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How do we best synergise climate mitigation actions to co-benefit biodiversity?

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Abstract:	A multitude of actions to protect, sustainably manage and restore natural and modified ecosystems can have co-benefits for both climate mitigation and biodiversity conservation. Reducing greenhouse emissions to limit warming to less than 1.5 or 2°C above preindustrial levels, as outlined in the Paris Agreement, can yield strong co-benefits for land, freshwater and marine biodiversity and reduce amplifying climate feedbacks from ecosystem changes. Not all climate mitigation strategies are equally effective at producing biodiversity co-benefits, some in fact are counterproductive. Moreover, social implications are often overlooked within the climate-biodiversity nexus. Protecting biodiverse and carbon-rich natural environments, ecological restoration of potentially biodiverse and carbon-rich habitats, the deliberate creation of novel habitats, taking into consideration a locally adapted and meaningful (i.e., full consequences considered) mix of these measures, can result in the most robust win-win solutions. These can be further

enhanced by avoidance of narrow goals, taking long term views and minimising further losses of intact ecosystems. In this review paper, we first discuss various climate mitigation actions that evidence demonstrates can negatively impact biodiversity, resulting in unseen and unintended negative consequences. We then examine climate mitigation actions that co-deliver biodiversity and societal benefits. We give examples of these win-win solutions, categorised as 'protect, restore, manage and create', in different regions of the world that could be expanded, upscaled and used for further innovation.

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Abstract

A multitude of actions to protect, sustainably manage and restore natural and modified ecosystems can have co-benefits for both climate mitigation and biodiversity conservation. Reducing greenhouse emissions to limit warming to less than 1.5 or 2°C above preindustrial levels, as outlined in the Paris Agreement, can yield strong co-benefits for land, freshwater and marine biodiversity and reduce amplifying climate feedbacks from ecosystem changes. Not all climate mitigation strategies are equally effective at producing biodiversity co-benefits, some in fact are counterproductive. Moreover, social implications are often overlooked within the climate-biodiversity nexus. Protecting biodiverse and carbon-rich natural environments, ecological restoration of potentially biodiverse and carbon-rich habitats, the deliberate creation of novel habitats, taking into consideration a locally adapted and meaningful (i.e., full consequences considered) mix of these measures, can result in the most robust win-win solutions. These can be further enhanced by avoidance of narrow goals, taking long term views and minimising further losses of intact ecosystems. In this review paper, we first discuss various climate mitigation actions that evidence demonstrates can negatively impact biodiversity, resulting in unseen and unintended negative consequences. We then examine climate mitigation actions that co-deliver biodiversity and societal benefits. We give examples of these win-win solutions, categorised as 'protect, restore, manage and create', in different regions of the world that could be expanded, upscaled and used for further innovation.

Keywords

Climate change mitigation, biodiversity, nature-based solutions, co-benefits, trade-offs

* This review is based on work conducted for section 3 of the report on the scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change (Pörtner et al., 2021).

1. Introduction

Presently, more than 50% of annual anthropogenic CO_2 emissions are (physically and biologically) absorbed in land and oceans (Friedlingstein et al., 2020); terrestrial and coastal ecosystems (blue carbon) store >5 times the amount of carbon than is contained in the atmosphere. Indeed, without land and ocean carbon sinks, the concentration of atmospheric CO_2 would be in excess of 600 ppm; (Friedlingstein et al., 2020). Maintaining or enhancing these natural sinks and ensuring long-term carbon storage in biomass, soils or sediments is an important aspect of climate change mitigation, and in avoiding exacerbating global warming (Ciais et al., 2013). Many different climate change mitigation measures exist (considering not only CO_2 emission and uptake, but also CH_4 and N_2O emissions) that target the use of terrestrial, freshwater and marine ecosystem processes or space. Each of these differ considerably in terms of their mitigation potential and the degree to which they have positive or negative impacts on human societies' adaptive capacity or on biodiversity, as well as in their scalability and cost-effectiveness.

Approaches can vary regionally both in terms of meeting mitigation targets and the consequences they have for biodiversity and human societies. In particular, some land-based negative emission technologies that claim a cumulative potential CO_2 uptake over the next century of hundreds of Gt have been criticized as being ecologically unrealistic, likely to impact negatively on local people's wellbeing, and leading to a false sense of security, which encourages the adoption of risky (delayed) emissions-reduction pathways (Arneth et al., 2019; Dooley & Kartha, 2018; Girardin et al., 2021; Smith et al., 2020). Some of these mitigation options are also vulnerable to climate change itself (e.g., net carbon fluxes into marine and land ecosystems can be reversed in warmer or drier climates) and thus contribute to positive climate feedbacks (Ciais et al., 2013). However at least some marine biodiversity and carbon sinks have increased coincident with climate change so far (Barnes et al., 2018; Bax et al., 2021) and may be robust to a 1°C, but as little a rise as 2°C may halt this (Ashton et al., 2017). West Antarctic open continental shelves have doubled the standing stock of carbon in response to seasonal sea ice losses over the last 25 years (Barnes 2015). Another example is that the number of West Antarctic glaciers retreating has increased as has their retreat rate, increasingly exposing fjords which are accumulating new biodiversity and carbon storage (Zwerschke et al. 2022).

While ecosystems can contribute to mitigation over time, the bulk of mitigation efforts need to come from rapid, ambitious emissions reductions in fossil fuel emissions to meet the Paris Agreement target of keeping climate change well below 2°C (Girardin et al., 2021; Hoegh-Guldberg et al., 2019). Ecosystem interventions do not necessarily deliver co-benefits for biodiversity or help with addressing other societal challenges, but many can do so, if implemented so that they enhance biodiversity and are community-led. In such cases, they can constitute nature-based solutions, the IUCN (2016) definition of which is as follows: "Nature-based solutions are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." The definition encompasses the definition of ecosystem-based adaptation, "the use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change". By biodiversity, we mean "the variety of life: the diversity of all living organisms from the various ecosystems of the planet. It includes diversity within species, between species and of ecosystems in which they live" (Secretariat of the Convention on Biological Diversity, 2005).

Nature-based solutions are not a substitute for the rapid decarbonisation of all sectors of the economy, but can be a complementary solution to effectively address the joint challenges of climate change and biodiversity loss. To achieve this they must be well-designed, properly implemented and efficiently managed, and longevity, target species, appropriate participatory approaches, state of current habitat and scale etc. need to be considered (Girardin et al., 2021). Nature-based solutions currently focus on the protection of intact ecosystems, managing working lands, restoring native cover and creating novel ecosystems in urban settings. Such activities score high on mitigation, biodiversity and adaptation co-benefits, and can be cost effective and scalable.

Evidence for policymakers is currently available to inform decision makers (i.e., target setting) regarding nature-based solutions for climate change mitigation. In this synthesis, we consider a range of specific mitigation approaches. We showcase actions that result in co-benefits for both biodiversity and climate change and people, demonstrating that adopting dynamic approaches to conservation will allow for flexible responses, and leverage nature's capacity to contribute to climate change mitigation (Shin et al., 2022) and adaptation. The most robust path to progress in limiting climate change while safeguarding biodiversity depends not just on the identification of the strongest win-win solutions to pursue by region, but also to eliminate demonstrably inadequate – or worse, lose-lose interventions. This needs to take place before counterproductive societal or environmental outcomes become 'locked-in' (Pascual et al., 2022). Nature-based solutions have been underutilized and could help in long term global cooling, but they must be designed for longevity and avoid a focus on rapid sequestration as a sole measure of value (Girardin et al., 2021).

