Actions to halt biodiversity loss generally benefit the climate

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Abstract

The two most urgent and interlinked environmental challenges humanity faces are climate change and biodiversity loss. We are entering a pivotal decade for both the international biodiversity and climate change agendas with the sharpening of ambitious strategies and targets by the Convention on Biological Diversity and the United Nations Framework Convention on Climate Change. Within their respective Conventions, the biodiversity and climate interlinked challenges have largely been addressed separately. There is evidence that conservation actions that halt, slow or reverse biodiversity loss can simultaneously slow anthropogenic mediated climate change significantly. This review highlights conservation actions which have the largest potential for mitigation of climate change. We note that conservation actions have mainly synergistic benefits and few antagonistic trade-offs with climate change mitigation. Specifically, we identify direct co-benefits in 14 out of the 21 action targets of the draft post-2020 global biodiversity framework of the Convention on Biological Diversity, notwithstanding the many indirect links that can also support both biodiversity conservation and climate change mitigation. These relationships are context and scale-dependent; therefore, we showcase examples of local biodiversity conservation actions that can be incentivized, guided and prioritized by global objectives and targets. The close interlinkages between biodiversity, climate change mitigation, other nature’s contributions to people and good quality of life are seldom as integrated as they should be in management and policy. This review aims to re-emphasize the vital relationships between biodiversity conservation actions and climate change mitigation in a timely manner, in support to major Conferences of Parties that are about to negotiate strategic frameworks and international goals for the decades to come.

Keywords: biodiversity conservation, climate change mitigation, Convention on Biological Diversity, restoration, nature-based solutions, carbon sequestration

1. Introduction

Increasing lines of evidence show the important contribution of nature to climate change mitigation. More than 30% of anthropogenic CO_2 emissions are estimated to be re-absorbed annually into the land surface (12.5 +- 3.3 $GtCO_2e$ y^{-1} (2010-2019), Friedlingstein et al. 2020) through forest regrowth, enhanced photosynthetic CO_2 uptake and sequestration (Pugh et al. 2019; Ahlström et al. 2015; Schimel et al. 2015). A further ca. 25% of anthropogenic CO_2 emissions is estimated to be absorbed by the ocean (9.2 +- 2.2 $GtCO_2e$ y^{-1} (2010-2019), Friedlingstein et al. 2020; IPCC 2019), due to both CO_2 dissolution 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 sediments. Uncertainties in these estimates are large, and reflect multiple challenges such as uncertain hindcasts of land-use change, diverging process representations in models that contribute to these estimates, different sensitivities of these models to inter-annual variation in weather and climate. The overall presence of a large natural sink is well constrained, however, by the measured increase of atmospheric CO_2 concentrations and the relatively well quantified fossil fuel and industrial emissions. These powerful land and ocean sinks are currently by far the leading natural climate mitigation processes globally. Their carbon sequestration potential can be protected, and even enhanced, through ecosystem management on land and in the oceans. In the UNFCCC (United Nations Framework Convention on Climate Change) and CBD (Convention on Biological Diversity), the concept of nature-based solutions has been proposed as a way to harness natural processes to help solve the climate challenge and reduce the loss of biodiversity, while providing other co-benefits for nature's contributions to people.

Implementing nature-based solutions therefore takes advantage of the strong connections between the climate system, the oceans, the land, and nature within these realms. Crucially, this needs to be managed without compromising the many nature's contributions to people (NCP) (Girardin et al. 2021). In this paper, we provide evidence of the potential effects of biodiversity conservation on the climate system including the greater storage of CO_2 emissions by land and marine ecosystems, lowering greenhouse gas (GHG) emissions, for example, by altered wildfire management and land use practices, and changing the reflection of solar energy from the land surface (albedo change). The central question we adress is the extent to which actions taken to halt or reverse biodiversity loss have consequences for these climate change mitigation processes, and how, when and where the form and strength of such links vary.

The last decade has seen increased concerns about biodiversity loss, with multiple lines of evidence that nature and its contributions to people are declining globally at unprecedented rates (Diaz et al. 2019; IPBES 2019; WWF 2020). National level responses have not been at the level of required actions, partially achieving only a handful of the Aichi Biodiversity Targets of the CBD Strategic Plan for Biodiversity 2011–2020 (Butchart et al. 2019; Secretariat of the Convention on Biological Diversity 2020). Thus, there are high expectations for the upcoming CBD fifteenth Conference of the Parties (CBD COP 15) which will be held in 2022 in Kunming (China) to finalize a new set of well-defined goals and targets that would incentivize strong and ambitious actions to reverse the loss of biodiversity. In the first draft of the post-2020 global biodiversity framework of the CBD released in July 2021 (CBD 2021), there is a dedicated target on mitigation and adaptation to climate change – "*Target 8: Minimize the impact of climate change on biodiversity, contribute to mitigation and adaptation through ecosystem-based approaches, contributing at least 10 Gt*CO_2*e per year to global mitigation efforts, and ensure that all mitigation and adaptation efforts avoid negative impacts on biodiversity".* The UNFCCC Paris Agreement, under Decision 1/CP.21, made a singular reference to biodiversity where Parties noted in the preamble "*the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity, recognized by some cultures as Mother Earth, and noting the importance for some of the concept of "climate justice", when taking action to address climate change*". Although we see a step forward in the recognition that biodiversity and climate change are interconnected by decision- and policy-makers in these two separate Conventions, the two issues are still largely addressed separately and in an unbalanced manner.

Based on the work conducted for section 5 of the scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change (Pörtner et al. 2021), we review recent scientific evidence relevant to assessing potential synergy between slowing and halting biodiversity loss and avoiding dangerous climate change. To what extent are these most urgent and important challenges facing humanity today interlinked by mechanistic links and feedbacks? Here, we focus on links between biodiversity conservation actions and climate change mitigation. Such actions and interventions are context and scale-dependent; therefore, we showcase examples of local biodiversity conservation actions that can be incentivized, guided and prioritized by global objectives and targets given all actions matter.

2. Post-2020 biodiversity goals have strong potential co-benefits for climate change mitigation

Many policy measures designed to address biodiversity loss and degradation of NCP have potential co-benefits with climate change mitigation (Girardin et al. 2021; Pörtner et al. 2021). The level of such co-benefits largely depends on which processes and nature components are targeted by management actions. 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., protected from microbial activity in soils and sediments for periods of centuries to millennia) (Bax et al. 2021; Siegel et al. 2021), understanding differences between carbon sinks and feedbacks also greatly aids understanding of climate and biodiversity interactions. Albedo feedbacks (and other feedbacks arising from biophysical processes at the land surface) on climate may be an important component of climate change, but they are currently ignored by UNFCCC guidelines in accounting for the climate benefits of actions taken in support of climate change mitigation (Duveiller et al. 2020; Perugini et al. 2017; Jia et al. 2019).

Carbon sinks result from net carbon capture and storage and can be mediated by physicochemical (e.g., direct oceanic uptake of CO_2 via the solubility pump, which leads to ocean acidification) or biological processes (photosynthesis and subsequent storage of the assimilated carbon). Sinks can be either local (the carbon is captured and stored in e.g., forests or peatlands) or act by exporting the carbon in remote sites (e.g., kelp forests exporting to deep seas, or the marine vertical biological pump). Many natural carbon sinks and the capacity of processes driving those sinks are reduced by climate change, thereby exacerbating climate change further (positive feedback; Arneth et al. 2010). In contrast, some carbon sinks, such as polar continental shelves and boreal forests (taiga) increase with climate change, so they strengthen mitigation (negative feedback; Zhu et al. 2016; Piao et al. 2006). Biodiversity conservation measures and nature-based climate solutions can be powerful in regulating climate when they concern natural carbon sinks that are large and have negative feedbacks on climate change.

The first draft of the post-2020 Global Biodiversity Framework provides 21 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 1), even though they were not primarily designed with this goal. Here, we highlight a subset of biodiversity measures that are shown to have impacts on the climate system, based on potential contributions to carbon capture, storage, and sequestration, the albedo effect, and non-CO_2 GHG fluxes.

***Table 1**: Action targets for 2030, from the first draft of the post-2020 global biodiversity framework of the CBD (please refer to CBD (2021) 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 Table S1 and main text). Target 8 is not colour coded as it is the outcome of all other targets, as documented in the table. (T: Target).*

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)
- High
- Medium
- Unresolved, insufficient evidence
- Low

Post-2020 Action targets for 2030	Biodiversity measures (and corresponding section in the main text)		Contribution to climate change mitigation	Reliability of mitigation outcome
Reducing threats to biodiversity				
T1. Biodiversity-inclusive spatial planning addressing land/sea use change, retaining intact and wilderness areas	2.1	Avoiding deforestation	Significantly positive	Medium
	2.1	Avoiding degradation of permafrost areas	Potentially positive	Medium
T2. Restoration of at least 20% of degraded ecosystems, ensured connectivity and focus on priority areas	2.1	Reforestation, avoided degradation of forests	Significantly positive	Medium
	2.1	Coastal restoration	Significantly positive	Medium
	2.1	Restoring degraded semi-arid ecosystems	Potentially positive	Unresolved
	2.1	Restoring inland wetlands	Unresolved	Unresolved
	2.1	Biodiversity offsets	Unresolved	Medium
T3. Well connected and effective system of protected areas, at least 30% of the planet	2.2	Expanding networks of protected areas and corridors	Significantly positive	High
T4. Recovery and conservation of species of fauna and flora	2.3	Rewilding with large terrestrial mammals	Unresolved	Unresolved
	2.3	Rebuilding marine megafauna	Potentially positive	Medium
T5. Sustainable, legal and safe harvesting, trade and use of wild species	2.4	Sustainable fishing	Potentially positive	Medium
T6. Prevention and reduced rate of introductions, control or eradication of invasive alien species			Loose or non-existent link	Loose or non-existent link
T7. Reduced pollution from all sources, including excess nutrients, pesticides, plastic waste	2.5	Reducing pollution from excess nutrients	Potentially positive	Medium
T8. Impacts of climate change on biodiversity minimized, contributions to climate change mitigation, adaptation				

Post-2020 Action targets for 2030	Biodiversity measures (and corresponding section in the main text)		Contribution to climate change mitigation	Reliability of mitigation outcome
Meeting people's needs through sustainable use and benefit-sharing				
T9. Ensured benefits, incl. food security, medicines, and livelihoods, through sustainable management of wild species	2.4	Sustainable harvesting of wild species		
T10. All areas under agriculture, aquaculture and forestry are managed sustainably, through biodiversity conservation and sustainable use, and increased productivity and resilience	2.6	Biodiversity-friendly agricultural systems		
	2.6	Intensive vs less intensive agriculture		
	2.6	Combatting woody plant encroachment		
T11. Contribution to regulation of air quality, hazards and extreme events and quality and quantity of water	2			
T12. Increased area of, access to, and benefits from green/blue spaces for health and well-being in urban areas	2.7	Increasing benefits from biodiversity and green/blue spaces in urban areas		
T13. Ensured access to and the fair and equitable sharing of benefits from genetic resources and traditional knowledge				
Tools and solutions for implementation and mainstreaming				
T14. Biodiversity values integrated into policies, regulations, planning, development, poverty reduction, accounts and assessments at all levels and across all sectors	2.8	Mainstreaming biodiversity		
T15. Dependencies and impacts on biodiversity assessed in all businesses, negative impacts halved, for sustainable extraction and production, sourcing and supply chains, use and disposal	2.4	Sustainable food production and supply chains		
T16. People are informed and enabled to make responsible choices, to halve the waste and reduce overconsumption of food and other materials where relevant	2.9	Sustainable consumption patterns		
T17. Preventing, managing or controlling potential adverse impacts of biotechnology on biodiversity and human health				
T18. Redirect, repurpose, reform or eliminate incentives harmful for biodiversity in a just and equitable way	2.10	Eliminating incentives harmful for biodiversity		
T19. Increasing financial resources from all sources and flows to developing countries, and ensuring capacity-building, technology transfer and scientific cooperation				
T20. Relevant knowledge, incl. traditional, indigenous and local knowledge, guides the management of biodiversity by promoting awareness, education and research				
T21. Equitable and effective participation in decision-making by indigenous peoples and local communities, respecting their rights over lands, territories and resources				

2.1 Restoring degraded natural areas and retaining existing intact wilderness areas (Targets 1 and 2)

Restoring degraded natural areas is a flagship target of the post-2020 global biodiversity framework of the CBD and put in the spotlight by the UN Decade on Ecosystem Restoration (2021-2030). Restoration is particularly critical where natural systems are so damaged that spontaneous recovery is unlikely or too slow compared to their degradation rate. Initially designed for protecting nature and its contributions to people, restoration programs provide opportunities for climate change mitigation, if selected ecosystems are both rich in species and potentially large carbon sinks.

