 2050 even under RCP 8.5, thereby, limiting the effects of climate change on the telecoupled dependence of salmon farming on Peruvian anchoveta (Lam *et al.*, 2020).

4.4.3.5 Aquaculture

There are many options for the adaptation of aquaculture to climate change, from simple management changes to complex engineering or biotechnology solutions. These can be applied at the farm management level or be driven by wider governance initiatives. Three categories have been identified: coping mechanisms at the local level (e.g., water quality management techniques), multilevel adaptive strategies (e.g., changing culture practices) and management approaches (e.g., adaptation planning, community-based adaptation) (Galappaththi *et al.*, 2020).

Some aquaculture sectors may be unable to adapt, while there will be opportunities for new sectors. Aquaculture has the capacity to adjust to environmental changes, achievable through adequate monitoring, control and surveillance for adherence to ecological considerations (Oyebola & Olatunde, 2019). Adaptation options in aquaculture may be focused on:

- diet quantity and quality
- genetics and biotechnology
- management and husbandry practices
- flooding and storm protection
- reallocation of farms
- real-time monitoring and prediction
- diversification of cultured aquatic species

Engineering and management solutions can reduce exposure to stressors or mitigate stressors through environmental control. Epigenetic adaptation may have the potential to improve stressor tolerance through parental or early life stage exposure. Stressor-resistant traits can be genetically selected for and maintaining adequate population variability can improve resilience and overall fitness. Information at appropriate time scales is crucial for adaptive response, such as real-time data on stressor levels and/or species' responses, early warning of deleterious events, or prediction of longer-term change. Diet quality and quantity have the potential to meet increasing energetic and nutritional demands associated with mitigating the effects of abiotic and biotic climate change stressors (Reid *et al.*, 2019). Some shellfish hatcheries have already relocated to less acidic waters (Reid *et al.*, 2019). GIS or remote sensing tools have been used for some time to select appropriate aquaculture locations (Ottinger *et al.*, 2016). Selective breeding programmes that cater for more temperature-tolerant species have been implemented. Initiatives to promote integrated aquaculture and agriculture systems, including using flooded/saline land and water bodies have also been in place in several countries.

Responses to flooding have included building higher pond dikes, netting and fencing around the low elevated ponds, community-based flood protection and changing stocking dates (Ahmed & Diana, 2016). Pumping out groundwater, changing fish culture accordingly and rainwater harvesting are some of the common responses documented for drought conditions (Lebel *et al.*, 2018).

Several adaptation measures have been in place for the sector as a whole (Bueno & Soto, 2017), which includes:

- changing focal species and opening new areas for cultivation
- developing heat-tolerant strains
- control of novel parasites and diseases
- risk assessment and management along the value chain and a feasibility assessment

Investments in research to identify new commercially viable strains for aquaculture species tolerant of low water quality, high temperatures and disease are needed. Future research should also look at whether different groups of aquaculture farmers (e.g., indigenous peoples) face and adapt differently to climate change; and the use of GIS and remote sensing as cost-effective tools for developing adaptation strategies and responses (Galappaththi *et al.*, 2020). Adaptation also includes research advancements in understanding how climate change affects aquaculture and will benefit most from a combination of empirical studies, modelling approaches, and observations at the farm level (Galappaththi *et al.*, 2020).

Moreover, the rehabilitation of coastal ecosystems which provide protection from storms and waves (mangroves, wetlands, marshes and coral reefs) should be part of adaptation plans, including identifying opportunities to access carbon finance for mangrove planting or restoration (IFAD, 2014).

Low trophic level aquaculture, and particularly seaweed mariculture has the potential to relieve emphasis on terrestrial agriculture, having per se an adaptation role to be highlighted.

4.4.4 Climate adaptation measures for infrastructure and human health

For most of the adaptation measures relating to infrastructure, there are nature-based alternatives (Table 4.6). In many cases, the nature-based alternatives have the advantage of providing a wide range of nature's contributions to people in addition to the intended climate adaptation objectives (Raymond *et al.*, 2017). For example, enhancing green infrastructure in cities can reduce urban heat island effects, and has also been shown to have positive effects on several measures of human health unrelated to climate (Mears *et al.*, 2019). As with all climate adaptation measures, biodiversity-based solutions are not without drawbacks. For example, reducing flood risks by creating wetlands can engender problems with insect pests and disease vectors if improperly managed (Hanford *et al.*, 2020), therefore, these measures must be evaluated based on the full range of their impacts and the context in which they are being implemented (Berry *et al.*, 2014).

Many technical, technological and societal measures have potentially large impacts on biodiversity. Measures like building dams and seawalls have been treated in previous sections. However, other measures, especially relocation of

Box ④ ② Climate-Smart Fisheries and Aquaculture.

The fisheries and aquaculture sectors have one of the lowest carbon footprints among all food production systems, while supporting livelihoods of millions of people. Climate-smart fisheries and aquaculture adaptation options can support the objectives of: (i) sustainably increasing output productivity/efficiency; (ii) reducing the vulnerability and increasing resilience of the fish production system(s) concerned and the people it supports; and (iii) reducing and removing greenhouse gas emissions from the sector. The adaptation measures that are available for both fisheries and aquaculture are important considerations for the development of National Adaptation Plans (NAP). As in other sectors, adaptation is place and context-based and should be viewed as an ongoing and iterative process. Disseminating climate change adaptation information and communicating it effectively to a broad range of fisheries and aquaculture stakeholders affected by climate change is one of the keystones of effectiveness. All segments of the fish value chain should be involved in determining adaptation goals, particularly the post-harvest sector, where the gender implications of adaptation activities are especially important.

Policy measures in support of the implementation of adaptation to climate change in fisheries and aquaculture can cover institutional adaptation, livelihoods adaptation, and risk reduction and resilience (Raymond et al., 2017; Brugere & De Young, 2020). Transboundary issues need to be considered when developing an adaptation strategy to ensure adaptation options of neighbouring countries are unaffected (Brugere & De Young, 2020).

people and infrastructure have potentially very large impacts, either positive or negative, on biodiversity depending on the areas these are relocated to. In addition, other measures like burying electric lines to avoid storm damage, building avalanche protection barriers or controlling invasive disease vectors may have more local effects on biodiversity, but could collectively have large impacts on biodiversity.

4.5 SYNTHESIS AND CONCLUSIONS

Even low levels of climate change will require some adaptive response, and high projected levels of climate change will exceed the adaptive capacity of most ecosystems and social-ecological systems leading to degradation of nature, nature's contributions to people and good quality of life. There is a wide range of measures that can enhance the capacity of systems to adapt to climate change, but many narrowly focused climate adaptation measures can have detrimental impacts on biodiversity or may be maladaptive and turn out to have unforeseen bad outcomes **(Figure 4.3)**.

Nature-based solutions (NbS) that focus on maintaining and restoring genetic and species diversity and abundance, or on preserving, restoring or creating healthy ecosystems can contribute to climate adaptation **(Figure 4.3)**. Many of these measures enhance adaptive capacity by reducing risk in the face of uncertain climate projections. However, these nature-based solutions can be imperilled by high levels of climate change or by other pressures such as land use change, overexploitation or pollution.

To avoid maladaptive responses, it is important to account for large uncertainties in future climate change and the response of socioecological systems to climate change.

Table ④ ⑥ **Examples of climate adaptation objectives for protecting life and property with a distinction between biodiversity-based approaches and technical, technological and social solutions.**

These measures are not mutually exclusive and can be complementary. Measures in red pose significant potential risks for biodiversity. This table is based on the IPCC AR5 WGII assessment, in particular (Revi *et al.*, 2014) (urban areas), (IPCC, 2014a) (key economic sectors) and (Smith *et al.*, 2014) (Human health: impacts, adaptation, and co-benefits), as well as references cited above.

Climate adaptation objective	Adaptation measures: Nature-based	Adaptation measures: Technical, Technological, Social
Health: minimize heat stress on people	Improve access to green spaces	**Relocate people; increase air conditioning (and accompanying GHG emissions)**; improve passive climate control of buildings; change behaviour
Health: reduce risk of climate-related increase in zoonotic disease	Maintain and reinforce species diversity in natural and semi-natural ecosystems (controversial); avoid deforestation; regulate wild animal use and trade	**Control populations of animal vectors**; develop health system strategies for avoiding pandemics
Health: ensure safe and sufficient water supply	Protect natural and semi-natural vegetation in watersheds	**Build dams and reservoirs**; increase efficiency of water use; reinforce technical, financial and institutional tools to ensure fair water distribution
Cities: reduce heat island effects	Enhance green infrastructure: green spaces, green roofs, trees along streets	Install cool roofs (e.g., reflective or evaporative) and cool roads; expand use of passive cooling of buildings; take climate into account in urban planning
Ports: storm surge and sea-level rise	Protect and restore natural barriers such as coral reefs, coastal wetlands and mangroves	**Reinforce, elevate or abandon vulnerable ports**; reinforce advance warning systems
Energy transmission: severe weather		**Burial of electric lines; reinforcement or repositioning of pipelines**
Natural disasters: minimize avalanche and landslide risks	Preserve and restore vegetation especially in hilly and mountainous areas	**Build hard avalanche and landslide protection**; abandon vulnerable housing and infrastructure; reinforce advance warning systems
Natural disasters: minimize flooding impacts life and property including bridges, roads and housing	Reduce flood risk by protecting and restoring wetlands and watersheds	**Control flooding with dams; reinforce, reposition or abandon vulnerable structures; relocate people**; avoid building in vulnerable sites; reinforce advance warning systems

This argues in favour of approaches to climate adaptation that put a strong emphasis on risk management, through strategies that can evolve over time and keep options open, as opposed to implementing strategies that focus on managing for a specific climate scenario, or that lack flexibility.

Risk management to cope with uncertainty in future climates and responses to climate change can greatly benefit biodiversity conservation actions, and vice versa. For example, diversification of agricultural land use types, the genetic variety of crops, and tree species helps spread risk.

Such diversification can make social-ecological systems more resilient to climate change and increase genetic, species and habitat diversity. Current economic incentives within agriculture, forestry and fisheries, however, do not promote such diversification and fail to reflect the multiple ecosystem services that contribute to human well-being (Section 4.4).

Technical, technological and socioeconomic measures for climate adaptation often have large negative impacts on biodiversity **(Figure 4.3)**, but also can be highly complementary to biodiversity-based measures. There is

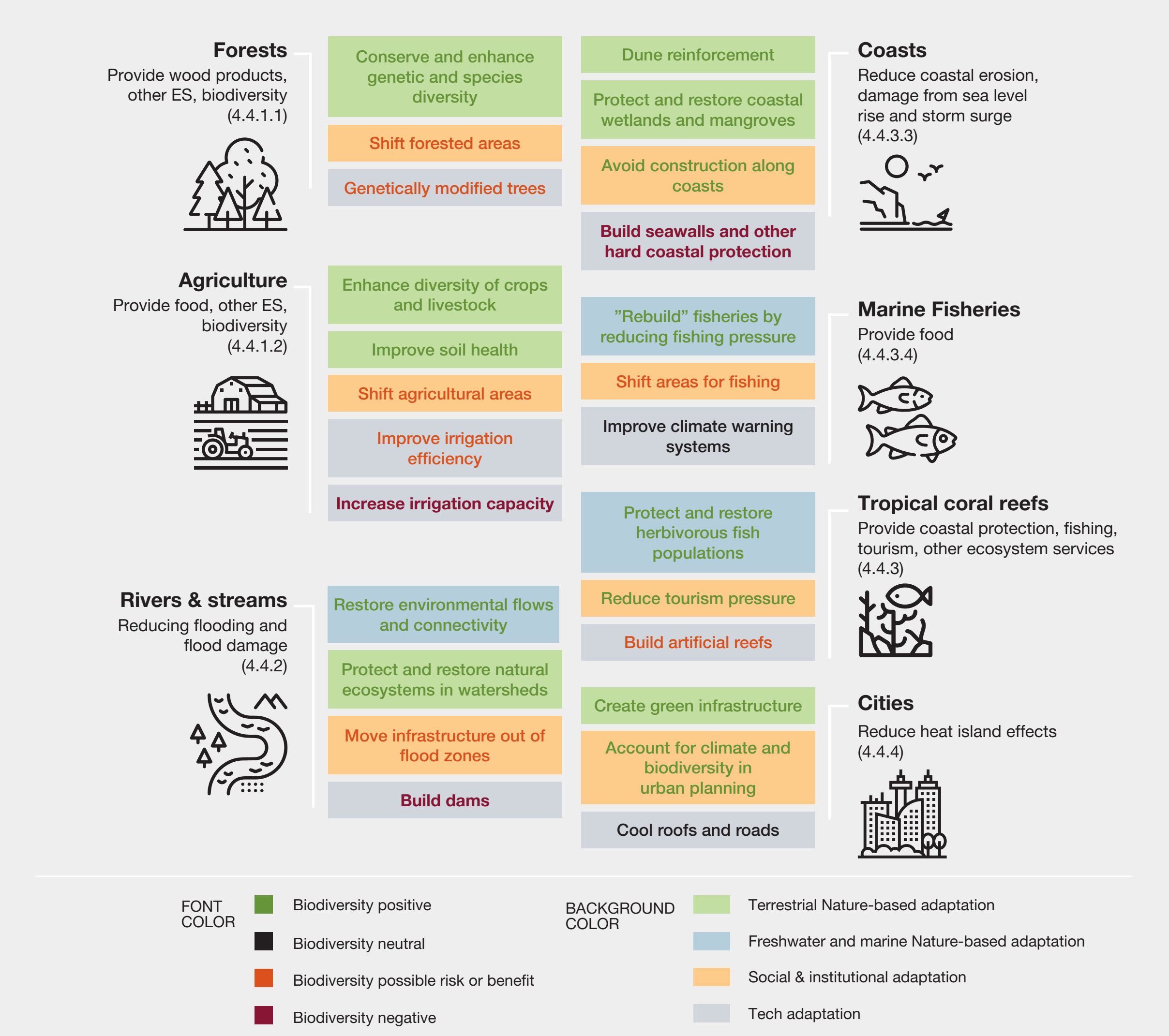

Figure 4 3 **Examples of climate adaptation measures.**

Nature-based solutions are shown in green (terrestrial) or blue (freshwater or marine), social and institutional measures in orange and technical and technological measures in grey boxes. Font colour indicates whether the measures are generally positive (green), negative (red), neutral (black) or negative or positive depending on context (orange) for biodiversity. More detailed explanations for each key system or sector are provided in the indicated subsections.

an urgent need to better understand and account for these impacts and complementarities. Of particular concern are adaptive measures for managing floods and droughts such as building dams and for managing sea-level rise with hard defences such as building sea walls **(Figure 4.3)**. Shifts in human populations and activities such as agriculture and fishing to adapt to climate change may also have considerable effects on biodiversity that are context dependent **(Figure 4.3)**. On the other hand, there is a wide range of adaptation measures such as creating green roofs for buildings or improving the efficiency of irrigation for agriculture that may have little impact on biodiversity, or that can have direct and indirect benefits **(Figure 4.3)**.

Adaptation is placed and context-based and should be viewed as an ongoing and iterative process. Disseminating climate change adaptation information and communicating it effectively to a broad range stakeholder affected by climate change is one of the keystones for effectiveness.


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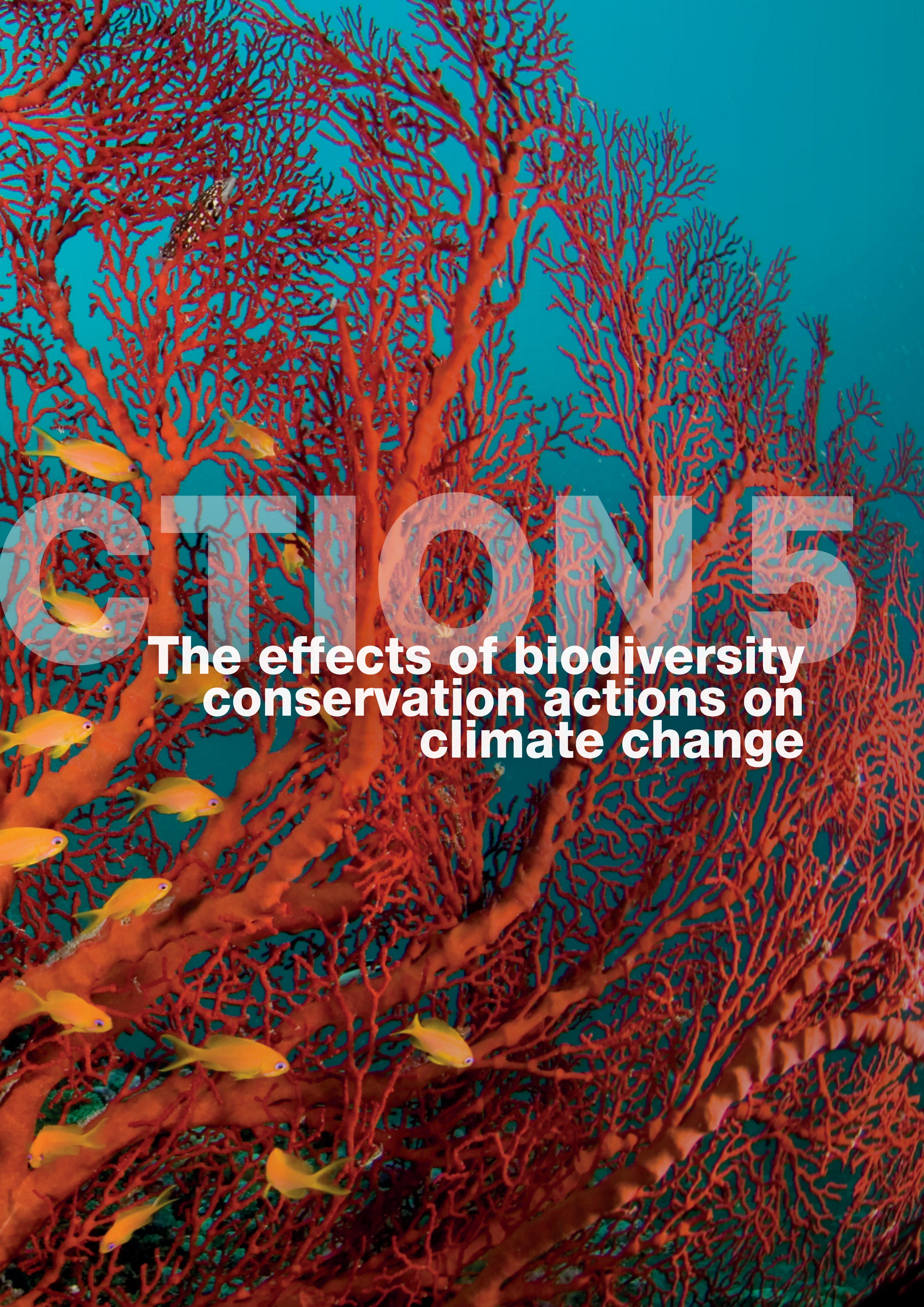


CTION 5

The effects of biodiversity conservation actions on climate change

SECTION 5

The effects of biodiversity conservation actions on climate change

INTRODUCTION

In this section, the effects of actions to halt or reverse biodiversity loss on the climate system are evaluated. We focus on links between conservation actions and climate change mitigation since links between biodiversity and adaptation are addressed in Section 2. The value of nature in mitigating climate change is well recognized and has been quantified globally. Almost 30% of anthropogenic CO_2 emissions are absorbed onto the land surface through forest regrowth (Pugh *et al.*, 2019), enhanced photosynthetic CO_2 uptake and sequestration, the vast majority likely occurring in natural and semi-natural ecosystems. A further ca. 25% of anthropogenic CO_2 emissions is absorbed by the ocean (Friedlingstein *et al.*, 2019; IPCC, 2019b), due to both CO_2 solubility in the ocean and the organic carbon cycle driven largely by photosynthesis, carbon sequestration in coastal vegetated habitats and the biological pump that moves carbon from the upper ocean layers to the deep ocean waters and ocean floor sediments. These powerful natural sinks are currently the leading natural mitigation processes globally. Their carbon sequestration potential can be enhanced, both through ecosystem management on land, and in the oceans, though not without risks in each case. In the UNFCCC and CBD, the concept of nature-based solutions (NbS) has been proposed as a way to harness natural processes in contributing to solving the climate challenge and that reduces the risk to biodiversity in particular and may have other co-benefits. NbS therefore aim to make use of the powerful interactions between the climate system, the oceans and the land, without causing damage to ecosystems providing the climate mitigation and adaptation services. The techniques proposed include the enhanced sequestration of anthropogenic CO_2 on land and in the oceans, reduction of greenhouse gas fluxes to the atmosphere associated with ecosystem management (e.g., wildfires, land cover change and agricultural practices), and increasing the reflectivity of the land surface (albedo change). Actions taken to halt or reverse biodiversity loss almost always have some consequence for these processes, although the form and strength of such links vary.

The level of contribution of biodiversity conservation measures to climate change mitigation highly depends on the processes affected and the nature component involved. Just as it is important to distinguish between carbon capture (e.g., by photosynthesis), storage (e.g., in the bodies of organisms) and sequestration (e.g., buried below microbial activity in sediments) (Bax *et al.*, 2021, Figure 1), understanding differences between sinks and feedbacks also greatly aids understanding of climate and biodiversity interactions. Albedo feedbacks on climate may be an important component of climate change, but they are currently ignored by UNFCCC guidelines regarding how to account for the climate benefits of actions taken in support of climate mitigation.

Sequestration of organic carbon in soils slows the rate at which the products of photosynthesis are returned to the atmosphere by the process of respiration. These forms of sequestration associated with terrestrial ecosystems are referred to as 'green carbon' (Mackey *et al.*, 2008). The sequestration of organic carbon in marine processes and ecosystems is referred to as 'blue carbon', by analogy to the oceanic origin of these forms of sequestered carbon dioxide and other greenhouse gases (Mcleod *et al.*, 2011).

Carbon sinks are the result of net carbon capture and storage. Such sinks can be physico-chemical (e.g., direct oceanic uptake of CO_2, which leads to ocean acidification) or biological (photosynthesis). The sink is usually *in situ* (e.g., forests, peatlands, agricultural soils or mangroves) but sometimes act by exporting the carbon elsewhere (e.g., kelp forests exporting to deep seas, or the marine vertical biological pump) and a portion of the carbon is usually (but not always) sequestered (i.e., effectively removed from the biospheric carbon cycle for periods of centuries to millennia, e.g., by burial (Bax *et al.*, 2021; Mao *et al.*, 2020). Many natural carbon sinks are reduced by climate change, so they capture and store less carbon, thereby exacerbating climate change further (positive feedback). In contrast, some carbon sinks, such as polar continental shelves and hyperboreal forests (taiga) increase with climate change, so they work as a negative feedback (strengthening mitigation). The current size and strength of carbon sinks are only partly related to the strength of climate feedback loops. Climate-induced sea ice losses around the Southern Ocean have increased phytoplankton blooms, which have doubled carbon storage by seafloor organisms in the last 25 years (Barnes *et al.*, 2018). This makes it a significant negative feedback on climate change, despite only being a small carbon sink at ~160 MtC yr^{-1}. When conservation measures and nature-based solutions concern natural carbon sinks having both large size and negative feedback on climate change, they can be powerful in driving global temperature.

5.1 PRACTICES WITH STRONG POTENTIAL CO-BENEFITS OR TRADE-OFFS

Many policy measures to address biodiversity loss and degradation of ecosystem services have co-benefits with climate change mitigation and some have trade-offs. The update of the zero draft of the post-2020 global biodiversity framework (CBD, 2020) provides 20 action-oriented targets for 2030 which aim to contribute to the 2050 Vision for Biodiversity. Most of the framework targets have direct or indirect impacts on climate change mitigation **(Table 5.1)**, even though they were not primarily designed with this intention. Here, we highlight a subset of biodiversity measures that are shown to result in potentially strong or moderate impacts on the climate system, based on potential contribution to carbon capture, storage, and sequestration, the albedo effect, and non-CO_2 greenhouse gas fluxes.

5.1.1 Reducing threats to biodiversity

5.1.1.1 Wetland restoration, including effects on both carbon dioxide and methane fluxes

Wetland ecosystems (e.g., mangroves, mudflats, saltmarsh) support a diverse natural biota and provide vital contributions to people, such as freshwater and food, water purification,

Table ⑤ ① **Action targets for 2030, from the zero draft of the post-2020 global biodiversity framework (see CBD/POST2020/PREP/2/1 for the full and exact wording of the targets), and examples of biodiversity measures with impacts on climate change mitigation (see main text).**

The effects of biodiversity measures on climate change mitigation are colour coded (see legend), as well as the reliability of achieving the mitigation outcome. The colour coding reflects expert-judgement based on scientific literature (see supplementary material) and is supported by the corresponding section in the main text. Note that when scientific evidence is too scarce for a biodiversity target (i.e., its impact on climate change mitigation), no biodiversity measure is documented (T10 and T18; T: target). T7 is not colour coded as it is the outcome of all other targets, as documented in the table.

Contribution to climate change mitigation

🟩	Significantly positive, strong scientific evidence
🟢	Potentially positive, incomplete evidence and quantification
🟨	Unresolved, lack of evidence, system-dependent, tradeoffs
🟧	Negative, strong scientific evidence
⬛	Indirect positive
⬜	Loose or non-existent link

Reliability of the mitigation outcome

🟩┅	Chance of achievement > 2/3
🟢┅	1/3 < chance of achievement < 2/3
🟨┅	Unresolved, conflicting/insufficient evidence
🟧┅	Chance of achievement < 1/3

Post-2020 Action targets for 2030	**Biodiversity measures** (and corresponding subsection in the main text)	**Effects on climate change mitigation**	**Reliability** mitigation outcome
⑤ ① Ⓐ **Reducing threats to biodiversity**			
T1. Spatial planning addressing land/sea use change, retaining existing intact wilderness areas, and restoring degraded natural areas	5.1.1.1. Inland wetland restoration	🟨	🟨┅
	5.1.1.2. Coastal restoration	🟩	🟢┅
	5.1.1.3. Reforestation and avoided degradation	🟩	🟢┅
	5.1.1.4. Restoring degraded semi-arid ecosystems	🟢	🟨┅
	5.1.1.8. Avoided deforestation	🟩	🟢┅
	5.1.1.11. Biodiversity offsets	🟨	🟢┅
T2. Well connected and effective system of protected areas, at least 30% of the planet	5.1.1.5. Protected areas and connectivity	🟩	🟩┅

Table ⑤ ①

Post-2020 Action targets for 2030	**Biodiversity measures** (and corresponding subsection in the main text)	**Effects on climate change mitigation**	**Reliability** mitigation outcome
T3. Recovery and conservation of wild species of fauna and flora	5.1.1.6. Rewilding with large terrestrial mammals	🟨	🟨
	5.1.1.7. Rebuilding marine megafauna	🟩	🟩
T4. Legal, sustainable and safe harvesting, trade and use of wild species of fauna and flora	5.1.1.9. Sustainable fishing	🟩	🟩
T5. Reduced rate of new introductions of invasive alien species, control or eradication of invasive alien species			
T6. Reduced pollution from all sources, incl. excess nutrients, biocides, plastic waste	5.1.1.10. Reducing pollution from all sources	🟩	🟩
T7. Increased contributions to climate change mitigation, adaptation and disaster risk reduction			
⑤ ① Ⓑ Meeting people's needs through sustainable use and benefit-sharing			
T8. Ensured benefits, incl. food security, livelihoods, health and well-being through sustainable management of wild species	See **T4** and **T14**	🟩	🟩
T9. Supporting the productivity, sustainability and resilience of biodiversity in agricultural and other managed ecosystems through conservation and sustainable use of such ecosystems	5.1.2.4. Regenerative agriculture	🟩	🟩
	5.1.2.5. Intensive vs less intensive agriculture	🟨	🟩
	5.1.2.1. Combatting woody plant encroachment	🟧	🟨
	5.1.2.2. Enhancing biodiversity conservation in transformed ecosystems	■	🟧
	5.1.2.3. Avoiding degradation of permafrost areas	🟩	🟩
T10. Contribution to regulation of air quality, hazards and extreme events and quality and quantity of water		🟨	🟨
T11. Increased benefits from biodiversity and green/blue spaces for human health and well-being	5.1.2.6. Biodiversity-friendly urban areas	🟩	🟩
T12. Ensured access to and the fair and equitable sharing of benefits arising from utilization of genetic resources and traditional knowledge			
⑤ ① Ⓒ Tools and solutions for implementation and mainstreaming			
T13. Biodiversity values mainstreamed across all sectors and integrated into policies, regulations, planning, development, poverty reduction and accounts at all levels	5.1.3.4. Mainstreaming biodiversity	🟩	🟩
T14. Reduced negative impacts on biodiversity through sustainable production practices and supply chains	5.1.3.1.Sustainable food production and supply chains	🟩	🟩
T15. Eliminating unsustainable consumption patterns, taking into account individual and national cultural and socioeconomic conditions	5.1.3.2. Sustainable consumption patterns	🟩	■

Table ⑤ ①

Post-2020 Action targets for 2030	**Biodiversity measures** (and corresponding subsection in the main text)	**Effects on climate change mitigation**	**Reliability** mitigation outcome
T16. Preventing, managing or controlling potential adverse impacts of biotechnology on biodiversity and human health			
T17. Measures to redirect, repurpose, reform or eliminate incentives harmful for biodiversity	5.1.3.3. Eliminating subsidies harmful to biodiversity	🟩	🟩
T18. Increasing financial resources and implementing the strategy for capacity-building, technology transfer and scientific cooperation		⬛	🟨
T19. Quality information, incl. traditional knowledge, is available for the effective management of biodiversity through promoting awareness, education and research			
T20. Equitable participation in decision-making related to biodiversity and ensured rights over relevant resources of indigenous peoples, local communities, women and youth			

and flood prevention. Humans have been enjoying such benefits for millennia for agriculture, aquaculture, and urban development, among other activities, which often led to widespread wetland degradation (IPBES, 2018). Although wetland restoration is valued and practiced in many regions, conflicts between economic interests of stakeholders, such as developers and conservationists, often hamper restoration progress (Marazzi *et al.*, 2018).

Wetlands are important for global carbon sequestration, but their disturbance could result in increases of greenhouse gases (Adhikari *et al.*, 2009). Conversion, drainage and degradation of tropical wetlands and peatlands are important drivers of current increases in the atmospheric concentration of CH_4 and its inter-annual variability (Shukla *et al.*, 2019). Irrigated rice cultivation, which takes place mostly in former wetlands is also an important contributor to CH_4 in the atmosphere (Shukla *et al.*, 2019), noting that many irrigated rice areas are sites for the protection of endangered species e.g., in terms of RAMSAR (Xi *et al.*, 2020). On the other hand, protection and restoration of wetlands, peatlands and coastal habitats reduces net carbon loss to the atmosphere (primarily from the oxidation of sediments and soil carbon) and provides continued or restored natural CO_2 removal (IPCC, 2019a; Section 4.9.4). Reducing annual emissions from peatland restoration could mitigate 0.15 to 0.81 $GtCO_2e\ y^{-1}$ up to 2050 (Couwenberg *et al.*, 2009; Griscom *et al.*, 2017; IPCC, 2019b; Section 2.7.1.4).

Wetland drainage and rewetting was included as a flux category under the second commitment period of the Kyoto Protocol, with significant management knowledge gained over the last decade (IPCC, 2013). However, there are high uncertainties as to the carbon storage and flux rates, in particular the balance between CH_4 sources and CO_2 sinks (IPCC, 2019a; Spencer *et al.*, 2016; Section 2.7.1.4). Peatlands, many of which harbour a specialized set of organisms, are often regarded as being of high value for biodiversity and thus are often a target of conservation measures with the aim to maintain or restore them. Climate change may increase carbon uptake by vegetation and carbon emissions due to respiration, with the balance being regionally dependent (IPCC, 2019a; Section 2.7.1.4), and one can expect the same ambiguity of the balance when mitigating climate impacts through restoration measures.

There is large uncertainty regarding the future of the peatland carbon sink globally. Some peatlands have been found to be resilient to climate change (Minayeva & Sirin, 2012), but the combination of land use change and climate change may make them vulnerable to fire (Sirin *et al.*, 2011). While models show mixed results for the future sink (Spahni *et al.*, 2013; Chaudhary *et al.*, 2017; Ise *et al.*, 2008), a study that used extensive historical data sets to project change under future warming scenarios suggested that the currently global peatland sink could increase slightly until 2100 and decline thereafter (Gallego-Sala *et al.*, 2018).

Recent evidence (IPCC, 2019a, Chapter 2) shows that tropical wetland CH_4 emissions are underestimated, perhaps by a factor of 2. One suggestion is that estimates do not account for release by tree stems (Pangala *et al.*, 2017). However, several authors have concluded that agriculture is a more probable source of increased emissions, and particularly from rice and livestock in the tropics, which is consistent with inventory data (Wolf *et al.*, 2017; Patra *et al.*, 2016; Schaefer *et al.*, 2016).

5.1.1.2 Coastal restoration

Coastal ecosystems are under pressure as a result of both local and global changes. They are exposed to changes in variables such as temperature, acidification, sea level rise, salinification and exposure to intensified storms, each of which are undergoing rapid changes under climate change (IPCC, 2014a, 2014b, 2018). Urbanization is also exerting a strong pressure on coastal ecosystems with increasing clustering of cities along the coasts (Barragán & de Andrés, 2015). The range of many coastal ecosystems has been contracting as a result (e.g., mangroves: (Babcock *et al.*, 2019); coral reefs: (IPCC, 2020); seagrass: (Waycott *et al.*, 2009)) or moving (Poloczanska *et al.*, 2016), threatening biodiversity and ecosystem services (see Section 5.2.3). Critically, the destruction and degradation of these habitats, the second most important drivers of biodiversity loss in marine ecosystems (IPBES, 2019) have led to reduced ‘blue carbon’ stocks as biomass accumulation slows and soils are exposed to increased oxidation of organic deposit (Mcleod *et al.*, 2011).

Coastal zones are highly productive areas with rich interactions across the transition from land to coastal and oceanic areas. Specific habitats and ecosystems are found along coastal regions, housing large amounts of biological diversity, and providing valuable ecosystem services to human communities (e.g., water quality, carbon sequestration, food, livelihoods, cultural services, coastal protection and increasing impacts from rising sea levels (Mcleod *et al.*, 2011)). The opportunity and ecosystem services provided by coastal plant communities presents very significant benefits to coastal communities and biodiversity. Blue carbon stocks relate to the sequestration of organic carbon from coastal productivity into ‘blue’ carbon that is stored in the soils and sediments of coastal ecosystems such as seagrasses, salt marsh and mangroves (Mcleod *et al.*, 2011). It is the marine twin of analogous stocks of buried organic carbon (i.e., ‘green’ carbon) from terrestrial ecosystems. While the total sequestration of carbon is much lower in coastal systems, the amount per m^2 is typically much higher. In combination, carbon sequestration can play a very significant role in trapping and preventing the oxidation of hundreds of years of organic carbon being sequestered in soils and sediments. Protecting these ecosystems has considerable benefits, with the protection and restoration of these areas of considerable value.

Increasingly, attention has focused on the restoration of coastal ecosystems, with adaptive responses accommodating the loss or movement of critical ecosystems (e.g., mangroves, seagrass, coral reefs, salt marshes) as sea temperature as well as sea level and storm impacts increase. The success of these options varies between ecosystems. For example, mangrove forests are capable of storing and sequestering a substantial proportion of carbon in both their biomass and soil substrates even when fringing dense urban development areas, as demonstrated in Singapore (Friess *et al.*, 2015). (Bayraktarov *et al.*, 2016) reviewed restoration costs across a range of coastal ecosystems and found that the average and median costs of restoration of marine coastal habitat was US$80,000 per hectare (2010) and US$1,600,000 ha^{-1} (2010), respectively. Coral reefs and seagrass beds were among the most expensive ecosystems to restore, while mangrove restoration projects were the least expensive per hectare with projects being larger. Restoration projects often did not last – they were often damaged by ongoing stress, including climate change.

5.1.1.3 Reforestation and avoided degradation of tropical and subtropical forests and woodlands

Land use change in tropical forests and subtropical woodlands and savannas drives multiple shifts in ecosystem structure and function (Baldi & Jobbágy, 2012; Baldi *et al.*, 2013), with globally negative impacts on biodiversity and carbon stocks (Mackey *et al.*, 2020). Agricultural expansion in these systems is the largest current threat to their conservation and biodiversity (e.g., Laurance *et al.*, 2014). Growing demand for food is likely to drive agricultural expansion by 100 million ha in sub-Saharan Africa, especially in woodlands and savannas with enough rainfall to support crops (Estes *et al.*, 2016).

Primary forest clearing is particularly significant for carbon stocks (estimated carbon recovery rate of 40-100+ years, (Mackey *et al.*, 2020)) and biodiversity, due to amplified adverse effects of forest cover loss on conservation value (Barlow *et al.*, 2016). Dryland forest and savanna deforestation and degradation have proceeded over many decades, threatening carbon stocks and the rich biodiversity in South America (Mustin *et al.*, 2017) (e.g., in Chaco and Cerrado systems (Mustin *et al.*, 2017), Asia (forest; Tölle *et al.*, 2017) and Australia (e.g., Eucalypt woodlands; Queensland Department of Science, Information Technology and Innovation, 2017), with high biodiversity African woodlands (Kier *et al.*, 2005) having some of the highest deforestation rates in the world (Zambia’s deforestation rate is 2500 – 3000 km^2 y^{-1}, (Vinya *et al.*, 2011)). Despite degradation affecting almost one fifth of southern African woodlands, biomass gains over about one half of the region balanced losses of carbon stocks between 2007 and 2010 (McNicol *et al.*, 2018).

Deforestation in some regions has led to problems of soil salinization, due to rising water tables, especially in Australian drylands (Bradshaw, 2012), but is also noted in dryland forests of South America (Marchesini *et al.*, 2017). Deforestation of woodlands for biofuel production (e.g., Jatropha planting) has been widespread (van Eijck *et al.*, 2014), and for African Miombo, woodlands have been found to create a carbon deficit, mainly relating to soil carbon losses (Romijn, 2011). Reforestation or restoration of degraded forests and woodlands with indigenous species plays a role in addressing losses of biodiversity and ecosystem services, including through recovering the soil carbon stocks of these ecosystems (e.g., Sileshi, 2016). Reforesting up to 369 million ha of degraded tropical forest (less than half the potentially reforestable area) could generate a potential C uptake of 5.5 PgCO^{2}e yr^{-1} by 2030, and contribute to the conservation of hundreds of threatened forest-dependent vertebrate species (Kemppinen *et al.*, 2020). Spatially targeted reforestation efforts could re-establish forest habitat continuity with outsize positive impacts (e.g. Atlantic Forest, (Newmark *et al.*, 2017)). Financial incentives currently encourage reforestation using monoculture plantations of non-indigenous species (e.g., Lewis *et al.*, 2019), and some massive silviculture programs are planned (e.g. Brazil (Mustin *et al.*, 2017), Ethiopia, (Pistorius *et al.*, 2017)) motivated both by financial and by mitigation objectives. Reforestation using non-indigenous species may be associated with significant risks (Reisman-Berman *et al.*, 2019), while contributing to carbon sequestration in above ground stocks (Guedes *et al.*, 2018).

Misidentification of subtropical grassland systems with high frequency disturbance regimes as degraded risks significant adverse biodiversity effects if this encourages their afforestation (Bond *et al.*, 2019). Even without direct afforestation efforts, Asian (Kumar *et al.*, 2020) and African (Pfeiffer *et al.*, 2020) mixed savannas and woodlands are at significant risk of conversion from grassland to woodland dominated systems due to climatic and CO$_2$-fertilization effects. Mixed tree-grass systems (woodlands and savannas) are threatened by woody plant encroachment globally (Stevens *et al.*, 2017) with adverse impacts on the biodiversity of species dependent on “open” systems (Bond & Parr, 2010). Suppression of wildfire represents an apparently attractive approach to enhance woody carbon stocks in mixed tree/grass systems, but increased carbon stocks (e.g., 1.2 Mg ha^{-1} year^{-1} accrued since 1986 in a fire-suppressed Brazilian Cerrado) likely lead to loss of diversity (richness declines for Brazilian Cerrado one quarter of plant and one third of ant species) (Abreu *et al.*, 2017).

5.1.1.4 Restoring degraded semi-arid ecosystems

Degradation of semi-arid ecosystems is often associated with significant losses of soil, and the carbon that is held in that soil (e.g., Chappell *et al.*, 2016, 2019). Reversal of soil degradation linked to desertification trends has long been a focus of the UN Convention to Combat Desertification (UNCCD), but progress may require greater focus than is currently the case in policy instruments such as the Sustainable Development Goal framework (Byron-Cox, 2020). Rebuilding soil (especially) and plant carbon stocks in semi-arid regions is seen as a potentially significant contribution to mitigation of CO$_2$ emissions due to their large extent but has seen contradictory claims of efficacy in the last decade (Yusuf *et al.*, 2015). The capacity of restoring degraded semi-arid systems using land use management approaches is thus somewhat contested (Gosnell *et al.*, 2020). Many semi-arid systems around the world have been observed through remote sensing as having “greening” trends (Fensholt *et al.*, 2012). This has been speculated as being due to the effects of rising atmospheric CO$_2$ in increasing plant water-use efficiency (Donohue *et al.*, 2013) thereby increasing the competitive advantage of woody plants over grasses and increasing woody cover in these ecosystems. Global analysis of remote-sensed data suggests that greening is generally associated with soil drying as a result of higher plant cover (Deng *et al.*, 2020), and woody encroachment also reduces grazing potential (Anadón *et al.*, 2014).

5.1.1.5 Increasing the area under protection and enhancing connectivity

Two of the main biodiversity and habitat conservation measures include establishing protected areas and enhancing ecological connectivity among protected areas and fragmented habitat patches (Dinerstein *et al.*, 2019; Kostyack *et al.*, 2011; Townsend & Masters, 2015). Habitat conservation by creating new protected areas and maintaining existing areas can mitigate climate change (Dinerstein *et al.*, 2020; UNEP, 2019) through carbon sequestration (Dawson *et al.*, 2011; Hagerman *et al.*, 2010; Soares-Filho *et al.*, 2010; UNEP, 2019). Globally, terrestrial and marine protected areas cover 265,908 (15.13% of terrestrial habitats) and 18,584 (7.68% of marine habitats) sites, respectively (UNEP-WCMC, 2021). Terrestrial protected areas store approximately 238 GtC (2,078.83 Gt CO^{2}e) (12% of land carbon stocks), and they sequester 0.5 GtC yr-1 (i.e., 1.835 GtCO$_2$e yr^{-1}, 20% of all terrestrial carbon stocks) (Melillo *et al.*, 2016). Protected areas also act as a negligible source of carbon export to the atmosphere. For example, 2018 protected areas from tropical countries store a total of 35.8∓ 15.7 GtC (131.386∓57.619 Gt CO$_2$e, 14.5% of total carbon biomass estimated in tropical countries), with a mean loss of 38∓17 MtC yr^{-1} (139.46 ∓ 62.39 Gt CO$_2$e) (Collins & Mitchard, 2017).

To reverse biodiversity loss, as well as enhancing climate change mitigation, it has been estimated that 30.6% of unprotected land surface (41 million km^2) would need to be added as protected areas, on top of the existing 15.1% of protected areas, which would contribute to continued storage of 1.49 GtC (5.473 Gt CO_2e) of carbon from such unprotected lands through conservation of diversity and abundance of terrestrial life as well as enhancement of carbon drawdown and storage (Dinerstein *et al.*, 2020). Interestingly, 92% of the area needing protection for enhancing carbon storage and drawdown are covered by the area needed to reverse biodiversity loss. (Hannah *et al.*, 2020) calculated that by limiting global warming to 2°C and conserving 30% of the terrestrial surface, aggregate extinction risk would be more than halved relative to a base case of unmitigated climate change and no increase in conserved areas. These studies emphasize the strong interlinkage between conservation, biodiversity, and climate change mitigation.

Currently, 7% of the global oceans are in protected areas (see Section 2). It is widely agreed that increased coverage of marine protected areas is required to protect marine biodiversity (30% protection by 2030 has been proposed) vis-à-vis mitigating climate change impacts by sequestering carbon in those areas (O'Leary *et al.*, 2016; Roberts *et al.*, 2017; Sala *et al.*, 2021). MPAs can act as wildlife refugia in the changing environment and prevent the loss of species, including those playing a key role as carbon sinks or mediators of C sequestration, and help restoring carbon-rich ecosystems (see Sections 5.1.1.6 and 5.1.1.7)

Establishing ecological corridors through landscape conservation or ecoregion-based approaches is essential to enhance the efficiency of protected areas in fragmented landscapes and seascapes (Dinerstein *et al.*, 2017; Keeley *et al.*, 2018; Littlefield *et al.*, 2019). A large number of corridors have carbon densities that approach or exceed those of the protected areas they connect, containing for example 15% of the total unprotected aboveground carbon in the tropical region (Jantz *et al.*, 2014). Under the 'Global Safety Net' plan that aims to reverse biodiversity loss and increase C storage and drawdown, only 4.3% of additional area (based on 2.5 km corridor width) would be required to connect all current protected areas by potential wildlife and climate corridors (Dinerstein *et al.*, 2020). In the marine realm, ecological representation and connectivity between marine protected areas would require at least 30% of sea protected with a focus on areas most affected by human activities (Roberts *et al.*, 2020).

The connectivity requirement is especially high in fragmented biomes that are functionally dependent on processes that operate over scales larger than the typical protected area or remnant fragments, for example tropical forests (including dry forests), temperate grasslands, and tropical grasslands (Dinerstein *et al.*, 2020). Successful connectivity conservation includes community involvement, habitat priority setting, forest landscape restoration, and environmental services payments that satisfy tenets of climate-smart conservation, improve the resilience of human and ecological communities (Littlefield *et al.*, 2019; Townsend & Masters, 2015). Progress in protecting and restoring habitat connectivity has been slow (Keeley *et al.*, 2018), and the climate benefits of connectivity conservation have not been fully explored.

In cities, natural and semi-natural areas are inevitably fragmented. To maximize biodiversity conservation, green infrastructures acting as ecological corridors can be set up: e.g., a) roadsides planted with multi-tiered planting with diverse native species (Chan, 2019), b) park connectors, rooftop and vertical greenery, and c) naturalizing drainage channels) that also contribute to climate change mitigation by reducing urban heat islands and increasing carbon sequestration and carbon sinks (see Sections 5.1.2.6 and 5.2.2).