In this synthesis, which was prepared as a contribution to the IPBES-IPCC co-sponsored workshop on biodiversity and climate change, we examine which interventions implemented to reduce greenhouse gas emissions and remove greenhouse gases from the atmosphere, risk harming biodiversity outcomes, and which provide synergies with biodiversity enhancement, before examining the context in light of the Paris Agreement and the CBD post-2020 global biodiversity framework, before providing conclusions.

2. Climate change mitigation actions that risk harming biodiversity outcomes

Not all interventions in land and ocean ecosystems that aim to deliver climate change mitigation are necessarily beneficial for biodiversity, so irrespective of the climate change or societal benefits that they may deliver, could not be considered nature-based solutions. In this section, we outline some of the ecosystem interventions, and technological interventions that affect land or ocean-based ecosystems, that risk harming biodiversity outcomes.

2.1 Challenges arising from competition for land

2.1.1 Planting trees over large areas

Reforestation and afforestation are considered relatively cost-effective climate change mitigation options (Fuss et al., 2018). Besides the carbon removal from the atmosphere and its storage in biomass during tree growth, which is a once-off benefit, there is a substantial potential (10-700 Tg (million tonnes of carbon), equivalent to 0.04-1.6 Gt CO_2e) for substituting emissions-intensive materials such as concrete and steel using timber-based materials. This carbon then becomes stored in buildings for decades, or even centuries (Churkina et al., 2020), and the forests can be repeatedly harvested.

Recent claims of a potential to reforest massive areas (up to 9 Mkm^2) (Bastin et al., 2019) have been criticised for having serious methodological flaws and ignoring important ecological and societal processes (Friedlingstein et al., 2019; Grainger et al., 2019; Lewis et al., 2019; Skidmore et al., 2019; Veldman et al., 2019). Existing international activities such as the "Bonn challenge", which aims to restore 3.5 Mkm^2 of forested landscapes by 2030, could, if successful in the long term deliver substantial mitigation benefits, and may do so with co-benefits to biodiversity in some situations –

such as if they help rehabilitate degraded lands or restore forests that have been cleared (e.g., Lewis et al., (2019). But if implemented poorly, they may promote the wasteful usage of the planted forests as sources of bioenergy and/or be detrimental to existing ecosystems' carbon storage, climate regulatory functions, biodiversity, and reduce food security (Abreu et al., 2017; Fuss et al., 2018; Holl & Brancalion, 2020; Veldman et al., 2015). Large expansion of land committed to forest (or to bioenergy crops; see 2.1.2) competes for land used for food production, either within a region or in the form of indirect land-use change, where the land uses they replace are simply moved to other areas (Fuss et al., 2018; Holl & Brancalion, 2020). Replacement of sparse seasonal vegetation by evergreen, high leaf area, rapidly transpiring forests or tree crops reduces freshwater availability in rivers (Cao et al., 2016; Zheng et al., 2016). Afforestation or other mitigation-oriented land uses may dispossess local people of access to land (Dooley & Kartha, 2018; Holl & Brancalion, 2020). Monocultural plantations have little or no positive impact on biodiversity, and can be detrimental if the planted species becomes invasive or outcompetes the native species (Brundu & Richardson, 2016). Relying on tree biomass for long-term carbon sequestration is risky, particularly in monocultures with high vulnerability to storms, fire or pest outbreak (Anderegg et al., 2020).

Mitigating climate change by devoting vast land areas globally to reforestation and afforestation, an assumption still integral to many climate change mitigation scenarios, should not be considered good solutions (Arneth et al., 2019; Fuss et al., 2018; Smith et al., 2020). By contrast, more modest reforestation projects that are adapted to the local socioecological context and consider local as well as distant trade-offs, can be an important component of climate change mitigation, biodiversity protection and contributions to a good quality of life (see section 3.3).

2.1.2 Large areas of bioenergy crops

Most global climate change mitigation pathways in the IPCC SR1.5 report (IPCC, 2018) rely heavily on the deployment of biomass for bioenergy, often used in conjunction with carbon capture and storage (BECCS) (full range: 40–310 EJ a^{-1}, primary energy, in 2050; (Rogelj et al., 2018); rates at the upper end of these scenarios are equivalent to >50% of today's total global primary energy consumption of approximately 580 EJ yr^{-1}). BECCS is expected to support the decarbonization of the energy system with annual removal rates up to 15 Gt CO_2 yr^{-1} (more than 1/3 of today's annual anthropogenic emissions of ca. 40 Gt CO_2) in 2100 (IPCC 2018) but in existing scenarios the required biomass is produced on the land with significant consequences for biodiversity and ecosystem services (Smith et al., 2020). In addition to jeopardizing Sustainable Development Goal (SDG) 15 (life on land), attempting to use millions of hectare of land for bioenergy rather than food production would seriously undermine the fight against hunger (SDG 2) (Dooley & Kartha, 2018).

In principle, when woody or perennial grass bioenergy crops are planted in severely degraded areas, or as a non-dominant component of agricultural landscapes previously dominated by single mono-cultural crops, biodiversity could benefit (Landis et al., 2018; Rowe et al., 2013) and enhance the portfolio of ecosystem services, especially when established in agricultural landscapes dominated by annual crop production. In these environments, bioenergy crops could increase landscape heterogeneity and hence habitat diversity. By contrast large areas of monoculture bioenergy crops that displace other land uses (especially land which is under natural or near-natural ecosystems) will have negative implications (Hof et al., 2018; Humpenöder et al., 2018; Newbold et al., 2016). In addition, nitrogen fertilizer and pesticide use on the bioenergy crop could affect biodiversity negatively in adjacent land, freshwater and marine ecosystems (Maxwell et al., 2016). Large-scale bioenergy crop production can affect freshwater ecosystems through changes in the magnitude of runoff or its water quality (Cibin et al., 2016), and by increasing agricultural water withdrawals for irrigation of dedicated bioenergy crops (Bonsch et al., 2016; Hejazi et al., 2014). Nitrogen fertilization can lead to freshwater and coastal eutrophication, harmful algal blooms and dead zones which are exacerbated by ocean warming. Harvesting high proportions of agricultural and forest residues for bioenergy can have negative implications on soil fertility, erosion risk, and soil carbon (Liska et al., 2014) . A global second generation bioenergy potential of 88 EJ yr^{-1} has been estimated after applying EU renewable energy sustainability criteria everywhere, with the authors cautioning that this may reduce to 50 EJ yr^{-1} when uncertainties related to future crop yields have been considered (Schueler et al., 2016). A potential of around 60 EJ yr^{-1} have also been suggested as a conservative estimate, based on studies that restrict bioenergy crops to 'marginal' land and exclude expansion into currently protected areas (Fuss et al., 2018).