Reforestation, avoided deforestation and degradation of forests

Large-scale degradation of tropical and subtropical forests and woodlands is mainly driven by agricultural expansion and biofuel production and adversely affects both biodiversity and carbon stocks (Laurance et al. 2014; Curtis et al. 2018; IPBES 2019; FAO 2020; Mackey et al. 2020). Tropical deforestation contributed to almost one fifth of global anthropogenic GHG emissions during the 1990s (~5.5 $GtCO_2e$ y^{-1}; Gullison et al. 2007). Recent remote sensing studies highlight that the increasing area over which tropical forest is being degraded may already match or exceed the area of tropical deforestation (Bullock et al. 2020; Matricardi et al. 2020). Above-ground carbon losses due to degradation could increase estimates of gross deforestation losses by between 25% and more than 600% (Baccini et al. 2017; Maxwell et al. 2019; Pearson et al. 2017). Additional losses from tropical forest soils are unknown. Dryland forest and savanna have been deforested and degraded for many decades, in South America (e.g., Chaco and Cerrado systems; Mustin et al. 2017), Australia (e.g., Eucalypt woodlands; Queensland Department of Science, Information Technology and Innovation 2017), and Asia (Tölle et al. 2017), with African woodlands having some of the highest deforestation rates in the world (e.g., 2500 - 3000 km^2 y^{-1} in Zambia; Vinya et al. 2011).

The adoption of the REDD+ mechanism (reducing emissions from deforestation and forest degradation in developing countries) by the UNFCCC in 2007, has provided a significant opportunity to align national climate change mitigation and biodiversity goals and has strengthened international efforts to slow and ultimately avoid deforestation (Johnson et al. 2019). Recent evidence shows that REDD+ projects have been effective in some regions, for example, leading to the avoidance of 1.5 (+/-0.4) $GtCO_2e$ emissions from tropical forest in Brazil alone, between 2006 and 2017 (West et al. 2019) but efforts are not always sustained over the long term and a range of barriers exists in some other tropical regions such as in Indonesia (Ekawati et al. 2019) and in Africa (Gizachew et al. 2017).

Reforestation or restoration of degraded forests and woodlands with indigenous species plays a role in addressing losses of biodiversity and NCP, including through recovering the soil carbon stocks of these ecosystems (e.g., Sileshi 2016, Edwards et al. 2021), and by targeting spatial spots that allow to re-establish forest habitat continuity with additional positive impacts (e.g. Atlantic Forest; Newmark et al. 2017; Strassburg et al. 2018). It has been estimated that reforesting up to 3.7 million km^2 of degraded tropical forest (less than half the potentially reforestable area) could support a carbon uptake rate of 5.5 $GtCO_2e$ yr^{-1} by 2030, while contributing to conservation of forest-dependent vertebrate species (Kemppinen et al. 2020). Reforestation using monoculture plantations of non-indigenous species (e.g., Lewis et al. 2019), as well as some large scale sylviculture programs (e.g., Brazil; Mustin et al. 2017;

Ethiopia; Pistorius et al. 2017) pose significant risks for nature and its contributions to people (Reisman-Berman et al. 2019) but these practices are currently being incentivized financially.

Coastal restoration

Coastal habitats and ecosystems (e.g., mangroves, seagrass, salt marshes, coral reefs) are highly productive areas, harboring large amounts of biological diversity, and providing valuable ecosystem services (e.g., water quality, carbon sequestration, food, livelihoods, cultural services, and coastal protection; Mcleod et al. 2011). Coastal ecosystems are exposed to increase in temperature, acidification, sea level rise, salinification, and exposure to intensified storms (IPCC 2014; Hoegh-Guldberg et al. 2018). Urbanisation and coastal hardening further exert a strong pressure with increasing clustering of cities and other forms of development along the coasts (Barragán & de Andrés 2015; Liu et al. 2018; Loke et al. 2019). All of these pressures have considerably shrunk the extent of many coastal ecosystems such as mangroves (Babcock et al. 2019), coral reefs (Oppenheimer et al. 2019) or seagrass (Waycott et al. 2009). Critically, the destruction and the degradation of these habitats result in reduced 'blue carbon' stocks by slowing biomass accumulation and exposing soils to increased oxidation of organic deposits (Mcleod et al. 2011). Compared to terrestrial forests, the global carbon sequestration is much lower in coastal systems due to their smaller extent, but the amount of carbon sequestration per unit of coastal vegetated area is typically much higher (Donato et al. 2011).

The success and costs of restoration options has varied between coastal ecosystems. Bayraktarov et al. (2016) reviewed restoration costs across a range of coastal ecosystems and found that coral reefs and seagrass beds were among the most expensive ecosystems to meaningfully restore, whilst mangrove restoration projects were the least expensive per unit area. It has also been shown that mangrove forests are capable of storing and sequestering a substantial proportion of carbon in both their biomass and soil substrates (Sanderman et al. 2018) even when fringing dense urban development areas (e.g., in Singapore; Friess et al. 2015).

Avoiding degradation of permafrost areas

The perennially frozen ground, known as permafrost, stores large amounts of organic carbon. The permafrost found in the Arctic and high mountains regions contains twice as much carbon as the atmosphere and about four times as much as all the carbon emitted by human activity from 1960 to 2019 (Canadell et al. 2021; Friedlingstein et al. 2020; Schädel et al. 2014). Permafrost wetlands degrade due to climate warming and commercial minerals extraction (CAFF 2021; Opekunova et al. 2018; Peterson 2001). Because of global warming, permafrost thaw, more frequent wildfires, and shifts in hydrological flows in the permafrost region are anticipated (Mishra et al. 2021; Canadell et al. 2021). The upshot is the release of the carbon stored in the soil, biogenic CO_2 and CH_4 emissions, and water quality reduction (Bruhwiler et al. 2021). These alterations impact biodiversity negatively because of soil moisture change and habitat loss, and increase the risk of extinction of wetland endemic and dependent species (Shin et al. 2019). Better management of permafrost wetlands, stopping destructive activities (drainage or excavation), preserving undamaged peatlands, rewetting artificially drained areas and restoring degraded areas will help maintaining their biodiversity and keeping carbon locked in the ground (Anisha et al. 2020; Avagyan et al. 2017). Such management actions have been successfully implemented by the plan on 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). In northern high-latitude ecosystems, introducing large herbivores compacts snow and decreases its depth due to winter grazing and animal movements. This substantially reduces the thermal insulation efficiency of snow during wintertime and exposes permafrost to colder temperatures, thereby preventing or decreasing CH_4 release from permafrost thawing. In addition, the selective grazing by large herbivores changes vegetation and soil properties, by decreasing shading and surface roughness, which may result in an increase of summer albedo (Cahoon et al. 2012; Falk et al. 2015; Schmitz et al. 2018; te Beest et al. 2016). Such an ecosystem-based management experience could be scaled up to the entire Arctic permafrost region as a strategy to support mitigation of the global climate (Table 2 and Case study 11 in Table S3).

Restoring degraded semi-arid ecosystems

Degradation of semi-arid ecosystems leads to significant carbon emissions via soil erosion and degradation (e.g., Chappell et al. 2016, 2019). Reversal of soil degradation is a longstanding focus of the UN Convention to Combat Desertification. Rebuilding soil (especially) and plant carbon stocks in semi-arid regions is seen as a potentially significant contribution to mitigation of CO_2 emissions because these regions are vast, and they appear to affect both the interannual variability and trend in the land carbon sink (Ahlström et al. 2015). But this view is not fully supported by the evidence (e.g., Yusuf et al. 2015), and the efficacy of restoring degraded semi-arid systems is thus somewhat contested (Gosnell et al. 2020). Many semi-arid systems have been observed as having “greening” trends (Fensholt et al. 2012; Leroux et al. 2017; Stevens et al. 2017), tentatively linked to plant fertilization by rising atmospheric CO_2 (Donohue et al. 2013; Zhu et al. 2016; Deng et al. 2021), with one of the outcomes being an increase in the competitive advantage of woody plants over grasses and increasing woody cover in these ecosystems. Global analysis suggests that this greening is associated with soil drying as a result of higher plant cover (Deng et al. 2020), and that associated shrub encroachment reduces grazing potential (Anadón et al. 2014).

Restoring inland wetlands

Inland wetland ecosystems provide vital services, such as food and freshwater, water purification, and flood prevention. Humans use inland wetlands intensively for agriculture, aquaculture, and urban development causing widespread degradation (IPBES 2018). While important for global carbon sequestration, the disturbance of wetlands could result in increases of GHGs (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 (Shukla et al. 2019). Notably, many irrigated rice areas are Ramsar sites for the protection of endangered species (Xi et al. 2020), but these are also important emitters of CH_4 in the atmosphere (Shukla et al. 2019).

The protection and restoration of wetlands and peatlands is expected to reduce net carbon loss to the atmosphere between 0.15 and 0.81 $GtCO_2e$ y^{-1} up to 2050 (Couwenberg et al. 2009; Griscom et al. 2017; IPCC 2019) and provide continued or restored natural CO_2 removal (IPCC 2019). There has been significant knowledge gained over the last decade on wetland drainage and rewetting practices (IPCC 2013), while the carbon storage and flux rates, in particular the balance between CH_4 sources and CO_2 sinks are still hard to quantify (IPCC 2019; Spencer et al. 2016). Recent evidence shows that tropical wetland CH_4 emissions are underestimated, perhaps by a factor of two (IPCC 2019). This could be due to the lack of inclusion of release by tree stems (Pangala et al. 2017). However, consistent with inventory data, agriculture may be a more probable source of increased emissions, e.g. from wetland rice and livestock production systems in the tropics (Wolf et al. 2017; Patra et al. 2016; Schaefer et al. 2016). For peatlands models show mixed results for their role as future sink (Spahni et al. 2013; Chaudhary et al. 2017; Ise et al. 2008). Extensive historical data sets suggest that the currently global peatland sink could increase slightly until 2100 and decline thereafter, under scenarios of future warming (Gallego-Sala et al. 2018).

Biodiversity offsets

Biodiversity offsetting is the practice of mitigating the negative impacts of developments on biodiversity (e.g., urban development, mining, agricultural expansion) by setting aside areas for restoring or protecting biodiversity elsewhere. Biodiversity offsets are meant to compensate for the services of carbon storage in biomass and soils through the development of newly restored or created habitats either in public or private lands. There are 12,983 listed biodiversity offsets under no net loss (NLL) principles implemented across 37 countries, predominantly forest ecosystems, covering about 153,679 km^2 (Bull & Strange 2018). The true benefits of biodiversity offsetting are currently being questioned. While a large number of offset projects are located in less industrialized and emerging economies, existing studies on biodiversity offsets focused on North America, Western Europe, and Australasia (Bull &Strange 2018). In addition, although biodiversity offset programs advocate NLL principles, a recent review revealed that only one third of biodiversity offsets met the NNL principle with varied performance across different ecosystems (Ermgassen et al. 2019), suggesting the limited capacity of existing biodiversity offsetting projects to regulate climate and compensate for biodiversity loss. It should also be noted that, even when the offsetting program meets the NNL principle and is successful in maintaining carbon storage for climate change mitigation, biodiversity offsets can limit local people's access to, or cause loss of benefits from, the biodiversity and NCP on which their livelihoods depend, and so impacting their adaptation to climate change (Jones et al. 2019). However, existing studies on biodiversity offsets rarely assess potential trade-offs between carbon storage and other ecosystem services (Sonter et al. 2020). Applying the NNL principle to offsetting programs will not necessarily minimize the trade-offs and disconnects between the loss of local benefits from biodiversity, with gains in remote or global benefits. To avoid such trade-offs, the type and distributions of NCP should be taken into consideration in the offsetting process along with the NNL principle, through more spatially explicit evaluation of NCP.

