INTOSAI
Working Group
on Environmental
Auditing

Climate – Biodiversity Nexus: Relationship of Climate Change Mitigation and Biodiversity Policy Measures

A literature review

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2023

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Foreword

Climate change and biodiversity loss are two colossal problems that drastically affect our economies and societies. They are also closely intertwined with each other, and it is becoming increasingly evident that this twin-crisis must be solved together.

Due to increased concern for the interaction between climate and biodiversity, the INTOSAI Working Group on Environmental Auditing (WGEA) included a project on the nexus between biodiversity and climate into its Work Plan for 2023-2025. The project is led by the Office of the Auditor General Canada, and it continues WGEA work on policy coherence in the context of the SDGs.

Many Supreme Audit Institutions (SAI) are currently conducting performance audits on implementation of climate policies. These audits can deal for example with climate strategies or energy policies and measures. To ensure policy coherence, it is of utmost importance that SAIs, while making assessments on the implementation of climate policies, also pay attention to their impacts on biodiversity. Furthermore, SAIs should notice the benefits that synergies between climate and biodiversity aspirations have.

The National Audit Office of Finland, as the Chair of the INTOSAI WGEA, commissioned this literature review from the Finnish Environment Institute to support the WGEA project entitled Nexus Area: Biodiversity and Climate. We warmly thank the researchers involved and hope that this research creates a solid base for developing audit approaches to climate and biodiversity and attracts interested readers also in the broader climate and biodiversity policy as well as research field.

Helsinki, 9 October 2023

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Acknowledgements

The authors would like to thank Finnish Environment Institute information specialists Simo Riikonen, Maria Söderholm and Henri Pitkänen for their valuable support in developing the literature search terms and initial listing of the literature. The authors would also like to express thanks to Vivi Niemenmaa from the National Audit Office of Finland for her valuable guidance and comments throughout the project, as well as the National Audit Offices of Canada, Maldives, Estonia and Czech Republic for their valuable comments on the draft report.

Executive summary

Climate change and biodiversity loss are inseparable threats to humankind and must be addressed together. Climate change negatively affects species and ecosystems and exacerbates the loss of biodiversity. Biodiversity protection, on the other hand, helps to mitigate climate change. Climate change mitigation, such as changes in our energy systems and ecosystem management, is paramount to curb the impacts of climate change. These mitigation measures may, however, come with adverse impacts on biodiversity. In order to identify and avoid these potential adverse impacts, careful impact assessments are necessary.

This literature review was based on the assumption that whereas biodiversity measures usually support climate policies, this may not always be the case the other way around. As the government external auditors are increasingly conducting performance audits on climate policies, funding schemes and individual measures, there is a risk that those audits may not pay attention to potential negative impacts of climate measures on biodiversity. The same may hold true for biodiversity policy impacts on climate. The purpose of the literature review was to provide a background study for the INTOSAI WGEA project entitled Nexus area: biodiversity and climate that would benefit from the review in developing tools and guidelines for government external auditors in identifying these adverse effects.

The literature review was conducted with searches using two global scientific databases, Web of Science and Scopus. The search query was performed by targeting the title, key words and abstracts of peer-reviewed articles published in English addressing four ecosystem types; coral reefs, boreal forests, freshwater ecosystems and deserts/semi-deserts and arid/semi-arid grasslands. Whilst based on a systematic literature search, some relevant documents might have gone unnoticed and therefore other mitigation measures with adverse climate/biodiversity impacts related to the selected ecosystem types beyond those described in this review might exist.

Boreal forests, the northernmost forests on earth, are vital ecosystems and form the largest terrestrial carbon storage on earth. Bio-based products from boreal forests, such as bioenergy, support the transition away from fossil-based economy, but logging can come with adverse biodiversity impacts. The growing emphasis on renewable energy production, such as wind power and solar energy, raises concerns about potential habitat loss and alterations to boreal forest ecosystems. Wind energy development on boreal forests also disrupts habitats for bats and birds, affecting their migration and breeding patterns. With two thirds of boreal forests under management, balancing economic interests with ecological preservation is important. Carbon pricing may promote practices that enhance carbon storage and biodiversity but may influence tree species selection towards more profitable species. Clear-cutting impacts soil fungi and reduces biodiversity, while practices like tree retention can protect, for example fungal diversity. Bioenergy and wood-based products play a pivotal role in boreal forest economies, affecting both carbon storage and biodiversity. Strategies like continuous cover forestry and promoting broad-leaf species enhance biodiversity and climate resilience. However, certain practices, such as harvesting deadwood or stumps for bioenergy, may compromise both carbon storage and biodiversity.

Coral reefs are biodiversity hotspots and important ecosystem engineers, but they are also highly sensitive to the effects of climate change. Whilst climate change mitigation measures greatly support coral reefs by limiting climate change, mitigation measures placed in, or in the vicinity of, ocean ecosystems, might inadvertently negatively affect coral reefs. Ocean-based mitigation measures include actions such as utilizing oceans for renewable energy production (e.g., wave and tidal power) or utilizing oceans for carbon capture and storage. Their impacts on coral reefs might occur through complex ecosystem interactions, such as through changes in temperature and nutrient levels. The interest for deep sea mineral mining may rise with the increasing demand for rare minerals to support energy transition. Literature reviewed highlighted the need for caution and called for an international moratorium on deep sea mining as simulations have revealed significant negative biodiversity and ecosystem impacts, including coral reef contamination. Similarly, ocean geo-engineering to artificially increase carbon sequestration has been deemed as highly risky and the London Convention has stated it should not be allowed. The literature emphasized that ocean-based nature-based solutions (“blue carbon”) can play an important role in global climate change mitigation. As seagrass beds, mangroves and salt marshes are hotspots for carbon storage, their protection and restoration could support global mitigation measures. The health of coral reefs is central to these blue carbon ecosystems, as coral reefs protect them from wind and wave damage. As impacts of mitigation measures on ocean ecosystems, including coral reefs are largely unknown, literature emphasized the need for careful impact assessment and paying attention to the interconnectedness of ocean ecosystems.