2.1.3 Fuel switching

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

2.1.4 The influence of supply chains

The expansion of global trade has brought about an increase from 22 billion tonnes in 1970 to 70 billion tonnes in 2010 in global material extraction (including fossil fuels, biomass, metal ores, and non-metallic minerals) (UNEP et al., 2016). Extraction rates are considered to be accelerating beyond sustainable levels (Bringezu, 2015). In 2011, carbon emissions embodied in trade accounted for 21% of global emissions (OECD, 2019). Many of the industries in this global trade generate large amounts of GHG such as agriculture and mining with direct and indirect (such as deforestation) impacts on biodiversity and ecosystem integrity. Between 1990 and 2010, an average of 32.8 Mt CO_2e emissions were embodied in meat (beef, pork and chicken) traded internationally (Caro et al., 2014), which brought important environmental and biodiversity costs to the country providing the goods (Galloway et al., 2007). The same is true for agricultural trade (Balogh & Jámbor, 2020). About 30% of global species threats are associated with the international trade of commodities (Lenzen et al., 2012).

2.2 Regional climate trade-offs and synergies arising from biophysical and biogeochemical processes

In addition to their climate effects through altering the atmospheric concentrations of CO_2 and other greenhouse gases, land-based mitigation measures can affect climate through biophysical mechanisms, including local climate feedbacks that may in some regions be different in terms of direction from global effects. These biophysical processes can even have climate impacts thousands of kilometres away, although these ‘teleconnections’ are still poorly understood (Jia et al., 2019). Many of these effects are not included in UNFCCC mitigation project guidelines, compromising the full quantification of mitigation effectiveness (Duveiller et al., 2020). ‘Biophysical’ processes are mostly related to changes in the surface energy balance though alteration of reflectance (albedo) and evapotranspiration (Perugini et al., 2017). Although the net climate impact from biophysical processes arising from land cover changes (including for climate change mitigation) is considered to be globally small, these processes can result in local or regional cooling or warming, as well as impacting precipitation (Jia et al., 2019; Perugini et al., 2017). For instance, forest restoration in tropical regions, with often large evapotranspiration rates, causes local cooling as a climate co-benefit (Alkama & Cescatti, 2016; Perugini et al., 2017). By contrast, reforestation in the boreal region can result in increased surface warming when dark, evergreen conifer foliage absorbs solar radiation that would otherwise have been reflected by a snowy background (i.e., a ‘climate trade off’). The local cooling due to the formation of secondary organic aerosols in boreal forests from emissions of biogenic volatile organic carbon (BVOC), which may offset part of this warming so far is difficult to quantify (Alkama & Cescatti, 2016; Carslaw et al., 2013; Perugini et al., 2017). Bioenergy plantations with large BVOC emissions (in particular the compound isoprene) may - depending on the overall atmospheric chemical environment - lead to increased ozone formation and thus ozone-related radiative forcing, and are furthermore detrimental to human and crop health (Ashworth et al., 2013; Rosenkranz et al., 2015). In marine ecosystems, climate change feedbacks due to altered emissions of dimethyl sulphate (which affects aerosol formation and cloud properties) are often discussed (Wang et al., 2018; Woodhouse et al., 2018), but there is not yet any evidence that proposes ocean-based mitigation measures will contribute to aerosol or other biophysical-related regional climate impacts.

2.3 Impacts on biodiversity arising from technological mitigation measures

Multiple technologically focussed mitigation measures are in place or under development on land and in the oceans. Many of these are less (land) area demanding and/or are considered to have high mitigation potential. For instance, solar radiation and wind energy are discussed as being amongst the most promising renewable energy sources. At present ca. 402 GW of solar energy and ca. 650 GW of wind energy are realised (Dhar et al., 2020), magnitudes lower than their theoretical upper limit. Likewise, hydropower supplies around 16% of the world’s total electricity (Wanger, 2011; Gernaat et al., 2017) with an estimated potential of around 13 PWh yr^{-1} and a remaining potential of close to 10 PWh yr^{-1} (Gernaat et al., 2017). These numbers highlight the large scope for climate change mitigation by promoting these renewable energy sources further. Tidal power is still in its infancy and although cheap when running requires high capital investment to build, but significant successful projects in Sihwa, South Korea and Orkney, UK (amongst others) are showing strong predictable energy generation potential (enough to support up to 500,000 homes) whilst showing very low carbon footprints and environmental impact. Nevertheless, all these mitigation measures could potentially harm the environment, including biodiversity and good quality of life, through the required inputs in terms of materials, resources and land for deployment, or through toxic waste products (Dhar et al., 2020). An important aspect therefore is to develop the necessary additional mining activity with strong environmental and social sustainability criteria in mind, and to emphasise the crucial importance of a circular economy.

2.3.1 Biodiversity impacts from mining in the ocean and on land

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

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

2.3.2. Biodiversity impacts of wind power

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

Popescu et al. (2020) approached energy source comparisons by specifically considering trade-offs between GHG emissions, energy costs and biodiversity priorities at both regional and larger scales. They found the clearest benefits were from wind turbines because emissions, electricity generated and biodiversity costs were all small, at least in British Columbia, Canada.

2.3.3 Biodiversity impacts of solar power

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

2.3.4 Biodiversity impacts of hydro power

Of rivers longer than 1000 km, only 37% remain free-flowing over their entire length, often in very remote regions (Grill et al., 2019). The building of dams for freshwater storage and hydropower creation alters habitats for all freshwater organisms and blocks fish migration, leading to range contraction and population decline (though this does not apply to run-of-the-river schemes). In recent years, many newer dam projects focussed at building multiple small ones rather than one big dam, aiming to reduce environmental impact (Lange et al., 2018). These efforts have also decentralised power supply (Lange et al., 2018; Tomczyk & Wiatkowski, 2020). Nonetheless, such smaller dams can create continued habitat fragmentation and degradation (Palmeirim & Gibson, 2021), and may also result in larger transport infrastructural requirements (Popescu et al., 2020). These impacts can be reduced by appropriate infrastructure (such as low-speed turbines), planning that includes basin-scale perspectives and ecological assessment method, and integrated schemes that capture needs of riverine societies (Jager et al., 2015; Lange et al., 2018; Tomczyk & Wiatkowski, 2020).

2.3.5 Biodiversity impacts of enhanced ocean carbon uptake

Enhanced ocean uptake of CO_2 can occur through three main pathways, a) creating and restoring "blue carbon" biological sinks such as mangrove swamps and other coastal ecosystems such as seagrass beds (technical potential: <1 Gt CO_2e yr^{-1}; estimated from Froehlich et al. (2019)), b) ocean fertilization, e.g. with iron, to increase surface primary production which increases the delivery of fixed CO_2 into the deep sea (technical potential: 1-3 Gt CO_2e yr^{-1} (Minx et al., 2018; Ryaboshapko & Revokatova, 2015)), and c) increasing the alkalinity of seawater through seeding the ocean with natural or artificial alkaline materials to sequester CO_2 as bicarbonate and carbonate ions (HCO_3-, CO_3^{2-}) in the ocean (technical potential: 1-100 Gt CO_2e yr^{-1} (Fuss et al., 2018)) – similar to enhancing mineral weathering (see 2.3.7). Additional approaches include the electrochemical splitting of water into hydrogen (H+) and hydroxide (OH-) ions, which can be used through various processes to capture CO_2 or to increase alkalinity of seawater. Another is growing macroalgae at very large scales and subsequently dumping it in the deep ocean or converting it to long-lived products such as biochar and thus sequestering CO_2 over large time scales (100s – 1000s years).