2.2 Implementing a well-connected and effective system of protected areas (Target 3)

Expanding the network of protected areas

As of July 2021, protected areas cover 15.7% of terrestrial habitats and 7.7% of marine habitats (UNEP-WCMC 2021). There is increasing evidence that creating new protected areas and maintaining existing ones can help mitigating climate change through carbon sequestration and storage on land (Soares-Filho et al. 2010; UNEP 2019; Dinerstein et al. 2020) and at sea (O'Leary et al. 2016; Roberts et al. 2017; Sala et al. 2021). At sea, 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). Most known, and nearly all measured examples of linking marine protection to climate change mitigation are in coastal wetlands, yet the vast majority of ocean (and protected ocean) is deep water.

Though little studied, deep water ecosystems can hold considerable and important seabed carbon, such as around remote islands and seamounts (Barnes et al. 2019), Arctic and Antarctic continental shelves (see Souster et al. 2020 and Bax et al. 2021, respectively). On land, it is estimated that current protected areas store between 12% and 16% of land carbon stocks (Melillo et al. 2016; Dinerstein et al. 2020). To both reverse biodiversity loss and stabilize the climate, Dinerstein et al. (2020) suggest that protected areas should cover 50.4% of the terrestrial realm, storing a total of 1420 GtC. There is a substantial overlap of 92% between areas that require reversing biodiversity loss and the areas needing protection for enhancing carbon storage and drawdown. It is argued that by limiting global warming to 2°C and conserving 30% of the terrestrial surface, aggregate extinction risk could be reduced by more than half compared to business as usual scenario of unmitigated climate change and no increase in conserved areas (Hannah et al. 2020) . These studies, while needing to be consolidated, suggest a stronger interlinkage between biodiversity conservation and climate change mitigation.

Establishing ecological corridors

Enhancing efficiency and effectiveness of protected areas in fragmented land- and sea-scapes require establishment of ecological corridors (Dinerstein et al. 2017; Keeley et al. 2018; Littlefield et al. 2019). The carbon densities found in most of the ecological corridors are similar to those found in the protected areas they connect (Jantz et al. 2014). The 'Global Safety Net' plan - that aims to reverse biodiversity loss and increase carbon storage and drawdown by connecting all protected areas- indicates the need of only 4.3% of additional areas (but based on 2.5km corridor width) (Dinerstein et al. 2020). Hallmarks of successful connectivity conservation includes community involvement, habitat priority setting, restoration actions, and environmental services payments that satisfy tenets of climate-smart conservation, and 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 their climate benefits have not been fully explored.

2.3 Recovering and conserving wild species (Target 4)

Gaining increasing attention and supported by the 2021-2030 UN's decade of ecosystem restoration (https://www.decadeonrestoration.org/), 'rewilding' conceives the restoration and protection of natural ecosystem processes, with no or little human interference following initial restoration. On land, vegetation and soils in most natural ecosystems store more carbon than systems managed for agriculture, forestry or grasslands. Rewilding is therefore considered a potentially important contribution to climate change mitigation, since the regrowing plants remove carbon dioxide from the atmosphere, storing this carbon in biomass and soils (Arneth et al. 2021; Smith et al. 2020; Strassburg et al. 2020). Rewilding, however, often also means trophic rewilding such as the reintroduction of large mammal herbivores or carnivores into ecosystems, supporting overall restoration efforts by rebuilding trophic cascades and promoting system self-regulation (Bakker and Svenning 2018; Sandom et al. 2020). Presence or absence of animals and the relative abundance of different animal groups affect ecosystem functioning e.g., by altering the amount of above-ground biomass, changing light transfer into the canopy, albedo and evapotranspiration, altering plant species composition, affecting wildfire, and mediating soil and ecosystem carbon and nitrogen turnover rates (Perino et al. 2019; Schmitz et al. 2018). It is widely accepted that the reintroduction of animals as part of rewilding will not only gain -often charismatic- species, but also bring their ecosystem function. The impact of ecosystem processes relevant for climate change mitigation may well be considerable, as inferred from experimental plots, satellite remote sensing analyses, as well as assessment of paleo-data (Cromsigt et al. 2018; Perino et al. 2019; Sandom et al. 2020; Schmitz et al. 2018). Whether or not trophic rewilding could be part of targeted mitigation strategies is unclear, however, and discussed controversially (Bakker and Svenning 2018; Cromsigt et al. 2018; Sandom et al. 2020; Schmitz et al. 2018). Trophic rewilding could trigger processes that support mitigation as well as opposing it (Bakker & Svenning 2018; Cromsigt et al. 2018; Sandom et al. 2020; Schmitz et al. 2018). Likely, the net climate impacts will differ strongly between regions and ecosystem types, and also how climate change will impact trophic interactions and species communities (Bakker and Svenning 2018; Cromsigt et al. 2018; Sandom et al. 2020; Schmitz et al. 2018).

At sea, 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. As for terrestrial mammals, the contribution of these emblematic species in the global carbon cycle has been neglected until recent studies show the role of these predators either as carbon sinks or mediators of carbon sequestration in the deep 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 animals has been particularly scrutinized in marine vegetated coastal habitats, identified as carbon-rich ecosystems, where predators are essential to control the abundance of herbivores and bioturbators which in turn impact the canopy height, root and shoot densities of the macrophytes, all characteristics playing a role in carbon capture and storage in plants, sequestration in sediments, and particle trapping (Atwood et al. 2015). Trophic downgrading triggered by the loss of predators can 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 high densities as a result of intense rewilding programs, and in the absence of predators (overexploited sharks), can overgraze and deplete seagrass beds (Heithaus et al. 2014).

In offshore waters, whales contribute to the biological pump, i.e., the removal of carbon from the euphotic zone to the deep sea and sea bottom where it can be sequestered for several centuries or more (Passow & Carlson 2012). While the sinking of whales' carcasses is negligible compared to other drivers of the biological pump, it serves as a synergistic positive outcome of rebuilding programs (Pershing et al. 2010). Possibly more important is the role played by whales' faecal plumes in fertilizing surface waters in allochthonous limiting nutrients, iron in particular, boosting primary production and thereby capturing atmospheric carbon down to deeper waters via the ocean biological pump (Lavery et al. 2010; Roman & McCarthy 2010).

2.4 Ensuring sustainable harvesting of wild species, food production and supply chains (Targets 5, 9 and 15)

With the global human population projected to reach over 9 billion by 2050 (Adam 2021), it is likely that we will need to produce more food, from land and the oceans, as well as to substantially reduce food loss and waste. Agriculture is one of the main causes of biodiversity loss on land (Green et al. 2005; Newbold et al. 2015, 2016; IPBES 2019), due to a wide range of impacts including agriculture expansion into natural ecosystems, conversion for livestock farming, pollution from pesticides and fertilizers and its contribution to climate change (Crist et al. 2017; IPBES 2019). The biodiversity status of agricultural land and food supply chains can be improved by interventions such as: a) sustainable intensification of production (Pretty et al. 2018), which allows land to be freed for nature conservation (Balmford et al. 2018; and see 2.6), b) less intensive farming practices, e.g. by adopting agroecological techniques (Albrecht et al. 2020; Tittonell et al. 2020; and see 2.6) - though this could exacerbate the clearance of natural ecosystems for agriculture if it resulted in lower productivity (Phalan et al. 2011), and c) demand-side changes in the food supply chain, such as dietary shifts toward more plant-based diets containing less meat and dairy (Bajželj et al. 2014; Alexander et al. 2016; Xu et al. 2021), and reducing food loss and waste (Gustavsson et al.

2011; Alexander et al. 2017), which reduces demand for products with a large land footprint (Hayek et al. 2021). These interventions to improve the biodiversity status of agricultural land also have significant climate change mitigation and adaptation benefits with mitigation potentials ranging from 0.1 to 8 $GtCO_2e$ y^{-1}, and adaptation benefits accruing to up to 2.3 billion people (Smith et al. 2020a).

In the ocean, fishing wild species as the main source of seafood production is a major driver of biodiversity loss as a result of overexploitation, bycatch and destruction of habitats (Rogers et al. 2020; IPBES 2019). Fishing can also impact carbon fluxes, by exporting ocean carbon to land and ultimately to the atmosphere that would otherwise be sequestered in the deep sea (Mariani et al. 2020; Sala et al. 2021). Downward passive transport of carbon from the surface to the deep ocean occurs through sinking of dead carcasses, faecal pellets of fish and invertebrates, and this has been shown to be a significant contribution to the biological pump. By preventing these natural processes to happen, large pelagic fisheries have released an estimated minimum of 0.73 $GtCO_2e$ since 1950 (Mariani et al. 2020). In addition, fishing impacts the biological pump by extracting organisms that realize active diurnal vertical migration (DVM), feeding at the surface at night, and then joining the deeper mesopelagic domain during daytime where they produce faecal pellets. The flux of carbon driven by DVM is estimated to be 3.85 ± 0.5 $GtCO_2$ y^{-1}, about 18% of the passive flux of carbon (Aumont et al. 2018). In the Southern Ocean, fishing krill (*Euphausia superba*) has the potential to impact the biological pump significantly as krill is estimated to be responsible for about 35% of the current export of carbon to the ocean floor in the marginal ice zone (Belcher et al. 2019). An additional effect of fishing 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). The release of carbon into the atmostphere is massive during the first years of bottom trawling. For the surface currently trawled each year (1.3% of the global ocean), in a fictitious scenario where this surface would be free from previous disturbance, carbon emissions after 1 year of trawling are estimated at 1.47 Gt aqueous CO_2, equivalent to about 15-20% of the atmospheric CO_2 absorbed by the ocean each year (Sala et al. 2021).

Concerns regarding unsustainable fish production have driven a number of efforts to minimise environmental impacts, including developing sustainable aquaculture practices. These efforts first focused on replacement of fish-derived protein and oil in aquaculture feeds with plant products resulting in a reduction of the trophic level of aquaculture species (Cottrell et al. 2021). This has a direct impact on fishing wild fish species for feed, with indirect consequences on the biological pump of carbon. There has also been a focus on development of integrated multitrophic aquaculture (IMTA) and cultivation of low trophic level species that do not require inputs from fisheries. IMTA relies on raising species from different trophic levels in close proximity to one another so that waste materials from one species cultivation serve as input food and nutrients for others (Knowler et al. 2020). Examples of IMTA include the cultivation of salmon with mussels and kelp or the growth of sea cucumbers with seaweeds and mussels (e.g., Knowler et al. 2020; Stenton-Dozey et al. 2020). Cultivation of seaweeds has been concentrated in south east Asia but is now expanding globally in areas suitable for growth (Cai et al. 2021). Seaweeds can be used as a healthy food source, as food additives (e.g. phycocolloids), as animal feeds (reducing methane production from ruminants) and a range of other products such as bioplastics (Ditchburn & Carballeira 2019; Kim et al. 2019). Seaweed cultivation can also have significant environmental benefits including removal of excess macronutrients such as N and P from coastal waters (Xiao et al. 2017), CO_2 capture (e.g., Sondak et al. 2016) and can form habitat for natural populations of marine animals such as fish (also for bivalve cultivation; Theuerkauf et al. 2021). Research is currently underway to determine the scope of expanding IMTA and low trophic level aquaculture geographically as well as the environmental carrying capacity of these forms of food production if it is to be undertaken sustainably (e.g., Froehlich et al. 2019; Stenton-Dozey et al. 2020; Cai et al. 2021).

2.5 Reducing pollution from excess nutrients (Target 7)

As the human population grows, so have the inputs of nutrients and organic matter to inland and coastal waters. Excess nitrogen, and in some cases phosphorus, originating from agricultural fertilizer runoff on land, industrial, wastewater and stormwater discharges, fossil-fuel burning or aquaculture facilities lead to algal blooms and in some cases hypoxia in fresh, estuarine and coastal waters (Jeppesen et al. 2010; Rabalais et al. 2014; Nazari-Sharabian et al. 2018; Deininger and Frigstad 2019). This phenomenon, termed eutrophication, can modify the biogeochemical cycles of carbon, nitrogen, phosphorus, sulphide and silica as well as food webs and other ecosystem processes (Jeppesen et al. 2010; Rabalais et al. 2014; Li et al. 2021). There are over 500 coastal locations and hundreds of freshwater lakes where oxygen loss occurs, accompanied by rising carbon dioxide levels due to microbial decomposition of excess primary and secondary production stimulated by eutrophication (Breitburg et al. 2018; Jane et al. 2021). Warming of fresh and ocean waters increases respiration rates and may tip eutrophic areas into hypoxia or anoxia, thus it can be difficult to attribute observed oxygen and pH declines solely to eutrophication versus climate change (e.g., Kessouri et al. 2021).