5.1.1.6 Rewilding with large terrestrial mammals

This topic is also discussed in Section 3.3.4. Rewilding includes fostering the regrowth of natural vegetation as well as the reintroduction of native fauna, such as large predators and herbivores. Vegetation regrowth, especially naturally regenerating trees and shrubs in rewilded areas, contributes to climate change mitigation by capturing carbon dioxide and enhancing above-ground carbon pools (see Section 3). Animals have long been considered irrelevant for carbon cycling in land ecosystems, simply because their biomass is orders of magnitude lower than that of plants and microbes (Bar-On *et al.*, 2018; Schmitz *et al.*, 2018). This view is being challenged by an increasing body of literature. Herbivory reduces above-ground live biomass, enhances light transfer into the canopy, and increases nutrient input to the soil through impact on litter amount and quality. Herbivory also affects canopy structure, ranging from shifts in the ratio of woody to herbaceous vegetation in grasslands and savannas, to age structure and species composition in forests (Sankaran *et al.*, 2013; Schmitz *et al.*, 2018; Tanentzap & Coomes, 2012). Cascading trophic effects triggered by top predators or the largest herbivores propagate through food webs and reverberate through the functioning of whole ecosystems, changing productivity and net carbon storage significantly (Malhi *et al.*, 2016; Schuldt *et al.*, 2018). Carnivore-herbivore-plant interactions mediate soil and ecosystem carbon and nitrogen turnover rates (Schmitz *et al.*, 2018; Tanentzap & Coomes, 2012), thus affecting fundamental properties of the terrestrial carbon cycle. The overall impact on carbon uptake (and thus climate change) is not yet well understood and likely will differ between regions and ecosystem types. These carbon side effects associated with rewilding would need to be monitored in order to determine the biodiversity-climate interactions of rewilding efforts.

5.1.1.7 Rebuilding marine megafauna

Marine mammals, sharks and big predatory fish have been severely overexploited for decades (Myers & Worm, 2003; Roman, 2003), and are now the focus of many conservation programs around the world. The functional role of these emblematic species in the global carbon cycle has often been neglected because of their relatively low biomass compared to other taxa, and historically low levels reached today. Recent studies show that these predators are important to consider either as carbon sinks or mediators of carbon sequestration in the ocean (Atwood *et al.*, 2015; Heithaus *et al.*, 2014; Lavery *et al.*, 2010; Mariani *et al.*, 2020; Passow & Carlson, 2012; Roman & McCarthy, 2010).

The role of predators has been particularly scrutinized in marine vegetated coastal habitats (seagrass meadows, mangroves, salt marshes), identified as carbon-rich ecosystems that bury C at fast rates, especially mangroves (Alongi, 2014), and contribute 50% of the total C buried in ocean sediments (Duarte *et al.*, 2005). In these coastal wetlands, predators are essential to control the behaviour, the abundance, the life history traits of herbivores and bioturbators which in turn impact the canopy height, root and shoot densities of the macrophytes, all characteristics playing a role in C capture and storage in plants, C sequestration in sediments, and particle trapping (Atwood *et al.*, 2015). Trophic downgrading triggered by the loss of predators can on the contrary lead to the complete loss of salt marshes and seagrass habitats (Atwood *et al.*, 2015), or severe reduction in the density of kelp forests (Wilmers *et al.*, 2012). The case of the green turtle, a vulnerable and emblematic species, poses an interesting conservation challenge, as this seagrass grazer, when at low to moderate densities, plays an important role in enhancing seagrass health by preventing the formation of sediment anoxia. However, at high densities subsequent to intense rewilding programs, and in the absence of overexploited sharks, their main predators, green turtles can overgraze and deplete seagrass beds (Heithaus *et al.*, 2014). Hence the necessity to envision and settle an integrated ecosystem-based conservation program, preserving healthy populations of both sharks and turtles to help restore seagrass habitats.

In offshore waters, whales contribute to the biological pump, i.e., the removal of C from the euphotic zone to the deep sea and sea bottom where it can be sequestered for several centuries or more (Passow & Carlson, 2012), either through the active vertical migration of animals (Aumont *et al.*, 2018) or through the passive sinking of feces, aggregates, and dead organisms. The sinking of whales' carcasses is negligible compared to other contributors to the biological pump, it is however a synergistic positive outcome of rebuilding programs (Pershing *et al.*, 2010). Maybe more important is the role played by whales' fecal plumes in fertilizing surface waters in allochthonous limiting nutrients, iron in particular, boosting primary production and thereby capturing atmospheric C through to the ocean biological pump (Lavery *et al.*, 2010; Roman & McCarthy, 2010).

5.1.1.8 Avoided Deforestation

Tropical deforestation is a key driver of biodiversity decline and contributed to almost one fifth of global anthropogenic greenhouse gas emissions during the 1990s (annual emissions of about ~1.5 GtC, Gullison *et al.*, 2007). International efforts to incentivize the slowing and ultimate avoidance of deforestation were accelerated in the mid-2000s with the negotiation of this modality under the UNFCCC from 2005. The REDD+ mechanism (reducing emissions from deforestation and forest degradation in developing countries, REDD+) was adopted by the UNFCCC in 2007. Potential synergies between mitigation and biodiversity goals have been described as an unprecedented opportunity, but a review of 80 REDD+ projects showed that biodiversity conservation goals lacked specificity, and that links between goals, actions and monitoring efforts were not coherent (Panfil & Harvey, 2015). National level reporting under UNFCCC and CBD frameworks provides a significant opportunity to align national mitigation and biodiversity goals relating to REDD+ (e.g., Johnson *et al.*, 2019).

Recent evidence shows that the REDD+ mechanism has been effective in some regions, for example, leading to the avoidance of 1.5 (+/-0.4) Pg (Gt) of CO_2 equivalent emissions from tropical forest in Brazil alone, due to the maintenance of 62,321 km^2 of forest between 2006 and 2017 (West *et al.*, 2019). However, barriers to full implementation of the mechanism are limiting its effectiveness in some tropical regions such as in Indonesia (Ekawati *et al.*, 2019) and in Africa (Gizachew *et al.*, 2017). Full cost benefit analysis of REDD+ projects and activities are challenging due to the fact that few studies quantify all elements. Indications are that the full cost of REDD+ on average, including opportunity, implementation and transaction costs, are below 25USD per ton of CO_2eq, but estimates of non-monetary and indirect benefits of REDD+ are lacking due to a lack of expertise and inadequate information about environmental and biodiversity benefits (Rakatama *et al.*, 2017).

5.1.1.9 Sustainable fishing

Fishing activities are the main driver of marine biodiversity loss (IPBES, 2019; Rogers *et al.*, 2020). There is increasing evidence that fishing, even at sustainable levels, could impact carbon fluxes and sequestration in the deep ocean and seafloor, and hence on climate change mitigation (Mariani *et al.*, 2020). Climate change should therefore become part of the broader ecosystem-based approach to fisheries management, not only in terms of adaptation (see Section 4) but also in terms of mitigation. Fisheries management currently does not take into account the potential role of exploited species in the carbon cycle and in biogeochemical processes, nor does it consider the potential for carbon release from sediment disturbance (Sala *et al.*, 2021). The most common management target for sustainable fisheries is the maximum sustainable yield (MSY) where all sources of mortality, including fishing mortality, are compensated by the intrinsic growth rate of the exploited population. This corresponds to removing about half of the pristine biomass, which can have important consequences for the ecosystem functioning, and on carbon fluxes. There are different pathways for C sequestration in the ocean that are mediated by exploited fish and invertebrate species.

A direct consequence of fishing on the carbon flux is the export of ocean C to land and ultimately to the atmosphere that would otherwise be sequestered in the deep sea for centuries or more (Mariani *et al.*, 2020; Saba *et al.*, 2021). Downward passive transport occurs through sinking of dead carcasses but also sinking of faecal pellets of fish and invertebrates, and this has been shown to be a significant contribution to the biological pump. In the Southern Ocean, krill (*Euphausia superba*) which is targeted by the largest fishery in the region (Cavan *et al.*, 2019), is estimated to be responsible for about 35% of current export of carbon to the ocean floor in the marginal ice zone, just through the rapid sinking of faecal pellets (Belcher *et al.*, 2019). Although the contribution of fishing to the extraction of blue carbon is yet to be quantified globally, first estimates show that direct fishing impacts are not negligible and so limiting them could add up to the panel of conservation measures that mitigate climate change. It was estimated that fisheries targeting large pelagic fish (tunas, billfishes, sharks and mackerels) have released a minimum of 0.73 Gt CO_2e since 1950 (Mariani *et al.*, 2020). In addition to disturbing the downward passive transport of carbon to the deep ocean, fishing also impacts the biological pump by extracting organisms that realize active diurnal vertical migration (DVM) through hundreds of meters. DVM is a widespread phenomenon across oceans involving about one third of the epipelagic biomass (Aumont *et al.*, 2018). Migratory organisms feed at the surface at night, and then join the deeper mesopelagic domain during daytime where they excrete and produce faecal pellets. The flux of carbon driven by DVM is estimated to be 1.05 ± 0.15 PgC/year, about 18% of the passive flux of carbon (Aumont *et al.*, 2018). Fishing these migratory species is expected to impact the strength of the biological pump, though it has not been quantified yet. In addition, the development of new fisheries on mesopelagic and deep-sea fish and invertebrates needs to be considered carefully not only in the light of biodiversity conservation, but also in terms of the potential disruption of the biological pump which in part relies on the trophic coupling between the mesopelagic community and the benthopelagic feeding demersal community that contributes to the long-term C sequestration in benthic sediments (Trueman *et al.*, 2014).

An additional effect of fishing on the carbon cycle comes from the disruption and resuspension of sediments by bottom trawling, enhancing remineralization of organic matter and releasing CO_2 in the water column (Atwood *et al.*, 2020). About 1.3% of the global ocean is trawled each year (Sala *et al.*, 2021); most of this occurs on continental margins where there is extensive long-term storage of organic carbon (Atwood *et al.*, 2020). If this seabed surface was undisturbed, global sediment carbon emissions after 1 year of trawling are estimated at 1.47 Pg aqueous CO_2, equivalent to about 15-20% of the atmospheric CO_2 absorbed by the ocean each year (Sala *et al.*, 2021). It was also suggested that ninety percent of trawling-induced carbon release could be eliminated by protecting 3.6% of the seafloor from fishing, targeting the areas of greatest carbon storage with the most intense trawling (Sala *et al.*, 2021). Additional investigation is needed into novel approaches to secure C stocks in the face of fishing disruption (e.g., through changes in target species, gear, target areas).

5.1.1.10 Reducing pollution from all sources

Eutrophication, the addition of excess nitrogen and phosphorus or organic matter to aquatic ecosystems, is a major form of inland water and coastal pollution, with many effects on the climate and on biogeochemical cycles of carbon, nitrogen, phosphorus, sulphide and silica (Rabalais *et al.*, 2014). Coastal and lake eutrophication can result from organic matter loading via sewage discharges or aquaculture, agricultural fertilizer runoff from land, or burning of fossil fuel (Breitburg *et al.*, 2018; Deininger & Frigstad, 2019). Excess primary and secondary production stimulated by the nutrient input leads to the consumption of oxygen and production of carbon dioxide due to microbial decomposition; this is exacerbated by warming temperatures and enhanced precipitation which may promote stratification and oxygen loss, while amplifying ocean acidification. Eutrophic ocean waters that become hypoxic or suboxic may experience denitrification and ammonium oxidation and release of nitrous oxide (Naqvi *et al.*, 2010), a potent greenhouse gas that results in negative climate feedback. Additionally, under anoxic conditions release of inorganic phosphate and iron from sediments stimulates further primary production and oxygen consumption, as is the case in the oxygen minimum zone (OMZ) waters off Peru and the Arabian Sea (Linsy *et al.*, 2018; Lomnitz *et al.*, 2016), and toxic hydrogen sulphide may be generated in water or sediments. In anoxic freshwater reservoirs, however, coupling of methanotrophy and denitrification may ameliorate N_2O release (Naqvi *et al.*, 2018). Also, eutrophic freshwater lakes (with > 30 ugTP l^{-1}) bury 5 times more organic carbon than non-eutrophic lakes (Anderson *et al.*, 2014).

Reduction of low oxygen zones through control of nutrient pollution (termed oligotrophication) may lead to a significant decrease in deoxygenation and the negative climate feedbacks associated with nitrous oxide, emissions or phosphorus and iron release. Use of wetlands to reduce nitrogen loads through river diversion (Engle, 2011) or through new construction (Jahangir *et al.*, 2016) may decrease coastal deoxygenation and associated N_2O or CH_4 emissions. However, efficiency of N removal in river diversion declines with increasing N load. Other benefits of reducing nutrient pollution include likely reduction of harmful algal blooms, which act as co-stressors by releasing toxins and contributing to deoxygenation (Griffith & Gobler, 2019; Pitcher & Jacinto, 2019).

5.1.1.11 Biodiversity offsets

Biodiversity offsetting is the practice of mitigating the residual biodiversity impacts of developments (e.g., mining, urban/housing development, agricultural expansion) by restoring the biodiversity, or setting aside areas for protection, elsewhere in the land- or seascape. The mechanism by which the practice of biodiversity offsetting could also mitigate climate change is through storage of carbon in biomass and soils in newly developed or restored habitats, either in public or private (often agricultural) lands. There are 12,983 listed biodiversity offsets under no net loss (NLL) principles implemented across 37 countries, predominantly forest ecosystems, covering 153,679 km^2 (estimates range between 89,456 and 178,692 km^2) (Bull & Strange, 2018). Much of the research on biodiversity offsets is concentrated in North America, Western Europe, and Australasia (Bull & Strange, 2018) and focuses on whether the NNL principle has been met in the offset program (e.g., (Ermgassen *et al.*, 2019). On the other hand, the trade-offs between biodiversity offsets, carbon storage and other nature's contributions to people have rarely been assessed (Sonter *et al.*, 2020). As for climate change mitigation, in principle, biodiversity offsets can compensate for forest loss with remote climate benefits in terms of carbon storage. For nature's contributions with widespread benefits such as global climate regulation, the spatial separation between the development sites and offset sites will not influence the benefits people obtain (Sonter *et al.*, 2020). However, a recent review indicated that only one third of biodiversity offsets met the NNL principle. None of the forest projects achieved NNL. Offsetting in wetland ecosystems was found to be more successful (Ermgassen *et al.*, 2019). This widespread failure raises concerns regarding the capacity of existing biodiversity offsetting implementation to mitigate climate change. There is also little evidence of the resilience of these offsets to climate change.

Where biodiversity offsets limit local people's access to, or loss of benefits from, the biodiversity and nature's contributions to people on which their livelihoods depend, it can have negative impacts on climate change adaptation (Jones *et al.*, 2019). For example, if nature (e.g., forests, wetlands, and mangroves) lost by development provided local people with benefits such as flood and storm surge regulation, then even though biodiversity offsets meet the NNL principle, if the location of the offsets are distant, local people are likely to lose nature's contributions that are vital for adapting to climate change. This suggests that biodiversity offsets can cause trade-offs and disconnects between local benefits from biodiversity, including capacities of adaptation to climate change, and nature's contributions with remote or global benefits. Such trade-offs are likely to be avoided or addressed more appropriately if the type and distribution of nature's contributions to people are considered in the offsetting process along with the NNL.

5.1.2 Meeting people's needs through sustainable use and benefit-sharing

5.1.2.1 Using fire and bush removal to combat woody plant encroachment

The process of bush encroachment has been observed on several continents, especially in tropical and subtropical latitudes. A poorly understood mix of management actions and climate change drivers, including (but not limited to) increasing CO_2 fertilization of tree growth, is leading to the conversion of formerly open ecosystems to a much more densely tree or bush-covered state (e.g., Stevens *et al.*, 2017). Among other impacts, this leads to reduced forage palatability and grazing capacity. The process occurs in disturbance-driven tropical ecosystems, which generally have much lower standing biomass than is potentially the case in the absence of disturbance (Bond & Midgley, 2012). Wildfire and browsing pressure maintain these systems in an "open" condition, and has done so for millennia, resulting in the iconic grassland and savanna landscapes and forest-averse diversity of tropical Africa, South America, and Australasia.

Experimental efforts using extreme fires and mechanical harvesting have been tested as a way of reversing bush encroachment (e.g., Smit *et al.*, 2016), with expected effects on biodiversity include reduced success of multiple species dependent on open, disturbance driven systems. Examples include the plains fauna of Africa, with clear direct negative impacts already visible for vulture, cheetah, and a myriad of smaller grassland bird species. By contrast, birds of woodlands and forests appear to be increasing in abundance in these regions. There are potentially substantive mitigation implications of bush encroachment and its reversal; in Namibia, for example, the extent of natural afforestation by bush encroachment is sufficiently large to offset national fossil fuel emissions (Ministry of Environment and Tourism, 2011). Nonetheless, it is to be noted that carbon stocks of grassland ecosystems may often be incorrectly discounted in comparison to woody ecosystems (Wigley *et al.*, 2020), due to the failure to account for below ground carbon stocks.

Maintenance of open ecosystems will ensure the persistence of disturbance driven habitats, and will also help to maintain streamflow (e.g., Creed *et al.*, 2019) and the maintenance of lower intensity wildfire regimes. Open ecosystems also provide multiple material benefits centred on subsistence livelihoods, including extensive grazing and thatching, and the irreplaceable cultural elements associated with these lifestyles. Recognition of the natural cooling effects of high albedo, and the plethora of benefits to people under threat in tropical open ecosystems would provide opportunities for sustainable management of these systems for both local and global benefit. In South Africa, active removal of woody encroachers has created millions of job opportunities, with some demonstrable results with respect to slowing alien plant encroachment (van Wilgen *et al.*, 2012).

5.1.2.2 Enhancing biodiversity conservation in transformed ecosystems

Transformation of ecosystems by human use has created a spectrum of ecosystems of different levels of biodiversity intactness (Newbold *et al.*, 2016), and biodiversity similarity (Newbold *et al.*, 2015). In transformed and highly managed ecosystems, *in situ* conservation of biodiversity remains important. It can be defined as measures to conserve and protect biodiversity at a range of scales (including genetic diversity – see paragraph below in this section, and also Section 2.2.5) (Oliveira & Bernard, 2017). For example, *in situ* conservation related to home gardens is a critical link to agrobiodiversity in urban areas (Ávila *et al.*, 2017), while *in situ* conservation in agriculture serves as the best demonstrated example of clear links to improved measures of biodiversity and its benefits to people (Babay *et al.*, 2020; Chimphango *et al.*, 2016; Malgas Rhoda *et al.*, 2008).

Measures to both protect and improve genetic diversity in managed ecosystems also are key to biodiversity and NCP in the agricultural sector (Rhoda *et al.*, 2008; IPBES, 2018, 2019), or in plantation forestry (Creed *et al.*, 2018). *In situ* conservation of biodiversity should be seen as one of a suite of practices effectively falling within agroecological principles. The contribution of conventional agriculture to biodiversity loss can be addressed through alternative agricultural systems, including sustainable intensification and complete redesign of farm management systems (e.g., ecological intensification and climate-smart agriculture) (VanBergen, 2020; Wanger *et al.*, 2020).

Although the links between these approaches and climate change adaptation are generally more widely known (see Section 2), measures addressing more sustainably managed ecosystems also have repercussions for climate change mitigation, via carbon sequestration and changes in albedo. (Samways *et al.*, 2020) discuss how addressing insect diversity loss through conventional agricultural practices may be better communicated through, for example, improved integration of insect conservation practices with climate-smart agricultural practices (including mitigation). Soil and water conservation measures in dryland agriculture potentially improve ground cover and soil carbon content (see Section 5.1.1.4 on drylands degradation; (VanBergen, 2020; Wanger *et al.*, 2020) and albedo (Creed *et al.*, 2018).

The body of evidence regarding the ability of the adoption of agroecological principles to achieve multiple benefits within agricultural landscapes (including improved conservation) is growing – although research gaps remain (see, for example, Wanger *et al.* (2020), and their discussion of a research agenda for agroecology). Increasingly, evidence should and, it is hoped, will be used to support agricultural transformation from conventional intensification systems to more sustainable alternatives – with the recognition that farmers cannot do it alone.

5.1.2.3 Avoiding degradation of permafrost areas

Northern and mountain permafrost contains twice as much carbon as the atmosphere and about four times more than all the carbon emitted by human activity in modern times, most of it occurs in perennially frozen soils and deposits (Ciais *et al.*, 2013; Schuur *et al.*, 2011; Tarnocai *et al.*, 2009). The Arctic rate of warming, 0.76°C decade^{-1} over 1998–2012, is greater than 6x Earth's average (Huang *et al.*, 2017). The degradation of permafrost due to climatic warming could change the global carbon cycle and enhance global climate change. Permafrost wetlands have been damaged by the minerals extraction industry (Opekunova *et al.*, 2018; Peterson, 2001), this leads to oxidation and the release of the carbon stored in their soils. Such changes are very likely to impact species richness negatively due to habitat loss and reduced water quality, increased risk of extinctions and extirpations of wetland endemic and dependent species (Shin *et al.*, 2019). Wise permafrost wetland management and restoration techniques will ensure that wetlands maintain their biodiversity and benefits to people such as water storage and sequestration of GHGs (Anisha *et al.*, 2020). Preservation of undamaged peatlands is essential in this regard, to keep carbon locked in the ground and to provide vital habitat for endangered species and requires stopping damaging practices involving drainage or excavation of peatlands and taking action to rewet and restore degraded peatlands (Avagyan & *et al.*, 2017). Successful management plans include the Long-Term Gravel Pad Reclamation in Alaska (Peterson, 2001) and the Strategic Plan for peatland conservation and wise use in Mongolia (Ariunbaatar & *et al.*, 2017).

Increasing the population density of large herbivores in northern high-latitude ecosystems increases snow density and hence decreases the insulation strength of snow during winter, thereby preventing or decreasing CH_4 release as a result of permafrost thaw. Besides, large herbivores provide summer albedo increase and additional carbon sequestration by soil. Such ecosystem management practices could be scaled up in Arctic permafrost areas as an ecosystem-based solution for global climate change mitigation strategy (see Sections 5.2.1, 5.2.2 and CS12 in Supplemental Material).

5.1.2.4 Regenerative agriculture

Climate mitigation response options related to land use are a key element of most modelled scenarios that provide strong mitigation. More stringent climate targets rely more heavily on land-based mitigation options, in particular carbon dioxide reduction (Jia *et al.*, 2019). However, these options describe more or less the opposite of what is generally meant by regenerative agriculture, which is closer to a NbS. Furthermore, estimates of the technical potential of individual response options are not necessarily additive. The largest potential for reducing agriculture, forestry and other land use (AFOLU) emissions are through reduced deforestation and forest degradation (0.4–5.8 $GtCO_2$-eq yr^{-1}), a shift towards plant-based diets (0.7–8.0 $GtCO_2$-eq yr^{-1}) and reduced food and agricultural waste (0.8–4.5 CO_2-eq yr^{-1}) (Jia *et al.*, 2019), while also restoring or avoiding use of peatlands have some reduction potential (see Section 5.1.1.1). This implies that regenerative agriculture might not add to achieving climate aims, unless it is heavily based on a drastically reduced meat production, while at the same time options for more diverse crops and cropping systems might come at the price of reduced climate mitigation.

For agroecological principles in regenerative agriculture see section 5.1.2.2, where alternative agricultural systems, including sustainable intensification and complete redesign of farm management systems (including climate-smart agriculture) are highlighted (VanBergen, 2020; Wanger *et al.*, 2020).

5.1.2.5 Intensive vs less intensive agriculture and the land sharing-land sparing debate

Scenarios that achieve climate change targets with less need for terrestrial CDR measures generally rely on agricultural demand-side changes (diet change, waste reduction), and changes in agricultural production such as agricultural intensification (IPCC, 2019a; Section 2.7.2). Such pathways that minimise land use for bioenergy and bioenergy with carbon capture and storage (BECCS) are characterised by rapid and early reduction of GHG emissions in all sectors, as well as earlier carbon dioxide removal (CDR) through afforestation. In contrast, delayed mitigation action would increase reliance on land-based CDR (IPCC, 2019a; Section 2.7.2).

Balmford *et al.* (2018) suggest that the impacts on biodiversity by agriculture would be greatly reduced through boosting yields. Intensification on existing farmland could in principle spare remaining natural habitats. They note that intensive high-yield farming raises other concerns because expressed per unit area it can generate high levels of externalities such as greenhouse gas emissions and nutrient losses. But such metrics also underestimate the overall impacts of lower-yield systems. Consequently, (Balmford *et al.*, 2018) developed a framework that instead compares externality and land costs per unit production. In their case studies it could be revealed that, rather than involving trade-offs, the externality and land costs of alternative production systems can co-vary positively: per unit production, land-efficient systems often produce lower externalities. For greenhouse gas emissions, these associations become more strongly positive once foregone sequestration is included.

Van Meijl *et al.*, (2017) however indicate that the demand for agricultural products is more influenced by population growth and changes in dietary preferences than for instance by GDP growth (van Meijl *et al.*, 2017). This implies that in the end, agricultural pathway choices are about quality vs. quantity, and that high yield agriculture based on high inputs of fertilizers or pesticides is to some extent obsolete. Unintended consequences for good quality of life however are not considered in either (Balmford *et al.*, 2018; van Meijl *et al.*, 2017). Outcomes are very system dependent and in addition intensive high-yield systems may move the provision of non-material benefits (aesthetics, sense of place etc.) to larger distances from people's centres of livelihood, in contrast to less intensive and often more biodiverse agriculture.

Excessive fertilization of crops results in N_2O emissions which is a potent GHG, and this results in dry and wet deposition of nitrogen into terrestrial ecosystems. N-fertilization can change community structure and reduce species richness. Moreover, these N_2O emissions can result in increased surface ozone which can reduce productivity of natural ecosystems.

Importantly, the different definitions of intensive agriculture must be kept in mind. Most commonly the term is associated with the degree of increase in input factors such as energy, fertilizers, pesticides, financial capital, and “technological sophistication” used, irrespective of the actual output or cost-benefit of the system, but as stated by (Netting, 1993), the relationship between these input factors and intensity is often assumed but rarely demonstrated as a component of industrial-scale agriculture. Any kind of agriculture is intensive to some degree; if output or productivity is taken as a reference, systems that would be considered extensive through input factors like energy and technology would instead emerge as very intensive – even if their ‘technology’ is very simple, labour and knowledge make some of them the most intensive systems of production anywhere.

5.1.2.6 Biodiversity-friendly urban areas

In 2018, the United Nations estimated that 55.3% of the world’s population lived in urban settlements (United Nations, Department of Economic and Social Affairs, Population Division, 2018). It is projected that the urbanization trend will continue to accelerate. The majority of greenhouse gas emissions are generated by urban dwellers (United Nations Economist Network, 2020). Contrary to common assumption that cities have no biodiversity, it has been shown that they do harbour rich biodiversity (Secretariat of the Convention on Biological Diversity, 2012; Chan, 2019). Cities must and can contribute to solutions for both biodiversity loss and climate change and do so in an integrated way. Cities such as Berlin, Edinburgh, Melbourne, Portland, Singapore, Toronto and Washington DC have taken the initiative that they adopt biodiversity-friendly, green and sustainable practices (Beatley, 2016; Plastrik & Cleveland, 2018), largely to make them a more liveable and desirable habitat for people.

Many of the methods used to conserve biodiversity in cities result in the enhancement of sinks for greenhouse gases (Epple *et al.*, 2016), thereby playing a role in mitigating climate change. In addition, they assist by lowering of ambient temperatures (see Section 3.3.4 for further details). In particular, one of the measures that cities have adopted to reduce emissions that is unique to cities is the greening of buildings. Instead of relying on energy to cool down buildings, designing biodiversity-friendly (‘biophilic’) buildings and building green infrastructure have gained much traction due to the multiple benefits that have been observed (Enzi *et al.*, 2017). Planting native plants that attract native fauna in vertical greenery and roof-top gardens provide habitats for wildlife as well as reduce ambient temperatures, thereby resulting in decreased energy consumption (Alhashimi *et al.*, 2018; Wong *et al.*, 2003). In addition to vertical greenery and rooftop gardens, other forms of green infrastructures result in multiple benefits such as the emulation of tropical rainforest with multi-tiered and multi-native species planting of roadsides, the creation of sponge cities (Yu, 2020), or the coverage of coastal walls with a range of different materials and forms that increase the establishment of marine biodiversity.

All of these measures are implemented to increase biodiversity and safeguard native ecosystems, with multiple benefits including the reduction in adverse effects of climate change (reduction of urban heat island effect, etc.), the improvement of regulating functions and benefits to people (water quality, air quality, increase permeability, soil retention, etc.), the enhancement of material ecosystem services (like urban agriculture in roof-top gardens), and the augmentation of non-material ecosystem services connecting people to nature to ensure their physical, psychological and mental well-being (World Health Organization, 2016). The extent to which greening cities also contribute to climate change mitigation has yet to be better quantified, and its potential to be prospected globally.

5.1.3 Tools and solutions for implementation and mainstreaming

5.1.3.1 Sustainable food production and supply chains

Human population is projected to grow to 10 billion or more by 2050 and so there will be a need to produce more food from land and sea, as well as to reduce wastes substantially.

Agriculture is a main driver of biodiversity loss on land (Green *et al.*, 2005), largely through conversion of natural ecosystems to agriculture, with conversion for animal agriculture being the main driver (Crist *et al.*, 2017; Section 3.3.3). Interventions to improve the biodiversity status of agricultural land and food supply chains include a) less intensive farming practices, such as agroecology, to reduce the adverse impacts of farming on nature and wildlife (Albrecht *et al.*, 2020; Tittonell *et al.*, 2020), though if this results in lower productivity this can simply displace activity elsewhere and exacerbate the clearance of natural ecosystems for agriculture (Phalan *et al.*, 2011), b) sustainable intensification of production (Pretty *et al.*, 2018), which allows land to be freed for nature conservation (Balmford *et al.*, 2018; Section 5.1.2.5) or c) demand-side changes in the food system supply chain, such as dietary change toward more plant-based diets with less meat and dairy (Bajželj *et al.*, 2014) and reducing food loss and waste (Gustavsson *et al.*, 2011) which reduces demand for products that use a lot of land, so potentially freeing land for nature conservation (Hayek *et al.*, 2021). As indicated in Section 3.3.3., these interventions to improve the biodiversity status of agricultural land and food supply chains also have significant climate change mitigation and adaptation benefits **(Table 3.1)** with mitigation potentials of these actions ranging from 0.1 to 8 Gt $CO_2e\ a^{-1}$, and adaptation benefits accruing to up to 2300 million people (Smith *et al.*, 2020; **Table 3.1**).

Fishing is the main current driver of biodiversity loss in the ocean both as a result of overexploitation, bycatch and destruction of habitats (Rogers *et al.*, 2020; IPBES, 2019). International adoption of guidelines and multilateral agreements to increase sustainability of fishing and eliminate illegal, unregulated and unreported (IUU) fishing are critical to moving fishing to sustainability (CBD Aichi Target 6, UN SDG 14.4, FAO Agreement on Port State Measures). In addition to taking all possible measures to rebuild overexploited wild marine populations, the development of new or emergent fisheries on remote living resources (far and deep: e.g., mesopelagic fish, krill, deep-sea fish) should be taken with all precaution given the potential effect these can have on carbon fluxes via the biological pump (see Section 5.1.1.9), but also the increase in fuel consumption these remote fisheries would entail. The GHG emissions (in CO_2eq) of fishing 1 kg of small pelagic fish was shown to be much lower than producing 1 kg of any kind of meat (Hilborn *et al.*, 2018), a fact that obviously needs to be taken into account when considering protein demand for human consumption. However, none of the assessments on which Hilborn *et al.* (2018) rely have considered the negative effects of fishing on carbon sequestration (Mariani *et al.*, 2020; Sala *et al.*, 2021), including in deep oceans (Boyd *et al.*, 2019) for vertically migrating mesopelagic fish) – but only fuel consumption –a process which can change the balance in net GHG emissions (Section 5.1.1.9). Furthermore, reducing fishing effort has the potential to increase fisheries catch for the one third of marine living resources that are currently overexploited or threatened (FAO, 2020), benefit marine biodiversity including some of the most threatened groups of species such as sharks and rays and enhance oceanic carbon sinks (Sections 5.1.1.7, 5.1.1.9).

Focusing of new aquaculture activities on low trophic level species as well as broadening the range of species cultivated, especially from unfed or environmentally friendly integrated aquaculture systems, are ways to increase global seafood production with minimal impact to the environment and biodiversity (SAPEA, 2017). Expanded cultivation of seaweed offers a potential route to reducing coastal eutrophication (Xiao *et al.*, 2017), avoiding related GHG emissions, sequestering CO_2 into long-term stores (e.g., deep-sea sediments; (Duarte *et al.*, 2017) and producing food, animal feed which reduces methane production by ruminants and a range of other products such as bioplastics (Ditchburn & Carballeira, 2019)). Science is required to understand the best places to expand such seaweed cultivation and what the environmental carrying capacity for it may be (Froehlich *et al.*, 2019).

Certification of food products that promote sustainable production, consumption, and trade can help guide consumer choice (Junior *et al.*, 2016) and ensure benefits for producers (Blackman & Rivera, 2011).

5.1.3.2 Sustainable consumption patterns

Sustainable consumption patterns have clear benefits to biodiversity and ecosystems, including in urban and peri-urban areas, where the benefits are often more immediately evident. Certain sustainable consumption patterns also have links to climate change mitigation. Consumer demand for products that have been sustainably harvested (for example, sustainably harvested timber) further impacts plantation forestry and timber production and harvesting practices (although measuring biodiversity-related benefits can be complex – see, for example, (Heilmayr *et al.*, 2020; Kuuluvainen *et al.*, 2019). Improved demand for water wise and biodiversity friendly labelling on foods such as, for example, honey, potatoes, tea, coffee, and other frequently consumed agricultural products is a clear trend in certain markets; and a substantial group of studies quantify, or attempt to quantify, the benefit to biodiversity and ecosystem services (Ruggeri *et al.*, 2020; Vogt, 2020).

The demand (and the market for) more sustainably harvested and produced wood products can improve forest cover and diversity, with results for both carbon sequestration and albedo (in dryland areas – see section above) (Heilmayr *et al.*, 2020). In addition, changes in demand for other areas of consumption can change sustainable consumption patterns – for example, the demand for different types of electronic goods and appliances, and for clothes that are sustainably produced (or not). Further, *in situ* conservation of biodiversity, products (including incentives for ecological restoration and those produced with improved grazing management) for which there is a demand that are sustainably farmed with *in situ* conservation measures as part of the required practice can also benefit carbon sequestration (again, there are clear examples of this in dryland areas). For example, (Lu *et al.*, 2018) found that implementing particular ecological restoration projects in forest, shrubland and grassland ecosystems in a number of regions in China found substantive contributions to CO_2 mitigation (132 Tg C y^{-1} (1 Tg = 1012 g); with > half (74 Tg C y^{-1}, 56%) attributed to project implementation). In a global scale review study, (Conant *et al.*, 2017) show how the improved management of grazing (e.g., reduced stocking rates and improved rotational strategies, which are often a requirement in the demand for more sustainably produced meat) can lead to an increase in soil carbon stocks – showing rates from 0.105 to more than 1 Mg $C{\cdot}ha^{-1}{\cdot}yr^{-1}$. A complicating factor here, of course, is the extent to which affordability of sustainably produced goods is frequently limited to the affluent.

5.1.3.3 Eliminating subsidies harmful to biodiversity

Subsidies are often inefficient, expensive, socially inequitable, and environmentally harmful, including in some cases contributing to climate change (OECD, 2005). In 2010 world governments agreed to eliminate, phase out or reform subsidies that harm biodiversity by 2020, but biodiversity-harmful subsidies continue. Data on potential impacts of such subsidies on biodiversity is either scant or unavailable (Dempsey *et al.*, 2020). In 2015 alone, OECD countries spent US$100 billion on agricultural subsidies potentially harmful to nature (OECD, 2019). The money allocated to promote and conserve biodiversity is outweighed by environmentally harmful subsidies by a factor of ten (OECD, 2019). Global fossil fuel subsidies are at a rate between US$300 and US$600 billion per year, resulting in estimated global damage of at least US$4 trillion in externalities (Coady *et al.*, 2019; Franks *et al.*, 2018). Fishing subsidy is estimated to be over US$35 billion per year, implicitly encouraging overfishing (Sumaila *et al.*, 2019), exploiting remote fishing areas, and using energy-intensive fishing gears such as bottom trawls.

The subsidies targeted for environmentally beneficial activities are heavily outweighed by the subsidies that nullify their beneficial effects. The positive vs harmful subsidies on deforestation and fisheries highlight this reality. For example, Brazil spent $158 million to stop deforestation while it spent $14 billion (88 times more) subsidizing activities linked to deforestation (McFarland *et al.*, 2015). Similarly, subsidies promoting sustainable fisheries amount to about $10 billion as compared to $22 billion in subsidies that promote overfishing (Sumaila *et al.*, 2019).

This happens partly due to difficulty in tracking such subsidies, and ignorance of the complexity of institutions. It is also partly due to political nature and interest-group lobbying, e.g., lobbying for domestic subsidies for palm oil in Indonesia (Maxton-Lee, 2018), petroleum lobbying in Canada (Blue *et al.*, 2018).

Halting biodiversity loss in synergy with mitigating climate change would be promoted by fast actions to eliminate harmful subsidies (IPBES, 2019). Actions could include enhancing the subsidy accountability culture among individuals and businesses and the reform of policies and practices towards eliminating harmful subsidies. Other interventions could include better transparency, reporting and assessments; and increasing the use of policy tools that can provide incentives for maintaining biodiversity, such as public procurement, taxes and fees (Barbier *et al.*, 2018; Barbier *et al.*, 2020; Lundberg & Marklund, 2018).

5.1.3.4 Mainstreaming biodiversity

Because biodiversity conservation in protected areas alone is insufficient to successfully safeguard biodiversity (and as shown earlier to contribute to climate change mitigation), biodiversity mainstreaming (i.e., making it a consideration in all sectors, rather than just in its own domain) is now accorded high priority in the CBD. This entails “embedding biodiversity considerations into policies, strategies and practices of key public and private actors that impact or rely on biodiversity, so that it is conserved, and sustainably used, both locally and globally” (Huntley & Redford, 2014). At CBD COP 14, a long-term strategic approach to mainstreaming was established. As biodiversity conservation and climate change challenges are intricately linked, it follows that biodiversity and climate change are most effectively mainstreamed together.

Mainstreaming can occur at multiple levels, cascading from national policies, strategies and land-use master planning to local plans down to business practices, and should encompass cross-cutting issues, intersectoral policies and regulatory frameworks. Some of the approaches include Reduced Emissions from Deforestation and Forest Degradation (REDD+), natural capital accounting, and the use of biodiversity offsets, all discussed elsewhere in this report (Sections 3, 5.1.1.8, 5.1.1.11, 5.2.4).

With a growing number of programmes and projects adopting the mainstreaming approach, there are now more case studies documenting their success stories, covering a range of achievements, such as those featured in 1) a key study by (Redford *et al.*, 2015): Working for Water programme (WfW) in South Africa, 2) Bioregional planning in South Africa, 3) mainstreaming nature in Costa Rica, and 4) the PINFOR and PINPEP forestry programmes in Guatemala (de Leon, 2010). The first two case studies demonstrate that successful implementation of mainstreaming resulted in controlling invasive alien species and speeded the rate of legal protection of areas of high biodiversity. It can be inferred that the mainstreaming approach could work for biodiversity actions that lead to positive climate change mitigation as well. The third case study features ecotourism in Costa Rican National Parks, where the policies and practices of several pertinent national Ministries of Environment, Agriculture, Planning and Finance synergised in a national sustainable development plan. It led to the creation of the Forest Incentives Programme where landowners could benefit from income derived from the conservation of forests. This would contribute to climate mitigation from biodiversity conservation actions. Under the circumstances where climate change mitigation measures could have negative impacts on biodiversity conservation or vice versa, a comprehensive exercise should be carried out to consider the trade-offs (Sections 3, 5.2.4).

Research work and documentation of the benefits from mainstreaming of biodiversity-to-biodiversity conservation and climate mitigation and trade-offs is ongoing but as yet insufficient.

5.2 INTEGRATED MANAGEMENT OF ECOSYSTEMS FOR MULTIPLE GOALS

Ecosystem management is tasked with achieving multiple goals simultaneously. This is being implemented via the concept of multifunctional land- and seascapes; with a specific focus on those land- and seascapes that fulfil multiple objectives, and, thus, have multiple benefits. A substantial fraction of net primary productivity and natural resources is diverted almost exclusively into human supply chains. Direct results include the spatial fragmentation of 'scapes and a loss of nature, with potential risks of the unrecoverable erosion of natural capital (IPBES, 2018, 2019). This risk has motivated a growing effort globally to achieve multiple goals in the management of ecosystems. Multiple-use 'scapes are the main context within which synergies and trade-offs between biodiversity conservation and climate mitigation can be realized. This subsection makes use of case studies (see supplementary material for details) to unpack, amongst other factors, the enabling environments (including, but not limited to, incentives and governance factors) that have been effective in fulfilling multiple 'scape objectives simultaneously.

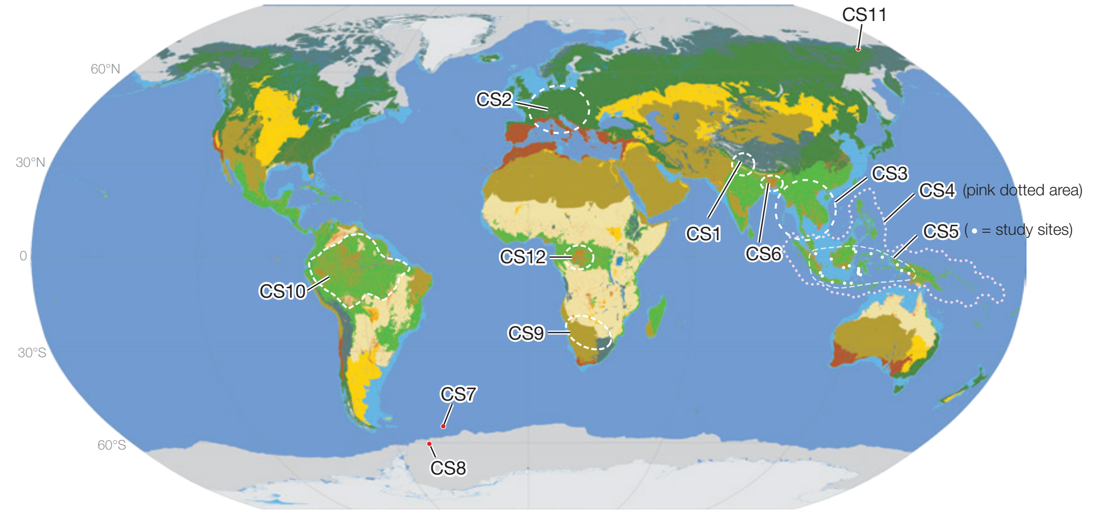
Protection of biodiversity is one of a range of functions fulfilled by a multi-functional, multi-use land- or seascape. A clear need going forward is for the ability to measure real multiple benefits in different contexts **(Figure 5.1)**, preferably with scope for comparison across cases.

5.2.1 Local to regional actions and the critical role of scale and linkages

The use and transformation of ecosystems by human society occurs at local scales, but these local effects accumulate at larger spatial scales, resulting in significant changes in regional and higher scale biodiversity and ecosystem functioning. In the terrestrial realm, land use and land cover change results from increasing and changing human demands for ecosystem goods and services and minerals, with the extent of change varying from place to place, moderated by complex interplay of biophysical, socioeconomic, and governance factors (see Case Studies 1, 2, 3, 6, 7, 8, 9, 10, 12). The Earth's land surface is now comprised of landscapes in a range of states of transformation (CS 1, 2, 3, 10). Increasingly, there is recognition that the configuration of these landscapes offers opportunities to achieve multiple objectives relating to both immediate human needs, and long-term sustainability objectives, including those relating to biodiversity and mitigation-related regulating benefits like carbon storage and sequestration (CS 1, 2, 3, 6, 9, 10, 11, 12). Likewise, achieving multiple objectives at local scales cumulates at the global scale: every local action contributing to climate change mitigation counts (all CS).

Land-use and land cover change reduces and fragments habitats and is currently the leading cause of terrestrial biodiversity loss (IPBES, 2018, 2019). These processes also almost always result in net carbon release to the atmosphere (IPCC, 2020), but also provide critical supplies of material benefits that maintain human society and contribute to good quality of life (CS 1, 2, 3, 9, 10, 12). Understanding of how land cover can be allocated between various uses is advancing and providing opportunities to optimize between multiple objectives (CS 2, 3). Such trade-offs may include assessing the balance between production of material benefits, carbon sequestration via reforestation (regulating services CS 10) and rewilding (regulating and cultural services, and biodiversity CS 11). For example, rewilding mammoth steppe with large herbivores in permafrost areas in Arctic tundra changes plant species composition, which tends to increase vegetation productivity, and decrease soil temperature in winter. Simultaneously, it may slow or avoid CH_4 release as a result of permafrost thaw while the megafauna provides summer albedo increase by selective foraging and additional carbon sequestration by soil (CS 11 and 5.1.2.3).