Many of these approaches are conceptually feasible or have been demonstrated in the laboratory, but their consequences for the ocean, including on its biodiversity are uncertain especially if applied at scale. For example, planting mangroves at too high a tree density can reduce, rather than enhance, biodiversity (Huang et al., 2012). Some approaches such as growing macroalgae may start with restoration of natural kelp forests as a blue carbon sink, which may deliver 173 Tg C yr^{-1} in terms of export to deep waters and sequestration (Krause-Jensen & Duarte, 2016). However, it is important to look beyond traditional blue carbon habitats to embrace wider blue carbon potential, such as bivalve reef restoration (zu Ermgassen et al., 2019). Overall creating, restoring and protecting blue carbon sinks should have positive impacts on biodiversity (Bax et al., 2021; Sanderman et al., 2018). However, there are significant risks to the extent of blue carbon gains and biodiversity associated with widespread ocean fertilization (Glibert et al., 2008).

2.3.6 Biodiversity impacts of ocean-based renewable energy

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

2.3.7 Biodiversity impacts of accelerated mineral weathering

Accelerated mineral weathering involves a) the mining of rocks containing minerals that naturally react with CO_2 from the atmosphere over geological timescales, b) the crushing of these rocks to increase the surface area, and c) the spreading of these crushed rocks on soils (or in the ocean) so that they absorb atmospheric CO_2 (Beerling et al., 2018). Construction waste and waste materials can also be used as a source material (technical potential: 3.7-95 Gt CO_2e yr^{-1} (Lenton, 2014; Strefler et al., 2018)). The biodiversity impacts are largely unquantified but raising the pH when spread on some acidic soils could enhance floral diversity (Beerling et al., 2018) , whereas an increase in mining operations would likely have an adverse local impact at these sites (Younger & Wolkersdorfer, 2004).

2.3.8 Biodiversity impacts of producing biochar

Biochar is produced by pyrolysis of biomass with the resulting product applied to soils (technical potential: 0.03-6 Gt CO_2e yr^{-1} (Smith et al., 2020)). Impacts of addition to soil are unlikely to have biodiversity consequences, but the production of feedstock for pyrolysis required to provide CO_2 removal on several Gt CO_2e yr^{-1} scale was assessed by (McElwee et al., 2020) to have potential negative impacts on biodiversity.

3. Actions that benefit both climate and biodiversity

Protection and restoration of biodiverse and carbon-rich ecosystems is the top priority from a joint climate change mitigation and biodiversity protection perspective. Nature-based solutions can be a complementary solution to address these joint challenges effectively, if well-designed, properly implemented and sustainably managed, where longevity, target species, appropriate participatory approaches, state of current habitat and scale are considered (Girardin et al., 2021). Nature-based solutions currently focus on the protection of remaining intact ecosystems, managing working lands and restoring native cover. Such activities can score high on mitigation, biodiversity and adaptation co-benefits (discussed in detail below - see Table 1) and can be cost effective and scalable to varying extents. However, even when existing direct human pressures (such as conversion and overextraction) are removed, climate change poses severe threats to many of these ecosystems (e.g., through permafrost thaw, increasing risk of wildfire and insect outbreak, mangrove or kelp-forest dieback or heat impacts on tropical forests) that cannot be alleviated without halting the drivers of warming. The ambition to protect, sustainably manage and restore natural ecosystems

(Arneth et al., 2020; Watson et al., 2020) will be difficult, if not impossible, to achieve, unless climate change is simultaneously mitigated through ambitious reductions in greenhouse gas emissions from fossil fuels (Anderson et al., 2019). While the direct impacts of climate change on biodiversity are important, not least for establishing a baseline against which the biodiversity impacts of interventions can be assessed, we do not review the topic here, as it is the subject of other reviews (see sections 1 and 2 of Pörtner et al., 2021).

3.1 Protect

3.1.1 Reduction of emissions from deforestation and forest degradation

Measures that prioritise avoided deforestation combined with restoration of existing but degraded forests have large climate mitigation potential and large biodiversity co-benefits. Reducing the loss of forests has the single largest potential for reducing GHG emissions through land-based actions, with estimates ranging from 0.4–5.8 Gt CO_2e yr^{-1} (Smith et al., 2020). Considering the loss of additional sink capacity associated with deforestation (estimated as 3.3 Gt CO_2 yr^{-1} (0.9 Gt C yr^{-1}) for years 2009-2018, (Friedlingstein et al., 2020) provides an additional large mitigation incentive. Globally, less than 30% of the world's forests are considered to be still intact (Arneth et al., 2019), and less than 40% of forest area has been estimated to contain forest older than 140 years (Pugh et al., 2019). Reducing forest degradation can thus contribute, at a minimum, a further 1-2.18 Gt CO_2e yr^{-1} in avoided GHG emissions. At least for tropical forests, the area of degraded forests could well equal or even exceed the area of deforestation in many regions (Bullock et al., 2020; Matricardi et al., 2020); associated above-ground carbon losses have been estimated to increase estimates of gross deforestation losses by ca. 25% up to >600% (Maxwell et al., 2019), with possibly additional, unknown carbon lost from soils. A successful Reduction of Emissions from Deforestation and forest Degradation (REDD+) or equivalent financed at 25 US$/tonne CO_2 could reduce projected species extinctions by 84%-93% (Strassburg et al., 2012). Degradation can double the biodiversity loss arising from deforestation (Barlow et al., 2016). Regarding societal co-benefits, a model experiment showed that an equitable allocation of REDD+ funds among eligible countries lead to a larger number of countries benefiting, without significantly compromising the carbon efficiency and biodiversity outcomes. Nevertheless, for a variety of broadly governance-related issues REDD+ so far has not yet achieved the hoped-for tangible results (Angelsen et al., 2017).