Rising eutrophication combined with warming may increase GHG emissions in freshwater bodies, creating a positive feedback loop that accelerates both climate change and eutrophication, but with some complex, counteracting effects. This loop involves enhanced methane (CH_4) release (Davidson et al. 2018); phytoplankton blooms that release CO_2 but also dimethyl sulfide (DMS) that reduces solar radiation; deposition of acid nitrogen and sulfur compounds that promote ammonium oxidation releasing nitrous oxide (N_2O); and warming-enhanced stratification that might limit CH_4 release and facilitate its storage (Li et al. 2021). Under eutrophication and anoxia in freshwater, the coupling of methanotrophy and denitrification may ameliorate N_2O release (Naqvi et al. 2018). Also, eutrophic freshwater lakes (with > 30 μgTP l^{-1}) bury 5 times more organic carbon than non-eutrophic lakes (Anderson et al. 2014). Biogeochemical feedbacks to climate from expanded coastal hypoxia may include increased denitrification and ammonium oxidation in coastal waters and release of N_20 (Naqvi et al. 2010). Release of inorganic phosphate and iron from sediments under anoxic conditions stimulates further primary production and oxygen consumption as is the case in several oxygen minimum zones (Linsy et al. 2018; Lomnitz et al. 2016). Under some circumstances hydrogen sulphide, which is highly toxic, may be generated in anoxic water or sediments.

Control of nutrient pollution (oligotrophication) may lead to a significant decrease in coastal deoxygenation and the climate feedbacks associated with CH_4 and N_2O emissions or phosphorus and iron release. Effective tools to decrease coastal deoxygenation and associated GHG emissions include altered agricultural practices, various eco-engineering approaches such as river diversions through wetlands to employ natural processes that reduce nitrogen loads (Engle 2011) or new wetland construction (Jahangir et al. 2016; Duarte and Krause-Jensen 2018). Both eutrophication and the incidence of red tides (phytoplankton blooms) and green tides (macroalgal blooms) are predicted to increase under future warming scenarios (Gao et al. 2017; Xiao et al. 2019; Gilbert 2020). The reduction of harmful algal blooms, which act as co-stressors by releasing toxins and consuming oxygen, is a co-benefit of oligotrophication (Griffith & Gobler 2019; Pitcher & Jacinto 2019).

By limiting nutrient inputs to both freshwater bodies and the ocean it is possible to address eutrophication and climate change simultaneously, in part by preventing the two-way feedbacks between eutrophication and climate. Societal choices about land and ocean management need to ensure that regionally rising precipitation (e.g., in the US or Asia) does not negate the nutrient removal benefits of these choices (Sinha et al. 2019).

2.6 Supporting the productivity, sustainability and resilience of biodiversity in agricultural and other managed ecosystems (Target 10)

Biodiversity-based and biodiversity friendly agricultural systems

Reducing biodiversity loss and enhancing biodiversity in agricultural systems can help mitigate climate change and enhance a wide range of NCP (Leippert et al. 2020; VanBergen et al. 2020; Wanger et al., 2020). Biodiversity can be promoted in agricultural systems directly – for example, through greater crop diversity, agroforestry or integration of crop production with livestock raising or aquaculture; or indirectly through practices that are biodiversity friendly – for example through organic amendments to soils, reduced tillage or reduced pesticide use (Smith et al. 2020a; Tamburini et al. 2020). In general, these practices do not compromise agricultural yields, and in addition to enhancing biodiversity, they reduce nutrient losses, reduce soil erosion and improve soil fertility (Tamburini et al. 2020). Biodiversity-based and biodiversity friendly agricultural practices also tend to increase carbon sequestration, but have highly variable effects on total GHG emissions, so identifying and implementing win-win practices for biodiversity and climate change mitigation need to be done with this in mind (Smith et al. 2020a; Tamburini et al. 2020). Practices that promote biodiversity in agricultural systems include agroecology (which relies in part on the use of ecological processes to substitute for chemical inputs), regenerative agriculture (which focuses on restoring soil health and reversing biodiversity loss) and organic agriculture, as well as certain aspects of climate-smart agriculture, conservation agriculture, and sustainable intensification (Doré et al. 2011; Pretty et al. 2018; FAO 2019a; Giller et al. 2021).

In situ conservation and restoration of biodiversity is one of a suite of practices falling within agroecological principles. Agroecology can also include promoting local and national food production, small-scale farming and local innovations and resource use (Altieri et al. 2012). Mbow et al. (2014) provide an example of African smallholder farmers using agroecological practices (agroforestry) such as diversification of trees on-farm and within the landscape to increase carbon content, prepare for climate extremes at the same time reduce and/or avoid crop failures. In dryland agriculture, soil and water conservation measures potentially improve ground cover and soil carbon content (VanBergen et al. 2020; Wanger et al. 2020) and albedo (Creed et al. 2018).

The three main objectives of climate-smart agriculture are to sustainably increase agricultural productivity and incomes; adapt to and build resilience to climate change, and reduce GHG emissions (FAO 2019a). Many of the practices promoted for climate-smart agriculture are also good for biodiversity. For example, the Government of India and its Indian Council of Agricultural Research identified the districts most vulnerable to climate change and implemented climate-smart agricultural interventions such as appropriate use of nitrogen fertilizers, which also reduces negative effects of nitrogen losses on non-agricultural ecosystems, and conservation tillage for increased soil carbon content, which also enhances soil biodiversity. In addition, these measures helped farming groups protect their agricultural systems for local food security and increase adaptive capacity (Rao et al. 2020; Vanbergen et al. 2020) in climate-smart villages (Aggarwal et al. 2018).

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

GHG emissions will continue to increase with continued agricultural expansion and continued conventional intensification (Vanbergen et al. 2020). Scenarios that achieve climate change targets generally require substantial changes in agricultural intensification and demand for agricultural products (IPCC 2019). One approach to conserving biodiversity could be to boost yields per unit area, through sustainable intensification on existing farmland that could in principle spare land for remaining natural habitats (Balmford et al. 2018; Smith et al. 2020a). However, intensive high-yield farming raises other concerns because it can generate high levels of GHG emissions and nutrient losses. For example, excessive fertilization of crops results in N_2O emissions which is a potent GHG, and also results in other gaseous nitrogen losses that contribute to dry and wet deposition of nitrogen into terrestrial ecosystems that can reduce species richness (Galloway et al. 2003; Gerber et al. 2016; Tian et al. 2020). Moreover, NO_x emissions can result in increased tropospheric ozone which can reduce productivity of natural ecosystems (Galloway et al. 2003). 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. Others have argued that the most beneficial approach to conserving biodiversity in agricultural landscapes is to "share" land more effectively with biodiversity, often by reducing agricultural intensity (Kremen 2015). However, this approach runs the risk of increasing land conversion elsewhere to compensate for reduced agricultural yields per unit area, resulting in an overall negative impact on biodiversity and climate change mitigation (Kremen 2015; Balmford et al. 2018). A growing consensus is that the benefits and drawbacks of these approaches are highly context dependent, not mutually exclusive and require careful spatial planning (Kremen 2015; Salles et al. 2017; Egli et al. 2018).

In terms of demand for agricultural products, Van Meijl et al. (2017) indicate that demand is more influenced by population growth and changes in dietary preferences than for instance by GDP growth. This implies that in the end, agricultural pathway choices are about quality vs. quantity, and that high yield agriculture based on high inputs of energy, fertilizers and pesticides may not be necessary if demand shifts to reduce overconsumption, reduce food waste and loss, and increase the fraction of plant-based foods (Clark et al. 2019).

Using fire and bush removal to combat woody plant encroachment

Woody plant encroachment has been observed on several continents, especially in tropical and subtropical latitudes, linked to a poorly understood mix of land management actions and climate change drivers, including CO_2 fertilization of woody plants (e.g., Stevens et al. 2017). Woody plant encroachment and its reversal may have important implications for both biodiversity and carbon sequestration. In Namibia, for example, the extent of bush encroachment is sufficient to offset national fossil fuel emissions (Ministry of Environment and Tourism 2011), and this may reduce incentives to combat this trend at the cost of iconic species that are dependent on open ecosystems.

Bush encroachment converts open ecosystems to a more densely tree or bush-covered state that alters biodiversity patterns significantly. For the open savanna plains fauna of Africa, clear direct negative impacts of bush encroachment are already visible for vulture, cheetah, and a myriad of smaller grassland bird species. Wildfire and browsing pressure used to maintain these systems in an "open" condition may no longer be effective (e.g., Bond and Midgley 2012), threatening the biodiversity of grassland and savanna landscapes across tropical Africa, South America, and Australasia. Experimental use of extreme fires and mechanical removal to reverse or halt bush encroachment have been tested (e.g., Smit et al. 2016), but the drive to maintain open ecosystems using disturbance can be misinterpreted as counter to the need for carbon sequestration. Apart from biodiversity benefits of reducing encroachment, maintenance of open grasslands can be motivated by the fact that carbon stocks of semi-arid grassland ecosystems may match that of alternative woody ecosystems (Wigley et al. 2020) when below ground carbon stocks are taken into account. Maintenance of open ecosystems also helps to maintain streamflow (e.g., Creed et al. 2019) and reduce the intensity of wildfire regimes. In addition, open ecosystems provide multiple material benefits for subsistence livelihoods, including extensive grazing and thatching, as well as the irreplaceable cultural elements associated with these lifestyles.

Recognition of the natural cooling effects of high albedo of grasslands, and the plethora of local and global benefits provided by tropical open ecosystems to people support the need for sustainably managing these systems. In South Africa, active removal of invasive non-indigenous woody plants has created millions of job opportunities, with some demonstrable results with respect to slowing woody plant encroachment rates (van Wilgen et al. 2012).

2.7 Increasing benefits from biodiversity and green/blue spaces in urban areas (Target 12)

The United Nations estimated that 55.3% of the world's population lived in urban settlements in 2018 (UNDESA 2019). It is projected that the urbanization trend will continue to accelerate, while the majority of GHG emissions are generated by urban dwellers (United Nations Economist Network, 2020). Contrary to common perception, it has been shown that cities can harbour rich biodiversity (Secretariat of the Convention on Biological Diversity 2012; Chan 2019). As highlighted in the Edinburgh Declaration that highlights the commitment of subnational governments, cities and local authorities to the delivery of the post-2020 Global Biodiversity Framework, cities can contribute to solutions for both biodiversity loss and climate change and do so in an integrated way across public, private and business sectors to be more effective. This has been the approach taken by cities such as Berlin, Edinburgh, Melbourne, Portland, Singapore, Toronto and Washington DC where biodiversity-friendly, green and sustainable practices have been adopted (Beatley 2016; Plastrik & Cleveland 2018), to make them a more liveable and desirable habitat for people and nature.

Many of the methods used to conserve biodiversity in cities result in the enhancement of sinks for GHGs (Epple et al. 2016). 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). 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 (Chan 2019), park connectors, the creation of sponge cities (Yu 2020), the naturalization of drainage channels 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, with multiple benefits including the reduction in adverse effects of climate change (reduction of urban heat island effect, etc.), the enhancement of regulating (water quality, air quality, soil retention, etc.), material (urban agriculture in roof-top gardens) and 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.

2.8 Mainstreaming biodiversity (Target 14)

The Convention on Biological Diversity has put a strong emphasis on the importance of biodiversity mainstreaming which 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). As biodiversity conservation and climate change challenges are intricately linked, it follows that biodiversity and climate are most effectively mainstreamed together (Pörtner et al. 2021).