Analysis suggests that at the landscape to national scales, an increase in conserved area from 20 to 30% increases the resilience of the conserved area network to climate change (i.e., more species may be assured of persistence, (Hannah *et al.*, 2020)). At regional and global scales, the unequal distribution of biodiversity means that some regions have higher concentrations of rare species (Enquist *et al.*, 2019), and thus emerge as priorities for reducing species loss, indicating that prioritizing conservation objectives in these relatively small regions may permit achievement of species conservation most efficiently (CS 1, 3, 4). Spatial planning methodologies exist that can be applied to maintain ecological functioning even in fragmented landscapes, through the consideration of zonation that leverages landscape heterogeneity across spatial scales (Harlio *et al.*, 2019; Moilanen *et al.*, 2005). While cities have generally low levels of biodiversity, many efforts are undertaken to green cities with multiple co-benefits for human well-being, with the potential to connect to surrounding natural or managed areas, and contribute to both biodiversity conservation and



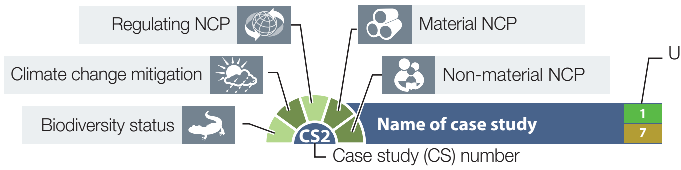
Units of Analyses (UoA)

1	Tropical and subtropical dry and humid forests
2	Temperate and boreal forests and woodlands
3	Mediterranean forests woodlands and scrub
4	Tundra and high mountain habitats
5	Tropical and subtropical savannas and grasslands
6	Temperate grasslands
7	Deserts and xeric shrublands
8	Wetlands*
9	Urban and semi urban areas**
10	Cultivated areas**
11	Cryosphere ⬜ Sea ice maximum extent
12	Aquaculture areas**
13	Inland surface waters and water bodies
14	Shelf ecosystems
15/16	Open ocean pelagic systems/Deep sea
17	Coastal areas intensively used by humans**

* Spatial representation of wetlands is limited to the tropical and subtropical wetlands

** No spatial representation

Impacts of biodiversity measures



🟩 Strong positive impacts

🟢 Moderate positive impacts

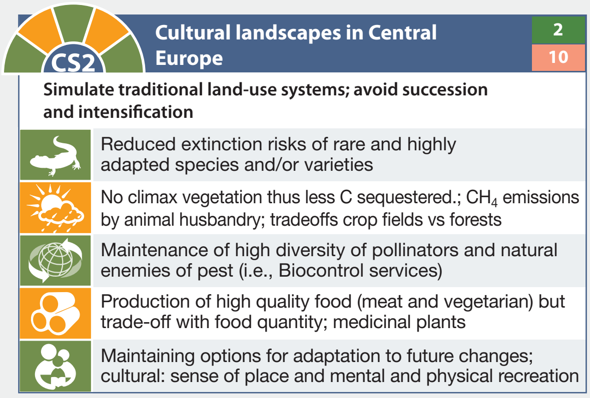
🟧 Unresolved / tradeoffs

🟥 Negative impacts

CS1 **Kailash Sacred Landscape conservation and development initiative** 1 7

Maintain/improve/restore forests and rangelands; practice sustainable land use

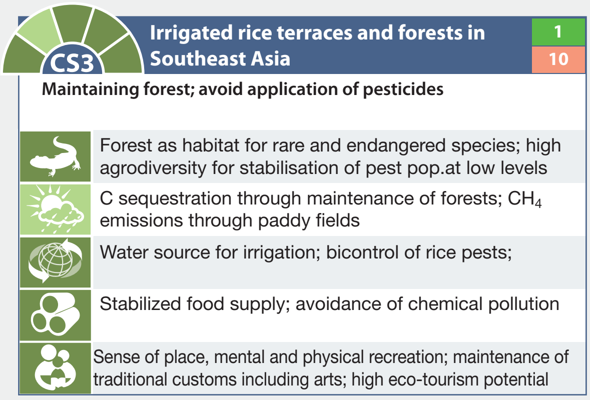
🟢	Habitats protected (for snow leopard, musk deer); biodiversity corridors established
🟩	C sequestered (on forests/rangelands/soils) by adopting ecosystem and farm management practices
🟢	Water source protected; springs rejuvenated
🟩	Provision of food, forest products, medicinal plant *O. sinensis*
🟩	Cultural heritage (Mount Kailash and Lake Mansarovar); Religious tourism



CS2 **Cultural landscapes in Central Europe** 2 10

Simulate traditional land-use systems; avoid succession and intensification

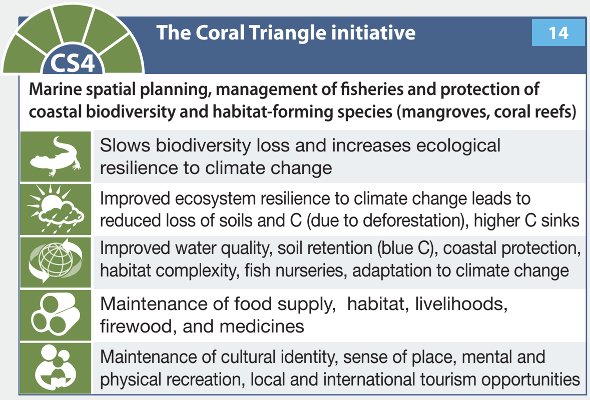
🟩	Reduced extinction risks of rare and highly adapted species and/or varieties
🟧	No climax vegetation thus less C sequestered.; CH_4 emissions by animal husbandry; tradeoffs crop fields vs forests
🟩	Maintenance of high diversity of pollinators and natural enemies of pest (i.e., Biocontrol services)
🟧	Production of high quality food (meat and vegetarian) but trade-off with food quantity; medicinal plants
🟩	Maintaining options for adaptation to future changes; cultural: sense of place and mental and physical recreation



CS3 **Irrigated rice terraces and forests in Southeast Asia** 1 10

Maintaining forest; avoid application of pesticides

🟩	Forest as habitat for rare and endangered species; high agrodiversity for stabilisation of pest pop.at low levels
🟢	C sequestration through maintenance of forests; CH_4 emissions through paddy fields
🟩	Water source for irrigation; bicontrol of rice pests;
🟩	Stabilized food supply; avoidance of chemical pollution
🟩	Sense of place, mental and physical recreation; maintenance of traditional customs including arts; high eco-tourism potential



CS4 **The Coral Triangle initiative** 14

Marine spatial planning, management of fisheries and protection of coastal biodiversity and habitat-forming species (mangroves, coral reefs)

🟩	Slows biodiversity loss and increases ecological resilience to climate change
🟩	Improved ecosystem resilience to climate change leads to reduced loss of soils and C (due to deforestation), higher C sinks
🟩	Improved water quality, soil retention (blue C), coastal protection, habitat complexity, fish nurseries, adaptation to climate change
🟩	Maintenance of food supply, habitat, livelihoods, firewood, and medicines
🟩	Maintenance of cultural identity, sense of place, mental and physical recreation, local and international tourism opportunities

Figure 5 1 **Implementation of biodiversity conservation measures at land- and seascape scale.**

Example case studies (full description and references in supplementary material) showing emerging synergies or trade-offs between biodiversity conservation, climate change mitigation and nature's contributions to people (NCP). The case studies cover a wide range of IPBES Units of analyses, and are located on different continents, oceans, and latitudes. For each case study, six pieces of information are provided: the biodiversity measure in place, the outcome on biodiversity status, the impacts on climate change mitigation, and the impacts on regulating, material and non-material NCP. On the banner at the top of each case study, we provide the corresponding IPBES unit(s) of analysis (on the right) as well as a pie chart illustrating the impacts of biodiversity measures (see supporting references in the supplementary material). The colour code is as follows: dark green codes for strong beneficial effects, light green for low to moderate beneficial effects, orange for unresolved effects or trade-offs. None of the biodiversity measures implemented in the case studies resulted in negative impacts (coded red), despite the fact that we had considered such negative impacts as possible in our assessment. C: carbon, CH_4: methane, CS: case study, pop.: population. Map of IPBES Units of analyses can be found at doi:10.5281/zenodo.3975694

climate change mitigation regionally, as is the case in coastal cities for example (Beatley, 2014; Section 5.1.2.6 and CS 5).

In the ocean realm, governance differs greatly from that on land, with very little private ownership, and large amounts of global commons (CS 7, 8). In addition, ecosystem transformation occurs mainly via harvesting of consumer species for material benefits, with relatively low rates of plant use, and far lower prevalence of high intensity food production systems. Important links between human use of the oceans and mitigation have been identified, with local and regional harvesting scaling up to significantly alter the global food chain, with important impacts of processes like ocean floor sequestration of carbon, and emissions of cloud-seeding compounds from the ocean surface.

5.2.2 Realizing co-benefits and synergies in land- and seascapes

Here we give some examples of biodiversity conservation measures that generate co-benefits and synergies with other environmental and societal objectives. Conservation of the rich biodiversity of the Amazonian rainforests has strong interlinkages with climate change mitigation through carbon sequestration and storage on trees and soils (Joly *et al.*, 2018; CS 10). In Kailash Sacred Landscape Conservation and Development Initiative (KSL) in India, Nepal and China (CS 1), conserving threatened species (i.e., snow leopard, musk deer) and their habitats through reforestation, rangeland and farmland management following ecosystem-based management approaches have generated climate change mitigation and adaptation co-benefits – carbon sequestration in trees, rangelands and soils (Aryal *et al.*, 2018; Joshi *et al.*, 2019; Liniger *et al.*, 2020; Uddin *et al.*, 2015). Introduction of herbivores to increase grazing pressures in Pleistocene Park (PlPark) in Siberia (CS 11), generated positive effect on carbon dynamics (decreased CH_4 release as a result of permafrost thaw and increased carbon sequestration by soils) and increase summer albedo by changing plant species composition, soil conditions and reduced shrub cover (Cahoon *et al.*, 2012; Falk *et al.*, 2015; Schmitz *et al.*, 2018; te Beest *et al.*, 2016). In the marine realm, conservation of the ocean biodiversity has directly contributed to climate change mitigation through storage and sequestration of blue carbon (CS 7) and protection of carbon rich mangrove forests (CS 6). In the Southern Ocean protection safeguards trophic components of carbon pathways (e.g., krill, fish but also benthic communities) so that increased phytoplankton blooms (driven by sea ice losses and glacier retreat) are converted to higher seabed carbon sequestration (CS 8) in oceans beyond national jurisdiction (Arrigo *et al.*, 2008; Barnes *et al.*, 2016).

Conservation measures applied to multi-use and multi-functional spaces synergistically contribute to improved human wellbeing or quality of life through the provisioning of context specific contributions to people as co-benefits (most CS). These co-benefits could take the form of nature's material contributions to people (food, timber, fuelwood, fodder, medicinal plants) or regulating benefits (water availability) or cultural/tourism related non-material benefits (sense of place, cultural or sacred/religious heritage protection, ecotourism), all of these benefits collectively and positively contribute to improved wellbeing of the affected people (CS 1, 3). KSL (Kailash Sacred Landscape, CS 1) has benefited local and distant users through a range of contributions from nature to people, such as timber, fodder, fuel wood, medicinal plants, water source protection and rejuvenation of springs (Badola *et al.*, 2017; Chaudhary *et al.*, 2020; Liniger *et al.*, 2020; Nepal *et al.*, 2018; Tewari *et al.*, 2020; Thapa *et al.*, 2018), protection of sacred cultural and religious sites – Kailash Mountain and Mansarovar – and promoting eco-tourism (Adler *et al.*, 2013; Pandey *et al.*, 2016). KSL also benefits distant downstream users of India, Nepal, and China through the (continued) provision of flowing waters for irrigation and other purposes (including hydropower generation) by protecting the sources. About 7.2 million people of India and Bangladesh, half of them are considered poor, rely on Sundarbans (CS 6) for multiple contributions from nature (carbon sequestration, gas regulation, disturbance regulation) (IUCN, 2017, 2020). Similarly, co-benefits of conservation measures have been demonstrated in cities (e.g., Beatley, 2016) which typically concentrate multi-uses and multi-functional spaces crossed by islands of biodiversity (see Section 5.1.2.6 and CS 5).

The Coral Triangle Initiative of six countries (Malaysia, Indonesia, Philippines, Timor-Leste, Solomon Islands and Papua New Guinea) (Veron *et al.*, 2009); CS 4) generates multiple benefits from nature of local to regional significance (Friess *et al.*, 2020), such as improvements to coastal water quality, nursery areas for fisheries, coastal protection, and maintenance of food, livelihoods, and cultural significance. Similarly, conservation of African peatlands yields high value water services to local people (CS 12). Not all of these benefits are equally prioritized due to the strong dependence of the livelihoods and income of poor people on material (fish, timber) and non-material (tourism) benefits from nature (CS 1, 2, 3; (Uddin *et al.*, 2013).

The success of conservation measures in multi-use and multi-functional land- and sea-scapes aiming to maximise co-benefits is sensitive to operational issues and governance challenges. In Amazon rainforests (CS 10), its global scale carbon sink function is being negatively impacted by deforestation and expansion of cattle and soybean production (Malhi *et al.*, 2008), mining activities (Rosa *et al.*, 2018), and construction of big dams (Fearnside, 2016). Similarly, in Pleistocene Park, CH_4 released by large animals could negatively affect the carbon cycle, and reduction of shrub cover and leaf area decreases CO_2 uptake (Falk *et al.*, 2015; Schmitz *et al.*, 2018) (CS 11). In Africa, the reforestation of dryland ecosystems (grasslands, savanna, forests) by exotic species (*Acacia* spp.) has created bush encroachment/invasion, impacting biodiversity negatively (number of vultures, cheetahs and grassland birds) and supply of nature's contributions to local people (fuelwood, fodder, water availability etc.), affecting their livelihoods and wellbeing (CS 9). Lack of strong policy and operational coherences between countries (i.e., India and Bangladesh for Sundarbans, and six south-east Asian countries for The Coral Triangle, and South Orkney Islands for the area beyond national jurisdiction) could lead to suboptimal outcomes of the conservation measures (CS 4, 6).

Biodiversity conservation successes to generate co-benefits, specifically climate change mitigation or adaptation, depend on consideration of values held by the key stakeholders, primarily the indigenous and local people, in conservation and management initiatives. Values reflect behaviour. Environmental interventions aimed to change human behaviour should thus be rooted in values held by concerned groups of people. Among the case studies examined, different types of values are held by different groups of people in conserving or managing the land- and sea-scapes. Examples include: cultural values attached to sacred places in the case of KSL (CS 1), strong dependency of indigenous people on forest resources for livelihoods and traditional significance in Amazon (CS 10), local people/fishermen and their dependency on material benefits from nature (fishing) in the case of The Coral Triangle (CS 4) and the Sundarbans (CS 6), and strong and traditional livelihood linkages of local people with the dryland ecosystems in Africa (CS 9).

Biodiversity conservation measures will have unintended consequences and challenges which need to be recognised, rectified and addressed through proper planning and governance mechanisms. This could be done through a holistic, integrated, consultative, and adaptive approach which would potentially be more likely to succeed in conserving biodiversity, mitigating climate change impacts, and contributing to human well-being or livelihoods through coherence of environmental and development policy within and across nations.

5.2.3 Locations where biodiversity and carbon sequestration objectives coincide

At the landscape or seascape level, areas of high species richness (particularly of endemic species) are most often given the highest priority for biodiversity conservation. It also happens that many of these same areas also are important carbon sinks through either the capture of carbon dioxide during photosynthesis, or the ability to sequester large amounts of organic carbon in sediments and soils (CS 4, 5).

The Amazon rainforest and mangrove forests are two biologically diverse ecosystems that are typified by high rates of carbon sequestration (Soares-Filho *et al.*, 2010; Donato *et al.*, 2011; Guannel *et al.*, 2016). The average annual carbon sequestration rates for mangroves ranges between 6-8 Mg CO_2e per ha (4 times more than some estimates for tropical forests, but the comparison should not conflate estimates for climax forests, which are approximately carbon-neutral, with early succession forests, which are actively taking up carbon). In the case of mangroves, these rates are thought to be sustained for hundreds of years as sediments build up in the quiet waters of estuaries. While mangroves only occupy 0.5% of the global coastal area, they bury 10-15 TgG y^{-1}, which adds significantly to carbon sequestration of these regions (cf. CS 5).

While high biodiversity areas may also be pronounced in areas of high levels of carbon sequestration, this is not always the case. Coral reefs represent an interesting case where primary productivity and the build-up of organic carbon (not skeletal calcium carbonate) over time is low, yet biodiversity is at least an order of magnitude higher than anywhere else in the ocean (Reaka-Kudla, 1997). In this case, coral reefs flourish in oligotrophic waters of tropical coastlines, relying on a low productivity and nutrient conserving symbiosis with single-celled mutualistic symbionts from the genus *Symbiodinium* (Muscatine & D'Elia, 1978).

There are also examples of high sequestration- low diversity ecosystems. For example, sequestration of organic carbon in the Southern Ocean is high, yet overall biodiversity is low compared to non-polar marine ecosystems (Bax *et al.*, 2021). Some caution needs to be exercised, however, given the relatively large proportion of species yet to be discovered in polar and deep-ocean ecosystems, relatively inaccessible habitats. Many tropical and temperate organisms are also close to their thermal maximum, with systems like the Southern Ocean may benefit from ice dynamics and the expansion of Antarctic waters.

5.2.4 Evaluating trade-offs

There are conservation measures and traditional land- and sea- uses that contribute to biodiversity conservation but have trade-offs with climate change mitigation (e.g., carbon storage and sequestration). In South Africa, wildfire management to limit bush encroachment contributes to maintaining species diversity in open ecosystems. These measures to maintain open ecosystems contribute to cooling effects (by high albedo land surface) and biodiversity as well as providing multiple material contributions centred on subsistence livelihoods, including extensive grazing and thatching, and the irreplaceable cultural elements associated with these lifestyles (e.g., Creed *et al.*, 2019). However, they would not result in apparent carbon storage and sequestration that can be obtained through large-scale afforestation as measured by standard accounting for above ground stocks, which ignores the potentially large below-ground stocks of grassland ecosystems (Wigley *et al.*, 2020). Also, the grazing of cattle, sheep, and goats in European landscapes contributes to shaping traditional cultural landscapes, and providing food (e.g., meat, milk, cheese), pollination for agricultural production nearby contributing to livelihood of locals. However, methane emissions from rumination by livestock is a known source of climate change (IPCC, 2019a) (CS 2). Similarly, rice cultivation in the sloping terraced rice fields of Southeast Asia contributes to food production, water flow regulation, sediment regulation along with traditional cultural landscapes (CS 3), but, on the other hand, rice paddies are known sources of methane emissions (Saunois *et al.*, 2016; Zhang *et al.*, 2020).

Trade-offs in NCPs have spatially differentiated consequences for their different beneficiaries. Providers and beneficiaries of NCP are often different, and their relationships vary according to the type of NCP (Fisher *et al.*, 2009). In Sundarbans, for instance, mangrove forests provide carbon storage and sequestration contributing to global climate change mitigation whose beneficiaries spread across the world (Sannigrahi *et al.*, 2020; Sannigrahi *et al.*, 2020a) while the other mangrove regulating services such as water and sediment retention and disturbance regulations (e.g., against cyclones and storm surges) are appreciated mostly by locals (IUCN, 2020; Sannigrahi *et al.*, 2020). Fish and shrimps nurtured through aquaculture relying on nutrient cycling of mangrove areas are often delivered to consumers in remote areas mediated by supply chains while some firewood and timber forest products are consumed locally for sustenance of locals (IUCN, 2020). The non-material benefits of forests, such as recreation and tourism are appreciated not only by locals but also by visitors who travel to the mangroves. In this way, stakeholders of the societal contributions of mangroves are diverse, and the use of one of such contributions (e.g., shrimp aquaculture) will affect the state of other contributions (e.g., carbon storage and water quality regulation) through the alteration of the mangrove forest.

In Sundarbans, although climate regulations, habitat provisions, and disturbance regulations (e.g., against cyclones and storm surge) are often evaluated to be the vital NCP (Sannigrahi *et al.*, 2020; Sannigrahi *et al.*, 2020a), local stakeholders including governments prioritize the production and use of NCP that lead to their economic benefits such as food (e.g., fish and shrimp) and tourism, which results in the decline in mangrove's capacity in climate change mitigation (Uddin *et al.*, 2013). Similar challenge was found in the areas managed by the Kailash Sacred Landscape Conservation and Development Initiative, as the growing trend of tourism activities often increase waste generation, energy consumption and enhance forest degradation, which is a trade-off relationship with climate change mitigation (Nepal *et al.*, 2018; Pandey *et al.*, 2016). This contrasts with consideration of climate change adaptation which has direct implications on local communities.

Effective biodiversity conservation often requires cooperation among multiple countries. Cross-border cooperation helps countries manage trade-offs among multiple NCPs while conserving biodiversity synergistically for climate change mitigation or adaptation. For instance, the Coral Triangle Initiative (CTI), focused on the conservation of the Coral Triangle between Pacific and Indian Ocean is participated by six countries (i.e., Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands and Timor-Leste) (Weeks *et al.*, 2014). The countries have worked jointly on the designation of priority seascapes, conservation planning, marine protected area networks, etc. (Asaad *et al.*, 2018), aiming to balance the biodiversity conservation and socioeconomic development of the region while coping with climate mitigation through the regeneration and restoration of coastal mangrove forests. Similarly, the Kailash Sacred Landscape Conservation and Development Initiative established by Nepal, India, and China for the conservation of biodiversity, NCP and cultural heritage of the pilgrimage to Mount Kailash, has contributed to establishing biodiversity corridors connecting protected areas located in three countries, adaptive ecosystem management, and improved livelihoods of local people (Zomer & Oli, 2011). For transboundary initiatives, the agreement of the countries concerned is essential. This is especially challenging in establishing protected areas on the high seas, which requires the agreement of member states for the multilateral environmental agreement. The South Orkney Islands Southern Shelf Marine Protected Area is a good example of a successful case and contributes also to climate mitigation with its high carbon storage and sequestration capacity (Barnes *et al.*, 2016; Trathan *et al.*, 2014).

5.3 CONCLUSIONS

Ecosystems and their component species play a central role in the climate system, due to their effects on the surface energy balance, water balance, consumption and production of radiatively active gases and aerosols. Conservation actions motivated by biodiversity concerns have traditionally not focused on this central role, but the recent recognition of the importance of this role demands an assessment of how conservation actions can best be aligned with climate goals, and where this alignment may be less feasible, irrelevant or conflictual.

We find here that many, but not all instances of conservation actions intended to halt, slow or reverse biodiversity loss can simultaneously slow anthropogenic climate change significantly. The conservation actions with the largest potential for mitigating climate change include avoided deforestation and ecosystem restoration (especially of high-carbon ecosystems such as forests, mangroves or seagrass meadows). The evidence suggests that conservation actions have, on balance, more mutually synergistic benefits than antagonistic trade-offs with respect to contributions regulating the climate system. Synergies between biodiversity, climate change mitigation, other nature's contributions to people and good quality of life are seldom fully quantified and integrated, and the evidence base for assessing these could be strengthened if this were done more routinely. The development of integrated indicators, models and scenarios would facilitate decision-making for mainstreaming and applying ecosystem-based integrative approaches that include biodiversity benefits.

At the landscape or seascape level, areas of high biodiversity are prioritized for biodiversity conservation measures, and many of these same areas have high rates of carbon sequestration (the Amazon rainforest and mangrove forests are two biologically diverse ecosystems that are typified by high rates of carbon sequestration). However, there are important exceptions to the generally positive synergy between conservation and climate mitigation. For example, disturbance management, such as through reducing wildfire frequency, has been shown to reduce biodiversity substantially due to the dependence of many wild species on disturbance regimes. The reintroduction of key animal species in rewilding efforts may also reduce standing carbon stocks through enhancing the disturbance regime. In some subtropical regions of the world where woody plant cover is increasing due to climate and CO_2 drivers, the use of enhanced disturbance regimes to control tree and shrub encroachment is conflictual with mitigation goals but may conserve biodiversity and enhance ecosystem services like water yield from catchments.

The implementation of appropriate mixed-use land- and seascapes through a holistic, integrated, consultative, and adaptive approach has the potential to enhance co-benefits between conserving biodiversity, mitigating climate change, and enhancing good quality of life. However, the realization of synergistic benefits and antagonistic trade-offs between biodiversity conservation, enhancement of nature's contributions to people and climate change mitigation are strongly dependent on which biomes, ecosystem uses, and sectoral interactions are under consideration. It may be impossible to achieve win-win synergies, or even manage the trade-offs between climate and biodiversity in every patch of a landscape, but achieving sustainable outcomes becomes progressively easier at larger scales.

Locally motivated biodiversity conservation actions can be incentivized, guided and prioritized by global objectives and targets, including climate benefits, but there are risks of overly simplified messages that assume positive synergies, such as unquestioning support for tree-planting campaigns regardless of local context. Local initiatives matter since the benefits of many small, local biodiversity measures accumulate at the global level while also having local benefits. For example, nature-based solutions in urban contexts can individually make a small contribution to global mitigation and biodiversity protection but provide local quality of life benefits.

The concept of substitutability among a slate of possible actions (such as 'biodiversity offsets'), if applied subject to strict conditions and exclusions, can introduce the flexibility required to achieve multiple competing objectives at regional scale. The exclusions include no replaceability in biodiversity action targets. Biodiversity conservation measures are specific, local, and regional, even when they contribute to global objectives such as mitigation of climate change. Substitution of one action for another is more likely to be synergistic (rather than a pure compromise) if it is guided by complementarity principles. Biodiversity offsets can involve the co-location of protected areas and ecosystem restoration efforts.

Evidence assessed here shows that actions undertaken for climate mitigation must consider the full, net climate impact of the action. Afforestation, i.e., the replacement of ecosystems with plantation forests, can provide carbon sequestration benefits but has several potentially serious negative consequences if inappropriately applied. These include loss of biodiversity when the replaced ecosystem is species rich or contains unique species, reduction of ecosystem services such as water yield, and loss of livelihoods that were dependent on the former land cover. The climate benefits may be offset by warming induced by the darkened land surface when the forest has a lower albedo than the land cover which it replaces. The relatively rapid lowering of albedo associated with reforestation and afforestation actions may overwhelm the longer-term carbon sequestration benefits both in the short and long term, depending on the details of the action taken, its geographic location and the time period over which the effect is calculated. Currently, lack of formal recognition of albedo feedbacks in UNFCCC mitigation project guidelines undermines the full quantification of the balance of climate forcing outcomes and does not guard against inappropriate and damaging climate mitigation actions.

SUPPLEMENTARY MATERIAL:

Full description of case studies (Figure 5.1 and Section 5.2)

CS 1: Kailash Sacred Landscape Conservation and Development Initiative

Biodiversity conservation and climate change impact mitigation or adaptation are important environmental management interventions in the Himalayan landscape. Conserving biodiversity through a (transboundary) landscape approach has been getting traction in the Hindu Kush Himalayas. With conservation and development objectives, Kailash Sacred Landscape (KSL) Conservation and Development Initiative was launched in 2010 covering 31,000 km^2 inhabited by 1,300,000 people among Nepal, India, and China (Tibet Autonomous Region) (Zomer & Oli, 2011). This landscape is vitally important for biodiversity conservation and ecosystem services (high altitude forests, rangelands, and globally threatened species – snow leopard *(Uncia uncia)* and Himalayan musk deer (*Moschus chrysogaster*); sacred sites for pilgrimage from Nepal and India: Mount Kailash and lake Mansarover; and source of water for Asia's four major rivers: the Indus, the Sutlej, the Brahmaputra, and the Karnali) (Uddin *et al.*, 2015; Zomer & Oli, 2011).

Restoration of forest and rangelands (Uddin *et al.*, 2015), protection of endangered species and their habitats (Sharma *et al.*, 2010), sustainable (farm) land management practices (Aryal *et al.*, 2018; Liniger *et al.*, 2020), heritage protection and cultural tourism (Adler *et al.*, 2013; Pandey *et al.*, 2016) were promoted as a way to conserve biodiversity, provide or generate ecosystem services (Nepal *et al.*, 2018), mitigate climate change (through carbon sequestration), and support livelihoods.

Recent review of the landscape initiative indicated that the transboundary landscape approach was successful in establishing biodiversity corridors, adopting approaches to ecosystem management and conservation, and also contributing to household incomes (Kotru *et al.*, 2020). In particular, the initiative contributed to conservation of snow leopard and musk deer – flagship threatened species of the region. Restoration of forests and rangelands and sustainable management of farmlands contributed to climate change mitigation through carbon sequestration.

The effect on regulating ecosystem services through landscape restoration include protection of water sources and rejuvenation of springs in the landscape, which contributed to increased availability of water (Liniger *et al.*, 2020; Badola *et al.*, 2017). As a forest by-product, honey and associated pollination services have also been observed in the landscape. It is important to note that shifting snowlines, rapid melting of snow, and formation of glacier lakes are significant risks of climate change in the KSL, affecting water availability and livelihoods of thousands of communities that rely on water supplied by the major rivers originating at KSL.

Medicinal plants, forest products (such as honey) and fodder by replacing invasive alien species are some of the key provisioning services generated in the KSL through restoration activities (Chaudhary *et al.*, 2020; Thapa *et al.*, 2018). The age-old pilgrimage to Kailash and Mansarovar (mainly) by Hindus is a non-material cultural and spiritual service offered by KSL.

The increased tourism activities in KLS could potentially have trade-offs between household livelihood support (through tourism, hotel and trekking services) and climate change impacts (through waste generation and forest degradation for fuel and other purposes). Raising environmental awareness and developing and implementing sustainable tourism practices will help to minimise the unintended impacts of tourism.

Climate change modelling in the KSL found that an upward shift in elevation of bioclimatic zones, decreases in area of the highest elevation zones, and large expansion of the lower tropical and subtropical zones can be expected by the year 2050 (Zomer *et al.*, 2014). This change would indicate a major threat to biodiversity and a high risk of extinction for species endemic to these strata, or adapted to its specific conditions, especially for those species which are already under environmental pressure from land use change and other anthropogenic processes. For example, the decline in production of caterpillar fungus (*Ophiocordyceps sinensis*) – a highly valued, commercially traded medicinal plant in the region – is attributed to both overharvesting and climate change (Hopping *et al.*, 2018), affecting livelihoods of local people. Conservation and sustainable development in KSL need to be tailored and modified considering the changing climatic conditions and shifting bioclimatic zones, ecoregions and species ranges in the landscapes. In addition, to achieve the twin goals of biodiversity conservation and climate change mitigation, apart from site specific interventions, policy and practice coordination among key stakeholders (government agencies, I/NGOs, local people) is needed to upscale the positive learnings from KSL to other part of the Hindu Kush Himalaya (Kotru *et al.*, 2020).

CS 2: Cultural landscapes in Central Europe

Biodiversity conservation in European cultural landscapes is heavily based on moderately used landscapes (Tieskens *et al.*, 2017). A core component are wet and dry grasslands which harbour the highest diversity of many insects (with many endangered species), especially flower visiting groups which often are also pollinators. Maintaining high diversity requires grazing by or mowing for cattle, sheep, goats. Especially cattle are a well-known methane source and thus biodiversity conservation has some negative climate impacts (but low stocking densities, which are required for the habitat management, should be quantitatively negligible), more importantly, such open areas are not available for carbon sequestration through (re)forestation. The areas are culturally/economically important as a source of high-quality meat (beef), culturally for recreation (nature's beauty), economically as insurance for sustainable pollination under modified ecosystem states (e.g., pollinator replacement in crops under climate change).

CS 3: Irrigated rice terraces and forests in South-East Asia

Conservation of natural forests in mountains of higher elevations in SE Asia (Indonesia, Vietnam, Philippines) guarantees water supply for the complex irrigated rice terrace systems, especially in areas with more pronounced dry seasons. As stability of terraces is dependent on continuous water supply, this continuity during dry seasons is guaranteed through the buffered (seasonally balanced) runoff of forests. In order to maintain these forests and their diversity the direct dependence of the land use system upon these is an important incentive for their preservation. The downside of the maintenance of the irrigated terraces is the methane they produce, the positive component is the diversity of human cultures, varieties and a contribution to food security (Settele *et al.*, 2018).

Irrigated rice agriculture has evolved over centuries and led to a well-balanced food web in paddies with an insect diversity even higher than in many (pristine) temperate forests. This diversity reduces the risk of pest outbreaks and stabilizes yield. Pesticides normally rather cause pest problems than solving them – and replacing irrigated rice with upland crops also puts stable production at risk. This often is combined with environmental pollution. Maintaining biodiversity in irrigated rice ecosystems stabilizes yields, but methane is a negative by-product of these systems, which often also act as wetland conservation sites within the Ramsar Convention.

CS 4: The Coral Triangle Initiative (CTI)

A quarter of the world's marine biodiversity is concentrated in an approximately triangular region shared by six countries (Malaysia, Indonesia, Philippines, Timor-Leste, Solomon Islands and Papua New Guinea) (Veron *et al.*, 2009). This region also is home to hundreds of millions of people who live largely coastally and depend on diverse ecosystems for food and income (Foale *et al.*, 2013). Both people and ecosystems are being threatened by a number of local (e.g., pollution, over-harvesting) and global (e.g., sea-level rise plus ocean warming and acidification) stressors (Burke *et al.*, 2012). Sea level rise is a considerable challenge with ecosystems such as mangroves and seagrass ecosystems, where shoreward migration due to sea level rise can be thwarted by coastal development by humans leading to 'coastal squeeze' (Mills *et al.*, 2016).

Due to the rising impacts from these threats, and demonstrable decreases in the health of coastal ecosystems throughout the Coral Triangle, Indonesian President Susilo Bambang Yudhoyono and the other leaders of the 5 CTI nations proposed a multilateral partnership in 2007 to safeguard the coastal resources of the CTI along with the many coastal communities and economies. The CTI was one of the first marine transboundary conservation and socioeconomic initiatives, establishing large integrated zoning across the six countries (Weeks *et al.*, 2014). Since 2007, the six CTI nations have worked collectively towards designating priority seascapes, applying ecosystem-based fisheries management, conservation planning, marine protected area networks, marine protected areas, marine reserves and multiple-use zoning, and actions to preserve threatened species (Asaad *et al.*, 2018). Increasingly, regeneration and restoration projects have begun to replant mangrove forests with reciprocal benefits in terms of biodiversity and climate mitigation (reforestation, storage of carbon in stabilised sediments (Loh *et al.*, 2018; Thorhaug *et al.*, 2020; Alongi *et al.*, 2016) and activities which benefit biodiversity (habitat for biodiversity, fisheries, nursery grounds). These benefits have the potential to stabilise coastal populations and reduce poverty, helping maintain biodiversity, protect people (Guannel *et al.*, 2016), and healthy coastal economies under climate change (Hoegh-Guldberg *et al.*, 2009).

The actions taken by the Coral Triangle initiative are expected to affect a range of ecosystem services as well as biodiversity. For example, actions taken to protect mangrove, coral reefs and seagrass ecosystems, and thereby biodiversity, also lead the preservation of regulating ecosystem services such as the provision of fish habitat, removal of sediment, nutrients and pollutants from water running into coastal areas, as well as the maintenance of soils and muds, protection from storms and coastal wave stress. Other actions are expected to impact material nature's contributions, such as food and fisheries, fuel for fires, medicinal products, among other contributions (Friess *et al.*, 2020). Many of the ecosystems along the coastlines of the Coral Triangle also play significant roles in the culture of many communities that occupy the coastal areas of the Coral Triangle. These non-material contributions are extremely valuable despite the fact that the strict economic evaluation of such benefits is often impossible (Barbier, 2017).

CS 5: Biodiversity-friendly cities and urban areas

Safeguarding mangrove ecosystems in cities can conserve the rich biodiversity that resides in them as well as assist in climate change adaptation and mitigation. It is increasingly being demonstrated that blue carbon ecosystems including mangroves, seagrass meadows, intertidal mud flats, saltmarshes, etc., play a major role in aquatic carbon fluxes and hence, contribute greatly to global climate change mitigation (Bulmer *et al.*, 2020). However, these coastal marine ecosystems in particular mangroves, coral reefs, etc., are also most profoundly affected by and vulnerable to climate change that cause sea-level rise and habitat destruction. These effects have a large negative impact on carbon sequestration and carbon stocks.

It has been shown that even in a highly densely populated city like Singapore, mangrove forests that account only for a very small amount of Singapore's area can play a disproportionate role in carbon storage across the urbanized area compared to other urban forest types (Friess *et al.*, 2015). Benefits of fringing mangrove ecosystems have also been documented in Mumbai, India (Everard *et al.*, 2014). Upscaling from a city level, the carbon storage capacity in Indonesia's coastal wetlands including mangrove ecosystems and seagrass meadows is of global significance (Alongi & Mukhopadhyay, 2015). Coastal forested ecosystems including mangroves may store more than three times that of terrestrial forests (Alongi, 2014; Alongi & Mukhopadhyay, 2015; Donato *et al.*, 2011), hence, helping in the mitigation of carbon emissions and augmentation of carbon stock. This could contribute to the offsetting of carbon emissions by anthropogenic activities associated with urbanisation, like residential, commercial and industrial land use. Hence, the higher carbon storage per unit area of mangroves compared to other vegetation types argues strongly for the conservation of mangroves in urban areas where trade-offs are crucial in decision-making.

In addition to carbon sequestration throughout the year and acting as a carbon sink, mangroves contribute multiple benefits, including provision of habitats for biodiversity, coastal protection, food sources and roosts for migratory birds, nurseries for marine organisms, recreation, education, etc. This demonstrates how nature-based solutions like safeguarding and restoration of mangroves in coastal cities contribute significantly and synergistically to biodiversity conservation and climate mitigation (Alongi, 2014; Alongi & Mukhopadhyay, 2015).

CS 6: The Sundarbans (India-Bangladesh)

The Sundarbans is the world's largest mangrove forest stretching over 10,263 km^2, located at the delta of the rivers Ganga, Brahmaputra and Meghna between Bangladesh (~60%) and India (~40%), which contains four protected areas designated as UNESCO's World Natural Heritage sites (one in India and three in Bangladesh). The biodiversity of this area, Bangladesh side alone, includes 355 species of birds, 49 species of mammals including Bengal tiger, 87 species of reptiles, 14 amphibians, 291 species of fish, and 334 species of plants (Mukul *et al.*, 2019). It also serves as a large sink of CO_2. The Sundarbans is home to about 7.2 million, half of which are landless and are dependent on rain-fed agriculture and provisioning services from mangroves for livelihoods (e.g., timber, honey, fish) (IUCN, 2017, 2020; Sannigrahi *et al.*, 2020). While mangrove extent in the Sundarbans has remained stable to date with very little net loss, an overall negative trend was observed (Awty-Carroll *et al.*, 2019). A part of highly degraded mudflats has been restored by the extensive utilization of native grass species (Begam *et al.*, 2017). Habitat services, gas regulation, carbon sequestration, and disturbance regulations (e.g., against cyclones and storm surge) are often evaluated to be the most important ecosystem services (Sannigrahi, Pilla, *et al.*, 2020; Sannigrahi, Zhang, *et al.*, 2020), but the provisioning services (e.g. timber, fish) and cultural services (e.g. tourism) are often prioritized in practice for revenue generation for locals (Uddin *et al.*, 2013). Similarly, non-food ecosystem services such as water availability and quality have deteriorated since the 1980s while improved food and inland fish production contributed to reducing the population below the poverty line (Hossain *et al.*, 2016). There are trade-offs between the pursuit of material benefits for local livelihood and regulating benefits (climate mitigation and water quality) through mangrove conservation. Recently, the mangroves and wildlife of the Sundarbans are becoming increasingly vulnerable to the combination of natural and anthropogenic direct drivers such as cyclone, sea-level rise, soil and water salinization, and flooding, industrial and urban development, embankment construction, aquaculture development and poaching of wildlife (Mehvar *et al.*, 2019; Mukul *et al.*, 2019; Sánchez-Triana *et al.*, 2018). Among the total loss of 107 km^2 of mangroves between the year 1975 and 2013, 60% was lost due to water erosion and 23% was converted to barren lands, and the potential CO_2 emission due to the loss and degradation of mangroves was estimated to be 1567.98 ± 551.69 Gg during this period (Akhand *et al.*, 2017). The Sundarbans stretch across two countries and socioeconomic activities in one country, whether within or outside of the Sundarbans, affects the ecosystems and ecosystem services of the Sundarbans in the other. Although the importance of transboundary cooperation has been recognized and the Memorandum of Understanding between Bangladesh and India on Conservation of the Sundarbans was signed in 2011, there has been no formalized joint management and surveillance protocol of the protected areas implemented to date (IUCN, 2017, 2020).

CS 7: Southern Ocean case study

South Georgia is a remote (UK overseas territory) island at the northernmost limit of the Southern Ocean, in the Atlantic sector. It is an extremely important site for biodiversity being a critical site for many whales, seals and many seabirds, including the most important site for iconic species such as the Wandering Albatross (Rogers *et al.*, 2015). There are very few non-indigenous invaders, most species are endemic, and there are more species known than around Galapagos (Hogg *et al.*, 2011; Rogers *et al.*, 2015). Two key biodiversity-focused change action measures at different scales have changed species survival prospects and climate mitigation potential. The global moratorium on whaling has particular significance at the baleen whale hotspot of South Georgia. Those waters are key feeding grounds and have just revealed recovery levels, e.g., of blue whales (Calderan *et al.*, 2020) which are also key carbon stores. The fishery (e.g., for Patagonian Toothfish) around SG has become one of the most tightly restricted. Very few vessels are accepted for licensing in the fishery, each is tracked, has an observer and unique hooks (so their presence in seabirds can be traced). This limited fishery now takes place in one of the world's largest Marine Protected Areas. With no bottom trawling or shallow longlining, the high surface productivity can be converted to benthic carbon storage, with crucially high genuine sequestration potential (Barnes & Sands, 2017). Such work has shown that seabed biodiversity hotspots are coincident with those of blue carbon storage and sequestration potential.

The Marine Protected Area created around South Georgia is one of the world's biggest and encapsulates a hotspot of endemism, population of endangered iconic species (e.g., Wandering Albatross), an important carbon sink of oceanic productivity and one of the tightest regulated fishery and tourism industries. In many ways it represents a model of minimising impacts on biodiversity and ecosystem services in a climate change hotspot.

CS 8: Marine Biodiversity Beyond National Jurisdiction, South Orkney Islands

Approximately 60% of ocean is area beyond national jurisdiction (ABNJ), but because most of this is remote ocean or polar land it can be societally 'out of sight and mind'. Such areas hold 50% of oceanic primary productivity and an important fraction of the planet's biodiversity and very significant current and future climate mitigation in the form of carbon storage. Global to local initiatives (within jurisdiction) have attempted to reduce biodiversity threats. For example, plastic waste reduction can have a disproportionately high (positive) effect in the high seas, as it is a massive sink. Specific actions focussed beyond ABNJ have included the recent establishment of High Seas Marine Protected Areas, such as south of the South Orkney Islands and part of the Ross Sea, both in the Southern Ocean (Trathan *et al.*, 2014). Such areas could be major targets of emerging mesopelagic fisheries and marine mining. The aim has been to safeguard unique and important areas with high seabird, seal and cetacean concentrations but also have anomalously high richness of endemic invertebrates and strong ecosystem services. The South Orkney Islands are a polar hotspot of carbon capture and storage, and unlike lower latitude hotspots, this is a rare and valuable negative feedback on climate change (Barnes *et al.*, 2016). Thus, protection of the South Orkney islands has added climate mitigation value beyond the natural capital of existing blue carbon storage because climate-forced glacier retreat and sea ice losses are increasing phytoplankton blooms (Arrigo *et al.*, 2008) and consequently benthic carbon storage (Barnes *et al.*, 2016) there.

Safeguarding hotspots of biodiversity and carbon sequestration is particularly difficult when it requires unanimous agreement from multiple nations, so there are few high seas protected areas – despite representing much of planet Earth. Amongst the world's first, around the South Orkney Islands, has >1200 species across 24 phyla, most are endemic, only two are non-native and it is a recognized polar carbon sequestration hotspot, due to highly productive ecosystem services.

CS 9: Bush encroachment, Southern Africa

Disturbance-driven tropical ecosystems generally have much lower standing biomass than is potentially the case in the absence of disturbance (Bond *et al.*, 2005). Wildfire and browsing pressure maintain these systems in an "open" condition, and has done so for millennia, resulting in the iconic grassland and savanna landscapes and forest-averse diversity of tropical Africa, South America, and Australasia. Substantial conservation effort is associated with maintaining high value nature-based tourism in Africa (in a range of areas), but this applies to a lesser extent on other continents.

A substantial portion of these lands have been targeted by aspirational afforestation programs, creating, in certain areas, a conflict between mitigation and biodiversity outcomes on a global scale (as well as with implications for forest-water interactions). In some of these regions, a poorly understood mix of management actions and climate change drivers, including (but not limited to) increasing CO_2

fertilization of tree growth, is leading to the conversion of these open ecosystems to a state of bush encroachment (Stevens *et al.*, 2017), with, amongst other impacts, reduced palatability and grazing capacity.

Experimental efforts using extreme fires and mechanical harvesting have been tested as a way of reversing these trends (Joubert *et al.*, 2012; Smit *et al.*, 2016). The expected effects on biodiversity include reduced success of multiple species dependent on open, disturbance driven systems. Examples include the plains fauna of Africa, with clear direct impacts already visible for vulture, cheetah, and a myriad of smaller grassland bird species. Birds of woodlands and forests appear to be increasing in abundance in these regions. There are potentially substantive mitigation implications. In Namibia, for example, the extent of natural afforestation by bush encroachment is sufficiently large to offset national fossil fuel emissions (Ministry of Environment and Tourism, 2011). Maintenance of these open ecosystems will ensure the persistence of disturbance driven habitats, with important effects on landscape level water use (e.g. Creed *et al.*, 2019) and the maintenance of lower intensity wildfire regimes. Open ecosystems also provide multiple material services centred on subsistence livelihoods, including extensive grazing and thatching, and the irreplaceable cultural elements associated with these lifestyles. Afforestation using non-indigenous tree species, in order to generate higher growth rates, has been shown to degrade almost every ecosystem service mentioned above, leading to woody plant invasions, drying up water flows, intensifying fire regimes, reducing biodiversity, and destroying historical livelihoods (Creed *et al.*, 2019; McNulty *et al.*, 2018). Recognition of the natural cooling effects of high albedo, and the plethora of ecosystem services under threat in tropical open ecosystems would provide opportunities for sustainable management of these systems for both local and global benefit. In South Africa, active removal of woody encroachers has created millions of job opportunities and slowed encroachment and protected endemic diversity over hundreds of thousands of hectares (van Wilgen *et al.*, 2012).

CS 10: Amazonian rainforest

The Amazon rainforest is more than a case; it is key to understanding the biodiversity-climate interlinkages at a global scale. The region harbours an impressive number of species, provides ecosystem services that operate at the planetary scale, many of them directly related to climate (i.e., carbon storage, water cycling), across nine countries where around 30 million persons live with different cultures (Joly *et al.*, 2018). The Amazon is responsible for delivering all sorts of ecosystem services, despite essential gaps in the scientific literature (Pires *et al.*, 2018). Forest products, such as 'açai', are responsible for mobilizing more than US$ 1.5 billion year-1 (Scarano *et al.*, 2020), but with an unexplored potential. Although recent estimates predict that the biome has around 82% of its original vegetation (Lapola *et al.*, 2014), it is quickly losing its ability to provide services (Solen *et al.*, 2018). Deforestation is the most critical threat to the biome and triggers several processes that speed up its degradation (i.e., forest fires, 'savannization', drought) (Barlow *et al.*, 2020; Nobre & Borma, 2009). In 2020, Brazil registered a total of 76.674 km^2 lost due to fire in the biome, which is equivalent to the area of Panamá.

Deforestation in the biome is centred in the Brazilian portion and along the Andean piedmont caused mainly by the expansion of cattle and soybean production (Malhi *et al.*, 2008). Although around 29% of the biome is in protected areas in Brazil, including indigenous lands, its management fails in preventing deforestation (Joly *et al.*, 2018). The biome faces other critical land-use pressures that can compromise the biodiversity therein and climate-related services. The building of big dams is expected to cause a substantial increase in the carbon dioxide (81 to 310 Tg of CO_2) and methane release (9 to 21 Tg of CH_4) (de Faria *et al.*, 2015). It is expected that in specific conditions, carbon emission of such a 'clean energy' production can be compared to fossil-based power plants (de Faria *et al.*, 2015; Fearnside, 2016). Mining is another driver of change in the biome that threatens biodiversity and human livelihood (Rosa *et al.*, 2018).

Thus, to conserve and manage protected areas, restoring degraded lands and strategic land planning in the region are identified as the main actions able to protect biodiversity and ecosystem services, at the same time as promoting climate mitigation (Soares-Filho *et al.*, 2010). Ensuring efficiency in the implementation of these protected areas is conditional on promoting such mitigation impact (Brienen *et al.*, 2015; Phillips *et al.*, 2017). For example, planning in the establishment of dams in the region could effectively reduce carbon emission and present better cost-benefit strategies (Almeida *et al.*, 2019). In this sense, the role of local and indigenous people is fundamental to protect forest areas and ensure those benefits (Joly *et al.*, 2018). Land degradation in indigenous lands is lower than in other categories of protected areas, and it is the most effective land tenure in reducing carbon emissions (Soares-Filho *et al.*, 2010). The participation of traditional and indigenous people on the decision processes will help to protect the Amazon and reach the ambitious planetary environmental targets in the coming years.