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

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

Mangroves, seagrass meadows, salt marshes and kelp forests are key marine and coastal ecosystems for carbon capture and storage. The former two accumulate their carbon *in situ* (though with some export see (Barnes et al., 2019; Li et al., 2018), kelp does so by export, and salt marsh through both in situ and export. These stores are called 'blue carbon'. Mangroves contain four times more carbon per unit area than tropical upland forest (Donato et al., 2011). Despite occupying <1% of global area mangroves held more than 6 Gt C (22 Gt CO_2e) in 2000 (Sanderman et al., 2018). There can be strong interdependence of adjacent environments, for example mangroves, seagrasses and coral reefs each conveying benefits to others in terms of functioning (e.g., in nutrient release, nursery grounds and hindering erosion) thereby enhancing collective societal benefits such as carbon storage. "Blue carbon environments" can also be disproportionally biodiversity rich (per area, see (Morrison et al., 2014) and host completely different suites of species as well as providing fish nursery grounds, coastal storm and erosion protection. Up to 2000 species can be present in mangroves in a single region (Saenger et al., 1983) so climate mitigation schemes preventing their deforestation could safeguard these as well as prevent 0.1-0.4 Gt CO_2e soil carbon lost (as has been in the last 15 years, (Sanderman et al., 2018)). Conservation of non-forest carbon rich land and coastal ecosystems have important climate benefits (Atwood et al., 2020; Sala et al., 2021) with co-benefits for biodiversity. To date blue carbon quantification, associated biodiversity assessments and conservation has focussed almost entirely on the coastal shallows, which represent less than 1% of ocean ecosystem space. Even tiny remote islands and seamounts support species-rich, deep water habitats with blue carbon natural capital to values of >£1 million GBP (Barnes et al., 2019). Furthermore, in the polar regions, enhanced biodiversity under ice shelf disintegration (Peck et al 2010), sea ice loss and glacier retreat (Barnes et al., 2019) are not only emerging as major carbon sinks (>0.6 GtCO_2e.yr^{-1} for Antarctic continental shelves alone, see (Gogarty et al., 2020) but work as powerful negative feedbacks on climate change. These opening up and new polar habitats with strong ecosystem services can also be anomalously rich in endemics but face many threats and are little protected (Cavanagh et al., 2021). Protection is complex in areas beyond national jurisdiction and requires strong international co-operation and perhaps new law (Gogarty et al., 2020) but there is growing awareness of the considerable climate and biodiversity benefits for protecting such near-pristine habitats (Bax et al., 2021).

3.2 Restore

3.2.1 Restoration of degraded ecosystems

Ecosystem restoration can provide major contributions to climate change mitigation. In forests alone, estimates of annual net carbon removal from forest area expansion range from 0.5–10.1 Gt CO_2e yr^{-1} (Smith et al., 2020; Roe et al., 2019). However, current scenarios used by the IPCC do not differentiate between natural forest regrowth, reforestation with plantations, and afforestation of land not previously tree-covered, which makes assessment of biodiversity impacts difficult (Chazdon & Brancalion, 2019; Temperton et al., 2019). Peatland restoration could remove 0.15–0.81 Gt CO_2e yr^{-1} and coastal wetlands restoration has a sequestration potential of 0.20–0.84 Gt CO_2e yr^{-1} (IPCC, 2019b). Ecosystem restoration provides opportunities for co-benefits for climate change mitigation and biodiversity conservation, which are maximised if restoration occurs in priority areas for both goals. For instance, restoring 30% of converted lands in priority areas for climate change mitigation and biodiversity conservation can simultaneously sequester 465 ± 59 Gt CO_2 and avoid 71±4% of current extinction debt (Strassburg et al., 2020) . These are long-term estimates, but tropical forests, where most global priorities are located, can recover up to half of their reference carbon stocks in the first 20 years after restoration, and 90% in 66 years (Poorter et al., 2016). Natural forest regeneration can generate substantial global CO_2 removal and is a key component of cost-effective large-scale restoration strategies (Strassburg et al., 2018). Related to the 'Bonn Challenge', encouraging natural forest regrowth may be >40 times more effective (in terms of storing carbon in biomass in 2100) compared to monoculture plantations (Lewis et al., 2019). The large historic loss of soil carbon (about 20 % to over 60 % (Olsson et al., 2019)) implies that agricultural soils, appropriately managed, have a significant future capacity to take up CO_2 from the atmosphere (e.g., 0.4-8.6 Gt CO_2 yr^{-1} (Smith et al., 2020)) and to store it in the form of soil carbon, potentially with a wide range of co-benefits in addition to climate change mitigation (Bossio et al., 2020). There have also been a wide variety of blue carbon habitat restoration projects, but to date small-scale projects using the voluntary carbon market or alternative financing tend to be among the more successful outcomes (e.g., in mangrove swamps and sea grass meadows, see Wylie et al., 2016).

Restoring already degraded wetlands can sequester carbon on a century scale, albeit at a very slow pace and possibly at the expense of increased CH_4 emissions, but with large potential to improve conditions for biodiversity (Hemes et al., 2019; Meli et al., 2014; Strassburg et al., 2020). Ecosystem restoration also provides multiple nature´s contribution to people, such as the regulation of water quality, regulation of the hydrological cycle, decrease the frequency and severity of floods and droughts and pollination services (Chazdon & Brancalion, 2019; IPBES, 2018). Ecosystem restoration can also provide multiple social benefits, such as creation of jobs and income, but in order to avoid negative social outcomes, its implementation must follow proper culturally inclusive decision-making and implementation, in particular when affecting indigenous peoples and local community lands (Reyes-García et al., 2019).

3.3 Manage

3.3.1. Climate- and biodiversity-friendly agricultural practices

Globally, the food system is responsible for a third of anthropogenic GHG emissions (Crippa et al., 2021). There is potential to reduce emissions both on the supply-side and the demand-side (see below). Supply-side measures include improved cropland management (technical potential: 1.4-2.3 Gt CO_2e $yr^{-1;}$ (Smith et al., 2020)) grazing land management (technical potential: 1.4-1.8 Gt CO_2e yr^{-1}; (Smith et al., 2020), and livestock management (technical potential: 0.2-2.4 Gt CO_2e yr^{-1}; (Smith et al., 2020) which together reduce methane emissions from enteric fermentation, livestock manure, rice production and biomass burning, and to reduce nitrous oxide emissions from fertilizer production and application and livestock manure, and also create soil carbon sinks (technical potential: 0.4-8.6 Gt CO_2e yr^{-1} (Smith et al., 2020)). Smith et al. (2018) assessed the impacts of these interventions on biodiversity to be neutral to positive at various scales. Another mitigation option is sustainable intensification (briefly defined as obtaining more yield from the same land area, while keeping the off-site environmental and social impacts low) with a technical potential >13 Gt CO_2e yr^{-1} (Smith et al., 2020)). Intensification can free land for biodiversity conservation, by sustainably increasing productivity per unit of agricultural area (Pretty et al. 2018). Whist bioenergy has a large mitigation potential (technical potential: 0.4-11.3 Gt CO_2e yr^{-1} (Smith *et al.*, 2020)), the widespread cultivation of energy crops to provide CO_2 removal on several Gt CO_2e yr^{-1} scale was assessed by Heck et al. (2018) and McElwee et al. (2020) to have potential negative impacts on biodiversity. However, at smaller scale, and when integrated into sustainably managed agricultural landscapes, the impact of energy crops on biodiversity could be neutral to positive (McElwee et al., 2020; Smith *et al.*, 2020).

3.3.2 Climate- and biodiversity-friendly forestry practices

Through species selection, and different management options during tree growth and harvest, foresters can guard the carbon stock in biomass, dead organic matter, and soil – with particularly large co-benefits if long-lived wood-based products support emissions reductions in other sectors through material substitution (Campioli et al., 2015; Churkina et al., 2020; Erb et al., 2018; Luyssaert et al., 2018; Nabuurs et al., 2017; Wäldchen et al., 2013). Preserving and enhancing carbon stocks in forests via sustainable management has the potential to mitigate 0.4–2.1 Gt CO_2-eq a^{-1} (IPCC 2019). Intensification of forest management schemes and associated fertilization may enhance productivity but would increase N_2O emissions and possibly have negative impacts on overall forest and aquatic biodiversity.