Several examples illustrate the variety of ways in which biodiversity issues can be mainstreamed, and how this mainstreaming can be beneficial for climate change mitigation. Biodiversity reporting and natural capital accounting can help mainstreaming in governments and policies by informing decision-making. In the case of the System of Environmental Economic Accounting (SEEA) framework, which has been implemented by more than twenty countries, national accounts are used to inform decision-making on biodiversity, climate change mitigation and other environmental issues across government agencies (SCBD 2005). Mainstreaming biodiversity in financial instruments, such as fiscal reforms, taxation models and fiscal incentives may also contribute to climate change mitigation. One of the most important and urgent reforms requiring cooperation across many actors are the reduction or elimination of subsidies that are harmful to both biodiversity and climate (see section 2.10 for examples). Better integration of biodiversity into business operations and practices might also benefit climate change mitigation. Businesses are increasingly using GHG emissions accounting to identify and reduce their contributions to climate change, but adoption of biodiversity accounting has lagged behind, in part due to low awareness of biodiversity as a major issue for businesses and to a lack of well-established biodiversity metrics for business to assess and value their impacts and dependencies on biodiversity (Smith et al. 2020b). Climate and biodiversity footprints of businesses are, however, intimately related because reducing biodiversity footprints depends on reducing GHG emissions, since climate change is one of the major factors impacting on biodiversity, and also relies on reducing the impacts of businesses on drivers that are common to both biodiversity loss and climate change such as deforestation, mining and unstainable agricultural practices (IPBES 2019). Mainstreaming biodiversity across society, for example through education can be beneficial for climate change especially when they are part of an overall strategy to raise environmental awareness. For example, an examination of educational curricula in 46 countries found that fewer than half of education policies and curricula mentioned climate change and only a fifth made reference to biodiversity, leading to a recommendation that "more emphasis should be given to environmental themes in education, with a particular need to expand integration of climate change and biodiversity" (UNESCO 2021).

With a growing number of programmes and projects adopting the mainstreaming approach, there are now more case studies documenting their success stories. The Working for Water programme (WfW) in South Africa (Redford et al. 2015) demonstrates that mainstreaming biodiversity resulted in controlling invasive alien species and speeded the rate of legal protection of areas of high biodiversity. In Costa Rica, the joint policies of several Ministries (Environment, Agriculture, Planning and Finance) resulted in a national sustainable development plan that 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 change mitigation from biodiversity conservation actions. Under the circumstances where climate change mitigation measures could have negative impacts on biodiversity conservation or vice versa, trade-offs should be considered and comprehensively analysed (cf. 3.3).

2.9 Eliminating unsustainable consumption patterns (Target 16)

Where sustainable consumption occurs, biodiversity and ecosystems have been frequently shown to benefit, with some further climate change mitigation benefits. The largest potential for reducing agriculture, forestry and other land use (AFOLU) emissions of GHG is through reduced deforestation and forest degradation (0.4–5.8 $GtCO_2e$ y^{-1}), a shift towards plant-based diets (0.7–8.0 $GtCO_2e$ y^{-1}) and reduced food and agricultural waste (0.8–4.5 CO_2e y^{-1}) (Jia et al. 2019). Thus, there is a high potential that consumers' choices can directly impact both biodiversity and the climate. For example, the market for wood products that are sustainably harvested and/or produced has shown clear benefits for forest cover and diversity – and this may result in improved measures in carbon sequestration and albedo (Di Sacco et al. 2021; Heilmayr et al. 2020). Further, the trend to demanding and consuming other products that are harvested or produced in a more biodiversity and climate friendly way is clear – some examples here include sustainably produced meat (including wildlife products; and meat produced using improved rangeland management; D'Aurea et al. 2021, Conant et al. 2017), sustainable fashion, potatoes, tea and coffee (Alom et al. 2021; Ruggeri et al. 2020; Vogt 2020; Zhao et al. 2021) – and work on the quantification of such benefits is a valuable and growing field.

On the food demand side, nearly 10% of the agricultural land area could be spared globally through halving consumer waste arising from over-consumption in some sectors of society (Alexander et al. 2017). In high-income countries, consumer behaviour significantly influences the amount of food wasted, so raising awareness of the consequences on biodiversity and climate change among consumers, but also along the whole supply chains involving industries and retailers, is of critical importance (FAO 2019b). Likewise, studies that explore dietary scenarios of reduced consumption of animal protein estimate that between 10% and 30% of today's area under agriculture could be freed for other purposes (Alexander et al. 2016; Shin et al. 2019). The aforementioned Conant et al. (2017) study shows, for example, how better grazing management can increase soil carbon stocks - showing rates from 10 to more than 1000 $MgC \cdot km^{-2} \cdot y^{-1}$.

2.10 Eliminating incentives harmful for biodiversity (Target 18)

Subsidies are often inefficient, expensive, socially inequitable, and environmentally harmful (OECD 2005; IPBES 2019). Despite the commitments of the governments to phase out or reform biodiversity harmful subsidies by 2020, they are still continuing but the detailed information on potential impacts of such subsidies is mostly unavailable (Dempsey et al. 2020). The financial resource allocated to environmentally harmful subsidies in various sectors outweigh the resources allocated to biodiversity conservation by a factor of 10 to 1 (OECD 2019), indicating the pervasiveness of such subsidies. For example, in the agriculture sector, OECD countries spent US$100 billion in 2015 in activities that are potentially harmful to nature (OECD 2019). Similarly, it is estimated that the annual global fossil fuel subsidies (US$300 to US$600 billion) generate negative externalities of at least US$4 trillion (Coady et al. 2019; Franks et al. 2018).

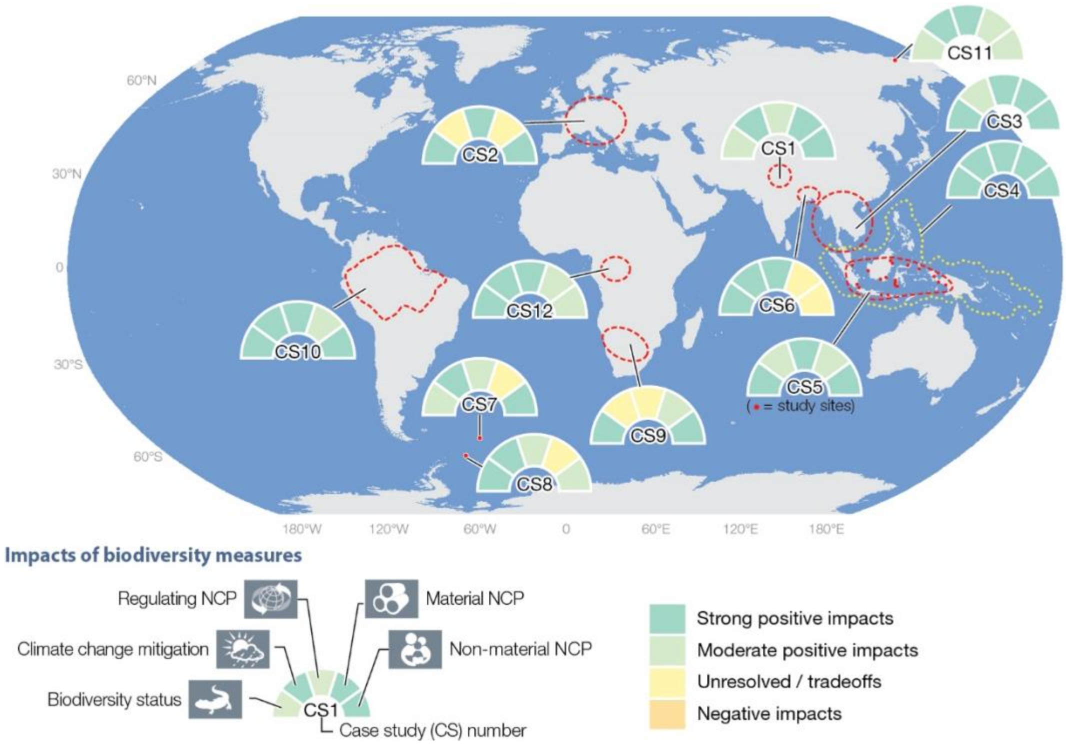
In the forestry sector, Brazil spent $14 billion (88 times more) subsidizing activities linked to deforestation compared to $158 million to stop deforestation (McFarland et al. 2015). In the fisheries sector, subsidies promoting sustainable exploitation are about $10 billion compared to $22 billion spent in causing overfishing (Sumaila et al. 2019). These discrepancies in environmentally beneficial and harmful subsidies arise partly due to difficulty in tracking such subsidies, and ignorance of the complexity of institutions. It is also partly due to activities around politicking and interest-group lobbying, e.g., for palm oil in Indonesia (Maxton-Lee 2018), and petroleum lobbying in Canada (Blue et al. 2018).

Further, difficulties arise from the effectiveness of environment-friendly subsidies. In Europe, the European Court of Auditors (ECA) found that the foreseen expenditure on 'farmland biodiversity' of the European Commission, amounting to €66 billion between 2014 and 2020, had little effect (https://www.eca.europa.eu/en/Pages/DocItem.aspx?did={B5A7E9DE-C42E-4C1D-A5D2-03CA1FADE6F8}). Over the same period, more than a quarter of the Commissions subsidies under the Common Agricultural Policy had aimed to target climate change mitigation and adaptation, but GHG emissions from European farms are not decreasing (https://www.eca.europa.eu/en/Pages/DocItem.aspx?did={D6EB02B9-C74E-4017-912B-EE46E75127B1}). The ECA raises numerous flaws in the ways the subsidies are oriented: the unreliable way the Commission tracks biodiversity expenditure, the low potential of the measures financed, the poor formulation of the agriculture targets, and the poor quality of the indicators used to track progress among the main reasons.

Fast and bold actions are needed to eliminate harmful subsidies to halt biodiversity loss and to mitigate climate change simultaneously (IPBES 2019). Such actions include enhancing a culture of subsidy accountability among individuals and businesses; reforming policies for better transparency, reporting and assessments; and using policy tools to incentivise individuals, communities and governments to maintain biodiversity, e.g., public procurement, taxes and fees (Barbier et al. 2018; Barbier et al. 2020; Lundberg & Marklund 2018; Girardin et al. 2021).

3. Integrating synergies and trade-offs between multiple goals at the level of landscapes and seascapes

The success of environmental measures, whether for biodiversity conservation or climate change mitigation, strongly depends on their context in a landscape or seascape, with consideration of the degree of its transformation, its multiple uses, local socio-economic conditions, and the quality of life of local communities. Ecosystem management is challenged with achieving multiple goals simultaneously in multifunctional and multiple-use land- and sea-scapes (hereafter referred to as ‘scapes), within which synergies and trade-offs between biodiversity conservation and climate change mitigation can be realized (see section 2 in Pörtner et al. 2021). The use and transformation of ecosystems by human society occur mainly 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. We therefore make use of local case studies (CS) to better understand how human appropriation of nature has resulted in the spatial fragmentation of ‘scapes and biodiversity loss and to unpack the enabling conditions (including incentives and governance factors) that have been effective in fulfilling multiple ‘scape objectives simultaneously (Table S3; Figure 1; Table 2). Protection of biodiversity is only one of a range of management objectives for a multi-functional and multi-use ‘scape. A clear need going forward is to improve our ability to mainstream biodiversity objectives and measure multiple benefits in specific contexts (Figure 1), but preferably with scope for upscaling and generalizing across cases. We propose an integrative analysis based on a selection of case studies that cover a wide range of IPBES units of analyses, and are located on different continents, oceans, and latitudes. Case studies also cover a diversity of conservation measures, types of NCP, needs of local communities, socio-economic contexts and governance situations.



<u>Figure 1</u>. Example case studies (see table 2 for more information, and supplementary material for full description of the case studies and references) showing emerging synergies or trade-offs between biodiversity conservation, climate change mitigation and nature's contributions to people (NCP). For each case study, five pieces of information are color-coded in a pie chart regarding the impacts of biodiversity conservation measures on: biodiversity, climate change mitigation, regulating, material and non-material NCP. None of the biodiversity measures implemented in the case studies resulted in negative impacts (indicated in orange), despite the fact that we had considered such negative impacts as possible in our assessment. CS: Case study, CS1: Kailash Sacred Landscape Conservation and Development Initiative, CS2: Cultural landscapes in Central Europe, CS3: Irrigated rice terraces and forests in Southeast Asia, CS4: The Coral Triangle initiative, CS5: Biodiversity-friendly cities and urban areas, CS6: The Sundarbans, India-Bangladesh, CS7: Southern Ocean, South Georgia Island, CS8: Marine BBNJ (Biodiversity Beyond National jurisdiction), South Orkney Islands, CS9: Bush encroachment, Southern Africa, CS10: Amazonian rainforest, CS11: Pleistocene Park, Northeastern Siberia, CS12: African Peatlands.