CS 11: Pleistocene Park, NE Siberia

Pleistocene Park (PlPark) was established to re-wild the mammoth steppe in the Kolyma river lowland north of the Arctic Circle near Chersky, Northeastern Siberia (Kintisch, 2015; Zimov, 2005). It was revealed that simultaneous prevention or at least postponement of permafrost thawing can be achieved. In 1996, a 2000-hectare area was fenced, and different herbivores (elk, moose, reindeer, yakutian horses, musk oxen, yaks and bison) were introduced into this park in order to study their effect on plant species composition, vegetation productivity, and soil temperature regime (Beer *et al.*, 2020). PlPark and the associated Northeast Science Station, in addition to the scientific advances made by the staff, provide a year-round base for international research in arctic biology, geophysics and atmospheric physics and serve as a teaching lab for undergraduate and graduate students (Kintisch, 2015). There is also a potential for employment and new tourism economies (Macias-Fauria *et al.*, 2020). Winter grazing and movements by the animals compact snow, thereby substantially decreasing the thermal insulation efficiency of snow. This allows much colder freezing of soil in winter, hence colder overall mean annual soil temperature. In the PlPark, an herbivore density of 114 individuals per km^2 led to an overall average reduction of snow depth by 50%. The mean annual difference of soil temperature at 90 cm depth inside and outside the PlPark is −1.9 °C (Beer *et al.*, 2020). Large herbivores grazing pressure on Arctic tundra ecosystems can have a positive effect on carbon dynamics by changing the plant species composition—including tundra herbs and shrubs, and boreal trees—by selectively foraging. Decrease in shrub cover and leaf area increases summer albedo (Cahoon *et al.*, 2012; Falk *et al.*, 2015; Schmitz *et al.*, 2018; te Beest *et al.*, 2016), however it decreases CO_2 uptake (Schmitz *et al.*, 2018) and decrease shading of the soil surface, so increases soil temperature. Megafauna in the Arctic promote grass establishment in slowly growing wet moss/shrubby tundra and allows a revival of a sustainable, highly productive ecosystem. Besides, grasses reduce soil moisture more effectively than mosses through high rates of evapotranspiration (Macias-Fauria *et al.*, 2020). This process already takes place in PlPark. Establishment of high productivity grasslands on the big territory can be a long-term sustainable mechanism for absorption of greenhouse gases from the atmosphere and carbon storage by soil, hence contributing to carbon sequestration in the Arctic. However, CH_4 release by large animals could have a negative effect on carbon cycle (Falk *et al.*, 2015; Schmitz *et al.*, 2018). Benefits and trade-offs of large herbivores grazing for climate change mitigation in the Arctic depend on ecosystem type, grazing pressure, time scale and/or grazer community (Falk *et al.*, 2015; Ylänne *et al.*, 2020). To better understand and quantify interaction of all the processes involved, future monitoring and research is needed (Macias-Fauria *et al.*, 2020). Soil cooling effect, albedo increase, and additional carbon sequestration may prevent or at least postpone permafrost thawing. Such ecosystem management practices could be scaled up in Arctic permafrost areas and play a significant role as an ecosystem-based solution for global climate change mitigation strategy.

CS 12: African peatlands

African peatlands are located mainly in African tropical forests where high rainfall and limited drainage support the accumulation of peat deposits. The peatlands of the central Congo Basin cover roughly 145,500 km^2 and store about 30.6 Pg of carbon (Dargie *et al.*, 2017). The peatlands support unique and iconic biodiversity, much of which is undocumented (e.g. fish, plant and invertebrate species), but including well documented populations of large vertebrates like lowland gorilla, forest elephant, chimpanzee, and bonobo (Fay & Agnagna, 1991; Inogwabini *et al.*, 2012; Rainey *et al.*, 2010), and smaller vertebrates including monkeys and dwarf crocodile (Riley & Huchzermeyer, 1999). These lands sustainably support indigenous populations that rely on small-scale agriculture and fishing (Dargie *et al.*, 2019). Current land use change includes active drainage and deforestation, which reduces carbon stocks above and below ground (Hooijer *et al.*, 2010; Könönen *et al.*, 2016), and can introduce wildfire (Jauhiainen *et al.*, 2012). While indigenous use appears sustainable, new concessions for palm oil production that may be encouraged by international funding and incentives, new road development, hydrocarbon exploration, and planned water transfer schemes in the Congo Basin (Dargie *et al.*, 2019) induces significant degradation of this carbon store. Only 11% of peatlands (16,600km^2 of the 145,500 km^2 of total area) is located within nationally recognised protected areas. (Dargie *et al.*, 2019) propose that conservation and mitigation objectives could be supported by climate, biodiversity and development funding, with clear synergistic benefits between these apparent in this case study.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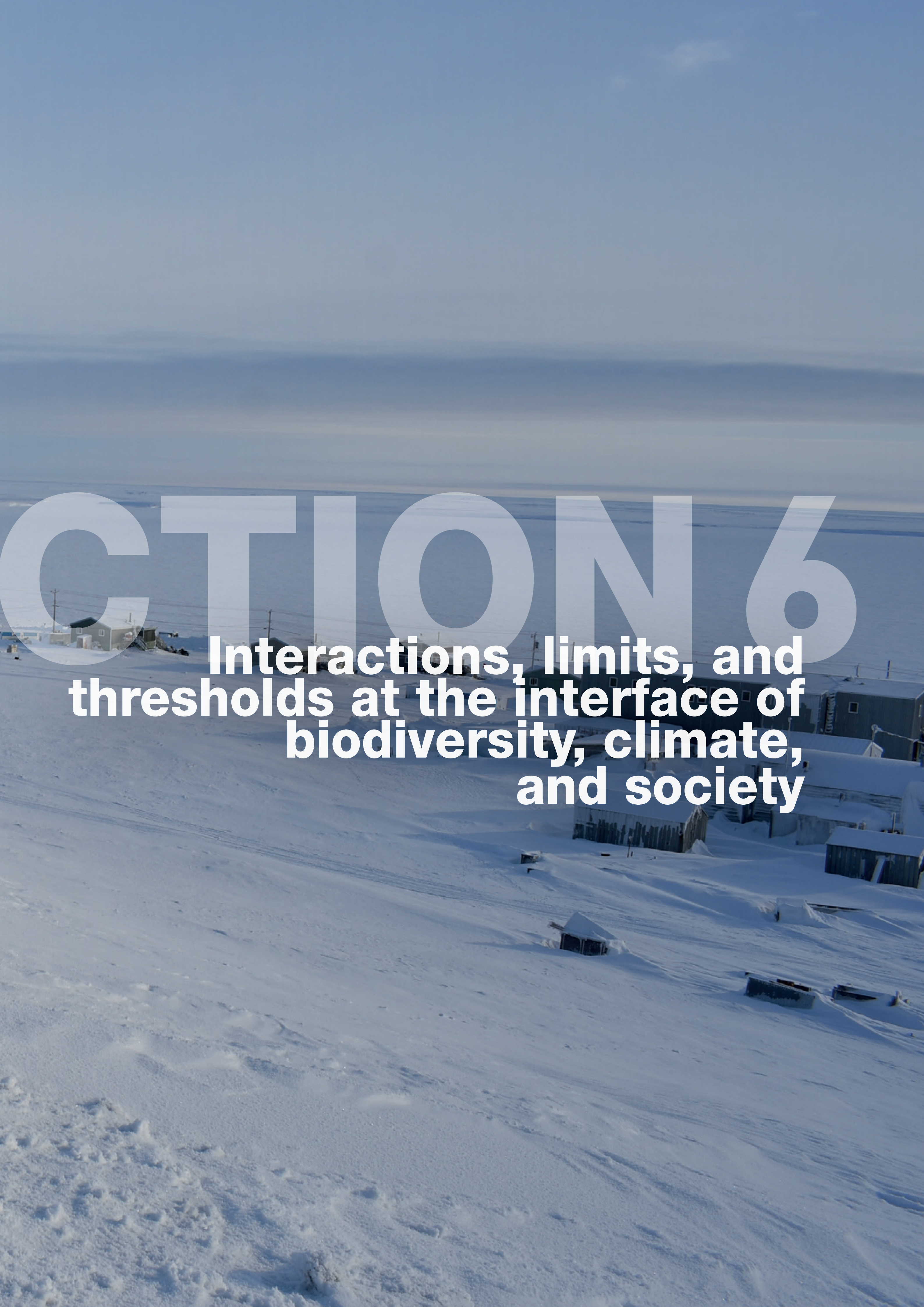


CTION 6

Interactions, limits, and thresholds at the interface of biodiversity, climate, and society

SECTION 6

Interactions, limits, and thresholds at the interface of biodiversity, climate, and society

6.1 INTRODUCTION: INTERACTIONS BETWEEN BIODIVERSITY AND CLIMATE IN SOCIAL-ECOLOGICAL SYSTEMS

This section aims to help policymakers identify and analyse the interactions among actions implemented to address biodiversity, climate mitigation and adaptation, and good quality of life. The information presented here is intended to provide a better understanding of the potential synergies and trade-offs resulting from policy formulation and implementation, with the objective of maximizing positive outcomes in all three components (biodiversity, climate, and society).

Biodiversity, climate, and society are profoundly intertwined (Section 1). Understanding their linkages is necessary to guide policies designed to address social, economic, and environmental issues, as they can result in diverse types of social and environmental outcomes. For example, while policies to promote economic development can have direct and indirect (diffuse, delayed, and distant) impacts on biodiversity and climate, these changes to biodiversity and climate can have profound social impacts on development, especially on poverty and inequality in many parts of the world. This section makes the social component explicit in terms of the socioeconomic and cultural context, and in terms of the impacts on the well-being for vulnerable people from changes to biodiversity and climate.

Given the complexity of the Biodiversity-Climate-Social (BCS) nexus, it can be simplified into several interacting subsystems. The biophysical parts are considered here to have two subsystems, those relating to biodiversity and its supporting processes, and those relating to the climate system, recognising the many connections between the two. Although ‘climate’ and ‘biodiversity’ are used as simple descriptors throughout this section, in effect, these are umbrella terms to describe the multifaceted nature of changes in climate and changes in biodiversity. The final component concerns how social factors influence and react to these changes in biodiversity and climate.

The social subsystems involve a broad range of human social dimensions, including people’s values and customs, behaviour, social institutions understood as norms and rules including policies and regulations (Ostrom, 2005). Any intervention in the social subsystem (or lack thereof) can be characterized by how it shapes outcomes in the biophysical subsystem. For example, deforestation of ecosystems with high diversity of plant species reduces carbon storage (Chen *et al.*, 2018; Liu *et al.*, 2018), reduces biodiversity, and contributes to climate change. Likewise, policy actions involving restoration that focuses on a few plant species with high carbon storage capacity can improve carbon storage potential but misses the opportunity to increase biodiversity and to create opportunities for local communities.

Earlier sections in this report, especially Sections 3, 4, and 5, have provided technical details regarding climate mitigation and adaptation measures and interventions to restore, manage, and protect biodiversity. Section 6 provides a broad summary of the nature of interactions between biodiversity and climate and their social outcomes. This section provides a framework for understanding different types of interactions including co-beneficial, co-detrimental, and trade-offs.
It examines the context-dependence of biodiversity and climate interactions, and how social factors both influence and are influenced by these types of interactions. With a deeper understanding of these interactions, this section then aims to identify the limits on biophysical and social systems to cope with change including critical thresholds and tipping points. While the surpassing of thresholds and tipping points might typically be viewed through a negative lens, i.e., as unfavourable pathways to avoid, there are also bright spots, such as through social tipping interventions that can catalyse change towards positive outcomes.

6.1.1 Biodiversity-Climate-Social interactions

Policy interventions that focus on either biodiversity (such as conservation or restoration) or climate (such as mitigation or adaptation) can lead to different types of outcomes for climate and biodiversity when their effects are considered jointly (Sections 3, 4, 5). Those outcomes can be placed into

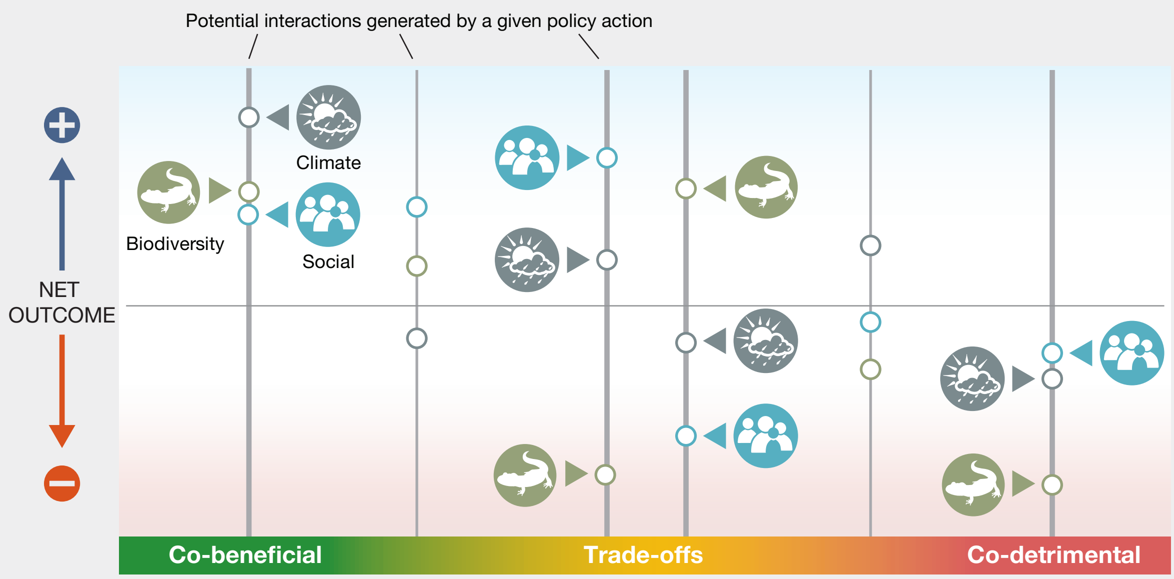


Figure 6.1 **Potential outcomes of interactions within the social-ecological system.**

Specifically, the plots represent hypothetical outcomes of an intervention in terms of biodiversity and climate, with implications for social dimensions. Note that the relative position of biodiversity, climate, and social outcomes is arbitrary and for general illustration purposes only. Co-benefits among climate, biodiversity, and social factors occur when all three elements have positive outcomes. Co-detrimental effects occur when all three elements have negative outcomes. Trade-offs occur when there is a mixture of positive and negative outcomes.

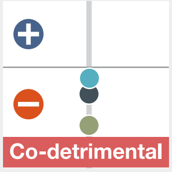
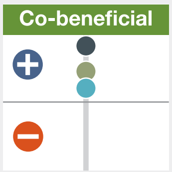
general categories including co-beneficial, co-detrimental, or trade-offs. A visualization of the potential interactions across climate, biodiversity and social components of the social-ecological system, generated from policy action is shown in **Figure 6.1**. All three components have to be considered simultaneously and evaluated in an integrated way when a given action or policy is to be implemented or proposed, as there is a gradient of impacts from co-detrimental (one action/policy leads to negative impacts on all three components) to co-beneficial (one action/policy leads to positive impacts on all three components).

While such categorization can be a useful tool to understand how biodiversity and climate interact, it is important to bear in mind that the particular shape of the interaction can be very complex. Specifically, certain policy interventions can lead to nonlinear positive or negative effects. Such non-linearities can even lead to the outcomes being positive up to a certain level, but negative above that (or vice versa). Further, the resulting outcomes from climate or biodiversity interventions in turn, can create off-stage (distant, diffuse, and delayed), environmental and social impacts which in turn may call for new types of interventions (Pascual *et al.*, 2017). Such feedback effects are usually difficult to trace given that those impacts tend to occur indirectly across the social components, affecting actors and stakeholders, locations (e.g., urban vs. rural), and socioeconomic sectors differently.

To provide both a broad summary of these biodiversity-climate-social interactions and a treatment of their nuances, **Table 6.1** uses illustrative examples and case studies to show the general patterns for co-beneficial, co-detrimental and trade-off interactions while the main text of the section deals with more of the complexity of these interactions. As an example of co-beneficial interactions, reducing deforestation, which generates positive outcomes for biodiversity, can reduce the exposure risk to zoonotic diseases (Dobson *et al.*, 2020; IPBES, 2020) while maintaining carbon stocks, contributing to carbon sequestration and storage, and leading to positive human health benefits both locally and globally (Reaser *et al.*, 2021). Another example involves indigenous peoples and community conservation areas (ICCAs). ICCAs are natural and/or modified ecosystems containing significant biodiversity values and ecological services, and which are voluntarily conserved by indigenous and local communities through customary laws or other means. While the intention may be to support their livelihoods and well-being, culture or spiritual values, the ICCA can lead to the conservation of these ecosystems, its biodiversity and associated benefits including those related to climate mitigation (Corrigan & Granziera, 2010; Kothari, 2008). External recognition (outside the ICCA initiating indigenous community) will support the conservation outcome. These positive outcomes derived from policy interventions can be classified as "easy wins".

Table ⑥ ① Types of biodiversity and climate interaction outcomes from biodiversity conservation and restoration interventions and climate mitigation and adaptation interventions, with examples of social outcomes derived from such interventions.

The content here is not intended to provide a comprehensive list of the different types of interventions, interactions, and outcomes, but rather an overview of the broad categories of interaction types including co-detrimental, trade-offs, and co-beneficial. These interactions can be context-dependent where the same type of intervention can have different outcomes depending on the particular context (e.g., they might have different outcomes across different regions), and they might have complex functional relationships including nonlinear relationships. These nuances are too detailed for the table but are instead explored in the text (Sections 6.1,6.2). The graphical representations of biodiversity and climate interactions and their social outcomes correspond with **Figure 6.1** (positive outcomes for biodiversity, climate, and/or society are above the horizontal line, whereas negative effects are below).

Types of outcomes	Description	Examples		
		Interventions	Outcomes	References
	Interventions result in negative outcomes in biodiversity and climate	**Fisheries subsidies to support distant-water fishing (Adaptation):** to enhance distant water fishing as a remedy to declining catches due to climate change	**Biodiversity (-):** increases the overexploitation of fish stocks **Climate (-):** increases carbon emissions from fuel used by industrial-scale fishing, re-mobilisation of carbon in sea bottom sediments by trawling, and reduces carbon sequestration potential of large pelagic fishes **Social (+):** temporarily increases economic benefits accruing to people working in the industrial fishery sector **Social (-):** large-scale, industrial operations harm the viability of small-scale fisheries and livelihoods of vulnerable artisanal fishers	{Section 4} (Kelman, 2020; Mariani *et al.*, 2020; Paradis *et al.*, 2021; Schuhbauer *et al.*, 2017; Sumaila *et al.*, 2019)
	Interventions result in a positive outcome in either biodiversity or climate with negative outcomes in the other The strength of such trade-offs can vary from weak to strong	**Afforestation and fire suppression in tropical savannas (Mitigation):** to increase carbon sequestration by increasing forest cover	**Biodiversity (-):** decreases species diversity, especially of tropical savanna specialists including many species of ants and plants **Climate (+):** increases carbon sequestration by increasing tree cover **Social (+):** provides forest products and social safety nets **Social (-):** diverting water to the afforested sites reduces the amount of water run-off to human settlements, e.g., water available for drinking; also, reducing land available for agriculture, potentially harms food security	{Sections 2,3} (Abreu *et al.*, 2017; Doelman *et al.*, 2020)
		Implementation of aquaculture (Adaptation): to provide alternative livelihoods for fishers when fisheries are impacted by climate change	**Biodiversity (+):** reduces fishing pressure on overexploited fish stocks **Climate (-):** can remove natural vegetation and habitats, releasing the stored carbon **Social (+):** provides alternative livelihoods and diversifies ocean economies **Social (-):** intensifies conflict in use of coastal and water resources by different stakeholders	{Section 4} (Ahmed & Thompson, 2019)
	Interventions result in positive outcomes in biodiversity and climate In some cases, trade-offs exist in the near term while positive biodiversity and climate outcomes can be achieved in the long term (see main text: Sections 6.1, 6.2)	**Restoration of high carbon-storage ecosystem (Mitigation):** to increase carbon sequestration	**Biodiversity (+):** provides critical habitats for species and improves local genetic and species diversities **Climate (+):** increases carbon storage capacity **Social (+):** provides products and safety nets for local communities, provides job opportunities on restoration, and access to carbon credit funds **Social (-):** increases conflicts with existing uses on the area for restoration that needs to be restricted or relocated	{Section 4} (Bindoff *et al.*, 2019; Churkina *et al.*, 2020; Dawson et al., 2011; Dinerstein *et al.*, 2020; Fuss *et al.*, 2018; Goldstein *et al.*, 2020; Hagerman *et al.*, 2010; Leo *et al.*, 2019; Soares-Filho *et al.*, 2010; UNEP, 2019)

Types of outcomes	Description	Examples		
		Interventions	Outcomes	References
		Establishment of forest protected areas with restricted use (Conservation): to protect vulnerable and endangered species and ecosystems	**Biodiversity (+):** provides immediate protection to existing biodiversity **Climate (+):** provides carbon sequestration and reduces carbon emission from land-use changes **Social (-):** can limit the use of forest products and social safety nets	{Section 5} (Sala *et al.*, 2021)

However, co-beneficial interactions between biodiversity and climate from policy interventions can exhibit more complex behaviour and dynamics than simply being mutually reinforcing. For example, the restoration of degraded high-carbon storage ecosystems might have relatively early positive effects on biodiversity, but slower-to-accumulate positive effects on carbon storage (Yang *et al.*, 2019); eventually, over longer time scales, increasing gains in carbon storage might begin to taper (Leo *et al.*, 2019; Bindoff *et al.*, 2019). Indeed, the key to understanding many of these nonlinear relationships is the time course of application of the interventions and their realized effects (Section 6.2). In contrast, it is possible that an intervention leads to positive outcomes for both climate and biodiversity only at very high values across those axes, regardless of the timing of the implementation. For example, the effects of emissions reduction on biodiversity conservation might only be seen at very high levels (Section 3).

While climate mitigation/adaptation and biodiversity co-benefits of an intervention represent an ideal scenario, interventions that result in trade-offs are also possible and can likewise take on nonlinear forms. In some negative interactions, there might initially be no detriment for one of the components, but the detriment becomes obvious at higher values along one axis. For example, at low levels and in the near-term, the implementation of aquaculture could protect against biodiversity declines by reducing pressure on overexploited fish stocks; however, at high levels and over longer time scales, such practices can remove natural vegetation and habitats leading to the release of stored carbon. Thus, depending on how aquaculture is deployed **(Table 6.1)**, it could exhibit this type of nonlinear, negative interaction behaviour.

Further, co-detrimental relationships where there are negative impacts on biodiversity and climate can also exhibit synergistic behaviour. That is, negative impacts on climate and biodiversity can lead to the intensification of negative impacts on one another through feedbacks. Such co-detrimental relationships are especially problematic because the negative consequences appear right away and continue to cause accelerating negative impacts. These types of negative interactions are exemplified by the effects of land degradation on climate and biodiversity and the feedback processes that result (Sections 1 and 2).

Other types of nonlinear interactions between biodiversity and climate involve non-monotonic relationships (i.e., both increasing and decreasing trends within the same relationship). One instance of these types of interactions are hump-shaped interactions which involve cases where a moderate change on one axis has benefits on the other, but negative outcomes are evident when moderate changes become large changes. For example, regional alkalinization of sea water may help counter the impacts of ocean acidification on coral reefs (Feng (冯玉铭) *et al.*, 2016), however, large-scale expansion of ocean alkalinization may impact biodiversity (Gattuso *et al.*, 2018).

Various types of more-or-less neutral interactions are also possible when changes in one dimension are approximately independent of the other. Qualifying these as 'more-or-less' neutral interactions is necessary, as it can be argued that even policy interventions with neutral outcomes for biodiversity or climate change could still alter outcomes due to intrinsic feedbacks between these two systems. For example, climate interventions with neutral consequences for biodiversity could nonetheless yield benefits by allowing biodiversity to thrive. In general, however, for neutral interactions, policies and interventions on biodiversity and climate do not need to consider outcomes of the other when negative impacts are not expected.

The Convention on International Trade of Endangered Species of Wild Flora and Fauna (CITES) actions, such as trade regulation, do not have direct effects on climate change, and therefore represent a neutral interaction. Similarly, the improvement in the efficiency of energy grid infrastructure can aid in achieving climate goals (Surana & Jordaan, 2019) without overall negative impacts on biodiversity. Note however, that there is a measure of context dependence here. If energy efficiency measures are applied as stand-alone actions, then climate and biodiversity might have neutral interactions in this context. However, if energy efficiency can be promoted in conjunction with bigger energy expansion plans where new energy generation, and consequent transmission and distribution lines are included in the planning, then there could be an effect on biodiversity depending on where this new or upgraded generation, transmission or distribution is planned. Likewise, tree planting in highly urban landscapes (urban greening) provides positive impacts on climate change mitigation and adaptation, but might have limited impacts on tree biodiversity due to the low number of tree species that are usually planted in urban areas (Oldfield *et al.*, 2013). However, in a broader context, this example could also fall under the category of co-benefits when considering that trees provide habitat for other species such as birds, which could promote biodiversity of these other taxonomic groups.

Policy inaction can also lead to different types of outcomes. For example, policy inaction leading to negative social impacts (e.g., not investing in food and water security) can have long-lasting effects on biodiversity and climate. The lack of human development policies to address food insecurities under climate change, can lead to potential negative impacts on biodiversity. For example, deforestation via industrial agricultural expansion (Turner *et al.*, 2010) can lead to reductions in: carbon stocks (West *et al.*, 2010); farmers' adaptive capacity to cope with climate change (Zavaleta *et al.*, 2018); and biodiversity (Hanspach *et al.*, 2017). Furthermore, some policy actions, even if aiming for win-wins for biodiversity and climate, may not lead to desired outcomes, due to hysteresis effects (i.e., lagged effects). For example, in the absence of sufficient planning for future conditions, restoration of certain ecosystem types may not be successful as the environmental conditions necessary for the establishment and growth of species in those places (e.g., high moisture levels) may no longer exist when plants reach their maturity, or be impossible to achieve (e.g., sea-ice ecosystems) (Section 2).

The foregoing serves to highlight the fact that while biodiversity-climate interactions and their social outcomes can be placed into co-beneficial, trade-off, or co-detrimental categories, these categorizations are subject to change by virtue of the fact that they are often dependent on a specific spatio-temporal context. Thus, the same policy measures taken in different spatio-temporal contexts could have positive effects on biodiversity or climate in one context, but negative effects in another. Further, the same policy measures could even be said to 'move' across categories (e.g., from trade-offs to co-beneficial outcomes) depending on where and how interventions are implemented, or where in the time course of implementation the interventions are measured. For example, afforestation practices such as presented in **Table 6.1**, could have very different biodiversity-climate interactions and social outcomes depending on the specific context of implementation. Depending on the diversity and growth rate habits of the tree species being planted, the scale at which afforestation is occurring, and the background environmental conditions where trees are being planted, outcomes could be positive or negative in any one of the biodiversity, climate, or social dimensions (Doelman *et al.*, 2020). For example, in mesic areas, water run-off for human settlements would be less problematic than in dry areas (Bond *et al.*, 2019). Or, similarly, if a site with high biodiversity undergoes afforestation with minimal tree diversity, then climate goals might benefit while biodiversity declines (Veldman *et al.*, 2019). Additionally, in this example, climate goals might be only marginally aided in the case of small-scale plantings. Further, afforestation might shift between categories over the course of implementation: in the case of diverse communities of slow-growing trees, trade-offs might be initially apparent due to enhanced diversity but delayed benefits of carbon sequestration. Eventually co-benefits might be attained as the trees mature and store more carbon (Oldfield *et al.*, 2013).

A common feature with regard to the links between climate, biodiversity and social components are the strong multi-scale linkages between drivers and responses. Policies addressing these challenges are often constrained by the spatial scale the policies are designed for (local, national, or international). However, these multi-scale linkages contribute to the trade-offs, unintended consequences, or co-benefits associated with these challenges and solutions. For example, global greenhouse gas emissions that drive climate change, a global-scale challenge, impact nature and its contributions to people on land and in the ocean, with consequences experienced by local communities. While climate adaptation measures at the local scale can reduce climate impacts and risks to a certain degree, there are limits to natural (ecological) adaptation particularly if the pace of change is too fast or if physical, biodiversity or social thresholds are crossed (e.g., under insufficient carbon mitigation at a global scale) and in contexts where technological and economic conditions limit effective policy interventions. The mismatch between solution options and drivers of the climate and biodiversity challenge may create negative incentives for sustainable actions, for example, incentives to overexploit natural resources (e.g., fish stocks) before such resources (e.g., fish populations) shift from one jurisdiction to another.

6.1.2 The social context matters in shaping and understanding biodiversity-climate interactions and their outcomes

It is important to be mindful of the social context to understand the potential effects of any policy intervention designed to have positive results for biodiversity and climate. In a similar way as the biophysical context (e.g., agroecological conditions) matters to identify conservation and mitigation/adaptation potential, understanding the social context is required to allow prioritizing place-based, socially desirable interventions compared to silver-bullet solutions, which may work in one place but not in another. For example, technological innovations to deal with climate mitigation (e.g., in the energy sector) may foster behavioural (production and consumption) changes in an incremental way provided such technology is tailored to the specific social-cultural context. When more transformational changes are required to deal with the outcomes from climate-biodiversity interactions, innovations in the sociocultural context may be required in order to enable shifts towards collective sustainable behaviour. Hence, taking into account the social context is key to foster 'socio-technical sustainability transitions', i.e., fundamental changes in the coevolution between social and technological relations (Geels, 2019; Markard *et al.*, 2020). Further, since the biophysical and the social systems are highly interconnected it is necessary to frame the climate and biodiversity nexus using a social-ecological systems approach.

Meeting environmental goals within the biodiversity-climate nexus requires being aware not only of how these interventions may impact social outcomes, directly and indirectly, but also of the ways in which the direction and size of the impacts of the interventions are dependent on the social context itself. Assessing social outcomes from biodiversity-climate interactions requires focusing on the multiple and contextual dimensions that determine people's good quality of life (GQL), which comprises manifold aspects such as access to food, water, energy and livelihood security, and health, good social relationships and equity, security, cultural identity, and freedom of choice and action (Díaz *et al.*, 2015); see also **Figure 6.2** and **Box 6.1** for a case study). Furthermore, people's interests, aspirations and values, and associated governance systems, can determine (constrain or promote) the type of desirable policy interventions, which will lead to certain biodiversity and climate outcomes.

The underlying social context can limit or create opportunities for intervening into the biophysical system in ways to meet environmental goals. But despite increased awareness that biophysical and social aspects are interrelated, the understanding of the social processes mediating biodiversity and climate outcomes has been particularly elusive (Ban *et al.*, 2013; Bennett *et al.*, 2017). For example, efforts to account for social equity into achieving biodiversity and climate goals have been limited (Halpern *et al.*, 2013; Zafra-Calvo *et al.*, 2019; Markkanen & Anger-Kraavi, 2019). The ways the social context (e.g., social values and governance systems) can determine the effectiveness of interventions shaping the climate-biodiversity nexus and how this feedbacks into the social system are much less understood.

Any intervention aiming at biophysical goals will have a range of social impacts, some positive, some negative, some uncertain, distributed in different ways among people and communities (now and in the future). If social safeguards are not in place, it is likely that in the context of highly skewed social power relations, asymmetric social outcomes may result from interventions aimed to address climate and biodiversity-issues. One reason is due to situations in which political and economic elites control (participatory and decentralized) decision-making processes (Persha & Andersson, 2014). This may create unintended social conflicts (Corbera *et al.*, 2019), and increase social inequity, for example via interventions aiming at 'benefit-sharing' from biodiversity conservation (Coolsaet *et al.*, 2020; Sandbrook & Adams, 2012), establishing biodiversity offset mechanisms (Bidaud *et al.*, 2018) and Payments for Ecosystem Services (PES) (Hendrickson & Corbera, 2015), including Reducing Emissions from Deforestation and Forest Degradation (REDD+) programmes (Andersson *et al.*, 2018). Of course, there is an enormous diversity of social contexts, some of which have not been sufficiently analysed, but which have strong global implications as they occur in biodiversity hotspots, including those where human communities are suffering from dire social conflicts, including armed conflicts (Clerici *et al.*, 2020; Gaynor *et al.*, 2016).

Interventions aiming at creating positive biodiversity-climate synergies can be designed so they enhance the good quality of life of people or at least do not create negative social impacts (do-no-harm type interventions). This difference may be important especially if policy aims at inclusiveness or not leaving anyone behind (e.g., improving or not harming the well-being of the worse-off and more vulnerable communities including poor people and marginalized Indigenous people). Such interventions are most needed to protect the poor and marginalised people, who are significantly more reliant on the natural resource base and who would lose out disproportionately from climate change and biodiversity loss (Barbier & Hochard, 2018; IPCC, 2019a, 2019b). For example, policies promoting efficient fuelwood cookstoves in rural areas do not usually take into account how such interventions may affect poor people's well-being via impacts on local biodiversity.

Addressing the trade-offs between social-ecological complexity and the ease of implementation of adaptive solutions is key. In general, policymakers prefer their rules to be as simple and universal as possible, but this conflicts with the diversity of natural and social realities on the ground. Given site-specific complexities, it is unlikely that any sectoral intervention focused on a single strategy can reconcile biodiversity conservation with climate change mitigation/adaptation and enhance people's quality of life, including poverty reduction (Barrett *et al.*, 2011).

Moving away from single intervention strategies to a policy-mix approach requires transferability of interdisciplinarity and place-based transdisciplinary approaches, that involves co-production of knowledge (Seppelt *et al.*, 2018). The need to utilize and strengthen all available knowledge systems is clearly highlighted in the Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019b). For example, in a polar context, but likely applicable elsewhere, the SROCC (IPCC, 2019b) indicates that knowledge co-production is necessary to respond to climate change more effectively as this requires a dual focus of short-term (reducing immediate risks) and long-term adaptation (building resilience to address expected and unexpected impacts). This involves recognizing the value of different types of knowledge such as scientific knowledge from observations, models and syntheses which provides local-to-global scale understandings of climate change, indigenous and local knowledge which provides context-specific and socioculturally relevant understandings for effective responses and policies, and education and climate literacy which enables climate action and adaptation. Such knowledge co-production in turn needs to be linked to decision-making geared to implementing ecosystem-based stewardship, and transformation of many existing institutions. The SROCC specifically states that innovative tools and practices in resource management and planning show strong potential in improving society's capacity to respond to climate change. Networks of protected areas, participatory scenario analysis, decision-support systems, community-based ecological monitoring that draws on local and indigenous knowledge, and self-assessments of community resilience contribute to strategic plans for sustaining biodiversity and limit risk to human livelihoods and well-being. Such practices are most effective when linked closely to the policy process. Enabling conditions for the involvement of local communities in climate adaptation planning include investments in human capital, engagement processes for knowledge co-production, and systems of adaptive governance (Meredith *et al.*, 2019).

6.1.3 Evaluating social outcomes from biodiversity-climate interactions

Evaluating the potential social outcomes of interventions often puts a premium on objectively measured impacts, which raises challenges in the social context. Logically, evaluation calls for inclusion of the voices of those who are impacted by policy. The distribution of positive and negative impacts (benefits and burdens) depends on context-dependent social values. Subjective perceptions of impacts of changes in biodiversity and climate on people's good quality of life is as important as objectively measured changes to key socioeconomic variables. It also follows that social complexity cannot be reduced to a single variable or applied in the same way in all social contexts. For example, biodiversity-related values that are associated with utilitarian or non-utilitarian perspectives are socially constructed, and as such they determine which objectives and means of conservation are deemed acceptable and which ones are not. For example, perceptions of equity and fairness, and feedbacks on biodiversity conservation and climate adaptation or mitigation are deeply context dependent. They are determined by place-specific social norms and other social factors that mediate how interventions play out in practice, as well as by the socially constructed conservation and human development objectives (Pascual *et al.*, 2021).

In addition, just as it is difficult to generalize across cases, one cannot simply generalize across social actors, because what may be an opportunity for one stakeholder may represent a risk for another (Pascual *et al.*, 2014). The fact that an intervention may support biodiversity and certain nature's contributions to people may not imply that those nature's contributions will enhance the quality of life of all people that are affected by such biophysical outcomes. For example, if a given intervention to support tree cover in the uplands offers some hydrological benefits downstream, this does not mean that upland farmers may accept this intervention if afforestation or precluding cutting down trees may decrease the value of land in terms of agricultural productivity. Hence, a mixed set of interventions may need to be put in place across social contexts to ensure equal distribution of benefits.

Moreover, when focusing on social impacts it is important to note that the social impacts may be assessed in terms of a) trade-offs or synergies at the social level (e.g., distribution of winners vs. losers from any intervention), and b) trade-offs or synergies between different constituents of good quality of life. Here we refer to social trade-offs as the outcomes of any interventions aimed at addressing biodiversity-climate change interactions, which generate benefits or burdens, and which in turn create winners and losers in society. This can be illustrated by focusing on REDD+ programs which have emerged across much of the developing world, especially in the tropics, as a policy instrument to create financial incentives to reduce tropical deforestation and enhance forest carbon stocks.

Although the main focus of REDD+ is on carbon, there is increased interest in its associated co-benefits and trade-offs (Panfil & Harvey, 2015; Turnhout *et al.*, 2017). This is because REDD+ has potential to yield co-benefits for biodiversity and nature's contributions to people, especially if high carbon density forests overlap with biodiversity rich forest areas. The program has evolved to account for broader environmental co-benefits, including biodiversity conservation. Numerous research projects have identified ecological indicators that could be used to help guide efforts to include biodiversity in REDD+, particularly in understanding baseline conditions and methods for combined biodiversity and carbon monitoring (Gardner *et al.*, 2012). Yet there is also potential for trade-offs and negative outcomes for biodiversity from REDD+, including from leakage (the displacement of deforestation to other locations) or from carbon funding competing with support for other conservation activities (Phelps *et al.*, 2012). Hence, unless explicitly connected and potential trade-offs are acknowledged, REDD+ might miss the opportunity to adequately address biodiversity co-benefits (Phelps *et al.*, 2012). A survey of 80 REDD+ projects found that while most touted biodiversity co-benefits, 40% had no specific goals on biodiversity or project interventions and monitoring aimed at measuring biodiversity impacts (Panfil & Harvey, 2015).

There may also be missed opportunities for integration of climate adaptation aspects in REDD+ programs (McElwee *et al.*, 2016). In addition, REDD+ programmes have raised various concerns regarding how they might affect social equity in particular social dynamics, which is particularly important because potential REDD+ country beneficiaries with a high proportion of their forest-dependent human communities in poverty are highly vulnerable to the impacts of climate change and biodiversity loss. Potential negative social impacts stem mainly from altering the provision of material nature's contributions to people, impacts on conservation funding and changes to local communities' rights in terms of access to forest resources, as well as broader territorial claims. Given such important social implications of REDD+, these programmes require a precautionary approach (Chhatre *et al.*, 2012). As a result, many REDD+ policies and projects have integrated social safeguards and context-specific social equity considerations into their design and implementation. Well known examples of how social risks (both perceived and expected) in REDD+ programs have affected their implementation include issues surrounding local resistance. In Ecuador, for example, REDD+ policies have faced strong opposition from indigenous communities, triggered by uncoordinated communication about REDD+ to the communities, and especially due to a lack of participation in the decision-making processes by the most vulnerable communities (Reed, 2011). Due to perceived risks stemming from the emergence of new social-power dynamics that run against indigenous and other forest dependent communities associated with REDD+ governance, there are substantial risks of non-cooperation by local forest communities. Similar tensions with forest-dependent communities have complicated REDD+ implementation in other various countries, including Indonesia and Panama (Pascual *et al.*, 2014).

In addressing climate change-related risk, impacts, and trade-offs together with social and ecological systems, climate-resilient development pathways (CRDPs) are being explored as an approach for combining scientific assessments, stakeholder participation, and forward-looking development planning. CRDPs involve a series of mitigation and adaptation choices, aligned with sustainable development, over time, balancing short-term and long-term goals and accommodating newly available knowledge. They accommodate both the interacting cultural, social, and ecosystem factors that influence multi-stakeholder decision-making processes, and the overall sustainability of climate adaptation measures. However, in that context, a shift of responsibility for resilience building onto the shoulders of vulnerable and resource-poor populations is indicated as potentially problematic (e.g., IPCC, 2019b).

6.1.4 Governing the biodiversity-climate-social nexus

Dealing with social outcomes from biodiversity-climate interactions requires nested governance approaches, which often need to involve local institutions (Section 7). Objectives related to governance of biodiversity-climate-social interactions may involve a) optimizing a given set of objectives to minimize climate risks while maximizing biodiversity protection, b) meeting most of the objectives in one domain by not fully satisfying the objectives in another domain but remaining above their minimum levels to avoid strong trade-offs or co-detrimental outcomes, and/or c) keeping options open through flexible and adaptive approaches (Section 7.4). An agreed governance principle may be that in managing the biodiversity-climate component of the nexus, society should have the right and capacity to decide about its future development pathway, based on their own expectations, values and political processes, without exceeding biophysical limits. At the moment, collectively set up institutional rules and norms rarely take into account such constrained optimization or satisficing problems.

Additionally, other key social trade-offs or synergies have implications for governing biodiversity-climate interactions. First, a given constituent of good quality of life for a given social group may hamper other good quality of life constituents for the same social group, e.g., productivity in terms of jobs or income versus stability of income (lowering risks). For instance, agricultural practices that favour agrobiodiversity (diversity of varieties, landraces, etc.) and agro-ecological approaches that adapt and create fewer CO_2 emissions could be less productive in terms of yields but more resilient to climate and market shocks, making them more stable in terms of income generation. Second, short term (realized) outcomes may be different from (potential) longer term outcomes. This relates to intergenerational equity, e.g., fixed costs in investments for restoration can yield benefits in the longer term while the costs are being borne in the present. Some interventions may require long-term contracts with landowners where fixed costs in the short term may be substantial and the likelihood of expected larger gains in the future remain uncertain. This may relate to land tenure rights and raises the question of how to treat discount rates of benefits and costs to assess the efficiency of any planned intervention on the biodiversity-climate nexus (expanded upon in Section 7).

Furthermore, it should be noted that enduring interventions may change institutional structures in the future (e.g., property rights), thereby changing norms, rules (of access to natural resources) and ultimately social values about them. Interventions may have direct effects on the level and distribution of benefits and burdens on different social groups and can have long-term enduring impacts through alteration of existing institutional structural aspects (norms and rules). These in turn may impact the effectiveness of ongoing or alternative interventions in the future. Hence, key aspects are to assess *a priori* whether interventions are demanded from local communities themselves, and to involve them in the design, implementation, monitoring and assessment of such interventions. It also follows that mapping local actors' priorities, motivations, expected distributions of benefits and burdens, preferences towards risk, and sociocultural values about nature's contributions to people, provides a contextual picture that needs to be overlaid with biophysical mapping of potential effects of policy interventions. This would require deliberative mechanisms adapted to the social context.

As mentioned above, depending how interventions are designed and implemented, climate mitigation and adaptation goals may be connected to biodiversity co-benefits, being mindful of social impacts. REDD+ is a good example; a key limitation of REDD+ to foster such synergistic positive interactions is due to the extra costs required to maintain biodiversity monitoring, as it is not clear how these costs will be absorbed into carbon pricing or as transactional expenses, for instance covered through traditional development aid (Phelps *et al.*, 2012; Pascual *et al.*, 2018). In addition to the local to national scale, governance of REDD+ and associated biodiversity-climate-social outcomes are dependent on the distribution of international funds. For instance, how existing global financial REDD+ resources are distributed in the world can have different impacts on different countries. Under the 2015 Paris Agreement, the Green Climate Fund (GCF) is 'expected' to mobilize 100 billion US$ per year by 2020 (Cui & Huang, 2018). According to various model results, including biodiversity as a key criterion for the allocation of results-based REDD+ payments is likely to significantly protect species richness without significantly compromising 'carbon efficiency' (Venter *et al.*, 2009; Palomo *et al.*, 2019). This implies that global REDD+ funding allocation decisions could indeed consider biodiversity conservation without loss in carbon efficiency. Further, adding a social equity criterion so that more countries could share international REDD+ funds would not likely compromise the carbon efficiency and biodiversity outcomes at the global level in significant ways (Palomo *et al.*, 2019).

6.1.5 Mobilizing knowledge about biodiversity-climate-society interactions to reach desirable social-ecological outcomes

Biodiversity and climate interact in complex ways following policy action (and inaction) with direct and indirect (off-stage, i.e., distant, diffused and delayed) outcomes on society and other environmental components in social-ecological systems. There is growing understanding of such complexity, especially through place-based interdisciplinary research around the world (Balvanera *et al.*, 2017). The key interactions and feedback mechanisms between biodiversity, climate, and society are shaped in many different ways. Assessing such interactions requires understanding of the social context, including culture, history, institutional setting (norms and rules in society), the values and aspirations of different people, distributional trade-offs arising from biodiversity and climate interactions, which in turn are largely determined by power relations in society. **Box 6.1** illustrates the connections among the biodiversity, climate, and social components with a case study of Arctic Inuit.

The critical role of governance in implementing effective climate adaptation are highlighted in (IPCC, 2019b) and (IPCC, 2018). However, as many current and projected ocean and cryosphere changes (e.g., ocean warming, acidification, deoxygenation, and sea-ice loss), for example, are expected to be irreversible on timescales relevant to humans and ecosystems, risks and challenges to adaptation emerge. The spatial and temporal scales of those changes further challenge the ability of communities, cultures, and nations to respond effectively within existing governance frameworks. The latter are further challenged by the interconnections between climate, biodiversity, and social change. This is due to a mix of slow and fast-changing variables which complicate the differentiation between climate governance and other governance efforts, the different time frames for social decision-making and government terms compared with the long-term commitment of climate change, the uncertainty about the rate and scale of change that will occur in the medium to long-term, and the progressive alteration of the environment through climate change, each of which demand continual innovation and adjustment of governance arrangements (IPCC, 2019b). The Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) highlights that profound socio-technical, economic and institutional transformations are needed if climate-resilient development is to be achieved. This includes technological innovation, transformative governance, international and transboundary cooperation, and greater empowerment and participation of local communities in the governance (planning, design, implementation, and decision-making process) of the ocean, coasts, and cryosphere in a changing climate. It also

Box 6 1 Biodiversity-climate-social interactions in a case study of Arctic Inuit.

Arctic Inuit are experiencing large changes in climate and biodiversity driving strong social impacts. Exhibiting remarkable resilience in an extreme environment for thousands of years, subsistence harvesting continues to be a key element of food and cultural security (AMAP, 2018; ICC-Canada, 2008; Steiner *et al.*, 2019). Arctic Inuit also have been historically marginalized and challenged by conflicting traditional and Western lifestyles. Potentially associated trauma might amplify climate-change related risks.