In some regions, climate change can provide net benefits to forests through lengthening the growing season (especially at high latitudes, but see Housset et al., (2015)) and CO_2 fertilization. However, climate change can also drastically reduce the mitigation potential of forest management due to an increase in extreme events like fires, insects and pathogens (Anderegg et al., 2020; Seidl et al., 2014), as well as drought and heat beyond thermal thresholds (Duffy et al., 2021; Sullivan et al., 2020). Adoption of measures such as reduced-impact logging or fire-control measures, together with (in formal mitigation projects) including carbon “buffer pools” to account for unintended carbon loss can help to address permanence risks (Anderegg et al., 2020; Sasaki et al., 2016). If planned carefully, forest management for climate change mitigation can be associated with a number of co-benefits for biodiversity conservation as well as regeneration (Mori et al., 2017; Triviño et al., 2017). In general, mixed-species forests should be maintained as they are likely to provide a wider range of benefits to society within the forest and for adjacent land uses. However, there are trade-offs between different benefits depending on the tree mixture and stand type involved (Brockerhoff et al., 2017; IPCC, 2019b).

3.3.3 Biodiversity-friendly fishing and aquaculture practices

The growth and increasing wealth of human populations forecast a considerable need to produce more food from the ocean, but fishing is the main current driver of biodiversity decline in the ocean (IPBES, 2019). Bottom trawling is particularly destructive, especially in deep water, from which biodiversity recovery may take decades (Clark *et al.*, 2016, 2019). In addition, elimination of illegal, unregulated and unreported (IUU) fishing is critical to moving the fisheries sector to sustainability. Reducing overfishing and bycatch, as well as focusing new aquaculture activities on low trophic level species (e.g., plankton feeders such as bivalve molluscs) and broadening the range of species cultivated could both increase global seafood production and reduce impact to the environment and biodiversity (Hilborn et al., 2018). Expanded cultivation of seaweed also offers biodiversity friendly possibilities for sequestering CO_2 and producing food.

3.3.4 Localisation of supply chains

There are important opportunities for reducing emission in global trade, by moving into less carbon intense and more biodiversity friendly practices (e.g., Griscom *et al.* (2017); Smith *et al.* (2018)). In particular, modifying the trade itself by providing incentives for the localization of supply chains and through the stipulation of higher environmental standard in the production of commodities to be traded among countries under free trade agreements (e.g., Kehoe et al. (2020)). Internationally adopted standards help to reduce the risk of generating countries with low level of environmental regulations and enforcements and specialized in the production of carbon intensive goods later exported to the rest of the world (OECD, 2019). Supply chain emissions account for around 30% of food system emissions (Crippa et al., 2021), and re-considering supply chain is a key tool to help achieve global temperature rise limits (e.g., 1.5-2°C). Localizing food supply chains is important even if fossil fuel emission is massively reduced or halted (Clark et al., 2020), mainly by reducing the GHG emissions caused by transportation and by building resilience to large scale disasters. However, practices such as just-in-time inventory (so that goods arrive as close as possible to when needed) can lead to frequent transport and more GHG emission (Ugarte et al., 2016).

3.3.5 Changes in consumption

Meat and dairy are responsible for 58% of GHG emissions from the global food system (IPCC, 2019b) and half of these emissions are due to cattle and sheep alone (Poore & Nemecek, 2018). One third of all cereals grown on the world are used to feed livestock rather than humans (Mottet et al., 2017). Animal agriculture is a major driver of deforestation and biodiversity decline (Crist et al., 2017). Ruminant meat has 10-100 times the climate impact of plant-based foods (Clark & Tilman, 2017; Poore & Nemecek, 2018) with a similarly greater adverse impact on land, water and energy use, and indicators of air and water quality. A third of all the food produced globally is lost or wasted, including through over-eating (Alexander et al., 2017). Demand-side measures encouraging reduced food loss and waste (technical potential: 0.8-4.5 Gt CO_2e yr^{-1}; (Smith et al., 2020) and dietary shifts, especially in rich countries, toward diets including more plant-based foods and less meat and dairy (technical potential: 0.7-8 Gt CO_2e yr^{-1}; (Smith et al., 2020)) have significant potential for climate change mitigation, as well as reducing the pressure on land that drives biodiversity loss (Roe et al., 2019). Additionally, the land spared by these actions greatly enhanced the potential for nature-based solutions, which benefit climate change and biodiversity alike (Seddon et al., 2021).

3.4 Create

3.4.1 Urban greening and biodiversity support

Cities, although occupying only 1% of the global ice-free land surface, play a role in the conservation of global biodiversity, particularly through the planning and management of urban green spaces (UGS) (Aronson et al., 2017). Although UGS research is recent (Aronson et al. 2017), urban greening has played a key role in most adaptation strategies (Butt et al., 2018). UGS and biodiversity protection increase carbon uptake (De la Sota et al., 2019) and deliver cooling effects that indirectly lead to reduced energy consumption (Alves et al., 2019). They also reduce air pollution, maintaining health, reduce, flooding, sand and dust, and assist in adapting to climate change (Capotorti et al., 2019; Carrus et al., 2015). In densely populated cities planting of trees has a larger potential to reduce heat impacts than green roofs, because of shade provisioning (Zolch et al., 2016). Carbon sequestration and storage in urban trees and gardens varies considerably between cities and location. UGS can contribute in a meaningful way to mitigating cities' GHG emissions, provide a local cooling effect or be co-beneficial to a cities' population food supply (Bellezoni et al., 2021). It is thus both possible and necessary to rationally design and manage UGS and biodiversity in combination with adaptation and/or mitigation measures (Butt et al., 2018; Sharifi, 2021).

3.4.2 Trophic rewilding

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

3.4.3 Combined technology and nature-based mitigation options

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

3.4.4. Mitigation opportunities on newly emerging habitats

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

Table 1 summarises the effects on biodiversity of global climate mitigation and adaptation practices based on land and ocean management discussed in sections 2 and 3.

Table 1 Summary of the effects on biodiversity of global climate mitigation and adaptation practices based on land and ocean management. Modified from (Barnes et al., 2018; Hoegh-Guldberg et al., 2019; Roe et al., 2019; Smith et al., 2020). See these sources for further references, uncertainties and confidence levels. Estimates for measures in coastal and marine ecosystems are for 2030 (Hoegh-Guldberg et al., 2019); estimates for land ecosystems are not specified but implicit for 2030-2050 (Smith et al., 2020). Biodiversity impact: judgement by authors.