<u>Table 2</u>: Impacts of biodiversity conservation measures on biodiversity, climate change mitigation and other NCP in twelve case studies (supporting references in table S2). BBNJ: Biodiversity Beyond National Jurisdiction, C: carbon, CC: climate change, CH_4: methane, CS: case study, ES: ecosystem service, GHG: greenhouse gas, mgmt: management, MPA: marine protected area, NCP: Nature's Contributions to People, PA: protected area, sp.: species, UoA: Unit of analysis.

Case study	IPBES UoA	Main biodiversity measures	Impacts on biodiversity status	Impacts on Climate Change Mitigation	Impacts on other regulating NCP (e.g., air & freshwater quality, soils, extreme events, adaptation to CC)	Impacts on material NCP (e.g., Food & feed, energy, materials, medicines)	Impacts on non material NCP (e.g., learning, inspiration, identities)
CS1: Kailash Sacred Landscape Conservation & Development Initiative	1 7	Maintain/improve/restore forests & rangelands; practice sustainable land use	Habitats protected (for Snow leopard, Musk deer); bioversity corridors established	C sequestered (on forests/rangelands/ soils); CC mitigated by adopting ecosystem & farm mgmt practices	Water sources protected; springs rejuvenated; CC increased risk of snow-line shift & glacier lake outburst	Provision of food, forest products, medicinal plant Yarsagumba O. sinensis	Cultural heritage (Mount Kailash & Lake Mansarovar); religious tourism
CS2: Cultural landscapes in Central Europe	2 10	Simulate traditional land-use systems; avoid succession to forests as well as intensification	Reduced extinction risks of rare & highly adapted species &/or varieties	No woody vegetation thus less C sequestered; CH_4 emissions by animal husbandry; trade-offs on crop fields vs. forests	Maintenance of high diversity of pollinators & natural enemies of pest (i.e. biocontrol services)	Production of high quality food (meat & plants) but trade-off: quantity vs. quality; ensured diverse plants with medicinal potential	Maintaining options for adaptation to future changes; cultural: sense of place & mental & physical recreation
CS3: Irrigated rice terraces & forests in Southeast Asia	1 10 13	Maintain forest; avoid pesticide use in agricultural areas	Forest as habitat for rare & endangered species; high agrodiversity for stabilisation of pest population at low levels	C sequestration through maintenance of forests; CH_4 emissions through paddy fields	Water source for irrigation; biocontrol of rice pests	Stabilized food supply; avoidance of chemical pollution	Cultural: sense of place & mental & physical recreation; maintenance of traditional customs including arts; high eco-tourism potential
CS4: The Coral Triangle initiative	14	Marine spatial planning, fisheries mgmt, protection of coastal biodiversity & habitat-forming species (mangroves, coral reefs)	Slows biodiversity loss & increases ecological resilience to CC	Improved ecosystem resilience to CC leads to reduced loss of soils & C (usually due to deforestation), greater C sink	Improved water quality, soil retention (blue C), coastal protection, habitat complexity, fish nurseries, adaptation to CC	Maintenance of food supply, habitat, livelihoods, firewood, & medicines	Maintenance of cultural identity, sense of place, mental & physical recreation, local & international tourism opportunities
CS5: Biodiversity-friendly cities & urban areas	9	Safeguard biodiversity & multiple ES in cities	Native ecosystems protected; habitat restored; increased connectivity & plant diversity	increased C storage & sequestration; regulation of C cycle by natural & artificial water bodies	Improved water quality, soil retention (blue C), coastal protection, habitat complexity, plus adaptation to & mitigation of CC	Increase in urban agriculture reduces long-distance transportation and energy consumption/C emission.	co-existence with nature essential for physical, psychological & mental well-being; serves education & recreation
CS6: The Sundarbans, India-Bangladesh	1 7 12 17	Maintain mangrove forests by implementing PAs	Mangroves are habitat for birds, mammals, reptiles, amphibians, fish including endangered Bengali tiger	Regulation of GHG emissions & C sequestration by mangroves	Attenuation of flood & storm surge impacts by mangroves	Provisioning services (e.g. timber, fish) & cultural services (e.g. tourism) are often prioritized over regulating services in the management system for revenue generation, resulting in the steady decline of mangrove forests	
CS7: Southern Ocean, South Georgia Island	15	MPA in a pivotal area for megafauna (e.g., baleen whales & albatrosses), control pollution, non-indigenous sp. & tourism	Reduced extinction risk of endangered sp.	C storage increases across trophic levels; efficient seabed sequestration pathways	Larger population & fewer stressors so stronger potential for tolerance or adaptation to aspects of CC	Although reducing access to local fisheries, higher productivity potentially benefits regional fisheries	Potential for ecotourism, education & understanding of polar issues
CS8: Marine BBNJ	15 16	Intergovernmental co-operation to protect hotspot of biodiversity & blue C	Reduced extinction risk for endemic & rare species. Minimizing other stressors helps biota adapt to CC	Enhanced blue C storage pathways to strengthen sequestration	Improve CC tolerance/adaptation; important at physical change hotspot	May reduce krill fisheries yield but boosts prey for predators (trade-offs)	Strengthen public interest, engagement & ecotourism of remote wildlife, including migratory megafauna
CS9: Bush encroachment, Southern Africa	5 6 7	Maintain mammal population with mgmt of fire regime, using enhanced fire intensity to reverse woody plant dominance in targeted areas	Increases the prevalence of high-light, open-ecosystem (grassland) dependent sp. (i.e. grazers, geophytes)	Reduces tree cover but enhances albedo	Enhances livelihoods & water quality & quantity, but reduces air quality during burning periods	Enhances food & fibre	Maintains traditional livelihoods, cultural practices & sense of place, & nature-based tourism
CS10: Amazonian rainforest	1	Maintain/restore forest areas; improve PAs mgmt	Protect sp., ES & traditional/indigenous communities	Conserve/increase C storage in land; control GHG emission by natural & artificial water bodies	Critical for water cycle & climate in the continent	Provisioning of forest products (i.e. food & medicines); fishing is the main source of protein for locals	Indigenous & traditional communities (i.e. 'seringueiros', 'ribeirinhos') with unique cultural aspects; great potential for employment & tourism
CS11: Pleistocene Park, Northeastern Siberia	4	Rewild the mammoth steppe	Restored plant biodiversity & soil of the re-wilded mammoth steppe	Attenuates permafrost thawing, increases albedo & C sequestration by soils	Soil moisture is reduced in wet moss/shrubby tundra, altered soil provides additional C sequestration	Co-benefits that might arise are C-negative wild meat & other C-negative products	Provides a year-round base for international research & students; potential for employment & new tourism economies
CS12: African Peatlands	8	Conserve unique biodiversity of tropical peatland forests	Reducing extinction risks of rare & highly adapted sp. &/or varieties	Reduced degradation & loss of land-based C storage; regulate C & water cycling (including CH_4 & CO_2 emission)	Maintain soils & water quality & water supply	Several forest product benefits	Preserve cultural identity & livelihoods of local people

3.1. Local to regional actions and the critical role of scale and linkages

Ecosystems are used and transformed by human societies at local scales, but effects on biodiversity and ecosystem functioning accumulate and can be amplified at larger spatial scales. For example, nature-based solutions in urban contexts can individually make a small contribution to global climate change mitigation and biodiversity protection, but given the high human densities in cities, all actions, collectively, have huge potential impact at the global scale, while improving the quality of life locally for a large share of the world population. On land, land use and land cover change result from increasing and changing human demands for nature's contributions, with the extent of change varying geographically, due to a complex interplay between biophysical, socioeconomic, and governance factors as illustrated by our set of case studies (figure 1, table 2 and tables S2-S3). The configuration of anthropogenic landscapes offers opportunities to achieve various objectives in different locations relating to both human needs and sustainability objectives, including biodiversity and mitigation-related regulating benefits like carbon storage and sequestration. Achieving specific objectives at local scales can together enable to reach multiple objectives at the 'scape and global scale.

Land-use and land cover change for increasing food provision or infrastructure expansion fragment and reduce the area of habitats and is currently the leading cause of terrestrial biodiversity loss (IPBES 2018, 2019). While these processes also almost always result in net carbon release to the atmosphere (IPCC 2019), they supply critical material benefits that maintain human society and contribute to good quality of life (Case studies CS 2, 3, 9, 10, 12, IPBES 2019). Understanding how land cover can be allocated between competing uses is advancing and offers opportunities to optimize between multiple objectives (CS 2, 3). Such trade-offs may include assessing the balance between biodiversity conservation, production of food and fiber (material NCP), carbon sequestration via reforestation (regulating NCP; CS 10) and restoration (regulating and cultural NCP; see CS 11 and 2.1 for the beneficial effects of rewilding mammoth steppe with large herbivores in Arctic permafrost areas).

Hannah et al. (2020) suggest that at the landscape to national scales, increasing conserved area from 20 to 30% significantly increases the resilience of the conserved area network to climate change (i.e., more species may be assured of persistence). The unequal distribution of biodiversity globally means that some regions have higher concentrations of rare species (Enquist et al. 2019) and prioritizing conservation objectives in these relatively small regions permits achievement of species conservation most efficiently (CS 1, 4). Spatial planning methodologies can be applied to maintain ecological functioning even in fragmented landscapes, through the consideration of zonation that takes into account landscape heterogeneity (Harlio et al. 2019; Moilanen et al. 2005). Many efforts are underway to green cities with multiple co-benefits for human well-being. Such efforts have the potential to connect cities to surrounding natural or managed areas and contribute to both biodiversity conservation and climate change mitigation regionally, as is the case in coastal cities for example (Beatley 2014; 2.7 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). Apart from coastal areas, marine ecosystem transformation occurs mainly via harvesting of consumer species for material benefits, with relatively low rates of plant use, and lower prevalence of high intensity food production systems. Important links between human use of the oceans and climate change mitigation have been identified, with local and regional harvesting scaling up to significantly alter the global food chain, with important impacts on processes like seabed sequestration of carbon and the biological pump of carbon (cf. 2.3, 2.4).

3.2. Realizing co-benefits and synergies in land- and sea-scapes

Species-rich areas are often prioritized for biodiversity conservation measures at the ‘scape level, and in many cases, these same areas coincide with important carbon stores and sinks (CS 4, 6, 10, 12; Strassburg et al. 2010), making conservation actions doubly beneficial. The Amazon rainforest (CS 10) and mangrove forests (CS 4, 6), in particular, are two species-rich iconic ecosystems that are typified by high rates of carbon sequestration (Soares-Filho et al. 2010; Donato et al. 2011; Guannel et al. 2016; Joly et al. 2018). Mangroves are estimated to sequester on average between 600-800 $MgCO_2e$ km^{-2} y^{-1} in the sediments. This represents an annual carbon sequestration rate that is about 4 times more per unit area than some estimates for tropical forests (Donato et al. 2011), although estimates for climax forests, which are almost carbon-neutral, should not be conflated with those for early succession forests, which are actively taking up carbon. By contrast, coral reefs that flourish in oligotrophic waters of tropical coastlines represent a counter example, where primary productivity and the build-up of organic carbon over time are low, yet biodiversity is at least an order of magnitude higher than anywhere else in the ocean (Reaka-Kudla 1997).

There are also ecosystems with low species diversity but high carbon sequestration rates. In the Southern Ocean for example, the sequestration of organic carbon is high while species richness is estimated to be lower than in non-polar marine ecosystems (Bax et al. 2021), although precautions must be taken as these environments are not easily accessible for sampling. Protection of these ecosystems safeguards the 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 storage, and possibly sequestration (CS 8) in oceans beyond national jurisdiction (Arrigo et al. 2008; Barnes et al. 2016).

In most of the case studies reported here (Figure 1, Table 2), conserving biodiversity in multi-use and multi-functional ‘scapes comes with a number of synergistic effects that help improve the quality of life of local people through the provisioning of context-specific NCP. Such NCP could be materials (food, timber, fuelwood, fodder, medicinal plants) or regulating (water availability), or cultural/tourism related non-material NCP (sense of place, cultural or sacred/religious heritage protection, ecotourism). In 2010, the Kailash Sacred Landscape Conservation and Development Initiative was launched covering parts of India, Nepal and China (CS 1) with the aim to contribute to local development and conservation – protecting threatened species (i.e., snow leopard, musk deer) and their habitats through a range of activities, such as reforestation, rangeland and farmland management. This initiative has great potential to generate climate change mitigation and adaptation co-benefits through carbon sequestration and storage in natural systems – in forests, rangelands and soils (Aryal et al. 2018; Joshi et al. 2019; Liniger et al. 2020; Uddin et al. 2015). In addition, the initiative has benefited local and distant users through a range of NCP, such as timber, fodder, fuel wood, medicinal plants, water (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 Kailash Mountain and Mansarovar (cultural/religious sites), and the promotion of eco-tourism (Adler et al. 2013; Pandey et al. 2016). Kailash Sacred Landscape also benefits distant downstream users through the (continued) provision of flowing waters for irrigation and other purposes (including hydro-power generation) by protecting the sources.