The biodiversity-climate-social interactions are mapped onto the IPBES conceptual framework (Díaz *et al.*, 2015). The framework includes six main elements, indicated as boxes in Figure 6.2, overlayed on a background of values and culture. Linkages among the main elements are indicated by arrows as described below. The main elements and the arrows linking them are interacting across a range of spatial scales and are changing over time. Good quality of life (GQL) for Inuit includes food security, environmental and cultural security. These are impacted through direct drivers, such as climate change (Arrow 9), e.g., changing sea ice may cause unsafe ice conditions, changing weather and seasonality, enhanced storminess and wave action may impact traditional harvesting methods and access to marine resources. GQL may also be impacted or by those drivers through changes in nature and nature's contributions to people (NCP, Arrows 3,4,8). This may include shifts in species composition and phenology including changes in primary production (both increases and decreases) that affect food availability and shifts in traditional harvesting times, locations and techniques (Fidel *et al.*, 2014; Loseto *et al.*, 2018; Rosales & Chapman, 2015; Waugh *et al.*, 2018). Some changes might be positive, others challenging or negative. Large, fast paced changes, including never seen before states, limit the application of traditional knowledge and may weaken the connection to Elders. Changes in the environment and food availability may lower species resilience, and increase bird and mammal mortalities (Huntington *et al.*, 2020). The sum of all changes impacts subsistence, mental health and the feeling of security and stability in the community.

A key direct driver of change is the emission of greenhouse gases, primarily generated outside the Arctic, which limits the capability within Inuit communities to reverse or decelerate the experienced changes. This highlights the central role of institutions and governance in linking drivers of change, nature and people. The status of an individuals' or a community's GQL feeds back onto institutions and governance (Arrow 1) and may include a push for Inuit representation in governance. On an international level, the Arctic Council which has six permanent Indigenous participants including the Inuit Circumpolar Council (ICC), has amplified the voice of Arctic people affected by the impacts of climate change and mobilized action (Koivurova, 2016). The ICC (a major international, non-government organization) represents ~180,000 Inuit of Alaska, Canada, Greenland, and Chukotka (Russia), and holds Consultative Status II at the United Nations (ICC, 2021). Based on the ICC's goals to strengthen circumpolar unity, promote Inuit rights and interests on an international level, including long-term policies that safeguard the Arctic environment, and seek full and active partnership in the development of circumpolar regions, the ICC developed a comprehensive Inuit Arctic Policy (Inuit Circumpolar Council, 2010). Within Canada, Inuit governance is established on national (Inuit Tapiriit Kanatami, ITK) and regional levels (Inuit land claim agreements among Inuit nations, federal and territorial governments in Canada). On all levels Inuit priorities highlight the protection and advancement of the rights and interests of Inuit and the support for healthy ecosystems, including the necessity to face climate change and support for science, knowledge and research meaningful for communities and decision-making (Inuit Tapiriit Kanatami, 2019). Institutions shape values (what is important for society), thus it influences the demand and supply of NCP as well as the extent of anthropogenic drivers (Arrows 7,2). Hence institutions and governance can drive and support mitigation and adaptation efforts either by directly influencing regulations and agreements regarding anthropogenic drivers (Arrow 2), or through ocean-based local measures impacting NCPs (Arrow 7). The latter may have limited effectiveness to mitigate climate change (IPCC, 2019b) but are useful to implement to address local risks, and may have co-benefits (e.g., biodiversity conservation). Examples are conservation measures such as MPAs and the protection of ecological corridors (see Section 3). To ensure benefits to Inuit, co-design and co-management by Inuit and national governance institutions is essential, e.g., Canada's Tuvaijuittuq marine protected area MPA (est. 2019) has been designated based on its sea-ice ecosystem and cultural and historical significance for Inuit travel and harvesting. Adaptation pathways can also be driven through the provision of anthropogenic assets which then enhance NCP and GQL (representing a co-production of NCP and GQL via anthropogenic assets, Arrows 5&6, 5&10) and may include technological advancements, such as ice thickness monitoring, improved and accessible weather forecast, climate and seasonal predictions (for travel and harvest planning), enhanced trauma-informed mental and physical health care, and co-production of knowledge and Inuit involvement in climate science. The latter may provide both knowledge transfers in support of NCP and additional income to help navigate harvesting difficulties, supporting GQL.

Any such measures require evaluation in terms of equity (who bears costs, who gets the benefits, now and in the future). This may refer to equity among Inuit or between Northern communities and subpolar communities and to equity within a community. With respect to the first, Canada's Climate Change 2050 strategy (Canada, 2020) strongly emphasizes leadership and self-determination of Inuit and Northerners in the development of climate research. This includes strengthening the capacity of Arctic and Northern communities and indigenous peoples to acquire and apply available data and research, participate in research, and develop methodologies and approaches for climate change science communication as well as professional capacity and

Box 6 1

competencies in climate change science, knowledge, and action. With respect to the second, regional governments or community organizations need to be involved in the distribution of benefits or compensation for trade-offs. In small communities a culture of sharing, if practiced, may address the equity issue. For example, if a community only has two hunters, supporting those two hunters to purchase a better boat, snowmobile or additional fuel may benefit the whole community.

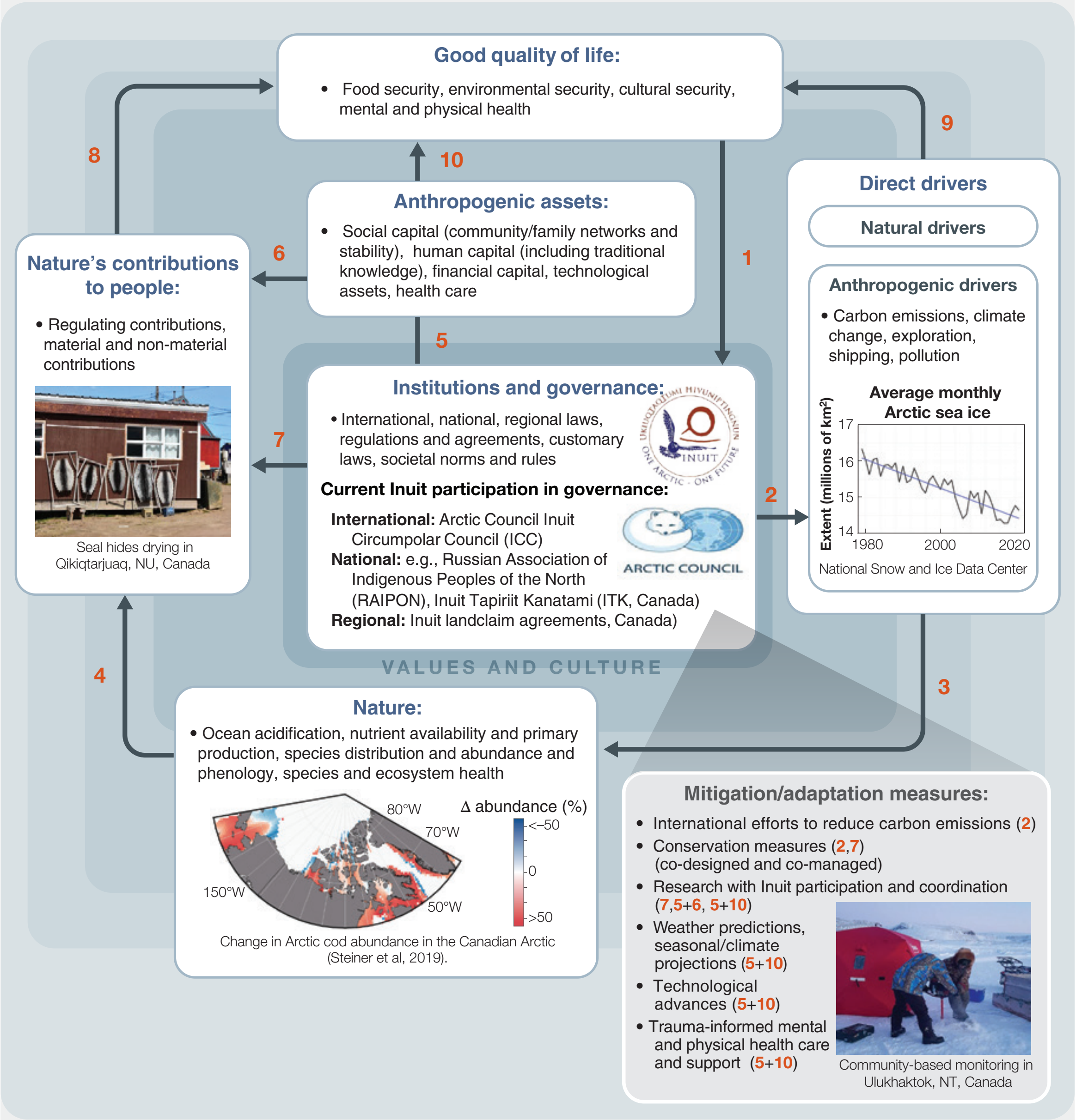


Figure 6 2 **Biodiversity-climate-social interactions through a case study of changes in marine and sea-ice ecosystems and impacts on Arctic Inuit communities, mapped onto the IPBES conceptual framework (Díaz *et al.*, 2015).**

Main elements are indicated as boxes which are linked through actions, impacts and feedbacks, indicated by numbered arrows which are referred to in the text. The lower right box provides an example of institutional or governance related actions which can work along different connections (indicated by arrow numbers) to mitigate or adapt to system changes. Blue shading indicates the underlying societal values and culture, centralized around the institutions and governance element. Societal values and culture both drive and are shaped by institutions and governance and through those intertwine with all other elements. Both the main elements and the interconnections are subject to change over time and spatial scales.

includes transformative adaptation, actions that go beyond coping and incremental strategies and that help societies to anticipate, guide and/or recover from radical climate change impacts (Fedele *et al.*, 2019). Transformative adaptation actions based on nature could provide a triple-win for biodiversity, climate, and society by redirecting people's land use decisions towards more sustainable pathways (Fedele *et al.*, 2020). The SROCC report indicates that the capacity of governance systems in polar regions to respond to climate change has strengthened recently, but not sufficiently rapidly or robustly to address the challenges and risks to societies posed by projected changes. The governance landscape remains insufficiently equipped to address cascading risks and uncertainty in an integrated and precautionary way within existing legal and policy frameworks (Meredith *et al.*, 2019).

6.2 CASCADES, HIERARCHICAL EFFECTS, AND ITERATIVE FEEDBACKS

Changes in physical drivers such as climate, habitats, or direct removal of organisms will affect biodiversity at different levels of organisations, from physiology to population and community levels. The impacts from and responses to the intertwined climate and biodiversity changes will alter actions and behaviour of human communities and social sectors. These chains of causes and responses along different levels of organizations of the coupled human-natural systems are hereafter referred to as 'cascades' of effects (**Figure 6.3**, (Gregr *et al.*, 2020). For example, within the biophysical system, climate change and some climate interventions such as solar radiation geoengineering may result in shifts in monsoonal systems (National Academies of Sciences & Medicine, 2021) or negatively impact biological growth in and under sea ice (Miller *et al.*, 2020). The changes in temperature and precipitation associated with shifting monsoonal systems are projected to increase uncertainties of production from agriculture systems in tropical regions. Such impacts will lead to cascades of impacts on human dependent communities.

Such impacts affect different constituents with respect to their quality of life and consequently may add to broader human security pressures which in turn can lead to political instability, civil unrest and migration, thereby transferring human pressure on ecosystems to other locations. In this way, changes in biophysical conditions and associated social responses will also compound cascades of impacts of climate and other non-climatic drivers on biodiversity. For example, in the ocean, climate change is driving losses of coastal vegetation and decreases in potential fisheries catches in some regions, with cascading effects on increasing the risks of economic hardship, loss of livelihoods and food insecurity for some coastal communities (**Figure 6.3**; (Bindoff *et al.*, 2019). The resulting erosion of basic life-supporting NCP that coastal communities are dependent on may then increase the intensity of anthropogenic pressures on other ecosystems to compensate for the declining ecosystem functions that once supported people. The intensification of some of these human activities such as development of coastal infrastructure, use of more destructive fishing activities, can impact the quality of life of especially vulnerable coastal communities, including Indigenous communities. Similar examples related to shifting the desert and forest biomes under climate change are discussed in Section 6.3 and 6.4.

These cascades of effects can follow the hierarchical levels across components of the social-ecological system, from direct and indirect drivers to policy responses and impacts on natural and human systems that transverse across spatial and temporal scales. For example, diverse factors are driving subsidies to fisheries and agriculture such as maintaining national food production capacity, sustaining livelihoods and viability of coastal and rural communities, and geo-politics. Fisheries and agriculture subsidies consequently affect the behaviours of specific sectors or communities such as intensification of fishing activities (Sumaila *et al.*, 2019), investment into industrial-scale agriculture that increases the carbon footprint of these food production sectors **(Table 6.1)**. Many of the consequences from these social-economic developments will interact with the direct and indirect drivers of climate and biodiversity losses. Further, it is important to recognize that the linkages between drivers or policy decisions and responses can extend beyond the specific location of the systems. Such 'telecoupling' properties are common in many biodiversity, climate, and social contexts, and have resulted in unexpected policy outcomes (Seppelt *et al.*, 2018). Examples include increasing demand for biofuel under climate mitigation policies from one region that drives changes in land use and agricultural production in other regions. Another example is the potential application of climate interventions such as solar geoengineering that aim to reduce global warming but will alter climate patterns in areas that are far from where the interventions were implemented, and consequently affect the natural and human systems there (National Academies of Sciences & Medicine, 2021).

The cascading responses to changing climate and biodiversity drivers can iterate over the pathways of development of the human and natural systems (hereafter called 'iterative feedbacks') (**Box 6.1**, **Figure 6.2**, **Figure 6.3**). The outcomes of such interactive feedbacks can be reinforcement or suppression. For example, one of the mechanisms is through increasing frequency and scale of forest fire as a result of modification of forest habitat (Bowman *et al.*, 2020). Simultaneously, human modification of tropical and temperate forest habitat

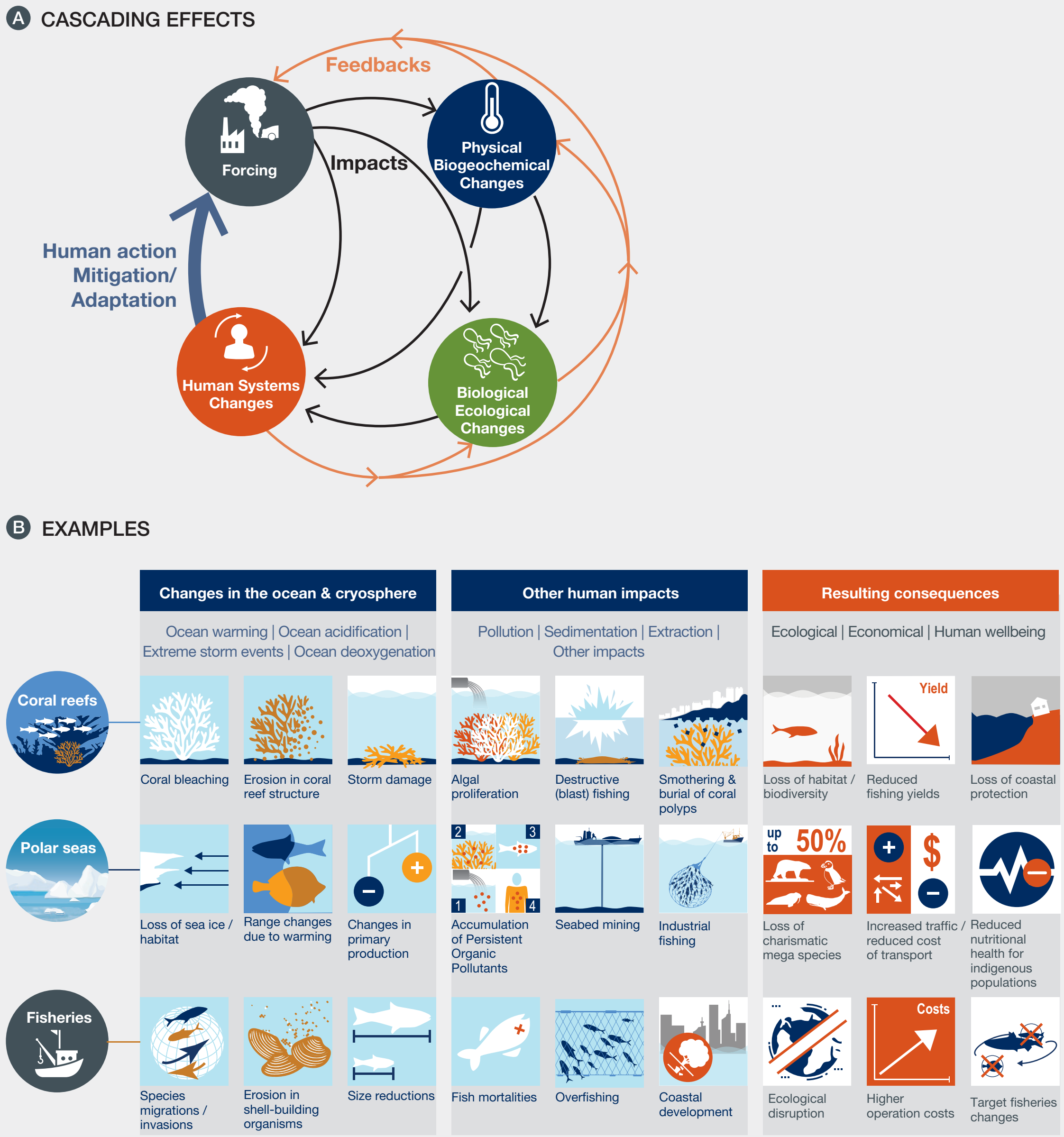


Figure ⑥ ③ **A schematic diagram illustrating the concept of cascades, hierarchical and iterative effects in climate-biodiversity-social interactions.**

Ⓐ Cascading effects, where changes in one part of a system inevitably affect the state in another, and so forth, ultimately affecting the state of the entire system. These cascading effects can also trigger feedbacks, altering the forcing. Ⓑ Examples illustrating impacts from these effects in the ocean (adapted from Abram *et al.* 2019, Bindoff *et al.*, 2019).

increases vulnerability to fire; climate change driven intensification of extreme weather events contributes to fire, leading to further increase in CO_2 emissions, exerting stronger pressure on humans to modify rainforest habitat. In contrast, suppressing interactions as a result of trade-offs or unintended consequences associated with climate actions and biodiversity conservation can reduce the effectiveness of these interventions over time. For instance, carbon offsetting measures through large-scale plantation schemes (in the tropics and elsewhere) may achieve climate mitigation but can lead to conflicts and social unrest through lack of self-determination and inequity in benefits and further impacts on ecosystems, as well as biodiversity if single or non-native species are used in restoration (Sections 3, 5).

The interplays between cascades, feedbacks and hierarchical effects of climate change, biodiversity conservation and social changes is what defines the biodiversity-climate-social nexus framed within the broader social-ecological system. To mitigate undesired trade-offs and enhance positive synergies towards climate and biodiversity goals, the structure and dynamics of the coupled social-ecological systems may sometimes require deliberate transformation (Section 7).

There are situations where biodiversity loss and poverty situations can quickly become mutually reinforcing responses to perturbations in the face of climate change. The 'shared vulnerability' for people and biodiversity to climate change implies the need to think of biodiversity as provider of 'natural insurance' in the face of external weather shocks (Barrett *et al.*, 2011) or as provider of multiple climate (mitigation and adaptation) benefits supporting sustainable development, especially in the context of developmental pathways to eradicate poverty (Roy *et al.*, 2018). For example, there may be places where there is a shared vulnerability for both people and threatened wildlife to stochastic severe weather events, triggered by climate change. Often conservation and aid agencies behave reactively to stochastic weather shocks, creating delays to response as donors and operational agencies need to mobilize resources to grapple with the biodiversity and social impacts. Such delays may create conditions for the social-ecological system to become a lose-lose situation for people and wildlife, where people respond in short-term, unsustainable ways to have their basic needs fulfilled, which can negatively impact biodiversity. In this situation, it is important to plan in advance for responses and via nature-based solutions, help people adapt, while protecting and restoring nature. For instance, index insurance mechanisms can be devised to provide swift responses in the event of weather-related shocks. (Chantarat *et al.*, 2011) examine how index insurance mechanisms may support local people and hornbill populations in Thailand. The mechanism is based on offering employment to local people in hornbill conservation efforts in the event of weather shocks, i.e., at a time when crops and jobs may be lost due to severe weather events.

6.3 LIMITATIONS TO THE CAPACITY OF BIOPHYSICAL AND SOCIAL SYSTEMS TO RESPOND TO CHANGE

There is a need to enhance understanding of the deep interlinkages among ecological and socioeconomic processes to grasp the key parameters and behaviours of human-managed ecosystems that give rise to biodiversity-climate interactions and key social concerns such as poverty and associated vulnerabilities to external shocks (Barrett *et al.*, 2011). In this context, it can be useful to consider these interlinkages as joint determinants of the capabilities of biophysical and social subsystems to cope with change. Understanding the limitations on the capacity of biophysical systems to maintain function and the limitations on social systems to respond and intervene, are critical for determining where thresholds and tipping points lie (Section 6.4).

Ecosystem function is often positively associated with biodiversity. As a consequence, biodiversity loss threatens the ability of ecosystems to perform critical ecosystem functions such as pollination, decomposition, and water filtration (Section 2, IPBES, 2019). Ecosystems can tolerate varying degrees of biodiversity loss through functional redundancy, the 'back-up' that is provided by having several species that perform similar functions (e.g., (Hoppe *et al.*, 2018). However, there are limits on the ability to maintain function in the face of progressive species loss (Oliver *et al.*, 2015). Relatedly, there are other types of ecosystem limits including on the degree to which they can tolerate, for example, resource exploitation or the amount of pollution they can absorb before functions are compromised (Kroel-Dulay *et al.* 2015). Recognizing that there are limits on ecosystems to cope with change, the compounding effects of climate change and habitat loss, degradation, and fragmentation on biodiversity loss, can lead to substantial vulnerabilities for ecosystem function (Section 2, Bergstrom *et al.*, 2021).

Similarly, there are limitations on social systems to cope with the consequences of limitations of biophysical systems to remain resilient in the face of climate change and biodiversity loss (Adger *et al.*, 2009; Evans *et al.*, 2016). For example, the IPCC 5th Assessment report contends that key social limits to climate adaptation are related to psycho-social and structural factors (Klein *et al.*, 2014). These may be related to a) the way current institutional structures (reflected in informal norms and formal rules) and vested interests preclude shaping alternative options/pathways for transformational change; b) ultimate goals set by society itself, underpinned by social values, ethics, knowledge and culture that affect the ways in which societies perceive, experience and respond to sustainability challenges and risks; and c) limitations in terms of altering individual behaviour given mismatches between values, rules, and knowledge in different decision-making contexts.

The limitations within each of the biophysical and social subsystems are clearly connected. For example, climate warming can cause some species to exceed their thermal tolerance limits, reducing biodiversity and key ecosystem functions and derived benefits to people (Section 2, Section 4). By the same token, positive action on climate mitigation can have positive downstream effects, i.e., by lessening the need for compensatory shifts in physiological tolerance, shifting the location of the limit and threshold farther away from current conditions, and allowing for higher retention of biodiversity and ecosystem functioning. Thus, it is important to consider the interplay between biophysical limitations and social limitations in addition to the interactions between climate and biodiversity within the biophysical subsystem when quantifying limits on system capacities to cope with change.

6.4 CLIMATE, BIODIVERSITY, AND SOCIAL TIPPING POINTS

Given their co-dependent nature with respect to a system's capacity to cope with change, the biodiversity, climate, and social axes should be considered jointly in order to accurately identify potential crossing of critical thresholds when making these assessments. Tipping points refer to a specific type of critical threshold, where system feedbacks propel the coupled system into a new state from which recovery is difficult and are often associated with changes in function ('red lines'). Failure to keep biophysical systems below critical thresholds will likely contribute to diminished or loss of ecosystem functioning and regime shifts, and could potentially contribute to global cascades of exceeding tipping points in a number of biomes and habitats (Lenton *et al.*, 2019). Such effects could further cascade through the social axis, leading to the crossing of social thresholds involving economic crises, political crises, social breakdowns, and a loss of critical cultural diversity (Ginkel *et al.*, 2020). Additionally, the crossing of social thresholds could be a cause for the crossing of biophysical thresholds through lack of climate mitigation and adaptation and actions to slow or remediate biodiversity loss.

There are many known climate- and biodiversity-related tipping points in key biomes across the globe (IPCC, 2014, 2019b, 2019a; Steffen *et al.*, 2015), even if the precise threshold is uncertain. For example, there are tipping points associated with the shift from net CO_2 uptake to net CO_2 emissions as a result of rising temperatures. Shifts in ecosystem function occur in many terrestrial and marine habitats as carbon sinks become carbon sources under climate change (e.g., (Lin *et al.*, 2020). For example, when desiccation thresholds for boreal peatlands and shallow lakes are exceeded, these high carbon storage environments can instead become sources of carbon (Holden, 2005; Helbig *et al.*, 2020). Similarly, when thermal limits are exceeded, the carbon sink function of tropical forests is reduced (Zhu *et al.*, 2018). The Arctic ocean is already experiencing limitations in uptake capacity (Cai *et al.*, 2010) and is suggested to convert to outgassing for some regions and seasons (AMAP, 2018; Steiner *et al.*, 2013). Similarly, changes in Antarctic ice cover, permafrost, Amazon rainforest, boreal forest, and peatlands approach thresholds in ecosystem function switching from carbon storage to emissions. These changes arise from a number of climate and biodiversity stressors including warming, altered pest dynamics, and altered fire regimes (both due to climate change and habitat degradation) (Lenton *et al.*, 2019).

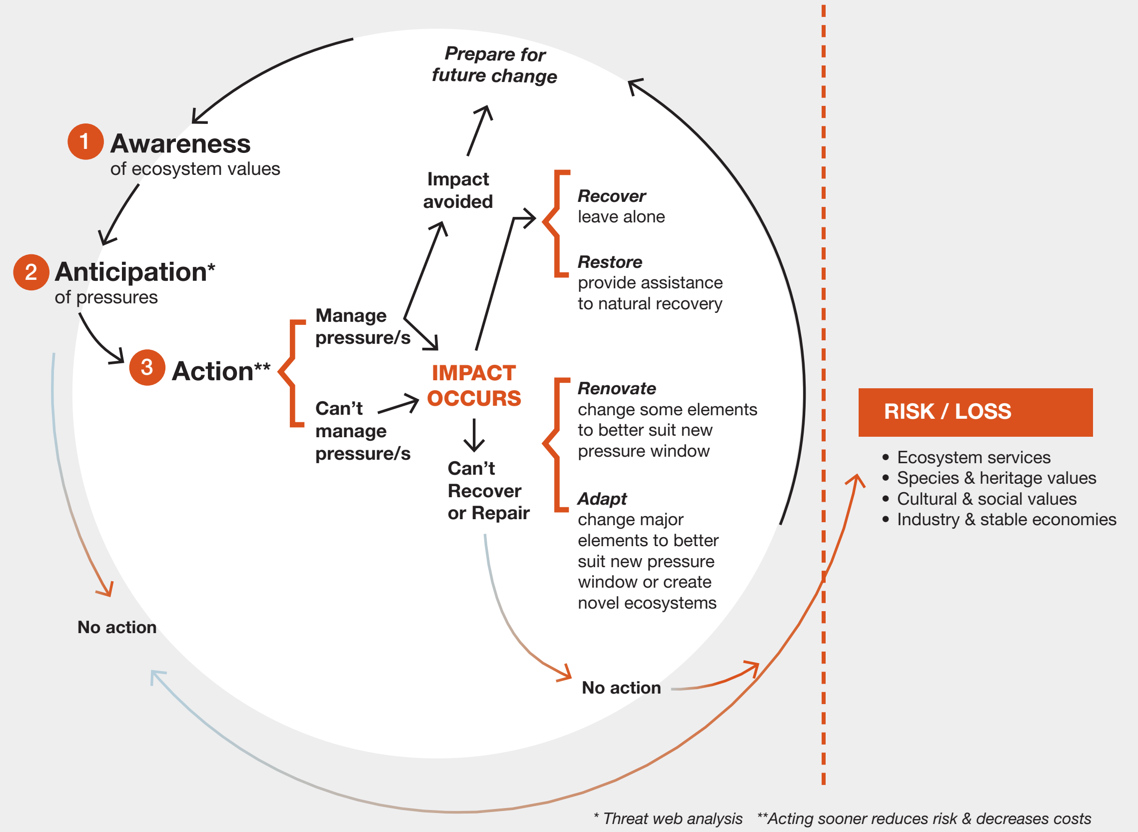
The major concern with tipping points is that they can push the system to a new state that is difficult to reverse or is irreversible, even with interventions such as climate mitigation or ecosystem restoration actions. Further, the new state can exhibit markedly different function, which itself can be difficult to predict. Climate systems can have their own tipping points (note however, this involves a complex set of multidimensional factors, and there is considerable uncertainty in precise level of climate change that results in the transgression of tipping points; (Collins *et al.*, 2019; Hoegh-Guldberg *et al.*, 2018; Hurlbert *et al.*, 2019). There are likely tipping points relating to the level of biodiversity loss and ecosystem function (IPBES, 2019; Jiang *et al.*, 2018). It is important to recognize that climate change and biodiversity loss interact with one another to alter their joint tipping points. For example, climate change effects can exacerbate biodiversity loss and lead to the crossing of a tipping point towards a new ecological regime with diminished ecosystem function.

There is evidence of these types of interactions and consequences for crossing tipping points from recent work across Australia: out of 19 ecosystems monitored, all ecosystems were experiencing 6 to 17 pressures and 12 were experiencing 10 or more pressures, many of which were acting simultaneously (Bergstrom *et al.*, 2021). These pressures included multifarious aspects of climate change ('press' stressors: precipitation, temperature, ocean acidification, sea level change, native species interactions; 'pulsed stressors': heat wave, flood, wildfire, storm) and regional human impacts pressures (invasive species, habitat change / loss, livestock / harvesting, water extraction, runoff / pollution, human-lit fire). Each of the 19 systems showed at least one collapse event over the last 30 years. Such biophysical tipping points can occur over different temporal trajectories with some being relatively gradual, others more abrupt, and still others that fluctuate between transition states.

There is growing concern that some tipping points might occur relatively quickly. For example, climate change could cause entire communities of organisms to exceed their climatic niche limits all at once (Trisos *et al.*, 2020), leading to widespread loss of biodiversity and ecosystem function within a narrow window of time. Importantly, the type of transition and the specific taxa within the ecosystem have effects on how long recovery time is and whether recovery is possible. For example, Australian mountain ash forest could take over a century to recover from an abrupt transition, within which long-term changes in fire regimes lessen chances of recovery (Colloff *et al.*, 2016), whereas bird and mammal populations with more gradual transitions could recover within a couple of decades (Bergstrom *et al.*, 2021).

While some systemic thresholds or tipping points are 'fixed', i.e., independent of human intervention (the melting point of ice is an example), others can be shifted through a variety of mechanisms. For example, compensatory mechanisms such as geographic and phenological shifts or the ability to physiologically tolerate change through phenotypic plasticity and evolutionary change, reduce vulnerability based on exceeding climatic niche limits and thus move populations and species farther away from their tipping point (Sections 1, 2, 4 and 6.3). In another example, assisted colonization in which climate-vulnerable species are moved to climatically suitable habitats could push ecosystems farther from a tipping point (Section 4). The 3As pathway (awareness, anticipation, action) for threat abatement and risk management of ecosystems can be a useful tool in this regard (**Figure 6.4**, (Bergstrom *et al.*, 2021). Awareness involves determining where and what kinds of biodiversity need protection. Vulnerability assessments (Weißhuhn *et al.*, 2018; Segan *et al.*, 2016) and threat web analysis of co-occurring pressures (such as from climate change and habitat loss) are used as early warning tools to anticipate if, when, and where interventions should occur (Geary *et al.*, 2019). Action involves interventions based on the outcomes from the awareness and anticipation analyses.

The crossing of biophysical tipping points can have negative consequences for human social outcomes. For example, the tipping point of shifts from coral to algal-dominated systems on reefs is driven by rising temperatures associated with climate change (and exacerbated by local stressors such as fishing and pollution) which have led to widespread bleaching of corals, thus allowing algal communities to become dominant and replace coral communities (Bruno *et al.*, 2019). In turn, this regime change eliminates an important ecosystem engineer (corals) which causes the reef-associated fish assemblage to shift, negatively impacting reef fisheries and the people who rely on them for income and food security (Ainsworth & Mumby, 2015). Similarly, the tipping point of shifts from sea-ice to open-water dominated systems involve transitions from predominantly sympagic and benthic productions to primarily pelagic production. In this case, thresholds on environmental temperature for retaining sea ice are exceeded, leading to changes in biological community composition with downstream consequences



* Threat web analysis **Acting sooner reduces risk & decreases costs

Figure ⑥ ④ **The 3As (Awareness, Anticipation and Action) Pathway (from Bergstrom *et al.* 2021).**

for humans (Steiner *et al.*, 2019; Tedesco *et al.*, 2019; Lannuzel *et al.*, 2020). Surpassing biophysical tipping points can lead to breaching of social limits and crossing of negative social tipping points. For example, extreme climatic events can trigger food and humanitarian crises with subsequent, cascading impacts on biodiversity through effects on protected areas (Sections 3, 4, 5). However, not all social tipping points are negative. Positive social tipping interventions and the crossing of positive social tipping points represent an area of opportunity for beneficial outcomes.

Mitigating negative interactions between climate and biodiversity change (i.e., strong trade-offs or co-detrimental outcomes) requires an understanding of how interventions within the social subsystem alter the outcome. Just as physically-defined ecological limits, which are associated with the ideas of 'ecological thresholds', 'ecological tipping points' and 'ecological cascading effects', describe those environmental and biological forces that precipitate or accelerate ecological outcomes, the concept of limits can be understood from a social perspective. These can be understood not as an external force, but as a metaphor associated with social goals and needs, which are socially limited or not attainable. This includes the possibility of a collective choice for 'self-limitation' (Kallis, 2021). In addition, social tipping dynamics refer to nonlinear processes in the social system that can trigger disruptive system changes. In social-ecological systems thinking, social tipping points are understood as situations within the social-ecological system where a small change triggers an accelerating positive feedback response, leading to a substantial and often irreversible change in the social system (Milkoreit *et al.*, 2018). That is, social tipping points are associated with situations that can lead to deliberate (desirable) social transformation in the face of sustainability challenges. Social tipping points are context dependent, as they are a function of phenomena such as social identity, power and inequality, agency, and decision making at individual and collective system scales, and thus hard to compare across different social contexts (Milkoreit *et al.*, 2018).

Positive social tipping interventions have been proposed to induce and catalyse positive contagious dynamics to stabilize the biodiversity-climate system. This may be through a mix of social norms/values-centred elements (e.g., revealing the moral implications of fossil fuels), development (e.g., carbon-neutral cities), and economic measures (e.g., divesting from fossil fuels and removing fossil-fuel subsidies) (Otto *et al.*, 2020). Social tipping interventions are akin to intervening in the social-ecological system to create disruptive (transformative) change and put societies quickly on more sustainable trajectories. For example, social tipping interventions may be designed to spread contagiously across social networks where social norms and values, behaviours, and knowledge can spread quickly and widely, leading to reorganization of the social-ecological system.

Activating social tipping interventions need to overcome resistance by vested interests (IPBES, 2019) and the rigidities inherent in political and economic decision making (Otto *et al.*, 2020), especially given the multiple complex interacting dimensions of human societies. In other words, transformative change requires breaking down self-stabilizing mechanisms that favour business as usual or status quo, particularly in cases of cultural or political inertia underpinned by social power structures. Given complex social contagion dynamics (Smith *et al.*, 2020), social tipping interventions require identifying the points in social-ecological systems at which a minor tendency (e.g., in terms of shifting values that are aligned with respect towards nature) may lead to activating stronger motivations for needed behavioural change that can spread quickly to become a major practice (Markard *et al.*, 2020). Key social tipping interventions that can induce such tipping processes need to be mobilized, particularly with respect to large-scale shifts in value systems which aim at human flourishing through respectful relationships with nature and care/stewardship of the integrity of social-ecological systems across scales. For example, 'sustainability learning' involves learning to develop the capacities to manage options for the adaptation of human societies to the limits and changing conditions imposed by social-ecological systems (Tàbara & Pahl-Wostl, 2007). This can be done in conjunction with revealing the ethical (e.g., justice) implications of negative cascading interactions between climate and biodiversity, for instance in terms of the impacts that this has on the most vulnerable people in society. Such social tipping interventions would involve investing in public education to shift the perceptions, values and cultural beliefs of the human role in shaping biodiversity, climate, and social interactions within social-ecological systems. This process can trigger changes in social norms that would ultimately shape regulations and laws. But the scaling-up of a shift of values, and an ethical perception of the problem in terms of the harm the biodiversity and climate crises creates to society at large, also requires ostracising political views and behaviours counter to such transformative change (Markard *et al.*, 2020; Otto *et al.*, 2020). Whether such normative change can be achieved within the limited window of opportunity in terms of time left to control and mitigate climate-biodiversity negative interactions and trade-offs, is an open question. The abolition of slavery and recognition of women's' political rights were triggered by social movements and took many decades to be achieved. There are signals around the world which attest to a potential nascent social tipping element spreading globally via environmental movements (an example is #FridaysforFuture).

6.5 CONCLUSIONS: CHALLENGES AND OPPORTUNITIES WITH BIODIVERSITY-CLIMATE INTERACTIONS IN SOCIAL-ECOLOGICAL SYSTEMS

This section provides a framework for understanding the complexity of the interactions between elements of the Biodiversity-Climate-Society (BCS) nexus. It does so by identifying co-beneficial, co-detrimental and trade-off interactions. Identifying the nature of these interactions can aid in identifying positive pathways through the coupled social-ecological system. A key theme emerging from this synthesis is that any change to one of the components can often have direct and indirect (and sometimes unexpected) impacts on the others. Further, these impacts can be context dependent, and vary over space, time, and across different groups. Thus, while some policy interventions might be beneficial to meeting the goals of individual components (i.e., biodiversity or climate goals), awareness of and accounting for the potential of trade-offs to arise can help guide interventions to avoid difficult to reverse or irreversible situations and find ways for compensating individuals or social groups that may be negatively impacted by the policy interventions.

The ultimate goal of interactions in the BCS nexus is for social-ecological stability and positive outcomes for people and nature. Improving facets of biodiversity, climate, and society simultaneously (or in a cascade-type way) can help the biodiversity-climate-social system to move towards a locally desirable stable equilibrium. Importantly, there may be other locally stable equilibria that are not so desirable and thus represent situations to avoid (e.g., improving both biodiversity and climate but at the cost of damaging social facets, or any other strong trade-off therein). Because there are various potentially stable equilibria (some desirable, some non-desirable) and various pathways leading there, interventions for climate adaptation and mitigation, and biodiversity conservation and restoration would benefit from accounting for these different options and moving towards outcomes that maximize positive outcomes in the biodiversity-climate-social interaction space **(Figure 6.5)**.

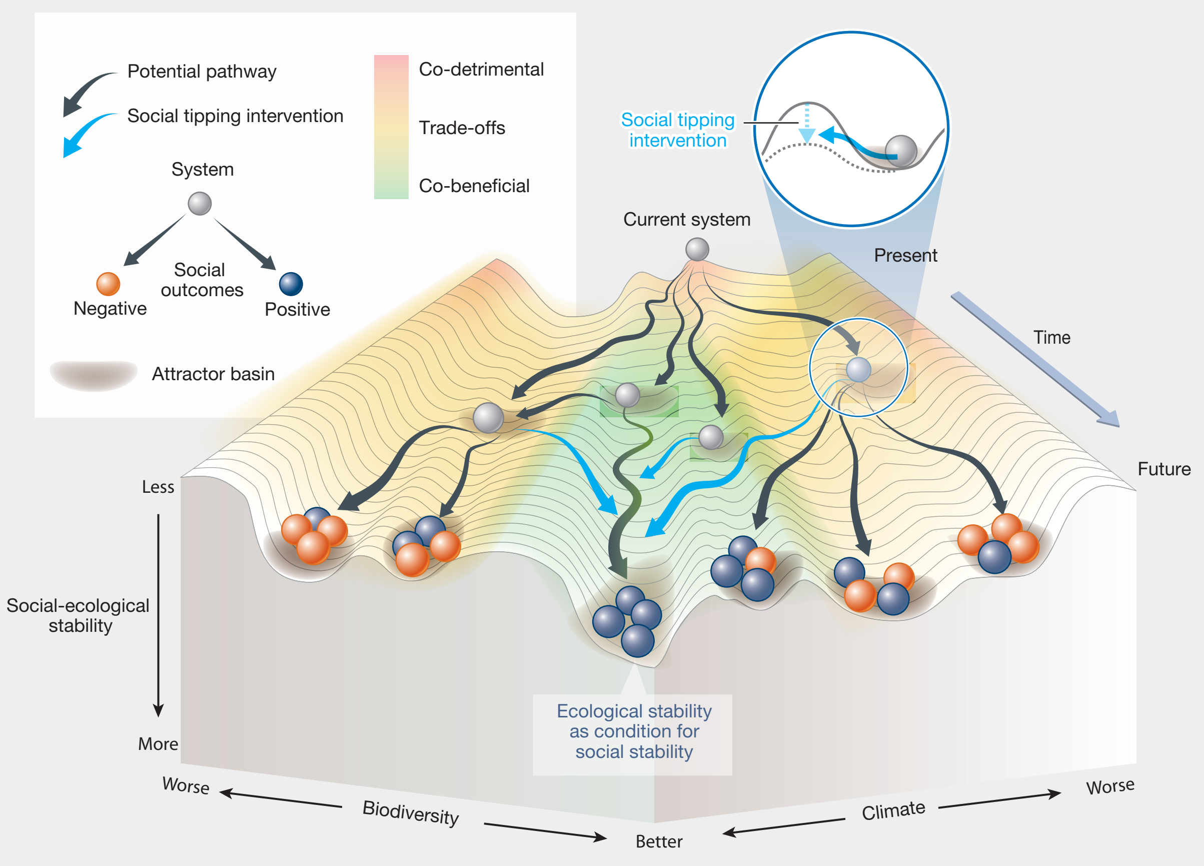


Figure 6 5 **Visualization of biodiversity-climate interactions in social-ecological systems with an explicit depiction of social outcomes for alternative pathways.**

The landscape represents the interaction space between biodiversity and climate. This landscape can include intrinsic

Figure ⑥ ⑤

interactions between biodiversity and climate, e.g., the feedbacks between biodiversity, ecosystem function, and NCP such as carbon sequestration. It can also include intervention interactions such as between climate mitigation and restoration of ecosystems. The current state of the system (the present) is represented by a ball at the top of the landscape. Potential future pathways are represented as arrows flowing away from this point. The landscape has different types of possible interactions: co-beneficial, depicted towards the centre of the landscape and which represent situations where, for example, measures to conserve biodiversity and reduce carbon emissions both have positive outcomes; trade-offs, depicted towards either side of the landscape and which represent situations where either biodiversity or climate measures come at the expense of the other; and co-detrimental, depicted to the farthest ends of the landscape and which represent situations where biodiversity and climate actions are mutually harmful. While "better" and "worse" situations for biodiversity and climate are used to indicate the different types of biodiversity-climate interactions, it is important to emphasize that they must be interpreted in a context-dependent manner, e.g., better biodiversity where and for whom. The landscape also has various attractor basins that attract the system as time progresses into the future. Deeper parts of the landscape and deeper attractor basins represent greater social-ecological system stability. Social outcomes are depicted by the colour shading of the balls representing the state of the system over time. Greater positive social outcomes are found with co-beneficial biodiversity-climate interactions, and negative social outcomes are more likely to be found with strong biodiversity-climate trade-offs. In this scenario, it is assumed that ecological stability is a condition for social stability. Finally, positive social tipping interventions can act in several ways. Social tipping interventions might hasten the movement of the system along a co-beneficial pathway towards desirable deep attractor basins, i.e., those which have positive biodiversity-climate interactions and associated social outcomes; or they might act by moving the system away from a shallow attractor basin, with biodiversity-climate interaction trade-offs and negative social outcomes, toward a more desirable state of the social-ecological system.

Although the necessary conditions for the avoidance of dangerous pathways in the BCS space can be discussed in a general sense, it is also important to discuss how this can practically be accomplished. Issues surrounding implementation relate to the key role of (positive) social tipping interventions to help guide humanity towards non-dangerous and positive local equilibrium (e.g., net-zero carbon emissions, and nature-positive and socially-just interventions). As a recent example, while the COVID-19 pandemic has distracted the world from the problem of biodiversity loss and the damaging ecological impacts from climate change, it has also allowed many expressions of positive social and environmental values to surface that can, in turn, be mobilized in ways to activate social tipping interventions. In a world that is unlikely to return to a pre-pandemic resource-extracting prosperity (McNeely, 2021), it is key to identify such opportunities.

While this section provides tools to describe interactions in the BCS nexus and help navigate away from negative ecosystem thresholds and negative social outcomes, Section 7 examines current and future governance and policy actions in context of biodiversity-climate interactions at the social-ecological interface.