[Table 1 here]

4. The Paris Agreement and the CBD post-2020 global biodiversity framework

4.1 Acknowledging the trade-offs

By 2050, in 1.5°C pathways, renewable energies (including bioenergy, hydro, wind, and solar) are expected to supply 52–67% (interquartile range) of primary energy. As food demand is projected to increase substantially and with the land area already today under large exploitation pressures, conversion of areas equivalent to about one third of today's food crop area or 10-15% of today's forest area for mitigation purposes (Rogelj et al., 2018) would jeopardise existing land- or marine-area related biodiversity conservation measures (Fuss et al., 2018; Hof et al., 2018; Veldkamp et al., 2020). It would also further aggravate hunger and the loss of nature's contributions to people contributing to the delivery of the SDGs (Shukla et al., 2019; Fuss et al. 2018; IPBES 2019). These results are particularly pertinent in the light of studies that have raised doubts on whether the projected cumulative carbon uptake on land at the massive scales proposed could, in fact, be achieved (Harper et al., 2018; Krause et al., 2017). The expected large mitigation contributions by various renewable energy sources and/or land and marine management highlight the profound challenges for sustainable management of demands on land and in the ocean (IPCC, 2019a). Land use plans can be optimised to identify, and to attempt to minimise trade-offs between biodiversity conservation and ecosystem services delivery for land-use decisions (Fastré et al., 2020).

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

4.2 Combinations of measures that are locally adjusted and societally accepted

Better alignment and fulfilment of the Paris Agreement commitments with CBD post-2020 global biodiversity framework goals and targets and the 2030 Agenda for Sustainable Development and its SDGs is essential to bring about social and economic transformations in order to achieve quality of life in parallel with nature (Pörtner et al., 2021). Approaches that are multi-pronged and emphasize decarbonization of economies and the energy sector in the short term, as well as implementing nature-based solutions that have strong capacity to sequester carbon as well as bringing benefits for local communities, have a better chance of success (Seddon et al., 2020). Though these options are time limited for mitigation because biological sinks saturate, nature-based solutions can provide significant mitigation potential this century (see Table 1). In published global assessments of mitigation potential, the fundamental context-specific interactions, opportunities and limits arising from a specific location (such as ecosystem type, local governance or the mix of decision-making actors) thus far have not be accounted for but are important when implementing mitigation measures "on the ground" (Griscom et al., 2017; Smith et al., 2020).

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

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

4.3 Social issues and the 'securitizing' of climate change

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

There is an increasing realization that climate change is a global security issue with potential to lead to social unrest, forced migration, and displacement of populations especially of less developed countries (Abel et al., 2019; Hoffmann et al., 2020; UNDP, 2020). This can be an important driver for international multilateralism and cooperation and an increased ambition in the framing of measures such as the Nationally Determined Contributions (NDCs) to reduce emissions and adapt to impacts of climate change. This 'securitization' of climate change, however, can backfire and lead to negative consequences, such as leading to fatalism, scepticism and inaction (Warner & Boas, 2019), disincentivising international cooperation and the adoption of nature-based solutions, especially if this securitization goes along with a communication strategy that tries to increase the sense of urgency appealing to fear, guilt, or shame (De Witt & Hedlund, 2017; Moser, 2007). To adequately communicate the up-to-date science of climate change, its impacts on biodiversity and the earth system, and catalyse urgent actions in people and governments, without overwhelming and paralyzing them is a complex issue (Moser, 2010). Among other considerations it is critical that statements regarding impacts of climate change adequately communicate uncertainty in projections (Bradshaw and Borchers, 2000), thus leading to actionable futures instead of inaction and fatalism. One way to achieve this is to promote social changes that lead to resilient governance systems, anchored in diversity, cooperation, social learning, and co-management, bolstering mitigation, adaptation, collective action, and quality of life (e.g., (Berkes, 2007; Oreskes, 2019; Ostrom, 2014; Tompkins & Adger, 2004)). Recognising that a broad set of people's values regarding material and non-material benefits from nature underpin motivation to change (Pascual et al., 2022; Pörtner et al., 2021). A good example is by granting access rights to local populations exploiting common pool resources, such as small scale fisheries (Wilen et al., 2012) as with granting access to ancestral lands for indigenous groups. These social changes can increase sustainable management, improve biodiversity and the carbon capture and storage capacity of ecosystems (Díaz et al., 2018; Fa et al., 2020; Gelcich et al., 2019; Herrmann, 2006; Köhler et al., 2019). They do so by reinforcing the sense of and the relationship with place, wherein lies the foundation for cultural practices through which environmental change is experienced, understood, resisted and responded to (Ford et al., 2020).

4.4 Good environment stewardship practices are dynamic

The outcomes of coupled climate-biodiversity-human systems are hard to predict. Even in a relatively simple system, such as the Southern Ocean with short food chains and few direct anthropogenic stressors, best environmental practice can be difficult to discern (Rogers et al., 2020). Species have widely varying levels of thermal sensitivity but many at high latitude or altitude are stenothermal, so they must shift range to maintain temperature envelopes. However, zones of marine management or protection usually have fixed geographic or bathymetric boundaries. Thus, effectiveness of stewardship practices will see changing climate mitigation and biodiversity yields unless management boundaries can flex with temperature. The West Antarctic Peninsula (WAP) may be an early warning sign of this. Less than 1°C of surface water warming there has sustained strong marine ice losses, both increasing and decreasing carbon capture in places and range shifting some species but not others (Montes-Hugo et al., 2009; Rogers et al., 2020). Such moderate (1°C) surface water warming can increase growth amongst polar benthos; life on WAP seabed now stores 0.4-0.04 Gt CO_2e yr^{-1} (Barnes, 2017) but in contrast there have been decreases in carbon stored in life on the Weddell seabed (Pineda-Metz et al., 2020). There is evidence that more severe warming is complicated and has unpredictable effects on species (e.g. in growth, see Ashton et al., 2017).

Both at sea and on land, adopting dynamic approaches to conservation, rather than static goals, will be allow flexible responses and leverage biodiversity's capacity to contribute to climate change mitigation and adaptation. In face of climate change, conservation will be about managing the change, since a return to the historical state will be impossible to achieve (Arneth et al., 2020; Shin et al., 2022).

5 Conclusions

"'Tain't What You Do (It's the Way That You Do It)"[1]

Climate change mitigation solutions that occupy very large areas of land (such planting of monoculture trees or energy crops) can have adverse effects on biodiversity and can compete with food production. Many technological mitigation measures on land and in the oceans, such as wind, tidal and solar energy generation, could also impact biodiversity, for example through mining of raw materials for their construction, direct impacts through construction of infrastructure, or through indirect impacts like displacement of production to other areas. However, many of these potential adverse impacts on biodiversity or context specific and can be minimised, or even negated, by careful implementation. For example, modest reforestation projects that are adapted to the local socioecological context and consider local as well as distant trade-offs, can be an important component of climate change mitigation, biodiversity protection and contributions to a good quality of life. Similarly, when woody or perennial grass bioenergy crops are planted in severely degraded areas, or as a non-dominant component of agricultural landscapes previously dominated by single mono-cultural crops, biodiversity could benefit and enhance the portfolio of ecosystem services, especially when established in agricultural landscapes dominated by annual crop production.

Many land- and ocean-based climate mitigation options are available, but not all are equally effective at producing co-benefits, with social co-benefits often being overlooked within the climate-biodiversity nexus (Pascual et al., 2022). Protecting biodiverse and carbon-rich natural environments, ecological restoration of potentially biodiverse and carbon rich habitats, the deliberate creation of novel habitats, taking into consideration a locally adapted and meaningful mix of these measures, can result in the best win-win solutions. By being more synergistic, holistic and long term in view, approaches to climate mitigation will not just benefit biodiversity and societal wellbeing but are also likely to be more robust and sustainable. Foremost, GHG emissions reduction is critical and stopping species and carbon-rich habitat loss is a key part of that process.