Other such co-benefits have been reported in various ‘scapes throughout the world. For example, about 50% of the poor people among the 7.2 million people of India and Bangladesh rely on Sundarbans (CS 6) for multiple benefits of nature (carbon sequestration, gas regulation, disturbance regulation) (IUCN 2017, 2020). Similarly, conservation measures have generated co-benefits to residents in cities (e.g., Beatley

2016) which typically concentrate multi-uses and multi-functional spaces crossed by islands of biodiversity (cf. 2.7 and CS 5). The Coral Triangle Initiative (CS 4) is another example that generates multiple benefits from nature of local to regional significance (Friess et al. 2020). Such co-benefits are captured in the form of improvements to coastal water quality, nursery areas for fish, coastal protection, and maintenance of food, livelihoods, and cultural significance. In Africa, conservation of African peatlands yields high value water services to local people (CS 12). However, not all forms of 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) contributions from nature (CS 1, 3, 4; Uddin et al. 2013).

The success of conservation measures is contingent on the extent of the operational and governance challenges encountered in implementing them. For example, in Amazonia (CS 10), the carbon sink function of rainforests is being negatively impacted by activities such as deforestation and the expansion of cattle and soybean production (Malhi et al. 2008), mining (Rosa et al. 2018), and the construction of big dams (Fearnside 2016). In Pleistocene Park, the CH_4 released by large re-introduced animals could negatively affect the carbon cycle (Falk et al. 2015; Schmitz et al. 2018) (CS 11). Similarly, biodiversity and nature's contributions to people (fuelwood, fodder, water availability) have been adversely affected by the reforestation of dryland ecosystems (grasslands, savannah, forests) with exotic species (*Acacia* spp.) in Africa (CS 9). In all cases, it appears that without strong policy and operational coherences between countries, outcomes of the conservation measures would remain sub-optimal (cf. 3.3).

Biodiversity conservation successes that generate climate change-related co-benefits depend on the consideration of the values held by the key stakeholders affected by such measures, primarily the indigenous and local people. Among the case studies examined, the differing values held by different groups of people are reflected in their actions in conservation or management of the 'scapes. Some examples include the cultural values attached to sacred places in the Kailash Sacred Landscape (CS 1), the strong dependency of indigenous people on forest resources for identity and livelihoods in Amazon (CS 10), fishermen and their dependency on material benefits from fishing in the Coral Triangle (CS 4) and the Sundarbans (CS 6), and the strong and traditional livelihood linkages of local people with their surrounding ecosystems in Africa (CS 9).

3.3. Evaluating trade-offs

Some biodiversity conservation measures and traditional land- and sea-scape management have trade-offs with climate change mitigation. In South Africa, wildfire management measures that limit bush encroachment and maintain open ecosystems contribute to surface cooling effects and biodiversity conservation by maintaining a high albedo surface, and provide a variety of NCP that support the livelihoods of local people (e.g., extensive grazing and thatching) (e.g., Creed et al. 2019). However, the carbon storage achieved through these measures are small compared to that provided by large-scale afforestation (Wigley et al. 2020). Similarly, traditional grazing of livestock in Europe such as cattle, sheep and goats, whose primary purpose is to produce food (meat, milk, cheese, etc), can also contribute to shaping and maintaining cultural landscapes as well as various ecosystem services such as water supply and flow regulation, carbon storage, erosion control, pollination (CS 2) (D'Ottavio et al. 2017). However, ruminant livestock produce large amounts of methane, but there is conflicting evidence about whether carbon storage achieved through grazing is sufficient to offset methane emission by livestock (Bengtsson et al. 2019). Trade-offs also appear with the paddy rice cultivation in terraced fields in Southeast Asia that provides various NCP to local people, such as food production, water flow regulation, and sediment control, while the traditional cultural landscape shaped by paddy farming is also an important tourism resource for the livelihoods of locals (CS 3). However, rice paddies are known to be very large sources of methane emissions (Saunois et al. 2016; Zhang et al. 2020), which is reportedly concentrated during the monsoon season (Hayashida et al. 2013).

Trade-offs in NCP have spatially differentiated consequences for their stakeholders with various types of flow of nature's contributions from providers to beneficiaries (Fisher et al. 2009; Syrbe & Walz 2012; Serna-Chavez et al. 2014). While beneficiaries of climate mitigation through improved carbon storage from, for instance, nature restoration, are spread across the globe, the restored nature can provide other NCP to locals such as water and soil regulation. Decisions on land- and sea-scape uses are mostly determined locally for the benefit of locals, but it sometimes go counter to global benefits. For instance, Sundarbans mangroves are one of the largest mangrove forests in the world stretching across India and Bangladesh (CS 6). These and other mangrove forests contribute to global scale climate mitigation. Mangrove forests also provide other vital contributions such as firewood and timbers, fish and shrimps, water quality, sediment retention, and disturbance regulation against extreme weathers such as cyclones and storm, most of which are benefited by locals to sustain their livelihood (IUCN 2020; Sannigrahi et al. 2020a), while other contributions such as recreation and tourism are appreciated not only by locals but also by visitors. The use of mangroves for one of such contributions (e.g., aquaculture of fish and shrimps) will inevitably affect the state of the other contributions (e.g., carbon storage, water and soil regulation). Many existing studies on Sundarbans mangroves demonstrated that climate regulation is one of the vital NCP along with habitat provision and disturbance regulation (Sannigrahi et al. 2020a, 2020b). However, these nature's contributions carry less weight in decision-making by locals who often prioritize the production and use of NCP that bring direct benefits and revenues to local stakeholders and governments, and, in the end, mangrove forests are altered to aquaculture and tourism sites, diminishing mangrove's contribution to climate change mitigation (Uddin et al. 2013). The Sacred Landscape of Kailash is faced with a similar challenge due to the growing demand of tourism in the area which results in increased water and energy consumption, forest degradation, causing a trade-off with climate change mitigation (Nepal et al. 2018; Pandey et al. 2016). This contrasts with consideration of climate change adaptation which has direct implications for local communities.

Biodiversity conservation measures can 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 within and across nations. Transboundary cooperation by multiple countries can help manage trade-offs among multiple NCP and simultaneously address biodiversity conservation, climate change mitigation and adaptation at regional level. For instance, the Coral Triangle Initiative (CS 4), which involves six participating countries (i.e., Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands and Timor-Leste) in the Pacific and Indian Ocean, has developed marine protected area networks along with other joint efforts such as the identification of priority seascapes and spatial planning (Weeks et al. 2014; Asaad et al. 2018) that balance biodiversity measures, climate measures, and socio-economic development at regional scale. In a similar manner, the Kailash Sacred Landscape Conservation and Development Initiative (CS 1) jointly established by China, India and Nepal, for the conservation of ecosystems, biodiversity, and quality of life along with cultural heritage of the pilgrimage to Mount Kailash, has contributed to establishing transboundary protected area networks and improving livelihood of locals (Zomer & Oli 2011). The consensus building process among concerned countries is key to make the transboundary initiatives successful. This is especially true for the establishment of protected areas on the high seas, where agreement of member states is required under a multilateral environmental instrument to protect biodiversity, and is currently under negotiation by the UN (Tessnow-von Wysocki & Vadrot 2020). The South Orkney Islands Southern Shelf Marine Protected Area (CS 8) is a good example of a successful transboundary conservation effort in high seas. While the primary objective is the conservation of biodiversity in the region, its high carbon storage and sequestration capacity also contributes to climate change mitigation (Barnes et al. 2016; Trathan et al. 2014).

4. Conclusion

Species and their habitats contribute to regulate the climate system, by modifying the energy and water cycles, the consumption and production of radiatively active gases and aerosols. Actions for biodiversity conservation have not focused on this central role so far, but its recent recognition requires conservation actions to be better aligned with climate goals, and demands an assessment of where this alignment may be feasible, relevant, and non-conflictual.

Our reviews shows that many instances of conservation actions intended to slow, halt or reverse biodiversity loss can simultaneously slow anthropogenic climate change. Specifically, we identified direct co-benefits in 14 out of the 21 action targets of the post-2020 global biodiversity framework of the CBD, notwithstanding the indirect links that can as well support both biodiversity conservation and climate change mitigation. Avoiding deforestation and restoring ecosystems (especially high-carbon ecosystems such as forests, mangroves, or seagrass meadows) are among the conservation actions having the largest potential for mitigating climate change. Our analysis shows that conservation actions generally generate more mutually synergistic benefits than antagonistic trade-offs with respect to climate change mitigation. Synergies between biodiversity conservation, climate change mitigation, other NCP and good quality of life are seldom quantified in an integrated way, and the evidence base for assessing these needs to be consolidated and collected routinely. The assessment of biodiversity and climate synergies would greatly benefit from the development of fully integrated indicators, models and scenarios which would also facilitate decision-making for mainstreaming and applying ecosystem-based integrative approaches, while recognizing the multi-use and multi-function dimension of 'scapes.

Improving the linkages between the different scales of actions is essential for successfully implementing joint biodiversity and climate actions. Locally motivated biodiversity conservation actions can be incentivized, guided and prioritized by international objectives and targets, including climate mitigation and adaptation objectives. However, this should be done rigorously and based on evidence to avoid oversimplified objectives that assume positive synergies between biodiversity and climate too systematically, such as subsidizing large-scale tree-planting campaigns regardless of local needs and socio-economic contexts. Choosing the right options locally is indeed crucial. Local initiatives matter since the benefits of many small and local biodiversity measures accumulate to make a large contribution to climate mitigation, while also providing multiple local benefits.

At the landscape or seascape level, many areas of high biodiversity have also high rates of carbon sequestration. However, there are exceptions to the generally positive synergy between biodiversity conservation and climate change mitigation. The realization of synergistic benefits 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 single small part of a landscape or seascape, but achieving synergies becomes progressively easier at the 'scape level. Therefore, local to global policies and practices designed for biodiversity conservation and climate change mitigation should be considered in an integrated and consultative way in mixed-use land- and sea-scapes so that win-win synergies and nature's contributions to people can be maximised.

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Author contribution

Y.J.S., G.F.M., H.T.N., S.H., R.P., O.H.G., J.S., L.C., G.I., E.A. conceived the initial ideas of the paper, and all authors reviewed the literature and wrote the manuscript.

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Supplementary Material

Actions to halt biodiversity loss generally benefit the climate

Shin, Y. J.*, Midgley, G. F., Archer, E., Arneth, A., Barnes, D. K., Chan, L., Hashimoto, S., Hoegh-Guldberg, O., Insarov, G., Leadley, P., Levin, L. A., Ngo, H. T., Pandit, R., Pires, A. P. F., Pörtner, H. O., Rogers, A. D., Scholes, R. J., Settele, J., Smith, P.