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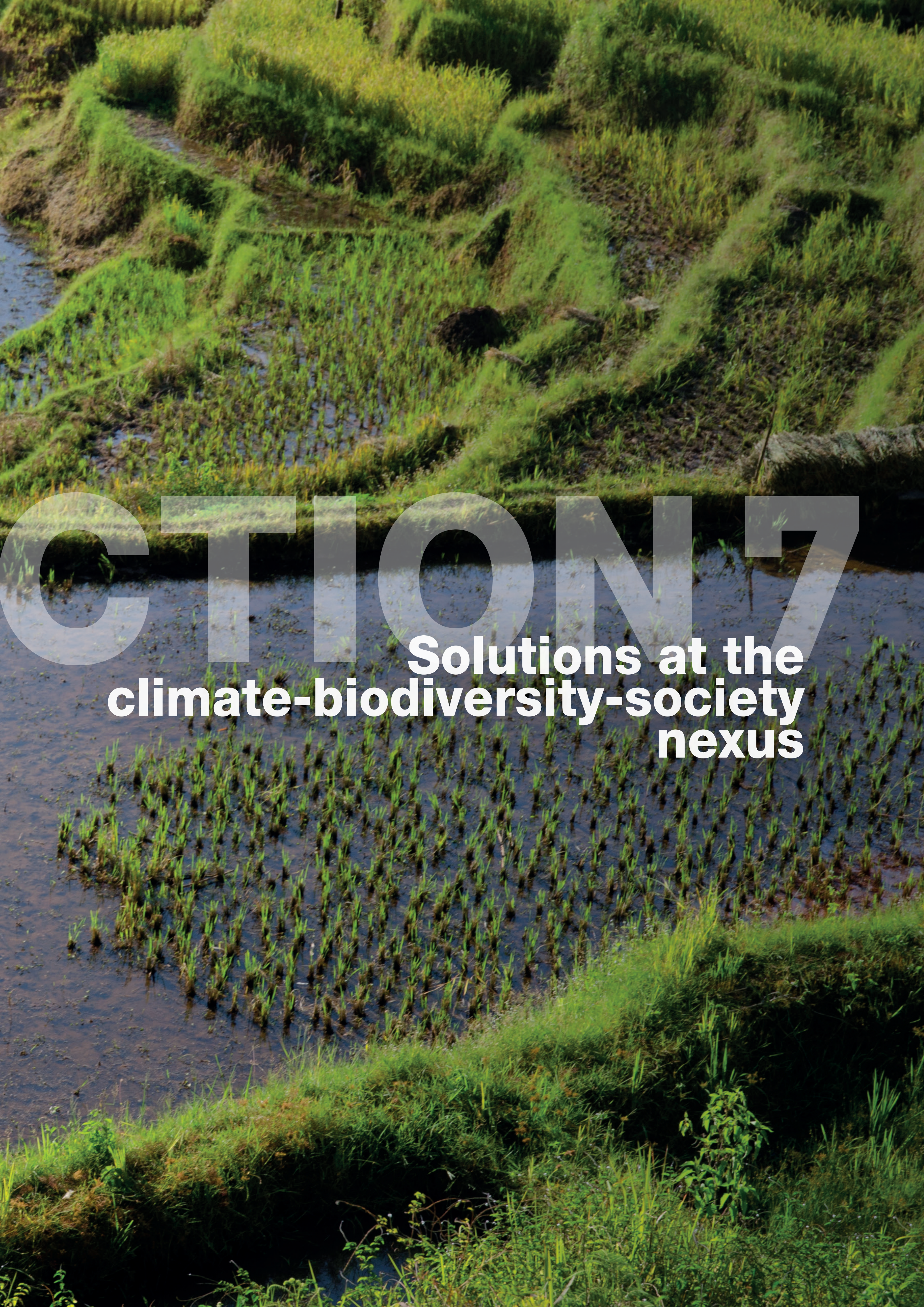

CTION 7

Solutions at the climate-biodiversity-society nexus

SECTION 7

Solutions at the climate-biodiversity-society nexus

7.1 INTRODUCTION

As the previous sections have indicated, the biodiversity and climate crises are inextricably linked, and impact the potential for more equitable human well-being and development. Climate change threatens future biodiversity conservation, particularly in highly vulnerable ecosystems, as well as fundamentally altering the distribution, performance and interactions of species, transforming ecosystems in profound ways (Section 2). Changes in land use and other alterations to ecosystems have contributed to climate change, and many climate mitigation actions have potential feedbacks on biodiversity, both positive and negative (Section 3). Well-managed ecosystems have greater adaptation potential, resisting and recovering more easily from the impacts of extreme climate events, besides providing a larger range of ecosystem services upon which people depend (Section 4). These complex feedbacks and interactions between the coupled components of the biosphere have the potential to threaten human well-being and quality of life, which have been underpinned by historically stable climate conditions and healthy ecosystems (Section 1). The window to deploy solutions that avoid irreversible impacts is rapidly closing on both the climate and biodiversity crises unless there is rapid but careful ramp-up of solutions that deliver co-benefits for both climate and biodiversity crises. At the same time, discussion of trade-offs is inevitable as not all potential solutions can be win-wins (Section 6).

The IPBES global assessment (2019) concluded that reversing processes of nature decline "may only be achieved through transformative changes across economic, social, political and technological factors" (IPBES, 2019). The IPCC Special Report on Global Warming of 1.5°C report also calls for "rapid and far-reaching transitions" and that "economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions" (IPCC, 2018b). Transformative change has been defined "as a fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values" (IPCC, 2018b). However, a key question remains of "who gets to imagine transformative change", which requires careful consideration of actors involved, and their visions and values (Beck & Forsyth, 2020). The evidence from existing policy challenges that we review in this section shows that transformative change depends on the design of new models for the climate-biodiversity nexus capable of integrating multi-actor and multi-scalar governance mechanisms.

This closing section examines the possibilities for integrated solutions that tackle multiple crises and delineates what these solutions might look like for the future of governance and policy options required at the climate-biodiversity nexus. While the evidence examined in this report thus far makes clear the importance of tackling biodiversity and climate as problems whose drivers and solutions are similar and intertwined, in reality, the existing governance frameworks to tackle these problems reveal significant barriers and challenges. Both the biodiversity and climate crises can be seen as typically 'wicked' problems: those in which there is some uncertainty around knowledge, contested values, and unclear decision-making pathways (Head, 2014). There are also often impositions of costs now to preserve benefits for future generations (Lazarus, 2009). Clear and easy solutions are not possible in such situations, and decisions will likely need to be made in an iterative and flexible manner that accounts for complexity and uneven dynamics among actors and scales (Ramm *et al.,* 2018).

There are also differences in governance across climate and biodiversity that can be highlighted. While clear quantitative targets such as 'net zero emissions by 2050' have been pledged by an increasing number of countries, biodiversity is not easily reduced to single indicators; suggestions have included 'no net loss of biodiversity' or 'keeping described species extinctions to well below 20 per year over the next 100 years' (Maron *et al.*, 2020; Rounsevell *et al.,* 2020), while others than suggested that biodiversity goals will be never be able to be encapsulated to a single quantitative target (Purvis, 2020). Scenarios and pathways for climate mitigation choices can be analysed through integrated modelling, while trade-off analyses for biodiversity are considerably more difficult given the different roles of species, the multifaceted nature of ecosystems and their contributions to people, and the absence of clear metrics to measure policy impact. For example, there is no biodiversity equivalent to a carbon price or social cost of carbon measure (Phelps *et al.,* 2012). All of these overarching challenges of goal setting, governance models, and understanding of future scenarios are discussed in this section, guided by a set of key questions **(Box 7.1)**.

Box ⑦ ① Five key governance challenges in addressing the Climate-Biodiversity-Society nexus.

- How do existing instruments and policies (UNFCCC, CBD, SDGs, Sendai Framework, etc.) integrate climate, biodiversity, and sustainable development, and what future integration would be required to deliver multiple goals?
- How can global targets for climate and biodiversity best be designed and governed?
- How can multiple actors contribute to jointly advance climate and biodiversity solutions?
- What are the key enablers to promote good governance that also generate joint biodiversity-climate benefits?
- What are the paths towards transformative change that address both the climate and biodiversity crises in an integrated manner?

Starting in Section 7.2 we discuss interactions to address biodiversity loss and mitigate climate change in order to identify solutions that deliver the highest co-benefits for both climate and biodiversity, including so-called nature-based solutions (NbS). An integrated planning approach designed to achieve transformative change will be needed that acknowledges co-benefits and trade-offs. Yet NbS are not a magic bullet, and many questions around governance, financing, and equity issues remain for NbS to fulfil its potential. Further, solving key challenges will require more attention to cross-sectoral policy action and integrated governance across key institutions and goals, including the Convention on Biological Diversity (CBD), UN Framework Convention on Climate Change (UNFCCC) and Sustainable Development Goals (SDGs). Current policy and legal regimes addressing the climate and biodiversity crises are disconnected at both local and global scales, which has led to missed opportunities to deploy actions that alleviate both these challenges. Tactically using solutions that help mitigate both the climate crisis and biodiversity can potentially also help advance the UN Sustainable Development Goals (SDGs) beyond those directly related to nature. There are potentially new opportunities in the wave of pledges to achieve net zero carbon emission by nations and corporations, and new stimulus packages to deliver a “green” (and blue) restart of the economy after COVID-19 that can be driven to maximize biodiversity and climate co-benefits.

In order to provide guidance for the deployment of solutions, we review current governance challenges across both biodiversity and climate in Section 7.3. We particularly discuss what the implications are of the current governing-by-goals approach taken by CBD, UNFCCC, the SDGs and the Sendai Framework for Disaster Risk Reduction, and the pros and cons of this form of international cooperation. Based on reviews of governance, policy and law literatures, we discuss how involvement of a broader range of actors can improve solutions by moving beyond state-centred international law to include indigenous peoples and local communities (IPLCs), as well as address the systems challenges inherent in the interactions of distant actors in a globalized world. We then address in Section 7.4 what steps move toward transformative change. This includes shifting behaviours, incentives and policies through the use of leverage points, including values, education, and measures for a good quality of life. These efforts are complemented by improved ways of forecasting desirable futures, through scenarios and models.

In Section 7.5 we discuss how transformative change builds on the development of research to understand and act on climate and biodiversity-resilient development pathways. Using levers in our socioecological systems, such as restructured incentives and economies, pre-emptive action, adaptive decision-making and strengthened environmental laws, we can begin to set the world on pathways that will achieve long term temperature and biodiversity conservation goals, as well as meeting needs for improved human development. It remains possible to reach the long-term goals of meeting the SDGs, Paris Agreement targets and post-2020 biodiversity agenda, but achieving this transformative change depends on rapid and far-reaching actions of a kind and scale never before attempted.

7.2 SOLUTIONS AT THE INTERSECTION OF CLIMATE CHANGE MITIGATION, ADAPTATION, BIODIVERSITY AND QUALITY OF LIFE

Sections 3-5 have outlined a number of potential solutions across climate mitigation and adaptation and biodiversity conservation, particularly those which can be applied to protect, restore, manage, and create ecosystems. The key question for Section 7 is how we can best use governance tools to achieve successful implementation of these solutions, how integrated approaches can be fostered, what synergies and co-benefits and potential negative trade-offs exist for many of these solutions, how risks can be addressed and managed, and how human well-being and good quality of life for all can be improved **(Box 7.2)**. As noted in **Box 7.2**, across multiple solutions, two overarching key governance challenges exist: the integration between climate, biodiversity and well-being, and the need for governance processes to acknowledge and deal with co-benefits, trade-offs and risks, which we explore in depth in this section. Nature-based solutions are also discussed as one class of actions that potentially meets the goals of integrative and synergistic solutions.

Box ⑦ ② Governance challenges across solutions.

Protect: *How can protected ecosystems be made more effective as well as contribute to human well-being?* As protected areas expand to meet new targets, such as 30% of the ocean area by 2030, the criteria used to guide the deployment of new protected areas could also consider climate mitigation and adaptation benefits, such as protecting climate-vulnerable ecosystems, including polar continental shelves or coral reefs (Roberts *et al.*, 2017), as well as threatened ecosystems, such as tropical forest and blue carbon habitats, as well as connectivity issues (Carrasco *et al.*, 2021). For example, well-managed marine protected areas (MPAs) have potential to contribute to climate change mitigation by enhancing marine carbon sinks, as well as adaptation by enhancing resilience to climate change pressures (Roberts *et al.*, 2017). At the same time, prioritizing benefits to human well-being, such as rebounding fishing stocks, can be part of these solutions, and can be particularly linked to fulfilment of Paris Agreement pledges to show the benefits of rapid mitigation actions (Sumaila *et al.*, 2019). There remains a need for multiple forms of governance and dynamic management tools for different protected areas systems (e.g., not only formal protected areas but also other area-based conservation measures (Tittensor *et al.*, 2019)), as well as attention to how justice and equity perceptions around human benefits can impact effectiveness (Dawson et al., 2018).

Restore: *How can restoration be improved and contribute to well-being?* Restoration is a key element to improve biodiversity and climate integration, particularly when targeting carbon-dense ecosystems such as coastal habitats, tidal and freshwater wetlands and forests. While restoring some ecosystems such as mangroves may be technically easy and provide multiple benefits, challenges can arise because of selection of inadequate location, species or planting density, or perceived lack of local benefits (Friess *et al.*, 2016). Suitable metrics of performance will need to prevail over headlines (e.g., record numbers of trees planted). Recent examples of priority setting for restoration have included a focus on uncontested lands that could be acquired at low cost (Xie *et al.*, 2020) as well as use of spatial datasets and modelling across multiple goals, such as carbon storage, feasibility or ecological intactness (Strassburg *et al.*, 2018; Brancalion *et al.*, 2019). Successful governance of landscape restoration has usually included multi-stakeholder dialogue over plural values and trade-offs associated with different approaches (Chazdon *et al.*, 2021; van Oosten *et al.*, 2021).

Manage: *How can improved planning and management across 'scapes' help deliver coupled biodiversity, climate and development goals?* Across agroecosystems, fisheries and urban environments, active ecosystem management practices can improve biodiversity and climate outcomes, ranging from improving soil health and carbon content, to multispecies agroforestry to urban green spaces (Lepczyk *et al.*, 2017; Udawatta *et al.*, 2019). For example, more can be done to increase potential co-benefits for climate mitigation and adaptation across human-dominated anthromes, such as planning for coastal cities to manage ecosystems with high carbon sequestration capacities (e.g., mangroves and saltmarshes) in their waterfronts (Duarte *et al.*, 2020). Sustainable fisheries management can contribute to improve biodiversity and mitigate climate change by rebuilding stocks of exploited fish populations and the carbon sequestration they support while simultaneously reducing fossil fuel use by the global fishing fleet (Duarte *et al.*, 2020; Mariani *et al.*, 2020). Achieving collaborative stewardship across contested multifunctional landscapes will be a primary goal for many countries, with only a few models for success thus far (Cockburn *et al.*, 2019). Policy support for such integrated solutions is likely to depend on succeeding in a number of actions: (1) building evidence for linkages; (2) increasing local institutional effectiveness; (3) fostering coherence between policies; and (4) linking financing to the solutions (Lipper *et al.*, 2014).

Create: *How can multiple objectives at the climate-biodiversity nexus be used to develop and manage new 'scapes'?* For example, efforts to rewild spaces can also be neutral to climate change or be designed to deliver potential climate co-benefits associated with ecosystem function, but human well-being is often less emphasized in discussions of these novel ecosystems (Sweeney *et al.*, 2019). Other 'created' 'scapes to address climate change, such as BECCS production sites or expansion of renewable energy facilities such as solar and wind farms at scale, can also have negative, neutral or positive contributions to biodiversity, depending on how negative impacts are minimized or avoided and if more ambitious goals to deliver positive impacts are embedded in planning. While offsets are an increasingly used tool to create new 'scapes in the face of development elsewhere, challenges have been raised about commensurability, and the equitable distribution of costs and benefits (Maron *et al.*, 2016).

Adapt: *How can socioecological systems prioritize benefits in terms of climate adaptation from different solutions?* Many of the above actions such as restoration can also promote

Box 7 2

successful adaptation. Ecosystem-based adaptation serves to help humans thrive in the face of climate challenges through actions such as natural flood management; creation and use of green space in urban settings to reduce temperatures; and vegetation to anchor land from extreme events (Morecroft *et al.*, 2019). Measuring and reporting progress on adaptation of both ecosystems and human society is challenging but could be met with particular indicator species or indexes (Ims & Yoccoz, 2017).

Transform: *How can we harness transformational change in the way we address the biodiversity-climate nexus?* Transforming human behaviours, such as sustainable intensification of agriculture and dietary changes toward healthy, sustainable diets can make significant impacts in both improving biodiversity and mitigating climate change (Leclère *et al.*, 2020; IPCC, 2019a), while simultaneously improving human health and well-being but has been challenging to implement due to vested interests and cultural preferences. Many solutions for transformational change will require shifts in values among individuals as well as larger structural incentives and policies in order to achieve multiple objectives across biodiversity, climate and good quality of life (Chan *et al.*, 2020)

7.2.1 Integration across solutions and governance institutions

The existence of the UNFCCC and CBD since 1992 and SDGs since 2015 is evidence of the considerable attention paid to biodiversity, climate and development problems; however, while these conventions and commitments can work together, they can also overlap or potentially lead to trade-offs against each other, and the degree to which the existing multilateral system is able to promote both policy coherence and policy integration remains limited (Jacquemont & Caparrós, 2002; Pittock, 2010). The overlap between the UNFCCC, CBD and UNCCD with regard to land is one example. In this case, interlinkages and synergies have been possible when consolidated indicators (such as for sustainable land management) can be agreed to and applied across sectors to meet multi-objective outcomes (Cowie *et al.,* 2007). Nexus approaches or policy clusters have been suggested as a solution to policy fragmentation. Such nexuses might occur around ‘ecosystem services and livelihoods’, or a ‘green economy’ in which multiple goals are pursued under a common long-term target (Timko *et al.,* 2018; Liu *et al.,* 2018).

However, both the CBD and UNFCCC tend to lack clear and effective mechanisms to find points of commonality or to explicitly consider the interactions between their domains and objectives. For example, the UNFCCC’s Marrakesh Accords only mentioned biodiversity a handful of times, including that it should be ‘taken into account’ in afforestation/reforestation, that land-use change for climate mitigation may ‘contribute’ to biodiversity, and that adaptation actions should be developed in a ‘complementary’ way to CBD goals. In reality, country-level mitigation mechanisms developed under the Kyoto Protocol reveal that integration of ecosystems into carbon trading (which might have promoted biodiversity) was challenging. The EU did not permit ecosystem-based approaches in the Emissions Trading System (ETS), while other countries such as Australia attempted to do so and were unable to adequately include biodiversity as a valued co-benefit for project developers (van Oosterzee, 2012).

Suggestions for integration continue to emerge under the Paris Agreement, but are not yet required by participating signatories. For example, Nationally Determined Contributions (NDCs) submitted are not required to specify if and how climate mitigation actions might have negative effects on biodiversity, although some country reports make these connections. Further, while many reports such as NDCs refer to activities across biodiversity and climate, integrated actions around ecosystems and climate tend to get lower priority in actionable proposals and plans (Pramova *et al.,* 2012). Overall, most current NDCs pay insufficient attention to agriculture and other land-use emissions, with questions about accounting across countries; underutilized attention to oceans as a source of mitigation and adaptation potential, and biodiversity impacts; and insufficient attention to NbS overall (Henders *et al.,* 2018; Northrop *et al.,* 2021; Seddon, Sengupta, *et al.,* 2019). Suggestions to improve this situation have included a focus on helping countries implement water-energy-food nexus policies within NDCs (Paim *et al.,* 2020).

With regard to adaptation, many National Adaptation Programmes of Action (NAPAs) are well integrated with development goals but lack more detailed attention to biodiversity impacts of some actions (e.g., expansion of hydropower or irrigation). The Sendai Framework for Disaster Risk Reduction discusses understanding disaster risk; strengthening disaster risk governance; investing in disaster reduction for resilience; and enhancing disaster preparedness for effective response, all of which might potentially enhance or overlap with some ecosystem-based solutions (e.g., mangrove rehabilitation for reducing coastal risks) (Wanger *et al.,* 2020), but more remains to be done to help countries realize opportunities in eco-disaster risk reduction (eco-DRR).

Silos and fragmentation are not unique to multilateral agreements, as national, state and local governments also encounter integration challenges. For example, in one study of Southeast Asian countries, no country had a single ministry for the forest sector that had responsibility for climate mitigation, adaptation and biodiversity (Morita & Matsumoto, 2018). This can create challenges, given that one of the more explicit interconnections between climate and biodiversity is in the development of the REDD+ mechanism (Secretariat of the Convention on Biological Diversity, 2011). Outside the formal UN agreements there have been other attempts to mainstream biodiversity and promote integration with climate mitigation and adaptation, such as through private producer agreements (e.g., sustainable seafood, roundtable on palm oil), or climate risk and nature risk disclosure projects for investment decision-making, with varying degrees of success.

When the SDGs are considered as well, the potentials and challenges for interlinkages increase. The SDGs explicitly recognize the value of biodiversity (Goals 14 life below water and 15 life on land) and the importance of climate action (Goal 13) and were designed to be interdependent; for example, there was clear hope that achieving one SDG would also contribute to achieving another, and many consider the environmental SDGs to be the 'foundations', or necessary requirements, for the achievement of other goals (Reyers & Selig, 2020). Elements of biodiversity in particular (ecosystems, species and genes) interact in various ways (including feedbacks, synergies and trade-offs) with all other SDGs (Blicharska *et al.,* 2019) **(Figure 7.1)**. However, the specific targets across the SDGs do not always reflect the integration between biodiversity and climate; for example, Goal 15.1 does not specifically call out high carbon sink areas for conservation, and thus countries themselves are tasked with making these connections (Stafford-Smith *et al.,* 2017).

Decisions in other policy fields such as energy, water, food, health and urbanisation have clear ramifications for climate and biodiversity as well (McElwee *et al.,* 2020; O'Neill *et al.,* 2017; Romero-Lankao *et al.,* 2017). The many interactions between other SDGs and the biodiversity and climate targets will likely require comprehensive, transparent and timely monitoring and assessment systems to assess progress towards targets and goals, locally, nationally and globally (Zeng *et al.,* 2020; Fuso Nerini *et al.,* 2019; Reyers & Selig, 2020). Yet how to assess all these interactions and complexities (Schipper *et al.,* 2020; Smith *et al.,* 2019) and how to prioritize them (Yang *et al.,* 2020)

Figure ⑦ ① **Interactions among the climate and biodiversity goals with other SDGs.**

The biodiversity (SDG 14, 15) and climate (SDG 13) goals are affected by other SDGs (right panel) and they in turn affect the other dimensions of sustainability (left panel). These interactions reinforce the potential of biodiversity and climate agenda in promoting the other dimensions and the risks and challenges of integrating some agendas.

remains challenging. Further, many have pointed out the contradictions and trade-offs within the SDGs themselves, such as between SDG 8 on economic growth and those related to climate and biodiversity, and mapping of SDG targets and goals against one another can reveal these types of potential co-benefits/synergies and trade-offs (Nilsson *et al.,* 2016; Kroll *et al.,* 2019).

Improving biodiversity and climate mainstreaming has been promoted as one way to achieve integration for multiple goals. For example, discussions of post-COVID-19 recovery packages have emphasized that any recovery should be consistent with Paris Agreement goals, thus 'mainstreaming' climate into current economic priorities (Hepburn *et al.,* 2020). Similar arguments have been made for biodiversity in COVID-19 recoveries (McElwee *et al.,* 2020). Yet evidence to date is that these recovery packages are not only not green, they are in many cases continuing to support degrading activities (Vivid Economics, 2021). Overall, the challenges of mainstreaming and realigning funding and policy priorities, even in a pivotal moment such as the current pandemic, should not be underestimated: for example, despite one previous Aichi Target on mainstreaming, less than half of signatory countries had achieved the goal of incorporating biodiversity into development and other planning by 2020 (Whitehorn *et al.,* 2019). Overall, while analysis shows that environmental policy integration has made progress in recent decades, particularly around reducing negative incentives, other barriers remain, including unclear indicators (particularly for biodiversity loss or improvement), time-limited actions (e.g., not concordant with long term planning), and financial limitations (Karlsson-Vinkhuyzen *et al.,* 2018).

7.2.2 Mapping synergies, avoiding trade-offs and managing risks

The CBD and the Paris Agreement have each set goals in terms of biodiversity and climate, respectively, but are largely agnostic as to how these goals and targets are to be achieved, leaving solutions to be developed by individual nations. While most of the Aichi Targets were not reached by 2020, the current post-2020 global biodiversity framework provides an opportunity to consider how new actions may generate co-benefits in terms of climate solutions. The current draft of the post-2020 global biodiversity framework includes four long-term goals for 2050 and twenty action-oriented targets to be achieved by 2030; these include expanded protected and conserved area (Target 2) as well as attention to climate change mitigation, adaptation and disaster-risk reduction from nature-based solutions and ecosystem-based approaches (Target 7).

Long-term climate action targets are articulated in the Paris Agreement, which pledges "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4.1). Nations have been busy determining their Nationally Determined Contributions (NDCs) toward Paris goals, using a number of elements. While enhanced pledges that were made in 2020 have increasingly considered NbS and other land-based actions that have biodiversity implications, tools and tangible mechanisms to promote integration or to provide safeguards against negative outcomes remain mostly lacking, and the carbon mitigation actions that achieve the highest GHG reductions unfortunately have few details on how co-benefits and trade-offs with biodiversity and human well-being will be managed (e.g., Gattuso *et al.,* 2018).

Such acknowledgement is needed, given that many of the proposed solutions to biodiversity and climate problems (including those addressed in Sections 3 to 5) will come with trade-offs. For example, proposals to expand protection to 30%-50% of the Earth's surface could mean declines in agricultural production and caloric access in many models, putting several SDGs at risk (Mehrabi *et al.,* 2018), and a 50% protection target would mean nearly 1 billion people would live in protected areas whose interests will need to be taken into account (Schleicher *et al.,* 2019), including numerous indigenous communities who are often excluded from protected area (PA) management (Tauli-Corpuz *et al.,* 2020). Mining required to build renewable energy devices will have impacts on biodiversity on both land (Sonter *et al.,* 2020) and ocean (Levin *et al.,* 2020), as well as on protected areas and other conservation areas (Rehbein *et al.,* 2020). Use of BECCS may raise a number of risks around food supply, biodiversity, and well-being (Section 3, McElwee, Calvin, *et al.,* 2020).

Mapping key trade-offs in advance can help decision-makers understand co-benefits and risks, particularly between climate actions and biodiversity actions **(Figure 7.2)**. In general, as previous sections have noted, most biodiversity actions have mostly positive effects on climate actions and can be considered co-benefits. However, numerous climate mitigation actions, particularly in the energy sector, raise concerns and risks for biodiversity actions, which need to be anticipated and well-managed.

Risk management across biodiversity and climate challenges in the Anthropocene is likely to require new attention to global socioecological complexity and interconnections (e.g., in telecouplings); cross-scale integration and feedbacks; and decision-making under uncertainty (Keys *et al.,* 2019). At the same time, some trade-offs can be managed through well-designed interventions. For example, the direct impacts on biodiversity seem to be reduced when renewable energy is deployed in the ocean, as offshore wind farms offer protection for marine biodiversity, as the concessions are typically no-take areas for fisheries, which may improve fish stocks (Hooper

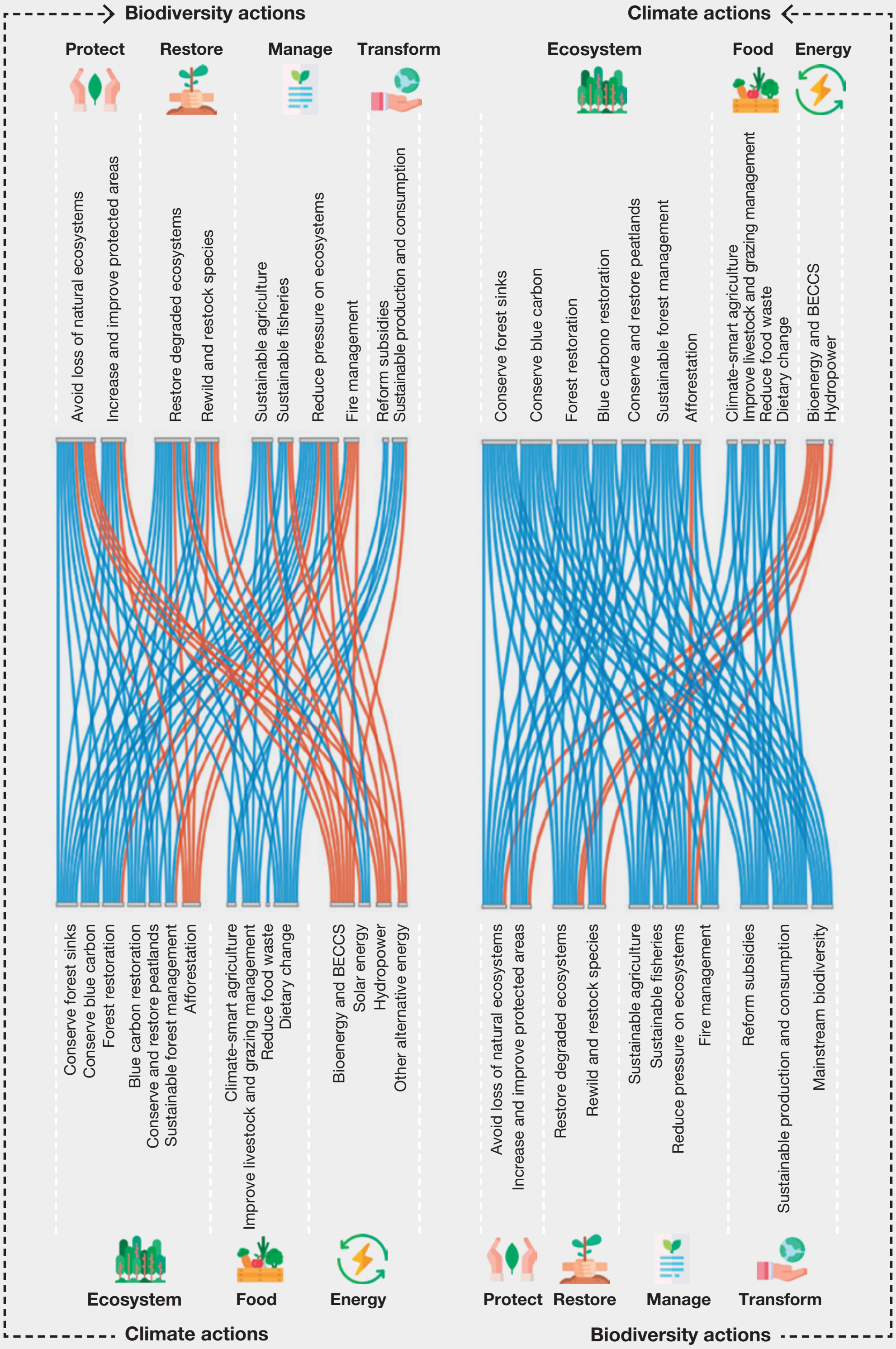

Figure ⑦ ② **Sankey diagram mapping the effects (positive and negative) of actions to mitigate climate change on actions to mitigate biodiversity loss (top), and of actions to mitigate biodiversity loss on actions to mitigate climate change (bottom).**

Blue lines represent positive effects, while orange lines represent negative effects. This network of interaction is evolving as many of the solutions are still in the ideation phase or have not yet been deployed at any sizable scale. Likewise, the strength of interactions may shift over time as the scale of solutions moves beyond the threshold at which unforeseen interactions, positive or negative, may occur. Supporting references may be found in the Appendix.

et al., 2017). Similarly, solar facilities that explicitly include provisions for protecting native habitat and grasslands can contribute to pollinator biodiversity (Walston *et al.,* 2021). Rather than tolerating trade-offs (Popescu *et al.,* 2020), a well-designed multi-objective strategy that maximizes actions to deliver positive synergies and co-benefits in addressing both climate mitigation, adaptation and biodiversity goals can improve policymaking. For example, well-designed marine protected areas can increase fish biodiversity, conserve ocean carbon stocks that might be disturbed by seabed trawling, and promote food provisioning and livelihood support, and identification of these 'triple-win' areas can help with prioritization (Sala *et al.,* 2021).

Many of the important trade-offs or co-benefits are also associated with specific biodiversity and climate feedbacks, which are not well captured in current SDG and other goal setting (Reyers & Selig, 2020), which calls for improvements in mapping climate-biodiversity actions, interactions and feedbacks in iterative processes (including use of indigenous and local knowledge) to help identify solutions that deliver the highest co-benefits or help ameliorate the most serious risks. Decisions on these trade-offs have to be made at multiple scales, from local siting decisions about renewable energy to international decisions about the legitimacy of solar radiation management, as examples demonstrating the need for mechanisms to be able to explicitly address trade-offs in decision-making. Such decision-support tools include game theory tools (Daher *et al.,* 2017), multicriteria decision-making (de Magalhães *et al.,* 2019), decision-support models (Bartke & Schwarze, 2015; Walston *et al.,* 2021), and scenarios that integrate across sectors (see Section 7.4.2). Similarly, addressing multiple objectives simultaneously will likely require governance systems that are capable of combining solutions into policy mixes. For example, solutions focused on protection and restoration are more likely to deliver benefits when combined together with demand-side reductions on consumption (such as meat or fossil fuels) and improved agro-food systems (Henry *et al.,* 2019; Theurl *et al.,* 2020; Leclère *et al.,* 2020).

7.2.3 Nature-based solutions (NbS) as integrative and co-beneficial options

As seen in **Table 7.1**, a number of solutions generate co-benefits for people and nature, and NbS in particular emerge with large potential to generate climate-biodiversity co-benefits, given that they are specifically designed to address multiple societal challenges through ecosystem management, such as tackling climate mitigation through afforestation, or addressing the urban heat-island effect with green roofs and expanded parks (Nesshöver *et al.,* 2017). Many different practices can fall under NbS, including "ecosystem-based adaptation" (use of ecosystems and biodiversity to adapt to climate change, such as mangrove management for storm protection); "green infrastructure" (natural and semi-natural areas designed to provide infrastructural benefits, such as storm-water projects, green roofs and walls, or permeable pavements); and forest landscape restoration, among others (Cohen-Shacham *et al.,* 2019). Many NbS produce multiple human co-benefits, such as improved mental and physical health, increased access to NCP, and other gains (Kabisch *et al.,* 2016). NbS can also play a powerful role in reducing temperatures in the long term, if used to support ambitious emission reduction plans and designed for longevity (Girardin *et al.,* 2021).

There has been rising support for better use of NbS as a way to potentially tackle both biodiversity and climate challenges, as well as to contribute to multiple SDGs such as 'no poverty', compared to technology-based solutions that do not generate additional benefits (Nesshöver *et al.,* 2017). For example, the analysis that a significant fraction of existing GHG emissions could be tackled with 'natural climate solutions' (e.g., Griscom *et al.,* 2017) has received widespread attention by policymakers. More broadly, ideally NbS not only generates climate and biodiversity co-benefits, but if considered in a broader context, they restore the flow of NCP to society, thereby propelling improvements across SDGs and human well-being (Seddon *et al.,* 2021). For example, NbS like urban green spaces and green infrastructure can help reduce health stresses among the vulnerable urban poor and promote resilience as well as improved job opportunities (Kalantari *et al.,* 2018). The many interlinkages between NbS and achieving the SDGs has emphasized a range of potential co-benefits, particularly for multifunctional NbS systems (Gómez Martín *et al.,* 2020). Indeed, recent research has suggested that NbS can play a crucial role in achieving transformative change through strong emphasis on appreciation of nature's values, recognition of diverse knowledge types, and opportunities for community engagement and improved nature management (Palomo *et al.,* 2021).

However, there has been concern that potentially everything can be seen as an NbS without clear criteria. For example, by some standards a traditional protected area would be an NbS, while to others it would not because it is aimed at conservation, not human-focused challenges (IUCN, 2020). For biodiversity, the recently published IUCN Global Standard has as core criteria that for something to be called an NbS, it must "result in a net gain to biodiversity and ecosystem integrity". Consequently, each ecosystem type (ocean, land, inland aquatic ecosystems, urban, etc.) would require NbS actions that are suitable to the specific risks and opportunities within those ecosystem functions. For example, studies suggest that species-rich communities may not buffer the impacts of climatic stressors despite their recognized buffering effects on other stressors (Pires *et al.,* 2018). Appropriate design of NbS is also needed.

Table ⑦ ① Land and ocean-based actions and their co-benefits and costs.

Actions	Potential for actions to contribute to GHG mitigation	Potential for actions to contribute to climate adaptation	Potential for actions to contribute to human well-being	Costs of actions	References
Actions to Protect					
Increase terrestrial protected area extent and/ or improve management	High	Moderate (human systems) to High (ecological systems)	Dependent on context, can be negative if exclusionary, can be high if inclusive	High	(Oldekop *et al.*, 2016; Swemmer *et al.*, 2017; Waldron *et al.*, 2020)
Increase marine protected areas extent and management	Low	High	Moderate to high (if access to some fishing allowed)	Low to Moderate	(Balmford *et al.*, 2004; Ban *et al.*, 2017)
REDD+	High	Moderate	Moderate (if payments are sufficient)	Moderate	(Smith *et al.*, 2020) (McElwee, Calvin, *et al.*, 2020)
Conserve blue carbon habitats	High	High	Moderate to high	Moderate	(Narayan *et al.*, 2016; Smith *et al.*, 2020)
Conserve peatlands	Moderate	Unknown	Dependent on context	Low to Moderate	(Roucoux *et al.*, 2017; Smith *et al.*, 2020)
Actions to Restore					
Mangrove and coastal restoration	High	High	High, if integrated with livelihoods needs	Depends on site mangroves low to moderate, seagrass and reefs higher	(Bayraktarov *et al.*, 2016; Smith *et al.*, 2020)
Afforestation	High	Moderate to high (dependent on species/location)	Low to moderate	Low	(Doelman *et al.*, 2020; McElwee, Calvin, *et al.*, 2020)
Peatlands rewetting/ restoration	Moderate	Unknown	Dependent on context	Moderate	(Hansson & Dargusch, 2018; Harrison *et al.*, 2020)
Fisheries restocking	Low	High	High	Low to moderate	(Abelson *et al.*, 2016; Taylor *et al.*, 2017)
Freshwater restoration	Low	High	High	Moderate	(Hassett *et al.*, 2005; Katz *et al.*, 2007; Mantyka-Pringle *et al.*, 2016)
Actions to Manage					
Integrated coastal planning	Low to moderate	High	High	Moderate	(Portman *et al.*, 2012; Tol *et al.*, 1996)
Agroforestry	High	High	High	Low	(McElwee, Calvin, *et al.*, 2020; Smith *et al.*, 2020; Torres *et al.*, 2010)
Soil carbon management	High	High	High	Low	(McElwee, Calvin, *et al.*, 2020; Tschakert, 2004)
Regenerative agriculture	Moderate	High	High	Moderate	(Gosnell *et al.*, 2019, 2020; LaCanne & Lundgren, 2018)
Fire management	High	Moderate	High	Low to moderate	(McElwee, Calvin, *et al.*, 2020; Smith *et al.*, 2020)

Table ⑦ ①

Actions	Potential for actions to contribute to GHG mitigation	Potential for actions to contribute to climate adaptation	Potential for actions to contribute to human well-being	Costs of actions	References
Sustainable fishing	Low	High	High	Low	(McDonald *et al.*, 2020; Suuronen *et al.*, 2012)
Actions to Create					
Rewilding	Moderate	Moderate	Low to moderate	Dependent on type; low to moderate	(Sandom *et al.*, 2019; Schou *et al.*, 2021)
Urban green spaces	Moderate	High	High	Low to moderate	(Aronson *et al.*, 2017; Wolch *et al.*, 2014)
Biodiversity offsets	Low	Moderate	Low (can be negative)	Low to moderate	(Bidaud *et al.*, 2018; Bull & Strange, 2018; Needham *et al.*, 2019)
Aquaculture	Low	High	High	Moderate	(Theuerkauf *et al.*, 2019)
Actions to adapt					
Green infrastructure	Moderate	High	High	High (although cost effective compared with grey infrastructure)	(Liberalesso *et al.*, 2020)
Ecosystem-based adaptation	Moderate	High	High	Moderate	(Daigneault *et al.*, 2016; Munang *et al.*, 2013; Roberts *et al.*, 2012)
Climate-smart agriculture	High	High	High	Moderate to High	(Branca *et al.*, 2021; Chandra *et al.*, 2018; Lipper *et al.*, 2014)
Actions to transform (not specifically NbS actions)					
Dietary change	High	Unknown	High	Low to moderate	(McElwee, Calvin, *et al.*, 2020; Willett *et al.*, 2019)
Integrated solar-biodiversity zones	High	Low	Unknown	High	(Cameron *et al.*, 2012; Sinha *et al.*, 2018)
Ocean-based renewable energy	High	Low	Moderate	High	(Appiott *et al.*, 2014; Esteban & Leary, 2012)
Marine bioenergy (with or without CCS)	High	Unknown	Unknown	High	(Beal *et al.*, 2018; Gattuso *et al.*, 2021)
BECCS	High	Low	Low (can be negative)	Moderate	(Azar *et al.*, 2013; McElwee, Calvin, *et al.*, 2020)

For example, the effects of green infrastructure on flooding mitigation are strongly dependent on the city and drainage configuration. In Curicó city, Chile, the implementation of 50% of green rooftops was able to avoid flooding, considering moderate rainfall events. In contrast, in the presence of strong rainfall events, only some semi-extensive and extensive green roofs could prevent flooding (Mora-Melià *et al.,* 2018).

Governance models for NbS also remain an open question: what combination of actors, levels, and information ensure successful implementation of NbS (Albert *et al.,* 2020;

Seddon *et al.,* 2020; Toxopeus *et al.,* 2020; Wamsler *et al.,* 2020)? Indigenous people in particular have expressed concern about the challenges in engaging with NbS and the need for attention to equity and knowledge issues (Townsend *et al.,* 2020). Evidence-based decision-making on NbS will likely rely on a tight collaboration between the private sector, researchers, and communities, among other actors, in which policymakers can take a leading role to deepen partnerships and advance standardized design and management by focusing on knowledge co-production, indicators for monitoring impacts and efficacy, and novel financing models (Frantzeskaki, 2019).

7.2.4 Balancing NbS as offsets for biodiversity and climate

It is important to emphasize that NbS are not a magic bullet and cannot be a singular solution to the climate and biodiversity crises (Seddon *et al.,* 2021). Scholars have raised concerns over “their reliability and cost-effectiveness compared to engineered alternatives, and their resilience to climate change” (Seddon *et al.,* 2020) as well as their effectiveness (Bai *et al.,* 2018). Measuring the impacts of NbS remains challenging, due to a lack of these quantitative indicators and questions around uncertainty (Ojea, 2015). There are also a number of potential trade-offs invoked; NbS are not automatically win-wins. For example, tree planting on the scale necessary to dramatically increase their use as carbon sinks would potentially introduce competition with food production (IPCC, 2019a) and may encourage monoculture plantations with little value for biodiversity (Seddon *et al.,* 2021). In urban parks, CO_2 emissions from managing the park could exceed the carbon sink benefit (Oliver-Solà *et al.,* 2007). It is also not clear to what extent NbS solutions actually tackle the drivers of biodiversity loss and climate change; for example, there has been a lot of attention to coastal restoration, but less to stopping activities that contribute to degradation in the first place or the role of global trade in commodities driving degradation (Henders *et al.,* 2018).

Offsets in particular raise complicated governance questions for both biodiversity and climate, and the effectiveness of regulations of these sectors is unclear. Both have been proposed as a way to compensate for losses (as in biodiversity), or to substitute for other actions (as in climate). Both sectors also have seen offsets as a way to increase financing, given that the amounts of money pledged to NbS and ecosystem approaches has also long remained significantly lower than financial support for other mitigation and adaptation measures (Stucki & Smith, 2011; Pramova *et al.,* 2012).

Biodiversity offsets are already in use in many countries and by many businesses, particularly where a ‘mitigation hierarchy’ has been adopted. This is a precautionary approach to decision-making that attempts to mitigate the impacts of a development project (e.g., infrastructure) on nature through a four-step process. First, decision-makers should try to avoid the impact (e.g., by relocating a project). Failing that, a second step is to minimize the impact (e.g., though project design, such as animal crossing grates under a road). Third is to restore ecosystems where some damage is unavoidable. Fourth is to offset the impact by doing something to increase biodiversity elsewhere, such that the project contributes to ‘no net loss’ of biodiversity (e.g., through offsets in another site) (Milner-Gulland *et al.,* 2020). However, around half of infrastructure-threatened biodiversity challenges occur within countries that have some kind of mandatory compensation policy for biodiversity loss (zu Ermgassen *et al.,* 2019), indicating that having a law alone does not solve these challenges for offsets. For example, key problems with no net loss policies for biodiversity which create markets for offsets include limiting impacts ‘counted’ as needing offsets, or allowing for exceptions to the policy (zu Ermgassen *et al.,* 2019).

In climate, questions have been raised about whether the existence of long-term net zero pledges or negative emissions technologies to be used to offset fossil fuel emissions creates a moral hazard that defers hard decisions that might highlight the need for more rapid near-term actions (Holz *et al.,* 2018). Allowing businesses to fund an NbS in return for continued fossil fuel emissions or biodiversity-damaging activities elsewhere diminishes the impact of the NbS (Seddon *et al.,* 2021). Further, the exponential rise in demands for carbon offsets has not maximized the biodiversity benefits of these actions. In fact, there are risks that fast-track approaches, such as the planting of billions of trees, may emphasize monocultures and exotic species, thus missing opportunities to contribute to mitigating biodiversity impacts (Lewis *et al.,* 2019; Seddon *et al.,* 2019). There is also a need to avoid double-counting of any offsets, whether for climate (Rogelj *et al.,* 2021) or biodiversity (Bull & Strange, 2018).

There is a particular gap in the literature regarding how biodiversity offsets and climate offsets might be combined together, or how each category might result in trade-offs with the other and with other NCP. There are also likely potential opportunities for integration of climate and biodiversity together in improved offsets. For example, the actions/solutions outlined in Box 2 previously of protect, restore, manage and create mirror the four steps of the Mitigation Hierarchy, while ‘adapt’ and ‘transform’ might be added to turn the Mitigation Hierarchy into an iterative decision-making tool that also addresses climate and well-being. Further, each step of protect, restore, manage and create can be extended to not only apply to avoiding biodiversity loss, but to affirming Paris-aligned climate goals (e.g., protecting existing forests before turning to creating new forests through afforestation as a climate solution). Researchers and other groups have proposed principles to improve the use of offsets (e.g., the Oxford Principles for Net-Zero Aligned Carbon Offsetting) but more formal processes within the UNFCCC and CBD will likely be needed for accounting purposes as offset use expands.

7.3 GOVERNANCE CHALLENGES FOR ACHIEVING TRANSFORMATIVE CHANGE

In this section, we discuss existing governance challenges for biodiversity and climate, and reflect on lessons learned for transitioning to new pathways and transformational change. The COVID-19 pandemic has disrupted both key events to set targets for both the post-2020 global biodiversity framework of the CBD and increased ambitions under the UNFCCC, leaving nations struggling to find the right tools to address the climate and biodiversity challenges in transformative ways. This tragic pandemic, which has taken a huge toll on human lives and the global economy, has drawn further attention to the need for improved risk management, shared governance, and pathways to transformative change.

7.3.1 Existing governance challenges

Some existing governance challenges are unique to either climate or biodiversity while other challenges are cross-cutting ones. For example, uncertainty, spatial diversity, controversy, and social complexity of problems have been identified as specific governance barriers to climate adaptation (Mees *et al.,* 2014). For biodiversity, specific problems include the need for improvements in performance of protected areas: e.g., MPAs with adequate staff capacity had beneficial ecological effects 2.9 times greater than MPAs without (Gill *et al.,* 2017). Across biodiversity conservation, climate change mitigation and adaptation, similar challenges include multi-scalar governance, the diversity of stakeholders (e.g., business and government as both stakeholders and targets of policy interventions), the emergence of new technologies, and other factors (Auld *et al.,* 2014). Possibilities of short-term economic gains by the primary actors (e.g., production sectors), fragmented decision-making, limited communication among stakeholders, short term visions and a severe lack of financial resources, time and knowledge for many problems present further challenges to governance (Whitehorn *et al.,* 2019). Lack of political will, complexity of the issues for any specific level of jurisdiction to grapple with, scale mismatches (temporal, spatial and institutional), lack of transparency and accountability, and institutional inertia also complicate the solution space (Bai *et al.,* 2016). Some key shared governance challenges for climate and biodiversity include:

Search for single silver bullet solutions. Often single bullets rely on overly optimistic assessments of success without accounting for counterfactuals or difficulties in scaling up (e.g., see Bastin *et al.,* 2019). Investing in interventions which offer resilience, rather than win-win outcomes, has been difficult, as has looking for no regret interventions rather than seeking universal panaceas (Vira & Adams, 2009). In many cases, ideal outcomes will only happen through the combination of multiple strategies across sectors. For example, avoiding habitat loss to agricultural expansion likely cannot be stopped by protected lands alone, but by combining this with closing yield gaps, eating healthier diets, and reducing food waste (Williams *et al.,* 2021). The pursuit of silver bullet solutions alone often carries the risk that valuable solutions are dismissed and not implemented because they only make limited contributions to solving the climate or biodiversity problem. Accepting solutions for multifunctionality are more likely to produce multiple benefits rather than maximizing performance on single indicators (such as GHG removal) (Brauman *et al.,* 2020; Gren *et al.,* 2010). Further, successful policy is often about building coalitions of support (Bergquist *et al.,* 2020), in which case toolboxes of solutions, rather than single silver bullets, are more likely to find broad success.