Both land- and ocean-based mitigation activities are already contributing to climate change mitigation and can further contribute to limiting warming to 1.5°C or 2°C, including nature-based solutions, but also by providing space for technical infrastructure (and the combination of the two). Trade-offs and compromises are inevitable and require careful management manage mitigation-related biodiversity and adaptation impacts.

On land, five options with large mitigation potential (>3 Gt CO_2eq yr^{-1}) and five with moderate potential (0.3-3 Gt CO_2eq yr^{-1}) have been identified in the IPCC SRCCL (2019), with no or only little adverse impacts on other land challenges. These options combine the carbon uptake potential from avoided conversion of natural land, restoration, enhancing yields through sustainably managing agricultural and forest lands, as well as reducing post-harvest losses. Likewise, by 2050 carbon taken up and stored in coastal and marine ecosystems and sea-beds could contribute an additional >3 Gt CO_2e yr^{-1}, while 5.4 Gt CO_2e yr^{-1} are estimated to be supplied from different ocean-based renewable energy such as offshore wind or tidal energy.

[1] 'Tain't What You Do (It's the Way That You Do It) - song written by jazz musicians Melvin "Sy" Oliver and James "Trummy" Young, first recorded in 1939 by Jimmie Lunceford, Harry James, and Ella Fitzgerald (https://en.wikipedia.org/wiki/%27Tain%27t_What_You_Do_(It%27s_the_Way_That_You_Do_It))

Both at sea and on land, adopting dynamic approaches to conservation, rather than static goals, will be allow flexible responses and leverage biodiversity's capacity to contribute to climate change mitigation and adaptation. In face of climate change, conservation will be about managing the change since restoring the historical state will be impossible to achieve.

While the greenhouse gas emission reduction or removal capacity can be relatively accurately estimated, biodiversity is generally poorly measured and represented by very few variables in a limited number of studies that assess the impacts of interventions on biodiversity. Enhancing the routine collection of biodiversity information in projects, and developing and harmonising metrics for measuring biodiversity, would greatly enhance our knowledge base for action.

Given the current over-exploitation of land and marine ecosystems, there is a clear need for transformative change in the land and ocean management, and food and energy production sectors to achieve these mitigation potentials and capitalise on their climate change adaptation and biodiversity conservation co-benefits. Better alignment and fulfilment of the Paris Agreement commitments with CBD post-2020 global biodiversity framework goals and targets and the 2030 Agenda for Sustainable Development and its SDGs is essential to bring about social and economic transformations, to achieve quality of life in parallel with nature.

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Practice	Mitigation potential	Adaptation potential (estimated number of people more resilient to climate change from intervention)	Biodiversity impact (positive unless otherwise stated)	Summary/synopsis of overall expected impact
A Ocean				
Carbon storage in seabed	0.5–2.0 Gt CO_2e yr^{-1}	No global estimates	Low	
Costal and marine ecosystems	0.5-1.38 Gt CO_2e yr^{-1}	No global estimates	Medium/High	
Fisheries, aquaculture and dietary shifts	0.48–1.24 Gt CO_2e yr^{-1}	No global estimates	Medium/High	
Ocean-based renewable energy	0.76-5.4 Gt CO_2e yr^{-1}	No global estimates	Low	
B Land				
Increased food productivity	>13 Gt CO_2e yr^{-1}	>163 million people	High[1] or Low[2]	
Improved cropland management	1.4–2.3 Gt CO_2e yr^{-1}	>25 million people	Medium	
Improved grazing land management	1.4–1.8 Gt CO_2e yr^{-1}	1–25 million people	Medium	
Improved livestock management	0.2–2.4 Gt CO_2e yr^{-1}	1–25 million people	Medium	
Agroforestry	0.1–5.7 Gt C_2e yr^{-1}	2300 million people	High	
Agricultural diversification	> 0	>25 million people	High	
Reduced grassland conversion to cropland	0.03–0.7 Gt CO_2e yr^{-1}	No global estimates	High[3]	
Integrated water management	0.1–0.72 Gt CO_2e yr^{-1}	250 million people	Medium	
Improved and sustainable forest management	0.4–2.1 Gt CO_2e yr^{-1}	> 25 million people	High	
Reduced deforestation and degradation	0.4–5.8 Gt CO_2e yr^{-1}	1–25 million people	High	
Reforestation and forest restoration	1.5–10.1 Gt CO_2e yr^{-1}	>25 million people	High	
Afforestation	See Reforestation	No global estimates	Negative/low positive[4]	
Increased soil organic carbon content	0.4–8.6 Gt CO_2e yr^{-1}	Up to 3200 million people	Medium	
Reduced soil erosion	Source of 1.36–3.67 to sink of 0.44–3.67 Gt CO_2e yr^{-1}	Up to 3200 million people	Low	
Biochar addition to soil	0.03–6.6 Gt CO_2e yr^{-1}	Up to 3200 million people; but potential negative (unquantified) impacts if arable land used for feedstock production	Low[5]	
Fire management	0.48–8.1 Gt CO_2e yr^{-1}	> 5.8 million people affected by wildfire; max. 0.5 million deaths per year by smoke	Low	
Management of invasive species / encroachment	No global estimates	No global estimates	High	
Restoration and reduced conversion of coastal wetlands	0.3–3.1 Gt CO_2e yr^{-1}	up to 93–310 million people	High	
Restoration and reduced conversion of peatlands	0.6–2.0 Gt CCO_2e yr^{-1}	No global estimates	High	

Practice	Mitigation potential	Adaptation potential (estimated number of people more resilient to climate change from intervention)	Biodiversity impact (positive unless otherwise stated)	Summary/synopsis of overall expected impact
B Land (continuted)				
Biodiversity conservation	0.9 Gt CO_2e-e yr $^{-1}$	Likely many millions	High	
Enhanced weathering of minerals	0.5–4.0 Gt CO_2e yr $^{-1}$	No global estimates	Insufficient data to make judgement	
Bioenergy and BECCS	0.4–11.3 Gt CO_2e yr $^{-1}$	Potentially large negative consequences from competition for arable land and water.	Negative/low positive[4]	
On-shore wind	Depends on what energy source is substituted	No global estimates	Low	
Solar panels on land	Depends on what energy source is substituted[6]			
C Demand changes (related to land)				
Dietary change	0.7–8.0 Gt CO_2e yr $^{-1}$ (land)	No global estimates	High[7]	
Reduced post-harvest losses	4.5 Gt CO_2e yr $^{-1}$	320–400 million people	Medium/High	
Reduced food waste (consumer or retailer)	0.8–4.5 Gt CO_2e yr $^{-1}$	No global estimates	Medium/High	
Management of supply chains	No global estimates	>100 million	Medium[8]	
Enhanced urban food systems	No global estimates	No global estimates	Medium	

Mitigation potential — Adaptation potential — Possible adaptation potential — Negative impacts on biodiversity — Positive impacts on biodiversity

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