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Content :

Table S1 : Literature references supporting Table 1

Table S2 : Literature references supporting Figure 1 and Table 2

Table S3 : Full description of case studies supporting Figure 1, Table 2 and section 3

References

Table S1 : Literature references supporting Table 1

Post2020 action targets	Biodiversity measures	Effects on climate change mitigation	Reliability of mitigation outcome
T1. Biodiversity-inclusive spatial planning addressing land/sea use change, retaining intact and wilderness areas	Avoiding degradation of permafrost areas	Cahoon et al. 2012; Falk et al. 2015; te Beest et al. 2016; Schmitz et al. 2018; Beer et al. 2020	Falk et al. 2015; Schmitz et al. 2018
	Avoided deforestation	Gullison et al 2007; Johnson et al., 2019 ; West et al., 2019	Ekawati et al 2019 ; Gizachew et al 2017
T2. Restoration of at least 20% of degraded ecosystems, ensured connectivity and focus on priority areas	Reforestation, avoided degradation of forests	Mackey et al 2020; McNicholl et al 2018 ; Romijn et al 2011 ; Sileshi 2016 ; Kemppinen et al 2020 ; Bond et al 2019; Abreu et al 2017	Mackey et al 2020 ; Laurance et al 2016 ; Queensland Dept Science, Information and Technology and Innovation 2017 ; McNicholl et al 2018 ; Sileshi 2016 ; Kemppinen et al 2020 ; Lewis et al 2019 ; Stevens et al 2017 ; Abreu et al 2017 ; Panfil & Harvey 2015
	Coastal restoration	Pendleton et al 2011; Stankovic et al. 2021; Lovelock and Duarte 2019; Pendleton et al 2012; Hoegh-Guldberg et al. 2019 a,b	Hoegh-Guldberg 2019b; Lovelock and Duarte 2019; Pendleton et al 2011; Bayraktarov et al. 2020
	Restoring degraded semi-arid ecosystems	Chappell et al 2016, 2019; Yusuf et al 2015 ; Fensholt et al 2012	Byron-Cox 2020 ; Yusuf et al 2015 ; Gosnall et al 2020
	Restoring inland wetlands	Spencer et al. 2016; Pangala et al. 2017	Gallego-Sala et al. 2018; Pangala et al. 2017
	Biodiversity offsets	Sonter et al. 2020; Ermgassen et al. 2019; Sonter et al. 2020	Bull and Strange 2018; Ermgassen et al. 2019
T3. Well-connected and effective system of protected areas, at least 30% of the planet	Expanding networks of protected areas and corridors	Melillo et al., 2016; Shi et al., 2020; Dinerstein et al., 2020; Jantz et al., 2014	Dinerstein et al., 2020
T4. Recovery and conservation of species of fauna and flora	Rewilding with large terrestrial mammals	Schmitz et al. 2018; Hooper et al. 2012	Schmitz et al. 2018; Hooper et al. 2012
	Rebuilding marine megafauna	Mariani et al. 2020 ; Lavery et al. 2010 ; Roman and McCarthy 2010 ; Passow and Carlson 2012 ; Heithaus et al. 2014 ; Atwood et al. 2015 ; Wilmers et al. 2012	Pershing et al. 2010 ; Atwood et al. 2015
T5. Sustainable, legal and safe harvesting, trade and use of wild species	Sustainable fishing	Mariani et al. 2020 ; Sala et al. 2021 ; Atwood et al. 2020 ; Saba et al. 2021	Mariani et al. 2020 ; Sala et al. 2021 ; Atwood et al. 2020 ; Saba et al. 2021
T7. Reduced pollution from all sources, including excess nutrients, pesticides, plastic waste	Reducing pollution from excess nutrients	Rabalais et al. 2014 ; Naqvi et al. 2010	Engle 2011 ; Jahangir et al. 2016
T9. Ensured benefits, incl. food security, medicines, and livelihoods, through sustainable management of wild species	Sustainable harvesting of wild species	Mariani et al. 2020 ; Sala et al. 2021 ; Atwood et al. 2020 ; Saba et al. 2021	Mariani et al. 2020 ; Sala et al. 2021 ; Atwood et al. 2020 ; Saba et al. 2021
T10. All areas under agriculture, aquaculture and forestry are managed sustainably, through biodiversity conservation and sustainable use, and increased productivity and resilience	Biodiversity friendly agricultural systems	Leippert et al., 2020; VanBergen, 2020; Wanger et al., 2020 ; Creed et al., 2018	Smith et al., 2020a; Tamburini et al., 2020
	Intensive vs less intensive agriculture	Van Meijl et al 2017; Balmford et al 2018	reliability depending on dietary preferences; Van Meijl et al 2017
	Combatting woody plant encroachment	Stevens et al., 2017; Bond & Midgley, 2012; Wigley et al., 2020; Ministry of Environment and Tourism, 2011	Smit et al., 2016; Creed et al., 2019; van Wilgen et al., 2012
T12. Increased area of, access to, and benefits from green/blue spaces	Increasing benefits from biodiversity and	UN DESA, 2018; UNEN, 2020; SCBD, 2012; Chan, 2019; Beatley, 2016; Epple et al,	Epple et al., 2016; Enzi et al., 2017; Alhashimi et al., 2018; Wong et al., 2003

for health and well-being in urban areas	green/blue spaces in urban areas	2016; Enzi et al., 2017; Wong et al., 2003; Alhashimi et al., 2018; Yu, 2020; WHO, 2016	
T14. Biodiversity values integrated into policies, regulations, planning, development, poverty reduction, accounts and assessments at all levels and across all sectors	Mainstreaming biodiversity	Huntley & Redford, 2014; Redford et al., 2015; Trumper et al., 2014 ; Smith et al. 2020b	Redford et al., 2015; de Leon, 2010
T15. Dependencies and impacts on biodiversity assessed in all businesses, negative impacts halved, for sustainable extraction and production, sourcing and supply chains, use and disposal	Sustainable food production and supply chains	Albrecht et al. 2020 ; Pretty et al. 2018 ; Bajželj et al., 2014 ; Gustavsson et al., 2011 ; Xiao et al. 2017 ; Duarte et al. 2017 ; Vijn et al. 2020 ; Froehlich et al. 2019 ; Mariani et al. 2020 ; Sala et al. 2021 ; Atwood et al. 2020 ; Saba et al. 2021	Phalan et al. 2011 ; Smith et al. 2020a ; Froehlich et al. 2019 ; Duarte et al. 2017 ; Mariani et al. 2020 ; Sala et al. 2021
T16. People are informed and enabled to make responsible choices, to halve the waste and reduce overconsumption of food and other materials where relevant	Sustainable consumption patterns	Kuuluvainen et al 2019 ; Heilmayr et al 2020 ; Jia et al. 2019	Kuuluvainen et al 2019 ; Heilmayr et al 2020 ; Jia et al. 2019
T18. Redirect, repurpose, reform or eliminate incentives harmful for biodiversity in a just and equitable way	Eliminating incentives harmful for biodiversity	Coady et al., 2019; Franks et al., 2018	OECD, 2019

Table S2 : Literature references supporting Figure 1 and Table 2 (CC : climate change ; NCP : Nature's Contributions to People)

	Case study	main biodiversity measures	impacts on biodiversity	impacts on CC Mitigation	impacts on other regulating NCP	impacts on material NCP	impacts on non-material NCP
CS1	Kailash Sacred Landscape Conservation and Development Initiative	Kotru et al., 2020; Sharma et al 2010; Zomer and Oli, 2011	Kotru et al. 2020	Uddin et al. 2015; Zomer et al., 2014	Badola et al., 2017; Liniger et al., 2020	Badola et al. 2017; Tewari et al., 2020; Thapa et al., 2018; and Chaudhary et al., 2020	Adler et al., 2013; Pandey et al., 2016; Nepal et al 2018
CS2	Cultural landscapes in Central Europe	Tieskens et al. 2017; Bengtsson et al. 2018	Tieskens et al. 2017; Bengtsson et al. 2018	Bengtsson et al. 2018	Bengtsson et al. 2018	Schaub et al. 2020	Tieskens et al. 2017; Bengtsson et al. 2018
CS3	Irrigated rice terraces and forests in South-East Asia	Dominik et al. 2018; Settele et al. 2018	Dominik et al. 2018, Settele et al. 2018	Saunois et al 2016; Zhang et al. 2020	Sattler et al. 2020	Settele et al. 2018	Settele et al. 2018
CS4	The Coral Triangle Initiative	Kleypas et al. 2021; Warren et al. 2018; Alongi 2014; Alongi & Mukhopadhyay, 2015)	Hoegh-Guldberg et al. 2009; Kleypas et al. 2021; Alongi 2014; Alongi & Mukhopadhyay, 2015; Williams et al. 2017	Stankovic et al. 2021; Kleypas et al. 2021; Lovelock and Duarte 2019; Hoegh-Guldberg et al. 2009; Alongi 2014; Alongi & Mukhopadhyay, 2015); Hoegh-Guldberg et al. 2019a,b	Stankovic et al. 2021; Quevedo et al 2021	Linggi et al. 2019; Anugrah et al. 2020; Quevedo et al 2021	Hoegh-Guldberg et al. 2009; Chan et al. 2019
CS5	Biodiversity-friendly cities and urban areas	Friess et al, 2015; Everard et al., 2014; Alongi 2014; Alongi & Mukhopadhyay, 2015)	Friess et al, 2015; Everard et al., 2014; Alongi 2014; Alongi & Mukhopadhyay, 2015)	Alongi 2014; Alongi & Mukhopadhyay, 2015; Alongi et al., 2016; Bulmer et al., 2020; Donato et al., 2011)	Friess et al., 2015	Alongi et al., 2016	Alongi et al., 2016; Alongi & Mukhopadhyay, 2015;
CS6	The Sundarbans (India-Bangladesh)	IUCN, 2017; Awty-Carroll et al., 2019; Mukul et al., 2019; IUCN, 2020	IUCN, 2017; Awty-Carroll et al., 2019; Mukul et al., 2019; IUCN, 2020	Sannigrahi et al., 2020a, b	Sannigrahi et al., 2020a, b	Uddin et al., 2013; Hossain et al., 2016	
CS7	Southern Ocean South Georgia Island	Barnes et al., 2011; Trathan et al., 2014	Hogg et al., 2011; Trathan et al., 2014	Barnes & Sands, 2017	Trathan et al., 2014; Cavanagh et al., 2021	Trathan et al., 2014; Cavanagh et al., 2021	Trathan et al., 2014; Cavanagh et al., 2021
CS8	Marine Biodiversity Beyond National Jurisdiction, South Orkney Islands	Trathan & Grant, 2020	Trathan & Grant, 2020	Barnes et al., 2016	Grant et al., 2013; Cavanagh et al., 2021	Grant et al., 2013; Cavanagh et al., 2021	Grant et al., 2013; Cavanagh et al., 2021
CS9	Bush encroachment Southern Africa	Joubert et al., 2012; Smit et al., 2016	Stevens et al., 2017	Ministry of Environment and Tourism, 2011); Bond et al., 2005, Stevens et al., 2017	Ministry of Environment and Tourism, 2011; Bond et al., 2005, Stevens et al., 2017	Creed et al., 2019; McNulty et al., 2018	van Wilgen et al., 2012
CS10	Amazonian rainforest	Soares-Filho et al 2010; Joly et al 2018; Scarano et al 2018	Ribeiro et al 2016; Joly et al 2018	Soares-Filho et al 2010; Hall 2008: Malhi et al	Hall 2008; Castello et al 2013; van Soesbergen &	Scarano et al 2020; Goulding et al	Soares-Filho et al 2010, Pires et al 2019; Joly et al 2018

				2008;Phillips et al 2017	Mulligan 2014; Joly et al 2018	2019; Joly et al 2018	
CS11	Pleistocene Park, Northeastern Siberia	Zimov 2005; Kintisch, 2015	Beer et al., 2020	Cahoon et al., 2012; Falk et al., 2015; te Beest et al., 2016; Schmitz et al., 2018	Macias-Fauria et al., 2020	Macias-Fauria et al., 2020	Kintisch, 2015; Macias-Fauria et al., 2020
CS12	African peatlands	Dargie et al., 2019)	Dargie et al., 2017, 2019; Fay and Agangna 1991; Rainey et al, 2010; Inogwabini et al. 2012; Riley and Huchzermeyer 1999	Dargie et al., 2017, 2019; Hooijer et al., 2010; Könönen et al., 2016	Dargie et al., 2019	Dargie et al., 2019; Jauhiainen et al. 2012	Dargie et al., 2019

Table S3 : Full description of case studies supporting Figure 1, Table 2 and section 3. Biodiversity and conservation objectives are described, as well as the potential effects on climate change mitigation, the main nature's contributions to people, the trade-offs and synergies between multiple uses and functions of the ecosystems, and when relevant the main governance challenges, underlying cross-sectoral and transboundary aspects.

Case Study number	Description
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). Honey and associated pollination services are also forest by-products. 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 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 marine 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-fishing) and global (e.g., sea-level rise, ocean warming and acidification) stressors (Burke et al., 2012). Sea level rise is a considerable challenge with ecosystems such as mangroves and seagrass beds, where shoreward migration 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 NCPs 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 NCPs, 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 even though 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 people, 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, Pilla, 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 South Georgia Island
	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 centered 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 y^{-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, Northeastern 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 M. 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; 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 GHGs 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 112.2 $GtCO_2e$ 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) 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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