Over-reliance on voluntary or economistic measures. Despite an increasing penchant for market or hybrid governance models, multiple studies have indicated that these approaches overall tend to be less effective, or associated with less impact (e.g., slower carbon reductions) than regulatory or governmental approaches (Auld *et al.,* 2014; Green, 2021). These trade-offs between efficiency and effectiveness require more attention. So too do trade-offs between market and non-market valuations and their respective uses, given that there is uneven application across climate and biodiversity. For example, tools such as the social cost of carbon that are used to create incentives or justify costs for climate regulations are unable to quantitatively value many important NCP or provide adequate damage estimates for inaction to ecosystems, especially to rare or at-risk ones (Bastien-Olvera & Moore, 2020).

Inadequate financing. Existing funding mechanisms for climate and biodiversity are both underfunded and not well integrated. Financial flows for biodiversity continue to lag behind projected needs: global conservation budgets for biodiversity were approximately $121.5 billion annually from 2008-2017, which showed steady increases but still falls short of needs (Seidl *et al.,* 2020). The estimated funds for the post-2020 agenda needs are likely to be between $151 to $895 billion annually (CBD, 2020). Climate financing, in turn, has expanded but is still far from the investments of US$2.7 trillion per year from 2015 to 2040 estimated to provide climate mitigation in line with goals of the Paris Agreement (Peake & Ekins, 2017). The challenges of a post-COVID recovery have made financing questions even more central, given unprecedented stimulus and recovery packages passed in 2020-1. Despite much discussion on the need for these stimulus packages to be designed to deliver a green re-start of the economy, possibly then serving to catalyse transformative change on the biodiversity and climate challenges, the OECD calculates that only 17% of the volume of the stimulus packages put forward by OECD nations and partner economies has had a climate or biodiversity positive focus (https://www.oecd.org/coronavirus/en/themes/green-recovery). Further measures to achieve transformative change, particularly of economic drivers of climate or biodiversity loss, have been mostly insufficiently addressed to date in these recovery packages (McElwee *et al.,* 2020).

Inadequate accountability mechanisms. Many commentators have noted the weak enforcement mechanisms of most global and local policies; for example, in the case of the CBD, there are no "strong binding rules and its implementation only relies on the good faith of its parties" (Jacquemont & Caparrós, 2002). There have been attempts to remedy this, such as through the 'ratchet' mechanisms that exist in the Paris Agreement requiring stronger pledges over time, but these do not yet have an equivalent corollary for biodiversity policy, although such a mechanism has been suggested for the post-2020 framework of 'minimum standards for ambition' (Xu *et al.,* 2021). There are also power imbalances across governance levels that affect enforcement (Di Gregorio *et al.,* 2019), as well as constraints on enforcement in the context of adaptive planning.

7.3.2 Governing through goals: challenges for transformative change

One important factor in future governance will be understanding the impacts of the move towards goals-based approaches, for which there is significant enthusiasm among the world's governments. Examples of this include the temperature target of well below 2 degrees in the Paris Agreement; the 17 aspirational Sustainable Development Goals; and the targets to prevent and reduce disaster risk under the Sendai Framework. The current zero draft of the Convention on Biological Diversity (CBD)'s post-2020 global biodiversity framework also continues the target-based approach of the CBD. Despite these developments, there remain key areas related to climate and biodiversity that are still missing goals and targets; for example, the lack of global goals for climate adaptation are a glaring omission. Further, goal setting as a global governance strategy would benefit from greater knowledge and understanding of the limits and opportunities of this approach (Kanie *et al.,* 2017). There is also the need to acknowledge challenges in downscaling the goals to local settings and in providing guidance on how to achieve this. Otherwise, goal-setting risks becoming slogans that motivate action but do not provide practical pathways to implementation.

Key differences in the goal-setting approach from the rulemaking approach of previous decades is that goals focus on aspiration while rulemaking generally includes behavioural prescriptions such as requirements and prohibitions. The former tends towards generating and maximising global interest by establishing priorities and galvanizing efforts, while the latter emphasises compliance and enforcement. The timeframes across the two approaches also generally tend to fixed-time frames for goal setting and enduring timeframes for binding legal agreements (Young, 2017). We outline below both the pros and cons of a goals-based approach broadly while emphasising the importance of attention to the design and content of goals as well as their legal status (i.e., where and whether they sit within existing binding instruments).

PROS: Goal setting can mobilize actors and encourage polycentricity: Multiple polycentric circles operating quasi independently while at the same time overlapping has been encouraged in governance (Aligica & Tarko, 2012), and goal setting can help facilitate this by encouraging multiple scales to take on singular goals. The work of Elinor Ostrom emphasizes that polycentric governance has two key advantages: one, there is more chance for experimentation and learning to improve over time, and two, communications and interactions increase among parties which helps build trust (Cole, 2015). One of the keys to success in polycentric governance is matching the boundaries of beneficiaries and managers with the boundary of the resource to be managed (Duncan *et al.,* 2020; Nagendra & Ostrom, 2012). There are many possible models: for example, in recent work looking at low carbon transition in Shanghai City, a nested structure of policy innovation played an important role, i.e., national government designated pilot cities to try out policies and measures, and each of these cities encouraged/conducted multiple experiments. Learning from individual experiments was then scaled up to inform city level policy, and city level learning used to inform national policy making (Peng & Bai, 2018).

Goals can shift global dialogue towards shared aspirations while generating momentum for broader consensus. Building on the points above, goal setting provides an important alternative to the conclusion of binding legal instruments particularly when it comes to generating enthusiasm for joint global objectives. Multilateral agreements can take decades to finalize and even longer to receive the required number of ratifications to come into force. In contrast, global goal setting provides the opportunity for galvanizing resources and maximising enthusiasm for global multi-scale cooperation and coordination within a much shorter timeframe (Young, 2017). The timeframes for global goals are also generally fixed. This facilitates timely review of progress through processes which turn attention on whether specific goals have been met.

Goal setting can allow for new targets to emerge iteratively. For example, while the Paris Agreement discusses a long-term temperature goal, current interpretations of how to reach that goal have resulted in increasing numbers of pledges from both companies and corporations to move to 'net-zero emissions.' While such ambitions are welcome, there is also a need to ensure that net-zero or other emissions targets are clear about their scope; whether or not they are adequate and fair; and what the roadmap to meet them will be (e.g., specific time-limited strategies) (Rogelj *et al.,* 2021).

CONS: Need for trust and values not just targets: Global targets alone are unlikely to generate the kind of trust and motivation that will result in success, and there are challenges to engaging local actors in issues framed at the global level which are fraught by the abstraction of place-based issues. Examples include the global climate target of limiting warming to two degrees, as climate change framed in this manner obscures the reality of multiple climates across the globe and the many different ways in which humans interact with climate (Turnhout *et al.,* 2016). This can make shared visions and common understanding of the plausible sustainability solutions for local communities difficult (McPhearson *et al.,* 2016). Thinking solely about technocratic issues, for example part per million of carbon in some quantitative climate scenario, does little to engage with underlying emotions that inspire transformative action e.g., fear, hope, grief and agency (L. Pereira *et al.,* 2019).

Uncertainties and inflexibilities in targets: While quantitative targets are common, there are mixed reviews on their effectiveness. For example, it remains unclear whether aggregation of local biodiversity impacts is an adequate indicator of large-scale or Earth-system ecological processes (Mace *et al.,* 2014), which has led to significant push-back against a singular biodiversity target across scientific and governance communities (Purvis, 2020). Many of the ecological SDG goals have lack a focus on ecosystem functions or integrity, as well as insufficient attention to feedbacks (Reyers & Selig, 2020). Further, global goals can obscure local problems: critiques of the 30% targets in the post-2020 biodiversity framework point out that lower levels of protection (for example, the 17% goal in the Aichi Target) are already underfunded, often incur trade-offs between protection and livelihoods, and are not well integrated into surrounding landscapes (Maxwell *et al.,* 2020). Finally, climate change will alter ecosystems to such a degree that fixed targets are likely to be inadequate in safeguarding ecosystem integrity (Arneth *et al.,* 2020), thus the question remains if target setting is distracting from other approaches that would be more effective in generating governance systems for dynamic change.

Need to adjust for qualitative targets: Quantitative targets also tend to overshadow any qualitative targets. For example, within Aichi Target 11 on protected areas, achieving 17% terrestrial/10% marine has tended to be the primary goal, rather than the qualitative elements regarding ecological representation, management equity and effectiveness, and integration into wider 'scapes' (Meehan *et al.,* 2020; Rees *et al.,* 2018). Similarly, NDCs to date have often provided more detail on quantitative mitigation targets while qualitative targets, such as those around climate adaptation, have been less prominent, although this is improving (UNFCCC, 2021). Suggestions to improve target-based planning includes better incorporation of stakeholders into the different stages of planning, use of multi-level strategies and focus (e.g., both economic and social) and attention to issues of scale (Lim, 2019; Mace *et al.,* 2014; Soberón & Peterson, 2015; Velázquez Gomar, 2014).

Allows governments to make claims to action with limited mechanisms for compelling compliance: The (usually) non-binding nature of global targets enables their relatively swift conclusion and support of the majority of nations. States naturally find the prospect of supporting broad global aspiration an easier consideration than signing up to obligations that compel them to act in a particular manner. Writing in 2011, at the conclusion of the Aichi Targets, several authors highlighted that "the status quo is unlikely to change without further development of clear obligations… with only aspirations rather than long-term commitments, it is highly likely that issues deriving from a supervening and short-term political event horizon will too easily supplant any quality or continuity of implementation," a prediction that turned out to be true (Harrop & Pritchard, 2011). Goal setting can also promote complacency by creating the perception that the 'work' has been done to address complex global issues and that there is no need to invest further time and resources in tackling the root causes of these issues. This creates the risk that parties that are unwilling to address governance challenges through a rules-based approach will use goal setting as a diversion (Young, 2017).

In sum, it is important that global governance through goals is not seen as an either-or with binding legal instruments; rather the two approaches should be seen as complementary tools in the contemporary governance toolbox. The design of global goals matters, as does the context and the legal regimes associated with particular goals. Effective goal setting calls for well-defined priorities framed in terms of explicit goals which galvanize attention and mobilise resources; a limited number of precise goals; and the allocation of resources in support of these goals (Xu *et al.,* 2021). For example, (Young, 2017) highlights limitations of goal setting where multiple actors with a range of conflicting interests attempt to achieve some level of compromise. The result is too many goals, framed in vague terms within a package that is incompatible or contradictory. This is exemplified in the 17 Goals and 169 targets of the Sustainable Development Goals which fail to include either an overarching end-goal or specific integration across a range of potentially conflicting complex goals and targets (Lim *et al.,* 2018).

The goal-based framing of climate appears to meet ideal criteria better than does biodiversity; for example, the Paris Agreement has a single long term temperature goal. Similarly, the Sendai Framework contains 7 clear targets which are partially quantified. In contrast, the current zero order post-2020 global biodiversity framework seeks a long-term qualitative goal of 'living in harmony with nature' which is open to interpretation. Other more definitive language around biodiversity goals that have been proposed have included 'no net loss' in the biodiversity pledges made by some nations (Maron *et al.,* 2018) or 'net positive outcomes for nature' (Bull *et al.,* 2020). The use of goals and targets that are clearer and better defined than the Aichi Targets, which are more explicitly socioecological (rather than one or the other), and which draw upon existing monitoring and indicators, have been suggested as improvements on past experience (Mace *et al.,* 2018; Reyers & Selig, 2020).

A further challenge is that effective global goal setting also depends on whether it sits within a binding legal regime. The Paris Agreement targets, for example, sit within the binding legal regime of the UNFCCC. The Paris Agreement also contains 'binding procedural requirements and normative expectations of progression' (Rajamani & Brunnée, 2017). The imperative 'shall' in Article 4.2 which states that 'Parties shall pursue domestic mitigation measures' enforces the binding nature of Paris pledges. While qualified by the second sentence of Article 4.2 where parties are 'not obliged to achieve a particular outcome', the wording of the article creates an 'obligation of conduct' to take adequate measures to realize mitigation targets (Mayer, 2018). Therefore, any party which sought to downgrade its pledges under the Paris Agreement would be at odds with the legal expectation of progression and, in the case of developed countries, would run afoul of the principle of common and differentiated responsibilities. Such action is also a potential breach of international law in its attempt to defeat the UNFCCC's object and purpose to 'prevent dangerous human interference with the climate system' (Rajamani & Brunnée, 2017).

In contrast, while the Aichi Targets and post-2020 global biodiversity framework sit within the Convention on Biological Diversity, their legal weight is undermined by the lack of binding-ness of the CBD itself which is largely couched in terms of 'as far as possible and as appropriate' (Lim, 2021). Nevertheless, occurring within a binding Multilateral Environmental Agreement, similar arguments to the Paris Targets could be made as to the obligations of states not to act contrary to the aspirations of CBD targets, as to do so would be contrary to the CBD's objectives of conservation, sustainable use and the equitable sharing of benefit, and a mix of binding and nonbinding elements could be part of the post-2020 global biodiversity framework (Xu *et al.,* 2021). The SDGs, on the other hand, sit on the other side of the spectrum. Not sitting within the framework of any convention the SDGs imply no legal obligations on UN member states. States negotiated the SDGs with this explicit understanding, thus underscoring the aspirational nature of the goals and targets.

7.3.3 Identifying systems and actors for transformative change

Overall, the interconnected nature of social-ecological systems at the nexus of climate change, biodiversity loss and good quality of life can guide successful transformations in global governance systems, and the COVID-19 pandemic has further heightened these connections and need for transformative change. Successful implementation builds on an understanding of the interactions of interdependent systems and the participation of a wide range of stakeholders in the modelling and design process (Sterman, 2003). Yet as noted previously, existing approaches to biodiversity, climate and human well-being are largely siloed, reflected in fragmented and often inconsistent legal regimes, while at the same time, current global governance approaches have nations-states at its core. As a result, these approaches do not sufficiently address causes and impacts at appropriate governance scales nor do they adequately engage the range of global and local actors who have divergent values around nature, ranging from corporations to cities to indigenous and local communities.

There have been increasing calls for policymakers to adopt systems approaches to governance across all levels (Newell *et al.,* 2012). This is particularly needed to enable collaborative governance across networks, actors and scales, while complex interlinkages across sectors and the cascading impacts (intended and unintended, synergies and trade-offs) of decisions are taken into consideration. Yet implementation of such systems approaches is often challenging, due to a range of enabling factors, including changed mental models to avoid siloed approaches and address the complexity of the issue; overcoming institutional inertia; building knowledge capacity and supporting tools; and overcoming the spatial, temporal and institutional scale mismatches at any given government level (Bai *et al.,* 2016; Webb *et al.,* 2018). Many of the proposed 'nexus' approaches to policy, for example decision-making around food-water-energy, move in the direction of systems approaches (Paim *et al.,* 2020).

However challenging, systems approaches can help address the increasingly telecoupled nature of global systems, as designing climate and biodiversity resilient pathways build on an understanding of the interconnections between climate change and biodiversity and also of the roles of faraway actors (Liu *et al.,* 2018). Such teleconnections in a globalized world further support expanding the framework of climate and biodiversity actions beyond states. The incorporation of systems theory into environmental law scholarship and design is nascent but growing (Craig, 2015). The literature acknowledges the need for environmental law to address complex ecological systems (Craig, 2013; Elliot, 1992) and has considered legal systems as complex systems in their own right (Kim & Mackey, 2014; LoPucki, 1996; Ruhl, 1997, 2008). Gaps remain, however, in moving beyond theoretical concerns to the design of practical frameworks but are essential to address fragmented legal and governance regimes across multiple governance scales.

With the bottom-up approach of the Paris Agreement a notable exception, other international instruments such as the CBD and UNFCCC are usually considered weak in the involvement of the broad range of actors needed for successful transnational governance. Involving and holding a range of actors accountable at the international scale is made more difficult by the international law system which has state-actors at its core (e.g., reporting actions from national governments, COPs consisting of delegations of signatory nations). Such approaches are increasingly anachronistic in dealing with coupled human-ecological systems on a large scale, such as ocean governance (Rudolph *et al.,* 2020). Though environmental treaties and regimes increasingly recognise non-state actors (including local and sub-national levels of government, indigenous peoples and local communities, foundations and philanthropy, and NGOs), and there are innovative platforms like the Nairobi Work Program within UNFCCC to encourage multi-stakeholder interactions, countries often remain the key focus of specific obligations. Increasingly, COPs for both biodiversity and climate include side events where civil society can have a voice, but this remains informal and a potential lost opportunity for stronger action. Greater non-governmental participation in the Ramsar Convention, for example, has been pointed to as one reason for its successes in greater transparency (Pittock, 2010). Potential promising examples include actions for "people's NDCs" to encourage civil society involvement in national processes (http://peoplesndc.org/).

The expansion of non-state actors in governance has brought both opportunities and challenges around legitimacy, justice, and effectiveness (Kuyper *et al.,* 2018). Non-state actors play increasingly important roles in monitoring in particular, as well as spearheading private sector initiatives, even while they remain outside formal negotiations and exert mostly soft power. Interestingly, developing countries have shown higher involvement of civil society and non-governmental actors during the preparation of NBSAPs (Whitehorn *et al.,* 2019). However, civil society actors face multiple challenges in engagement. Even more concerningly, rising conflicts around energy, mining and other development projects have resulted in a growing number of violent encounters and deaths among indigenous peoples and local communities on the front line, with inadequate investigations, protections and accountability for perpetrators (Scheidel *et al.,* 2020), an issue that IPLCs have raised as highly important to address in the post-2020 biodiversity framework as well as in other forums.

Other new coalitions of actors in the biodiversity-climate space have also emerged in recent years, including coalitions such as the High Ambition Coalition (HAC) for Nature and People, the Nature Based Solutions coalition, or the Soy Buyers Coalition. Other new civil society actors like the Science-based Targets Initiative that encourages companies to use Paris Agreement targets to set business sustainability goals, have bridged the NGO-private sector divide.

However, despite the growing role of multinational corporations in driving biodiversity loss and climate change, there is insufficient attention to how to engage them in identifying solutions. Not all non-state actors are equal, and it is largely the case in biodiversity at least that the actors pushing conservation solutions are not the actors that drive biodiversity loss (Milner-Gulland *et al.,* 2020). The private sector is a driver of GHG emissions and biodiversity loss while often representing powerful and vested interests (IPBES, 2019; Nyström *et al.,* 2019). At the same time, corporations supply products and services that support good quality of life and contribute to social and economic development (Baumgartner & Rauter, 2017), which is why actions targeting consumers and behaviour change have also been identified as keys to transformative change (see Section 7.4.1).

It is also important to recognize that the private sector is also made up of myriad types of actors, for example, in climate, there are private finance institutions lending or investing in corporations generating carbon emissions combined with the everyday actions of consumers driving cars or eating meat, while global value chains that are implicated in much land and sea use change involve multiple actors from smallholders to large agribusiness and seafood conglomerates (Österblom *et al.,* 2015; Folke *et al.,* 2019; Nyström *et al.,* 2019). Yet despite the power of the private sector, they often remain disconnected from the development of international targets and agreements. As an example, private-sector businesses were only involved in the development of half of all NBSAPs, while still being a major driver of biodiversity loss (Whitehorn *et al.,* 2019). While it is recognised that involvement of the corporate sector will be key to the success of the SDGs, there is scant explicit acknowledgement of corporations within the SDG text. Corporations only appear once – in Target 12.6 which addresses waste generation, a critical omission which is potentially reflective of the lack of transformative intentions of state parties negotiating the SDGs (Lim *et al.,* 2018). Cross-national issues relating to power and finance among vested interests, including problems of corruption, influence-peddling, greenwashing, and lobbying (Teichmann *et al.,* 2020; Kenner & Heede, 2021; Supran & Oreskes, 2021), remain a vexing problem for governance across scales and sectors.

7.3.4 Creating enabling conditions for transformative governance

To address the many governance challenges enumerated above, enabling conditions or factors that can contribute to success, such as finance, access to technology, capacity building, policy coherence and partnerships, adaptive monitoring and accountability, have been identified (Stafford-Smith *et al.,* 2017). For example, alignments of public opinion, new governance contexts (change in parties or a precipitating event), presence of policy champions, international support, and feedback mechanisms were all associated with success in policy implementation and outcomes in a review of nearly 300 different policies promoting renewable energy (Auld *et al.,* 2014). Focusing governance on effective risk management is also seen as key to adapting to the novel conditions that characterize the Anthropocene (Keys *et al.,* 2019). Some key enabling conditions for integrated biodiversity/climate governance, as well as promising new and emergent initiatives, are noted below:

Policy integration across sectors and scales. Strong and functioning vertical (e.g., upper and lower-level government levels) and horizontal (across different sectors, contexts, stakeholders) linkages are essential for innovative and successful practices to spread across jurisdictions and be broadened, and to influence and transform upper scale governance and management practices (Bai *et al.,* 2009). For example, in the case of developing ‘sponge city’ approaches in China to increase uptake of NbS, a multiscale approach was led by the national government with funding commitments which encouraged cities to come up with their own plans and innovative practices (Peng & Bai, 2018). Evidence from decentralized and community-based approaches to climate adaptation also show successes when “local governance structures are given a central role in linking available support systems to complex and changing conditions on the ground” (Fischer, 2021), with benefits often extending to poorer and more marginalized peoples who might otherwise be excluded.

Other examples of solutions that pay attention to the importance of both cross-scale and cross-stakeholder models include “jurisdictional approaches”, which are “governance initiatives that promote sustainable resource use at the scale of jurisdictions through a formalized collaboration between government entities and actors from civil society and/or the private sector, based on practices and policies intended to apply to all affected stakeholders within the jurisdiction” (Essen & Lambin, 2021). These range from sustainable commodity agreements to REDD+ and other policies. Jurisdictional approaches attempt to overcome challenges from previous approaches, including lack of development integration, selection bias for voluntary measures (thus decreasing additionality), project level scales with little extended impact, and leakage by upscaling efforts across regions or ecosystems to meet global goals. The potential for success of these approaches depends on engagement of multiple stakeholders, buy-in across policy scales to remove concerns of leakage, and efficiency of investments (Essen & Lambin, 2021).

Experimental policy mixes. Moving from deterring or stopping net negative actions to promoting net positive ones has been the focus of incentive and other programs, which have often been contrasted to regulatory approaches. However, voluntary and incentive policies for climate mitigation working alone have often been less successful than mandatory and regulatory ones (Green, 2021). Thus, experiments with policy mixes that incorporate both incentives and regulations can be more successful than singular approaches. Such mixes can be facilitated by new tools for economic and ecological accounting, which may help to make the case for net positive actions, including the current move to adopt a UN System of Environmental Economic Accounting (SEEA) that accounts for natural capital and assets (Keith *et al.,* 2017), among other forms of incentives. Further, enforcement of compensation for damages, as part of well-designed offsets or other mitigation frameworks, can help create incentives for conservation as well.

Mechanisms for learning and scaling-up. Scaling up successful good practices is important to achieving transformation. For innovative practices to be widely adopted, willingness and aptitude to learn and adopt innovative practices on the recipient side is critical. Meanwhile front runners can be proactive in influencing others (Irvine & Bai, 2019). In addition, access to information, knowledge and education enhance credibility, legitimacy, relevance and other factors of success (Sarkki *et al.,* 2015). While these are especially challenging in multi-scalar governance contexts (von Heland *et al.,* 2014), adaptive evaluation and monitoring and regular sharing across boundary organizations have been pointed to as keys to success (Di Gregorio *et al.,* 2019). Anticipatory and adaptive decision-making, particularly focused on the idea of "flexible, collaborative decision-making" rather than top-down bureaucratic decisions, and social learning and collaborative co-management have been highlighted (Wyborn, 2015). Adaptive governance makes use of networks and multi-scalar connections to deal with complexity, with diversity of agents and the quality of their interactions among keys to success (Innes & Booher, 2018). Such mechanisms can help ensure reflexive evaluation and learning over time but scaling them up remains challenging.

Strong equity considerations. Equity refers to ensuring access to both processes of governance and its benefits, including economic, social, environmental and political opportunities, given that there have been unfair distribution of costs and benefits of biodiversity and climate change impacts, as well as unfair benefits and burdens in solutions (Leach *et al.,* 2018). Building equity into different governance processes relates to having inclusive processes to guarantee participation from affected communities from the start, such as in planning processes for goals before solutions are even attempted (Hill *et al.,* 2016), as well as mechanisms to ensure fair benefit-sharing or safeguards to prevent uneven or negative impacts. For example, inclusion of women and the elimination of gender inequities has been highlighted as key to achieving both climate and biodiversity policy objectives (Alvarez & Lovera, 2016; Andrijevic *et al.,* 2020; Lau, 2020), and the role of IPLCs is increasingly recognized as essential to the post-2020 biodiversity framework and climate mitigation targets (Brugnach *et al.,* 2017; Reyes-García *et al.,* 2021; Vierros *et al.,* 2020). Yet achieving shared visions has been difficult as solutions for biodiversity loss are often not able to make up for existing social inequities and wider structural problems outside the ecosystem scale (Verde Selva *et al.,* 2020). Further, the degree to which equity affects conservation success is context dependent, highlighting the need to be explicit about the kinds of equity desired, and ways to manage trade-offs among types of equity and between equity and conservation outcomes (Klein *et al.,* 2015).

Expanded mechanisms for participation. There are tensions between democratic processes and many of the solutions proposed by states to climate and biodiversity problems, ranging from biodiversity offsetting to BECCS (Takacs, 2020). Inclusive processes tend to reduce conflict and increase awareness of biodiversity values (Whitehorn *et al.,* 2019). For inclusion to be effective there needs to be full and effective participation at all stages of the decision-making process (i.e., from planning to implementation). There has been a trend toward embracing 'politics' rather than relying on solutions from non-political experts, that is, making explicit where power resides, who has it, and what impact it has on issues such as vulnerability (Eriksen *et al.,* 2015). There are particularly important roles for indigenous peoples and local communities and their 'knowledge, innovations and practices, institutions and values', which are seen as critical to protecting nature and NCP (IPBES, 2019). IPLCs are key actors in addressing the interconnected issues of biodiversity, climate change and human well-being, and can play key roles in creation and implementation of NbS (IUCN, 2020). These critical contributions can be enabled by the recognition of land, access and resource rights, as well as application of principles of free, prior and informed consent and fair, equitable sharing of benefits, along with equitable co-management arrangements (IPBES, 2019).

Rights-based approaches can be one way to address equity and participation concerns; for example, the UNFCCC discusses the need to "fully respect human rights" in climate approaches, and multiple studies have noted that climate change impacts currently threaten or prevent rights to life, health, water, food, housing, and an adequate standard of living (UNEP, 2015). The implementation of rights-based approaches usually concerns the need for participation, non-discrimination and accountability in governance (Karimova, 2016). A rights-based approach to climate action for example would specify climate targets must be compatible with the ability to achieve equitable livelihoods (UNEP, 2015) or children's futures (Tanner, 2010). Similarly, rights-based approaches in biodiversity would acknowledge the important roles of IPLCs in the management of large areas of terrestrial biodiversity (Tauli-Corpuz *et al.,* 2020). Additionally, solutions to climate change, whether mitigation, adaptation or geoengineering, will need to be compliant with human rights goals, as some proposed measures have the potential to violate existing recognized rights to water or food (e.g., BECCS).

7.4 MOVING TOWARDS TRANSFORMATIVE CHANGE

Human-caused climate change and unprecedented biodiversity loss are symptoms of widespread unsustainable relationships with the planet. Transformative change will ensure planetary futures which are just and sustainable, and are increasingly recognized within the SDGs, UNFCCC and CBD mechanisms. Transformative change is defined as "fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values" (IPBES, 2019). As noted in the previous Section 6, transformative change addresses the mix of complex interacting environmental problems by expanding beyond the direct drivers of environmental degradation to include indirect drivers such as economic activities and governance systems which fuel the direct drivers (Chan *et al.,* 2020; Díaz *et al.,* 2015).

Transformative change builds on a deliberate process that challenges and shifts routine values and practices, in contrast to merely incremental changes. The scale and durability of such transformations, as well as whether or not they will be positive, remains difficult to predict (Nalau & Handmer, 2015). The IPBES GA identified a nexus of interlinkages with potential positive benefits to facilitate transformative change, including recognition that:

- Consumption and production patterns are a fundamental driver of material extraction, production, and flows, but they too are driven by worldviews and notions of good quality of life and are subject to transformative change.
- Behaviour change pervades all aspects of transformative change—supply chains and their management, but also conservation and restoration.
- Inequalities and inclusiveness are key underlying problems—good planning processes help, but power disparities remain an issue and impacts at the climate change-biodiversity nexus often disproportionately affect the poor and disenfranchised.
- Larger structural issues underpin all of the above factors—telecouplings, technology, innovation, investment, education and knowledge transmission.
- Governance instruments and approaches are fundamental, such as incentives, adaptive management, law and its enforcement.

In this section, we address these challenges and discuss how tools can help to envision the pathways towards transformative change.

7.4.1 Leverage points for transformative change

The IPBES global assessment identified key leverage points for transformational change in relation to biodiversity, and many of these points are equally relevant to climate and well-being, as they are important components of climate resilient development pathways (Singh & Chudasama, 2021; discussed further in 7.5). The concept of 'leverage points' suggests a series of integrated actions linking both individual and structural changes, as noted in eight areas below.

Embracing diverse visions of good quality of life for all. Understanding what makes for good quality of life (GQL) requires accounting for multiple values and different ways of measuring well-being (see Section 6). It also requires shifts across the range of unsustainable values which are currently perpetuated by dominant worldviews. For example, decoupling consumption and well-being is one path, as a better life experience might for example involve spending more time with family and friends (Jax *et al.,* 2018). This will require shifting dominant narratives, particularly those which frame human development as diametrically opposed to ecological integrity. Tools for enabling these transformations include thinking about alternative accounting systems that move away from income and other quantitative measures alone to more encompassing ones that include notions of sufficiency within well-being (Hickel, 2020). There is also a need to go beyond cost-benefit framing in assessing both biodiversity and climate change interventions to focus on service provision and human well-being (Creutzig *et al.,* 2018). The elevation of indigenous and local knowledge in governance and legal models (e.g., IPBES, 2019) is an additional response to this need.

Reduce total consumption and waste. The insight from this leverage point is that per capita material consumption tends to rise as income rises, putting further pressure on the environment through waste production and biodiversity loss (Ehrlich & Pringle, 2008), as well as creating inequities with regard to waste and pollution disposal (Ádám *et al.,* 2021). Transformative change in consumption patterns is particularly important for wealthier nations compared to poorer nations who may need to increase their per capita consumption while tackling population growth. Steps to reduce excess consumption can include both incentives and regulations: targeting consumer behaviour with tools such as education initiatives, choice architecture, and collaborative consumption (such as sharing and reuse), as well as resource-use caps and taxes and changes in subsidies on the supply side (Bengtsson *et al.,* 2018). Circular economy approaches have promoted manufacturing models that emphasize 'closed circle' production, encompassing reuse and recycling of materials throughout the life-cycle, as well as theories of decoupling energy use from economic growth to slow climate change impacts in particular (Korhonen *et al.,* 2018), but biodiversity loss has tended to be less well addressed in these approaches (Buchmann-Duck & Beazley, 2020). Focusing on service provision can allow for a broader framework to "avoid, shift, and improve" for both supply and demand; such approaches can achieve significant emission reductions while being largely beneficial in improving well-being (Creutzig *et al.,* 2021).

Shifting values. There is growing recognition that the predominant economistic worldview is a driver of inequity and unsustainability (Bai *et al.,* 2016; Leach *et al.,* 2018; Malm & Hornborg, 2014; Steffen & Stafford-Smith, 2013), and which can create untenable equivalences between human well-being and economic activity (Malm & Hornborg, 2014; Steffen & Stafford-Smith, 2013). Sustainable behaviour can be enabled by context-specific policies and social initiatives that foster social norms and widespread action (including virtues and principles regarding human relationships involving nature, such as responsibility, stewardship and care) (Chan *et al.,* 2018). Other ways of reconnecting with nature may reflect multiple values: economic, cognitive, emotional and otherwise, all of which could be important leverage points for changes towards sustainability (Ives *et al.,* 2018). In order to be effective, transformative governance would need to be cognizant of these multiple values, connections to nature, relationships and power dynamics. This includes championing alternatives to capitalism, such as the popularisation of the term buen vivir (as in the Ecuadorian constitution) and concepts such as sumak kawsay (from the Quechua language), which are central to a range of indigenous worldviews.[1] These ontologies emphasise 'community centric, ecologically balanced and culturally sensitive' ways of living (Berros, 2019; Lim, 2019).

Reduce inequalities. Inequality often reflects excessive use of resources or power by vested interests at the expense of others, resulting in the distribution of unequal shares of finite resources and often degrading nature (Stiglitz, 2013). Economic inequality is problematic on its own but also generates poorer environmental outcomes; for example, income inequality is associated with excess consumption, waste, and higher carbon emissions (Otto *et al.,* 2019), as well as biodiversity loss (Holland *et al.,* 2009). The exact mechanisms are often complicated and diverse; for example, financial investments by high-net worth individuals have been shown to drive ecosystem conversions (Ceddia, 2020). Land inequality is another growing problem, particularly through processes of land concentration, land tenure conflicts or poor recognition of customary tenure; currently 1% of farms operate more than 70% of the world's farmland through integration into the global food systems, while over 80% of farms are smallholdings of less than two hectares (Land Inequality Initiative, 2020). Land inequality can lead to unemployment, outmigration, and worsening livelihood situations, and can be a driver of biodiversity loss or GHG emissions as well (Ceddia *et al.,* 2019), demonstrating the need for better understanding of the links between inequality and conservation or climate outcomes.

Practice justice and inclusion. Ensuring that equity is accounted for in proposed solutions goes under many names, such as 'inclusive development', 'procedural and/or distributive justice' or 'intergenerational justice'. Other approaches that emphasize equity include concepts of "fair adaptation" and "just transitions" (providing for those harmed by mitigation measures like reductions in fossil fuel use, for example) (Robinson & Shine, 2018). Inclusion relates to having a full suite of stakeholders in any decision-making process, particularly those harmed by or benefiting from an action. A good example of this perception is the engagement of IPLCs in protected areas governance in recognition of their traditional and sustainable use of NCP in landscapes and seascapes (Ban *et al.,* 2013). Evidence shows that recognition of land rights to IPLCs has been associated with decreases in deforestation and improved land sparing (Ceddia *et al.,* 2019), while rights-based approaches in fisheries involve allocation of territorial use rights to rectify unequal access to resources (Rudolph *et al.,* 2020).

Further, recognition of the harms done to land defenders, who have suffered from violence and death in recent decades, with strong measures and policy incentives in a post-2020 global biodiversity framework could further rights-based policies (Larsen *et al.,* 2020). An alternative emerging approach is that of scholars such as (Burdon, 2020) who propose a shift in focus on rights to broader framings of obligations. Such approaches suggest an elevation of the obligations to nature embodied within a range of indigenous worldviews and practices. Rights approaches, (Burdon, 2020) argues, perpetuate an individualism which is readily accommodated within capitalist systems and allows the externalization of the causes of human-induced global environmental change. Obligations in contrast, allow addressing the root cause of the Anthropocene by placing 'human power at the centre of our legal and ethical frameworks.' Obligations are therefore seen as a more appropriate tool for facilitating pluralism while restraining human action and ensuring intergenerational equity (Burdon, 2020).

Internalize externalities. Achieving global sustainability goals involves assessing the distant effects of local actions manifested in telecouplings (Liu *et al.,* 2015) as well as the under-priced impacts of production goods. For example, some environmental policies enable countries to meet targets by externalizing impacts to other jurisdictions (e.g., some mining, agricultural production and greenhouse gas emissions) (Pascual *et al.,* 2017) or by explicitly offsetting them. Externalities such as GHG emissions or nitrogen runoff are serious concerns; for example, food production is a particular sector in which the climate and biodiversity impacts are inadequately reflected in prices (Pieper *et al.,* 2020). Tools such as ecosystem services valuation, carbon pricing and other forms of economic and social incentives, can enable positive feedback within socioecological systems (Lubchenco *et al.,* 2016), although they cannot solve all problems by themselves.

Ensure responsible technology, innovation and investment. Transformative change can galvanize private investment in nature and its public benefits (Keohane &

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[1] Both *buen vivir* and *sumak kawsay* can be roughly translated as "good living" or "a full life" and refers to alternative visions of development within indigenous communities, often including more relational approaches to nature and community (Villaba 2013).

Olmstead, 2016). Yet existing finance mechanisms for both biodiversity and climate are fragmented and inadequate, both in North-South flows and South-South sharing. Private sector financing for biodiversity in particular lags significantly behind climate (e.g., there are few green investment banks or bonds for biodiversity while these are increasingly common for climate), yet both remain far behind what would support success. Private financing for biodiversity protection and climate accountability could be realized through disclosures of financial risk, target setting, and other mechanisms, leading to de-risking of investments with long-term time horizons (La Rovere *et al.,* 2018). Investment standards like the Carbon Disclosure Project and new Task Forces on Climate-Related Risk Disclosures and Nature-Related risks provide opportunities to improve these financing goals. However, access to finance alone does not always explain adoption of low carbon policies, which is also influenced by historical pathways, levels of development and other factors, as well as a function of networks, in which competition, learning and emulation, as well as coercion may drive change more than access to finance (Stadelmann & Castro, 2014).

Promote education and learning. Environmental education and knowledge sharing can enhance values such as connectedness, care, and kinship (Gould *et al.,* 2018). Improving education and learning about biodiversity and climate can help build citizen support for actions and initiatives, as can recognition of the power of storytelling and narratives. There is also promise in child to parent intergenerational learning for conveying information across ideological barriers (such as denial of climate change) and promoting sustainability behaviours, as well as encouraging children's engagement with the natural world (Peterson *et al.,* 2019). Alternative learning approaches that do not rely on linear models of expertise such as co-production models and citizen science have been championed in recent years (Bela *et al.,* 2016), by dissolving the boundaries between science and society and building tools for creators and users of knowledge to work together (Armitage *et al.,* 2011). Co-production often draws heavily on boundary organizations for iterative learning and collaboration (Rosenzweig *et al.,* 2011) and the outcomes can often be more positive than those derived solely from expert planning alone, which often ignores the normative values that people hold (Wyborn, 2015). "Participatory Action Research" is another model with widespread applicability to natural resources management and climate change in which both scientific and lay knowledge can combine with reflexivity towards the research process to generate actionable outcomes (Campos *et al.,* 2016). There is also anticipatory learning, which is forward-looking and reflexive, building in planning for surprises and opportunities for re-calibrating pathways in more dynamic and participatory ways, using tools of envisioning, backcasting, experimenting, and reflection (Tschakert & Dietrich, 2010). For example, the concept of "triple loop learning" refers to the process of 'learning about learning' to correct mistakes and challenges. Role-playing and simulations are two ways new forms of learning can be introduced to policymakers that show promise (Rumore *et al.,* 2016). All these new ways of planning and learning contribute to the types of transformative governance of socioecological systems that are envisioned to be successful (Colloff *et al.,* 2017).

Overall, achieving transformative change can use the above leverage points to help identify new pathways through understanding the key drivers of change (both biophysical and socioeconomic) within systems; looking for examples of innovation and experimentation that have shifted systems dynamics towards sustainability; and identifying and highlighting regime responses that have emerged (Rudolph *et al.,* 2020). It is critical, however, the focus is not only on futures of impending doom, as doing so risks creating self-fulfilling prophecies, but rather on imagining and exploring inspirational future possibilities (Bai *et al.,* 2016; Bennett *et al.,* 2016) and developing governance approaches which allow achieving a future planet where people and nature thrive. Tools and methods to help visualize these new pathways are discussed below.

7.4.2 Tools for imagining synergistic futures and transformative change

Scenario-based modelling is a powerful tool to describe future trajectories with or without policy interventions and their consequences for biodiversity, NCP, and climate change. Scenarios explore future conditions by assuming future trends in different drivers (e.g., land, energy and water use; and trends in demography, technology and economy; and international relationships). Scenarios differ from forecasts or predictions, as multiple scenarios are used to explore the future of complex systems under large uncertainties and all these scenarios are equally plausible (a what-if analysis), while predictions provide a single most likely outcome, often with an added specific probability. Projections are thus suitable for conditions where systemic behaviour and uncertainties are well understood. For certain driver trends, scenarios can rely on predictions, but generally the scenario domain is created by assuming largely different trends for the drivers with the largest uncertainties (Alcamo, 2008). Assessing the future of wicked problems such as climate change and biodiversity decline is generally done by scenarios analysis and models. Although such analyses can inform policy processes, broader approaches support an understanding of the problem framing, policy design, policy capacity and the contexts of policy implementations (Head, 2019; Termeer *et al.,* 2019).

Scenario development and applications have a long history in IPCC (Carter *et al.,* 2001; Mearns, L *et al.,* 2001). Initially, global emission scenarios were developed for different business-as-usual trends e.g., the Special Report on Emissions Scenarios (SRES) scenarios (IPCC, 2000), to determine future atmospheric concentrations of greenhouse gases and climate change. The increase in global mean temperatures projected from these SRES scenarios ranged from 2.0°C to 4.5°C in 2100 (or 1.5°C to 6.0°C with all uncertainties included). Many earlier studies on climate change impacts on biodiversity, ecosystems and ecosystem services were based on these SRES scenarios (e.g., Knouft & Ficklin, 2017; Schröter *et al.,* 2005). Recently, IPCC started to use a different scenario approach: the Representative Concentration Pathways (RCPs) (O'Neill *et al.,* 2014) and the Shared Socioeconomic Pathways (SSPs) (O'Neill *et al.* 2017). The RCPs span the range of current climate change scenarios in CO_2-equivalent greenhouse gas concentrations from 400ppm to 1200ppm and in global mean temperature increases by 2.6°C to 8.5°C in 2300 (or 1.5°C to 10.0°C with all uncertainties included). These RCPs are simulated by many different state-of-the-art climate models (Meehl *et al.,* 2000), resulting in various regional patterns of climate change and probabilities of extreme events etc. The SSPs intend to describe worlds in which different societal trends facilitate mitigation of or adaptation to climate change without explicitly considering climate change itself. SSP1 mimics few challenges for adaptation and mitigation and describes a 'green road'; SSP2 mimics intermediate challenges and describes a 'middle road'; SSP3 mimics large challenges and describes a 'rocky road'; SSP4 mimics serious adaptation challenges and describes a 'divided road; and SSP5 mimics mitigation challenges, which describe taking the 'fossil-fuel highway'. These SSPs are also useful to address sustainable development and biodiversity contexts because the socioeconomic challenges to mitigation and adaptation are closely linked to different trends in socioeconomic development and sustainability. Currently, almost all scenario analysis, including those for biodiversity, use aspects of these SSPS and RCPs (e.g., van Vuuren *et al.,* 2015). Although this reduces their potential richness and utility, it enhances the comparability of different studies.

The future of biodiversity is much more difficult to assess with a scenario analysis than changes in climate as changes in biodiversity are determined by many, often interacting (including feedbacks) local and regional factors, synergies and trade-offs. Ecosystem dynamics and responses depend on the available species, their traits and histories, their communities, habitats and ecosystems in which they thrive, environmental properties and environmental changes (including the timing of these changes). Many of these changes are driven by factors that are external to specific ecosystems (e.g., increased atmospheric CO_2 concentrations and consecutive changes in climate and weather, and land use), but other changes emerge from ecosystem processes, such as facilitation (e.g., Butterfield *et al.,* 2010) and succession (e.g., Kropelin *et al.,* 2008; Granath *et al.,* 2010). All these complexities are modelled to explore future changes in biodiversity.

Scenario-based biodiversity modelling explores the consequences of changes in, for example, climate, land use and water availability on biodiversity and NCP, resulting in quantitative estimates of future changes in biodiversity. These estimates typically result from the coupling of several approaches and methods, including species distribution models (e.g., Araujo & Rahbek, 2006; Bellard *et al.,* 2012) and scenarios for climate change, land use and exploitation of ecosystem services (e.g., Leadley *et al.,* 2010). Global and regional scenarios of changes in biodiversity have been developed for different time spans (e.g., Sala, 2000; Pereira *et al.,* 2010; Kok *et al.,* 2018; Priess *et al.,* 2018). These scenarios consistently report biodiversity losses over this century; however, they often assume a 'no-dispersal' world or an immediate dispersal option. Frequently, species may adapt or disperse to some extent (Barnosky *et al.,* 2017), but this is rarely considered in scenarios studies, and thus their results could overestimate biodiversity losses. Recently, changes in future biodiversity were assessed by combining RCPs and SSPs. (Popp *et al.,* 2017), for example, developed a series of comprehensive land-use scenarios and determined the consequences of different pathways for climate change mitigation by different land uses (improved agricultural and forestry management, bioenergy or carbon sequestration). Each SSP showed different land-use extents and patterns (e.g., SSP1 decreased the land-use extent by over 700 Mha, while SSP3 increased land-use extent by over 1050 Mha). They conclude that, generally, low agricultural demand, increased agricultural productivity and trade (i.e., SSP1) likely enhances the extent of natural ecosystems and thus biodiversity, but this was not explicitly calculated.

Schipper *et al.* (2020) has added this step by using the GLOBIO model (Alkemade *et al.* 2009) to obtain an overall biodiversity risk. Their result shows that biodiversity declines in all SSP-RCP combinations but least in the 'green road (i.e., SSP1xRCP2.6) scenario and most in the 'rocky road' (i.e., SSP3xRCP6.0) and 'fossil-fuel highway' (i.e., SSP5xRCP8.5) scenarios. Large regional differences can be observed, however. In the 'green road' scenario, impacts are largely benign (i.e., compared to current biodiversity levels) and in some areas biodiversity increases, likely caused by SSP1's more sustainable land use. The 'rocky road' and 'fossil-fuel highway' scenarios show declines everywhere, but the largest declines occur in tropical Africa or the Arctic. This seems to be caused directly by the difference in climate change patterns and levels in the RCPs.

One of the most comprehensive and integrated biodiversity-scenario studies with different policy measures was done for UNEP's project on The Economics of Ecosystems and Biodiversity (TEEB) (Netherlands Environmental Assessment Agency *et al.* 2010). This study determined the effect of different conservation, agricultural, ecosystem management and climate change policies **(Table 7.2)**. Conservation policies which increased protected areas by 20% or up to 50% reduced the decline of biodiversity a little but not substantially, partly because factors such as climate change continue to have an impact. Reducing deforestation affects the carbon flux to the atmosphere and slows the CO_2 build-up, thus mitigating climate change. Agricultural expansion is a major driver of climate change and currently most available agricultural land is occupied (and often degraded). However, agricultural productivity can easily increase in many regions, losses can be minimized, and fisheries can become much more sustainable. This reduces the necessity to expand agricultural land further. Additionally, shifting prosperous diets with much red meat to diets with less meat (flexitarians) or no meat diets (vegetarians) reduces the demand for grazing land and fodder crops, slowing deforestation, and reducing methane emissions from ruminants (IPCC, 2019b). A vegetarian diet would half the amount of current agricultural products used now (Stehfest *et al.,* 2009). Overall, in this scenario study, no single measure alone protects biodiversity; when measures were combined, the results improved but even all measures combined do not stop the biodiversity decline, partly due to increasing consumption of a more prosperous population worldwide. The general conclusion of all these scenario studies is that halting biodiversity decline is extremely challenging. Although clever strategies combine many measures, they only slow the decline. However, many of these scenarios also provide positive effects for food security, hunger, health and climate change.

7.4.3 From scenarios to transformative decision-making

Science-policy scenarios and model projections to achieve multiple concurrent goals synthesize knowledge about the socioecological consequences of unsustainable development to stimulate political action at local, national and international decision-making levels. The capacity of these scenarios and models to address complexity and dynamics increases their utility for developing and evaluating targets and policies and improving conservation outcomes (Nicholson *et al.,* 2019) Scenario-based modelling thus contributes to appraise the effectiveness of biodiversity-conservation measures and to inform decision-making (van Vuuren *et al.,* 2015). This has already been done for assessing progress towards the Aichi Targets (e.g., Tittensor *et al.,* 2014) and for specific ecosystems, such as wetlands (Davidson, 2014). For example, Díaz *et al.* (2020) note that none of the targets has been achieved and only six have been partially achieved. They propose for the next phase after CBD COP 15 far more ambitious targets up to 2050 to, for example, halt the net loss of natural ecosystems' extent and integrity, reduce extinction risks and restore local species abundances and maintain genetic biodiversity.

Progress towards the Paris Agreement target for climate protection of well below 2°C (or if possible 1.5°C) was

Table ⑦ ② **Integrated policy scenarios for UNEP's TEEB project (Brink, 2010).**

Priority setting in conservation		
1	**Expanding protected areas**	Conserving rare and valuable habitats, endemic species, hotspots, and a representative selection of ecoregions.
2	**Reducing deforestation**	Maintaining carbon uptake and storage in forests; synergy with climate change mitigation.
Reduced agricultural expansion and eutrophication		
3	**Closing the yield gap**	Increasing agricultural yields to reduce agricultural expansion.
4	**Reducing post-harvest losses**	… in the food chain, thus lowering agricultural production and reducing expansion of agricultural land.
5	**Changing diets**	… to less meat consumption patterns, reducing the agricultural area for cattle feed and grazing.
Reduce overexploitation of habitats		
6	**Improving forest management**	More forestry plantations with high productivity, and more reduced-impact logging outside plantations.
7	**Reducing marine fishing efforts**	Bringing potential future marine catches to a higher, but sustainable level.
Limit climate change		
8	**Mitigating climate change**	Reducing the impact of climate change with and without bioenergy to investigate the trade-offs from growing energy crops.

also insufficient (Rogelj *et al.,* 2016). The earlier Intended Nationally Determined Contributions (INDCs) result in a median warming between 2.6°C and 3.1°C by 2100 emphasizing the importance of much stricter INDCs that aim at reducing emissions more significantly and earlier (Höhne *et al.,* 2020). In 2020, several countries already proposed stricter NDCs (e.g., EU, China, Japan and US) and if enacted these will move the world much closer to the 2°C target. However, some climate change mitigation measures (e.g., large-scale use of biomass for energy (Haga *et al.,* 2020) or carbon-sequestration plans (Richards *et al.,* 1997) could well jeopardize biodiversity. Climate change and biodiversity-decline policy scenarios can be conflictual in that the former often rely on large-scale land-based mitigation measures, involving bioenergy crops, reforestation or afforestation. Although unmitigated warming is likely detrimental for biodiversity, mitigation measures can negatively affect biodiversity, food production and water demand (IPCC, 2018b; Molnár & Berkes, 2018). This dilemma calls for a nexus approach, which reconciles multiple concurrent targets and exploits possible synergies and trade-offs (Liu *et al.,* 2018; Haga *et al.* 2020).

Lacobuta *et al.* (2021) assessed possible transitions to low-carbon economies under the 2030 SDG Agenda to minimize trade-offs between and enhance possible co-benefits of climate change action and the SDGs (Lacobuta *et al.,* 2021). They developed a framework that comprehensively scores impacts of different climate change actions on SDG targets based on directionality (i.e., trade-offs or co-benefits) and likelihood of occurrence (i.e., ubiquitous or context dependent), and categorized each action for its specific attributes (i.e., geography, governance, time horizon and natural resource limitations). They found that climate-change mitigation measures directly affect 15 out of 17 SDGs and most SDG targets, and they identified mostly co-benefits. This suggests a high potential for simultaneously tackling climate change and SDGs or other development issues. For example, improving energy efficiency, reducing energy demand and switching to renewables provide most co-benefits, but carbon capture and storage and nuclear energy create most trade-offs. The choice of location and governance approach are essential to create robust climate change and SDG interactions. All these insights help to facilitate beneficial policy designs and policy mixes by identifying relevant contexts and enhancing policy coherence across climate change, biodiversity and SDGs. Further, target-seeking scenarios can also make use of multi-scalar and participatory mechanisms, such as scenario co-design, to help bridge global to local scales (Aguiar *et al.* 2020).

Overall, science to inform policymaking needs to help actors understand how to make decisions that are both robust and adaptive to cope with any uncertainties. As recent IPCC reports have noted, there can be questions around uncertainties within scenarios (known unknowns); some uncertainties prevail around the climate system and biodiversity responses to stressors and pressures (unknown unknowns); and uncertainties exist around the scale of impacts. Given some uncertainties, it has been useful to explore storylines of low likelihood but physically plausible outcomes that are important to inform risk assessments (IPCC, 2019b). Other examples of tools for decision-making under uncertainty include iterative risk management and strategic Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot *et al.,* 2013). In DAPP, a plan is “conceptualized as a series of actions over time (pathways), … at predetermined trigger points the course can change while still achieving the objectives… The plan is monitored for signals that indicate when the next step of a pathway should be implemented or whether reassessment of the plan is needed.” (Lawrence & Haasnoot, 2017). While there is a desire for better decision-support modelling for such decisions (Ramm *et al.,* 2018), there are also clear tensions between technical models for optimization and more participatory approaches. There are also barriers for these approaches to be more widely adopted, such as data requirements, lack of examples in actual decision-making, limited applicability for surprise events, and resource constraints are likely to constrain successful application of innovative approaches in developing countries (Bhave *et al.,* 2016). These barriers should be addressed by IPBES’s Task Force on models and scenarios, who is charged to develop scenarios that link biodiversity, climate, and society.

7.5 ACHIEVING TRANSFORMATIVE CHANGE

Biodiversity loss, climate change and securing a good quality of life for all lie at the centre of the challenges for a thriving planet in the Anthropocene, and a sustainable global future for people and nature remains possible. However, it can only be achieved if economic, social and governance systems are fundamentally redesigned and reoriented (IPBES, 2019) **(Figure 7.3)**. The concept of pathways is increasingly driving future policy goal setting as a way to link short and long-term actions, and to acknowledge the problems of path-dependency in policymaking. A biodiversity and climate resilient development pathway is possible but depends on building political will (Chan *et al.,* 2020). Pathways-oriented thinking and development pays attention to normative dimensions, not just biophysical measures or planetary boundaries, and a move away from linear understanding of adaptation or development to instead be anticipatory rather than reactive (Wyborn *et al.,* 2016). Policymaking for conservation, for example, is unlikely to be able to draw solely on past conditions in defining future measures, such as location of protected areas or quantified targets. Linear understandings of development or improvement are not realistic for how

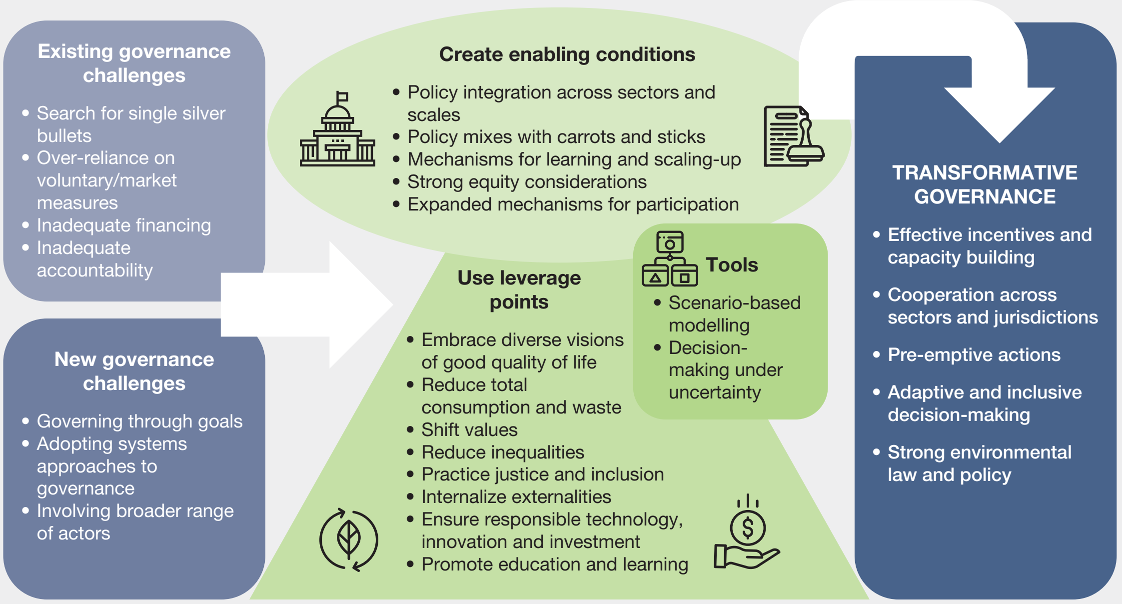

Figure ⑦ ③ **Moving governance towards transformative change.**

change happens in the real world and can also prevent 'off-ramps' or opportunities for change through 'learning by doing'.

7.5.1 Leveraging transformative change

One of the gaps identified in current efforts towards transformative change is the limited role of values, including principles, preferences, and virtues about relationships involving nature (Moisander, 2007). (Chan *et al.,* 2020) have pointed to a set of five potentially transformative policy and governance actions, which can be used to transition to new biodiversity and climate resilient pathways. These include:

Effective incentives and capacity building. The idea is to introduce policies that incentivise behaviour that achieves the SDG's, Aichi Biodiversity Targets and Paris Agreement while discontinuing harmful subsidies and disincentives. A critical component will be to remove subsidies and incentives that encourage material production with environmental impacts such as increasing greenhouse gas emissions (Chan *et al.,* 2017). This will likely require a continued evolution of positive subsidies and incentive programs, coupled with capacity building to foster conservation and stewardship practices while cultivating appropriate norms and values. Incentive programs involve both positive and negative incentives via both regulations and market-based instruments, rather than simply one or the other (IPBES, 2019).

Cooperation across sectors and jurisdictions. As noted throughout this section, removal of administrative silos and use of an integrated approach supports the mainstreaming of environmental objectives across institutions within and among all sectors (e.g., fishing, transportation, shipping, oil & gas, renewable energy). A transnational, systems-based integrated approach provides a way to embed systems perspectives across governance while incorporating the various actors that act across scales. These transnational approaches move beyond the traditional state-based approach of international law and governance as well as the limitations created by this type of regulatory regime and enable the inclusion and consideration of a range of state and non-state actors, formal and informal rules and institutions (Kotzé & Soyapi, 2016). Transnational governance approaches are therefore critical to facilitating the multi-scalar and multi-jurisdictional issues of the Anthropocene (Etty *et al.,* 2018). A significant recent example includes the European Union's Climate law which brings global supply chains into its purview and allows it to target a range of actors and sectors such as multinational corporations and governments that are failing to act on climate change. By focusing on actors, values and interests at multiple geographical and institutional levels, transnational approaches have also provided a useful lens to address issues of corruption and telecoupled issues of deforestation involving foreign corporations (Harris, 2019). Transnational efforts also identify and address unequal power relations at multiple governance scales. This includes the relative power of nation-states and the relative capacity of various actors to influence domestic governments (Schroeder, 2010). Not only is diverse representation in such processes important, but representatives should also have legitimate authority to speak for particular groups. Other options to consider include the appointment of legal custodians to speak for future generations (Dryzek & Pickering, 2019; Schlosberg, 2007) and non-human subjects (e.g., the Whanganui River).

The use of bottom-up approaches in multilateral instruments, such as the Paris Agreement, facilitates the involvement of a greater range of actors beyond nation states. The approach taken in Paris, where states are tasked with the determination of their own climate pledges, also enables greater interactions across governance scales and between international and domestic legal systems. Domestic climate litigation has, for example, provided a complimentary additional mechanism for citizens to hold national governments accountable both in relation to ambitious pledges under Paris but also in its implementation. The bottom-up architecture of Paris provides a way for non-state actors (e.g., NGOs) to take direct action in the domestic sphere (Wegener, 2020). The role of domestic courts in advancing transformative governance is also observed in the adoption of Earth jurisprudence and rights of nature in judgments across a range of jurisdictions. In contrast to the interactions between Paris and domestic climate litigation, recognition of the legal personhood of nature has emerged in the absence of a corresponding multilateral instrument. Nevertheless, cross-fertilization of rights of nature approaches have occurred across varied jurisdictions ranging from New Zealand (O'Bryan, 2017) to Ecuador (Berros, 2017) to India (O'Donnell & Talbot Jones, 2018). Similarly, to climate litigation, rights of nature has been incorporated into diverse legal systems in a multitude of ways which take into account the nature of each distinct domestic legal system.

Pre-emptive action. Pre-emptive action requires addressing phase-shifts and emerging risks in a precautionary way before proof of impact has been established. In systems that may react negatively and irreversibly once a biophysical threshold is reached; it is important to design anticipatory policy that avoids actually reaching those thresholds. Determining where thresholds will be met, however, is challenging and builds on more attention to socio-political thresholds as well as biophysical ones (Werners *et al.,* 2013), and more expansive futures thinking considers the trade-offs and consequences of 'current choices, decisions and actions' while also facilitating interrogation of the values which should be sustained into the future and whose values count (Wyborn *et al.,* 2020). In other words, this includes consideration of the political ecologies and power dynamics of determining what futures are desirable, how we might get there, and the winners and losers of the choices that are made.

Inclusive and adaptive decision-making. Keys to successful adaptive planning include processes that are able to account for divergent preferences, regular communication channels across scientists and stakeholders, and which centre active learning processes. For example, there are empirical examples of the ways societal values, existing institutional rules and scientific and other forms of knowledge (known as a V-R-K framework) come together to either facilitate or constrain adaptation planning (Gorddard *et al.,* 2016). Once constraints have been identified, interventions can be planned, such as changing values (for example through education campaigns), rules (such as changing incentives) and knowledge (identifying and filling gaps in information) (Prober *et al.,* 2017). In taking societal constraints as seriously as biophysical ones, decision makers and other stakeholders can facilitate co-evolutionary, multi-scalar change towards transformative practices (Pelling, 2011). New approaches to decision-making can help move away from standard cost-benefit analysis of decisions, given uncertainty. For example, new ways of recalibrating these decisions might instead make use of portfolio analysis, real-option analysis, or no-regrets analysis (Dittrich *et al.,* 2016). In conservation decision-making, information gap theory is used to assess how much uncertainty can be tolerated before a decision on management would change (Regan *et al.,* 2005). Policies and programs that seek optimal outcomes and are designed to be robust to uncertainty and to adaptively cultivate system resilience, including at the expense of program efficiency, may be more effective and efficient in the long term (Levin & Lubchenco, 2008). As another example, "upward-scaling tipping cascades", whereby the nonlinear nature of change is harnessed to encourage adoption of low carbon technologies, could accelerate progress in tackling climate change (Sharpe & Lenton, 2021).

Strong environmental law and implementation. Improved implementation of international and domestic environmental law is an essential prerequisite for protecting the environment and reducing biodiversity loss in the interest of the public and future generations (Wang & McBeath, 2017). At the same time, this would be supported by a redesign of current legal frameworks. Existing legal and governance frameworks are often reactive, responding to crises as they occur, yet the 2020 fires in Australia and the USA, as well as COVID-19, reveal that anticipatory approaches to law and governance are essential in the face of global change. This parallels an emerging emphasis on the importance of anticipatory governance approaches within the literature (see for e.g., Muiderman *et al.,* 2020; Quay, 2010; Serrao-Neumann *et al.,* 2013) and within calls for reform of legal frameworks. For example, the final report of the once-in-ten-year legally mandated review of Australia's primary national environmental legislation recommends the consideration of climate scenarios in the future approval of development proposals (Samuel *et al.,* 2020), and if implemented, would represent a ground-breaking futures-oriented shift in existing law.

7.5.2 Identifying plausible pathways

Different types of pathways towards transformative change have been suggested in the literature to date. For example, low emissions development strategies (LEDS) are mentioned in Section 4.19 of the Paris Agreement as a means to marry economy-wide policies for long-term development objectives with specific implementation plans to reduce GHGs. For example, suggestions have been made to match mid-century temperature goals and targets (such as carbon neutrality by 2050) with measurable goals for achieving the SDGs (which aim at a shorter time frame of 2030) (OECD, 2019). 'Backcasting' in this way can help avoid policy lock-in and encourage innovation (Waisman *et al.,* 2019). Tools to assist in these efforts include analysis of marginal cost abatement curves across sectors, partial equilibrium agricultural and land use models, or integrated assessment models (IAMs), which can be combined with indicators from SDG goals (Cox *et al.,* 2014; De Pinto *et al.,* 2016).

However, most LEDS to date have paid less attention to the land-use mitigation side or to biodiversity; similarly, exercises such as the Deep Decarbonization Pathways Project primarily focus on energy sources. Thus, in expanding their focus to land-use, LEDS could also be combined with biodiversity indicators (including risks of loss or costs of protection), although there are currently no known examples where this has been attempted. One key to success in developing LEDS strategies has been creating and using regional and international networks (such as the Climate Technology Centre and Network and the LEDS Global Partnership) and knowledge platforms (e.g., policy 'dashboards' that can be compared across countries); more engagement of the private sector is warranted (Benioff *et al.,* 2013; Waisman *et al.,* 2019). The benefits of LEDS approaches are that climate mitigation policies tend to be stronger and more accepted when linked explicitly to development benefits and existing policy priorities (Garibaldi *et al.,* 2014).

In addition to LEDS, *climate-resilient development pathways (CRDPs)* have been used as a framing device in recent IPCC reports (Denton *et al.,* 2014). According to the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018a), nearly all 1.5°C pathways include both mitigation actions and negative emission technologies such as carbon dioxide removal by afforestation. Key actions to transition to these pathways include, among others, "shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing 'green infrastructure', such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities" (IPCC, 2018a). Low-energy demand scenarios in general provide the clearest pathways without use of BECCS or other NETs that might harm biodiversity (as noted in Section 3) (Grubler *et al.,* 2018). These pathways assume an increase in annual investments in low-carbon energy technologies and energy efficiency by roughly a factor of four to ten by 2050 compared to 2015 (IPCC, 2018a).

"Adaptation pathways" is another way to envision future transitions as those which are driven by the need to adjust to climate realities. Such pathways interact with biodiversity in that they require attention to "adaptation services" that are supplied by ecosystems (which are themselves subject to transformational change) as one way to link biophysical dynamics to human development contexts (Colloff *et al.,* 2017). Adaptation services can be novel (e.g., shifts in ecosystem type leading to new availability of timber in a previous grassland) or latent (e.g., new uses for older services), which may be difficult to anticipate. However, existing adaptation funding and actions reveal challenges, particularly around 'shallow' understandings of vulnerability; (ii) inequitable stakeholder participation in both design and implementation; (iii) a retrofitting of adaptation into existing development agendas; and (iv) a lack of critical engagement with how 'adaptation success' is defined (Eriksen *et al.,* 2021). These processes can reproduce existing vulnerabilities rather than leading into new transformative pathways. Inclusion of rights-based approaches could assist here; for example, adaptation pathways that seek to be compliant with rights-based approaches would for example pay attention to the ways in which equality, transparency, accountability and empowerment are embedded in adaptation funding and program implementation (Ensor *et al.,* 2015). A rights-based framing would expose the processes of marginalisation and exclusion that lead to differentiation in adaptive capacity, but at the same time help identify concrete actions that can be taken to shape the pathway to the future.

There is also increasing attention to the idea of "just transitions" towards sustainability, given that equity and sustainability are inextricably intertwined (Leach *et al.,* 2018). Although much of the just transition literature is associated with climate, it can also be equally applicable to biodiversity, such as the potential displacements that can occur associated with expanding protected areas. Such just transitions would not only recognise existing inequities and injustices but also avoid perpetuating them while identifying means of overcoming sustainability challenges (Pickering, 2021), given that transformative change is regularly characterised overly simplistically as being universally beneficial. However, given that changing the status quo is the central objective of transformative change it inevitably results in winners and losers (Blythe *et al.,* 2018; Morrison *et al.,* 2017; Patterson *et al.,* 2017). Acknowledging that some solutions will result in inequities, and uneven winners and losers, as well as encouraging consideration of the mitigation of these impacts in the design of solutions, will be critical. It is therefore important to consider the politics and power dynamics of whose values, interests and worldviews take precedence in transformation efforts (Blythe *et al.,* 2018; Patterson *et al.,* 2017; Pickering, 2021). The inherently political nature of transformative change needs to be acknowledged if just transformations are to be achieved (Pickering, 2021).

7.5.3 Achieving resilient and transformative pathways

The implementation of resilient and transformative pathways going forward to simultaneously tackle biodiversity and climate challenges remains a key challenge facing policymakers seeking solutions for sustainability **(Figure 7.4)**. One first step is to clarify the difference in the definitions between sustainability and resilience, as the two terms often cause confusion by being used interchangeably. Sustainability is often narrowly interpreted as just increased resource efficiency (e.g., energy use), whereas resilience is usually interpreted as the ability to buffer challenges, return to the normal state and bounce back to normal following disasters. A useful new framework lays out the complementarity between sustainability, resilience and the constantly changing dynamics of complex adaptive systems (Elmqvist *et al.,* 2019; Levin, 1998) that can lead to a policy agenda for transformative change. The nature of stable states that change over time is long established (Folke *et al.,* 2010). This has led to the insight that there might be multiple possible development pathways (Bai *et al.,* 2016; Enfors, 2013; Leach *et al.,* 2010) (see flexible braided blue and green lines in **Figure 7.4**). Resilience is conceived as the capacity to strengthen, represented in **Figure 7.4** as a flexible braid surrounding a trajectory. The tightness of the braid width represents the tolerance of the system to external disturbances while staying on the same trajectory. The width can be widened by applying resilience thinking to make a system stay on a desirable trajectory and allow for transformation change or narrowed to catalyse a fundamental abrupt transformation leap to a more desirable trajectory (see leverage points in **Figure**

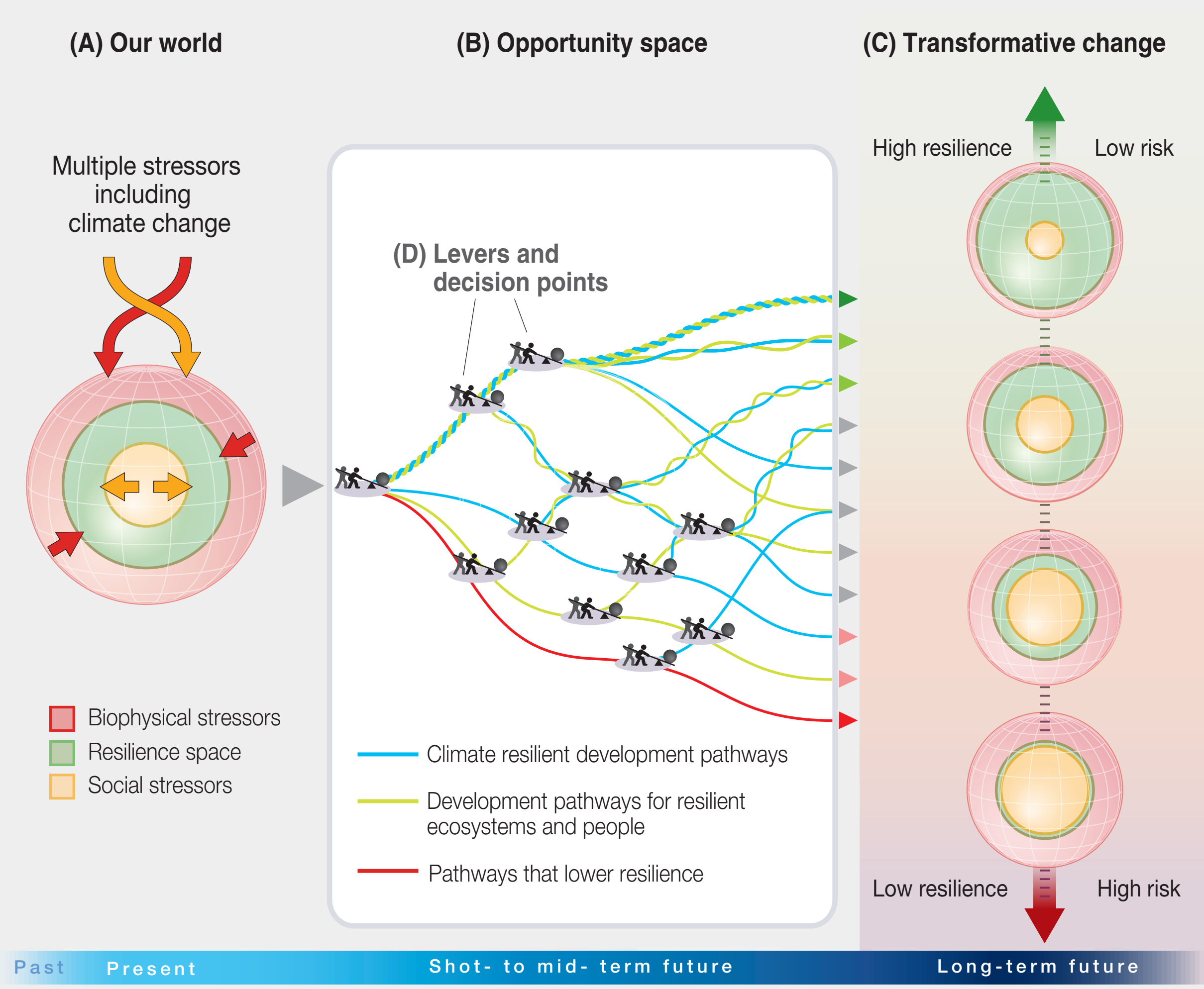

Figure 7 4 **Moving governance towards transformative change.**

7.3 and **Figure 7.4**). Directed transformation will depend on a proactive approach compared to adaptation, which is regarded as a more reactive response. The capacity to adapt and transform to advance sustainability are the core concepts of resilience thinking (Folke *et al.,* 2010; Walker *et al.,* 2004), which emphasises the need to continuously engage with problem solving and system reorganization. Advancing sustainability builds on interlinking and analyzing numerous alternative initiatives at multiple scales, rather than concentrating on optimization within narrow sectors.

Building off of discussions around climate-resilient development pathways as developed in the recent AR5 Working Group 2 report (Denton *et al.,* 2014), there is also a need to better recognize biodiversity and ecosystem resilience within these pathways, as well as the impacts of biodiversity loss on well-being. Ideally, transformative development pathways would account for both climate resilience and biodiversity resilience, as well as the need to engage in climate mitigation and in actions to mitigate biodiversity loss **(Figure 7.4)**. The idea of biodiversity-resilient pathways to ensure both resilient ecosystems and people could include within it attention to addressing biodiversity loss towards nature positive outcomes (Mace *et al.,* 2018), given the strong links between biodiversity and ecosystem resilience, as well as encompassing the use of resilient ecosystems for human adaptation and well-being (see Section 4). In other words, both people and natural systems need to become more adaptive while simultaneously reducing impacts on nature to reach sustainable development endpoints.

The increasing complexity, nonlinearity and uncertainty of scenarios for both biodiversity and climate means that science will be increasingly challenged to develop transformative solutions to the problems that societies face. The outcomes of the proposed solutions are also hard to predict because intentions often have unintended outcomes, and there are heterogeneities in, and mismatches between, the temporal, spatial and institutional distribution of the intentional actions and unintended outcomes (Bai *et al.,* 2010; Duraiappah *et al.,* 2014). Bai *et al.,* (2016) propose three concrete policy steps to deal with the challenges as the way forward that might assist in developing resilient pathways, including: (1) a different way of measuring societal progress; (2) a new modelling approach for looking into the future; and (3) a different science–practice relationship.

Typically, most decision makers use Gross Domestic Product (GDP) as the primary measure used in assessing progress in improving human well-being, based on the presumption that income and material goods are the primary link to improving well-being. Yet these assumptions have been challenged and largely shown to be erroneous (Rogers *et al.,* 2012). To expand different ways of measuring societal progress, an alternative is focusing on the productive base required to provide the material flows that lead to human well-being. Recent economics literature identifies human and natural capital as key inputs, which are also constituents of the productive base of economies (Dasgupta, 2001; Agarwala *et al.,* 2014). As a result, the tactical goal in sustainability analysis should be to track and monitor the productive base of the economy. A possible alternative is the Inclusive Wealth Index, based on a theory of sustainability on the social value of the capital assets a country owns (Dasgupta & Duraiappah, 2012). It can be estimated by multiplying the stocks of assets with the social or shadow price of the asset or the social or natural capital value of the assets. In some cases, the social prices can be represented by market prices while in other instances the actual value society places on these goods and services will have to be determined. Positive changes in the inclusive wealth of a country are equivalent to the changes in the well-being of the country at the aggregate level and can help push toward sustainability (Dasgupta *et al.,* 2021), including with the new UN System of Environmental-Economic Accounting (SEEA) (https://seea.un.org/). Other integrative measures include “Green Growth” indicators that measure progress targets across SDGs, Paris and Aichi Biodiversity Targets to assess efficient and sustainable use of resources, natural capital, green investment opportunities, and social inclusion (https://greengrowthindex.gggi.org/). New approaches in measuring wealth have also been accompanied by increasing attention to the problematics of endless economic growth on both biodiversity and climate, leading to a growing literature examining ways to include alternative trajectories within scenarios (Otero *et al.,* 2020).

In regard to finding a new way to look at scenarios of the future, one approach suggested is to make scenarios the starting point rather than the end of the argument. The key question is how to change human behaviour to mitigate climate change and reduce biodiversity loss? Rather than present deviations from an existing trajectory in exploratory scenarios, scientific research can stimulate a better understanding of potential futures and its implications, including possible unintended consequences. This approach would open up the question of the relationship between feedback and feed-forward (anticipation), which is fundamental to human behaviour (we all live between past and future), but is not usually included how we model or construct scenarios (Montanari *et al.,* 2013; Sivapalan *et al.,* 2014). In light of achieving more desirable futures, fundamental questions to be asked are: “How did the structure come about, and how might it change?”, “What are the regulatory mechanisms involved?”, “What happens when an existing structure becomes more and more complex?”, “Does it become more efficient and/or resilient?”, “What does that mean for its adaptability, its capacity to change?”. A promising, emerging field of study is therefore the attempt to bring evolutionary thinking and complex systems approaches together with behavioural and other kinds of economics. A broader use of scenarios in public deliberations and collective decision-making would involve the option to explore the multiple relations with the situated knowledge of multiple stakeholders.

The final pragmatic issue is how to initiate a new science-practice relationship to bring about purposeful interventions to initiate and accelerate transition towards a desirable future. The traditional linear model of knowledge production, where knowledge is normally produced by academia and then applied in society to address major societal challenges for the future, has shown major limitations (Future Earth, 2013). This model cannot often assist in quick decision making leading to action, even when scientific knowledge and information is sufficient to take action. The issue is made even more difficult based on the range of different political and cultural contexts around the world. The suggested way forward is for science and academia to focus on interdisciplinary and trans-disciplinary solution-oriented research questions closely linked to major societal challenges, with linkages to multiple stakeholders, or in other words, 'find problems worth solving' (Lubchenco, 1998). This approach would advance the ability to understand the psychology of society at different levels.

7.6 CONCLUSION

The biodiversity and climate crises risk jeopardizing the achievement of UN SDGs as well as putting more equitable human well-being and development increasingly out of reach. The negative prospects of insufficient efforts to put the world on track to achieve both climate and biodiversity goals are cast in a wave of pessimism, particularly among young people whose future is jeopardized. The current COVID-19 pandemic not only exacerbates and challenges current (insufficient) actions, but it also highlights the urgency of rethinking climate change and biodiversity strategies into the future. The narrative of intersecting and increasing risks is important but also can be counterbalanced by an emphasis on the deployment of solutions that build an alternative future road map, one that inspires hope that a sustainable future is possible.

As shown in this section, there are potential solutions that provide co-benefits for climate and biodiversity, as well as potential impacts and trade-offs. Biodiversity and climate change are both wicked problems with high uncertainty, contested values, and unclear policy pathways, yet high urgency to act. Recognizing the interactions between goals for climate, biodiversity, and good quality of life for all can help identify solutions that deliver the highest co-benefits for both climate and biodiversity, including NbS, as well as increased awareness on risks of trade-offs that will need to be managed. To avoid maladaptive responses, decisions following an iterative and flexible procedure that accounts for the complexity and uneven power dynamics among actors and scales are likely to be more successful. This argues in favour of approaches to biodiversity loss and climate adaptation that put a strong emphasis on risk management and the capacity to evolve over time, as opposed to implementing strategies that focus continually on managing for a specific future scenario and that lacks flexibility once implemented.

Achieving a sustainable future builds on a vision to be co-created, allowing for multiple actors to design a diversity of flexible and iterative goals and targets. Mainstreaming of biodiversity into climate and vice versa has been promoted as one way to achieve climate and biodiversity integration for multiple goals. However, there are no single silver bullet solutions, and several key problems wait to be tackled, such as over-reliance on voluntary or economistic measures, inadequate financing, difficulties in contextualizing quantitative targets, and inadequate accountability mechanisms. Mechanisms that can contribute to success in meeting goals or achieving effective policy solutions include polycentric governance, attention to equity and modes of participation, integrated and adaptive management, reflexive evaluation and learning, and adequate financing. With the expansion of involving non-state actors in governance, opportunities and challenges surrounding legitimacy, justice, and effectiveness can increase awareness of alternative visions and values of nature. Participatory space broadened beyond states includes local and regional government, communities, indigenous groups, the private sector and other non-governmental organizations. This calls for deepened partnerships and knowledge co-production, indicators for monitoring of impacts, mechanisms for efficacy, advances in technologies, and novel financing models.

This section has pointed out that using leverage points in current governance and socio-ecological systems can help to promote the shifts towards transformative governance, which entails embracing alternative visions of good quality of life for all, rethinking consumption and waste, shifting values, recognizing different knowledge systems, reducing inequality, and promoting education and learning. To achieve the long-term goals of meeting SDGs, Paris Agreement targets, and the post-2020 biodiversity agenda and to put society on the pathway to transformative change will depend on appropriate attention to and planning of climate and biodiversity resilient pathways that allow for different ways of measuring societal progress; on better tools for multi-sectoral scenario planning and modelling that acknowledge different visions of a good life and possible futures for nature and climate; and on a remade science–practice relationship. All of these approaches will help to enact transformative change for sustainable and resilient futures for nature and people.

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APPENDIX 1
List of peer reviewers

This appendix sets out a list of external scientists selected by the co-sponsored workshop scientific steering committee who reviewed both the Workshop Report and the Scientific Outcome.

Lilibeth Acosta-Michlik
Global Green Growth Institute

Ana Paula de Aguiar
Stockholm Resilience Centre

Sally Archibald
University of Witwatersrand

Pam Berry
University of Oxford

Betsy Beymer-Farris
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Kirsten Davies
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UK Centre of Ecology
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Mahendra Kumar
Independent Consultant/ Australian National
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Hsing-Juh Lin
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Brendan Mackey
Griffith University

Bernabé Moreno
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Mark Rounsevell
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David Schoeman
University of the Sunshine Coast

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Stellenbosch University

Polina Shulbaeva
Center for support of indigenous peoples
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Boris Worm
Dalhousie University

Ming Xu
Rutgers University

APPENDIX 2

Glossary

This report uses existing definitions from IPBES, IPCC, IUCN or UNEP and specifies which definition was used, except for a few words marked with an asterisk where a definition is used for the purposes of this workshop report only. IPCC AR6 considered the glossaries of the three Special Reports (IPCC 2018b, 2019a, 2019b) were considered.

A

Adaptation

The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities in order to moderate harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2014).

Acclimatization

A change in functional or morphological traits occurring once or repeatedly (e.g., seasonally) during the lifetime of an individual organism in its natural environment. Through acclimatization the individual maintains performance across a range of environmental conditions. For a clear differentiation between findings in laboratory and field studies, the term acclimation is used in ecophysiology for the respective phenomena when observed in well-defined experimental settings. The term (adaptive) plasticity characterises the generally limited scope of changes in phenotype that an individual can reach through the process of acclimatization (IPCC, 2020).

B

Biodiversity

The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part. This includes variation in genetic, phenotypic, phylogenetic, and functional attributes, as well as changes in abundance and distribution over time and space within and among species, biological communities and ecosystems (https://www.ipbes.net/glossary/biodiversity).

Biodiversity in the wider sense, is increasingly used in policy circles as well as in public communication, to refer to living nature, independent of variability. See Nature.

C

Carbon dioxide equivalent (CO_2e)

A way to place emissions of various radiative forcing agents on a common footing by accounting for their effect on climate. It describes, for a given mixture and amount of greenhouse gases, the amount of CO_2 that would have the same global warming ability, when measured over a specified time period. For the purpose of this report, greenhouse gas emissions (unless otherwise specified) are the sum of the basket of greenhouse gases listed in Annex A to the Kyoto Protocol, expressed as CO_2e assuming a 100-year global warming potential (United Nations Environment Programme, 2021).

Climate

Climate is the average weather, or more rigorously, its statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. In the ocean, climate change is manifested as altered hydrologic conditions including temperature, oxygen, sea level, the carbonate system, and related changes in productivity, mixing and circulation (IPCC, 2018a; Pörtner *et al.*, 2014).

Climate change

A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes (IPCC, 2020).

Climatic driver

A changing aspect of the climate system that influences a component of a human or natural system (IPCC, 2014).

D

Direct drivers (of biodiversity)

Direct drivers are those natural and anthropogenic factors that affect biodiversity directly. Anthropogenic direct drivers can be conceptualized as the set of activities performed by humans that result in biodiversity loss (e.g., land clearance, intensification of agriculture, overexploitation of living resources, introduction of invasive species, pollution, climate change) while natural direct drivers are not the result of human activity and are beyond human control (e.g., earthquakes, volcanic eruptions) (IPBES, 2018).

E

Ecosystem services
The benefits people obtain from nature (MEA, 2003; Diaz *et al.*, 2005).
This is the original IPBES definition, inherited from the Millennium Ecosystem Assessment and the literature which preceded it, and is the one most widely used in the research and policy community and the technical literature. IPCC defines ecosystem services as "ecological processes or functions which have value to individuals or society", which is consistent with, and slightly more precise than, the IPBES definition, but is less widely used in the community. Within IPBES, the term "ecosystem services" and its subtypes have since 2018 been superseded by the terminology associated with the conceptual framework referred to as "nature's contributions to people" (see Natures Contributions to People for explanation of the logic of the change). This includes most – but not all –of the specific components previously under ecosystem services. What were formerly known as supporting services are excluded, largely to avoid double-accounting.

Evolutionary adaptation
The process whereby a species or population becomes better able to live in a changing environment, through the selection of heritable traits. Biologists usually distinguish evolutionary adaptation from acclimatisation, with the latter occurring within an organism's lifetime (IPCC, 2020).

G

***Good quality of life**
The achievement of a fulfilled human life. IPCC does not define this term. The full IPBES definition is "the achievement of a fulfilled human life, a notion which varies strongly across different societies and groups within societies. It is thus a context-dependent state of individuals and human groups, comprising aspects such as access to food, water, energy and livelihood security, and also health, good social relationships and equity, security, cultural identity, and freedom of choice and action". "Living in harmony with nature", "living-well in balance and harmony with Mother Earth" and "human well-being" are examples of different perspectives on a "Good quality of life". It is a phrase intended to be inclusive and deliberately not associated with a particular value, culture or epistemology.

H

Human well-being
A state of existence that fulfils various human needs, including material living conditions and quality of life, as well as the ability to pursue one's goals, to thrive, and feel satisfied with one's life (IPCC, 2020). The IPBES definition is consistent with this definition but notes that well-being also includes non-material living conditions and cultural identity. The phrase 'Good quality of Life' as used in this report (see glossary entry) is intended to be inclusive of both the human well-being definitions given above.

I

Indirect drivers (of biodiversity)
Indirect drivers are the forces that underlie and shape the extent, severity and combination of anthropogenic direct drivers that operate in a given place. They include key institutional and governance structures in addition to social, economic and cultural contexts. They are the underlying causes of biodiversity loss and can be external to the system in question. Indirect drivers operate almost always in concert and across multiple scales and varying levels of proximity from the location in question, from the global (markets, commodity prices, consumption patterns), to the national and regional (demographic change, migration, domestic markets, national policies, governance, cultural and technological change) to the local (poverty, economic opportunities) (IPBES, 2018).

M

Mitigation (of climate change)
A human intervention to reduce emissions or enhance the sinks of greenhouse gases (IPCC, 2014).

Multifunctional 'scape
where 'scape is shorthand for 'land-, freshwater- and sea-scape', is a contiguous area defined by major geomorphological (e.g., major watersheds, geological systems and major biomes) and/or oceanographic processes (major current regimes, biogeochemical processes). Scale may vary with the application. A 'scape may include a mosaic of habitats across all conditions of nature from intact in 'wild spaces', through modified and altered in 'shared spaces' where humans have a significant impact on the biota and may alter function considerably, to 'anthromes' or fully transformed agricultural and urban areas where the coverage of natural habitats is very low or even zero. (IPBES, 2019; Locke *et al.*, 2019; Ellis et al., 2010).

N

***Nature**
The living parts of the biosphere, including their diversity and abundance and functional interactions with one another and with the abiotic parts of the earth system. Increasingly, nature is modified by human influences. Many features of nature have been co-produced by humans.
This is a definition specifically made for the IPBES-IPCC workshop report, since neither IPBES nor IPCC has an existing definition. The closest is the IPBES Global Assessment Chapter 1 box 1.2 definition of Nature: " Nature: the nonhuman world, including co-produced features, with particular emphasis on living organisms, their diversity, their interactions among themselves and with their abiotic environment." [It goes on with a long elaboration in many epistemologies, cultures and languages]. In the IPBES-IPCC Workshop Report, 'Nature' is shorthand for everything that is within one of the three linked subsystems (climate, nature and human) considered.

Nature-based solutions
Nature-based solutions are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN, 2016).

Nature's contributions to people
All the contributions, both positive and negative, of living nature (i.e. diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life of people. This is the core IPBES definition (which is used by IPCC in AR6 Special Reports). The IPBES definition goes on to elaborate as follows: "Beneficial contributions from nature include such things as

food provision, water purification, flood control, and artistic inspiration, whereas detrimental contributions include disease transmission and predation that damages people or their assets. Many NCP may be perceived as benefits or detriments depending on the cultural, temporal or spatial context.” The creation of a new term to supersede ecosystem services had several justifications. First, the original ecosystem services definition went on to define four subtypes (provisioning, cultural, regulatory and supporting), but practitioners recognised that many services fit into more than one of the four categories. Secondly, IPBES wished to make explicit that positive and negative effects were included. Thirdly, the term ‘services’ had its origin in economics, which was perceived in some worldviews to be too narrow a formulation of the relationships between nature and people. The new language is considered more inclusive.

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Telecoupling
Telecoupling refers to the phenomenon that natural or anthropogenic processes in one part of the globe have an effect on a distant part of the world (Friis et al., 2016).
This concept thus enables the description of flows and impacts between globally distant places in a common language. Synonym in the literature is global inter-regional connectedness.

Teleconnections
A statistical association between climate variables at widely separated, geographically-fixed spatial locations. Teleconnections are caused by large spatial structures such as basin-wide coupled modes of ocean-atmosphere variability, Rossby wave-trains, mid-latitude jets and storm tracks, etc. (IPCC, 2020)

Transformative change
A system wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale (IPCC, 2020).

Tipping point
A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated (IPCC, 2019c).

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APPENDIX 3
List of acronyms

AFOLU	Agriculture, Forestry and Other Land Use
AMAP	Arctic Monitoring and Assessment Programme
AR4/5/6	Fourth/Fifth/Sixth Assessment Report
BCS	Biodiversity-Climate-Social
BECCS	bioenergy with carbon capture and storage
BVOC	biogenic volatile organic carbon
CBD	Convention on Biological Diversity
CDR	Carbon Dioxide Removal
CITES	Convention on International Trade of Endangered Species of Wild Flora and Fauna
CRDP	climate-resilient development pathway
CTI	The Coral Triangle Initiative
COP	Conference of the Parties
COVID	Coronavirus disease
CVT	Climate velocity trajectory/ies
DAPP	Dynamic Adaptive Policy Pathways
DGVM	Dynamic Global Vegetation Models
DVM	diurnal vertical migration
EEZ	exclusive economic zone
FAO	Food and Agriculture Organization of the United Nations
FLA	Functional Landscape Approach
GCF	Green Climate Fund
GDP	Gross Domestic Product
GHG	greenhouse gas
GIS	geographic information system
GMT	global mean temperatures
GQL	good quality of life
ICCA	Indigenous Peoples’ and Community Conserved Areas and Territories
IFAD	International Fund for Agricultural Development
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPLC	Indigenous Peoples and Local Communities
IUCN	International Union for Conservation of Nature
IUU	illegal, unregulated and unreported
KBA	Key Biodiversity Area
LEDS	low emissions development strategies
MPA	Marine Protected Area
NAPAs	National Adaptation Programmes of Action
NbS	Nature-based solutions
NBSAP	National Biodiversity Strategies and Action Plan
NCP	nature’s contributions to people
NDC	Nationally Determined Contributions
NGO	Non-governmental organization
NNL	No Net Loss
OECD	Organisation for Economic Co-operation and Development
OECM	Other effective area-based conservation measures
RCP	Representative Concentration Pathways
REDD	Reducing Emissions from Deforestation in Developing countries
REDD+	Reducing Emissions from Deforestation and forest Degradation
SDG	Sustainable Development Goals
SEEA	System of Environmental Economic Accounting
SRCCL	Special Report on Climate Change and Land
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate
SSP	Shared Socioeconomic Pathways
TEEB	The Economics of Ecosystems and Biodiversity
UNCCD	United Nations Convention to Combat Desertification
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WCMC	World Conservation Monitoring Centre
WCPA	World Commission on Protected Areas
WfW	Working for Water programme