Deserts/semi-deserts and arid/semi-arid grasslands harbour rich biodiversity and are also home to some of the most vulnerable and marginalized groups of people. Some of these areas, particularly grasslands, are under high land-use change pressure. These areas are also used to support climate change mitigation measures, as these open lands are often ideal for renewable energy installations due to their high wind resources and ample sunlight. However, as arid areas support unique ecosystems and species it is important to carefully evaluate the ecological consequences of renewable energy projects. Mitigation action in these arid/semi-arid areas include for example renewable energy, particularly solar and wind, production. Whilst renewable energy production helps to move away from fossil-based energy, it can also come with adverse biodiversity effects such as habitat loss and fragmentation, loss of keystone species and animal disturbance and mortality. Clearing land for solar development in arid/semi-arid regions can negatively affect carbon dynamics and even affect local microclimate. As solar production is water intensive, water demand is an important consideration for solar developments in these regions. Also, bioenergy production as a means to replace fossil fuels is practiced in arid/semi-arid regions, particularly in grassland ecosystems. Bioenergy production in grasslands varies in its impacts on local biodiversity and ecosystem services depending on the area and crop selection. Bioenergy production can cause landscape transformations and land use change, which is an important driver of biodiversity loss. As grasslands are oftentimes mistaken as degraded woodlands, afforestation of grasslands has also been proposed as a mitigation measure. However, afforesting natural grasslands comes with negative biodiversity impacts and may also negatively impact soil carbon and water cycles. Since grasslands have an important role in carbon cycles particularly in terms of soil carbon, sustainable grassland management is important for climate change mitigation. Grassland conservation, avoided conversion and restoration of grasslands can support climate change mitigation efforts.

Freshwater ecosystems are crucial for supporting global biodiversity and contain a disproportionately high percentage of the world's species. Freshwater ecosystems also provide numerous ecosystem services that benefit human societies. Human impacts have, however, degraded freshwater habitats and groundwater systems. Energy production is highly water intensive and has multiple biodiversity impacts on the surrounding nature. Biodiversity protection policies should establish standards for assessing the impacts of renewable energy projects within their scope. For example, dams have various negative effects on water flow, cause habitat fragmentation and pose risks to fish. Small-scale, run-of-the-river hydropower schemes generally have fewer negative impacts on biodiversity compared to large dams, but the impacts should be assessed from installation to decommission. In the case of solar power, construction and operation of solar plants can contribute to water pollution, but floating photovoltaic may also have positive effects by reducing evaporation. The ecosystem impact of cultivating biofuel is similar to those of other farm crops, including intensive fertilizer use, pesticide application, and other agricultural practices that may be detrimental, but erosion control practices may be beneficial for freshwater biodiversity. Efforts to manage inland water ecosystems in a sustainable way can have significant benefits for biodiversity conservation. The protection of forests from degradation can also help reduce soil erosion, protect water resources, and conserve biodiversity in the watershed, while afforestation may lead to increased water use and reductions in streamflow. Healthy freshwater bodies can act as greenhouse gas sinks and protect human well-being as well.

The literature showcased that climate change mitigation measures may carry both positive and adverse biodiversity impacts. Particularly ecosystem-based mitigation measures were found to benefit both climate and biodiversity targets. The literature review found cases of biodiversity policies positively affecting climate but found no examples of biodiversity policies with negative climate impacts.

1 Introduction

1.1 Overview of the climate change - biodiversity nexus

Biodiversity (the variety of life on Earth) is critical for human wellbeing by providing food, feed, energy, medicines, genetic resources and a variety of materials (IPBES, 2019). Maintaining and protecting biodiversity in different ecosystems is crucial for the existence and well-being of all life on earth. Biodiversity is equally important for human societies (e.g., through food and water security and culture or spirituality), as it is for human health. While nature contact is important for both physical and psychological health (Mygind et al., 2019), the diversity of microbiota one comes into contact with is directly linked with the development of a stronger immune system, especially on young children (Lehtimäki et al., 2017; Roslund et al., 2020). Biodiversity conservation also has the potential to reduce the risk of zoonotic diseases and pathogen transmission between wildlife, livestock and humans (Van Langevelde et al., 2020).

Climate change, caused by human activities, principally greenhouse gas emissions, is affecting the living conditions on earth through increased temperatures and extreme weather events (IPCC, 2023). Climate-related hazards are projected to increasingly affect all regions of the world posing multiple risks to ecosystems and humans. These projected impacts include heat-related mortality, mental health challenges, diseases, floods, landslides, loss of land and ecosystems, loss of biodiversity, and decrease in food production.

Climate change and the loss of biodiversity are inextricably interlinked (IPCC-IPBES, 2021). Climate change contributes to biodiversity loss and biodiversity loss can further accelerate climate change. Mitigating climate change can help to protect biodiversity and biodiversity protection can help in climate change mitigation. Since climate change and the loss of biodiversity are inseparable threats to humankind, they must be addressed together (Pörtner et al., 2021).

In the second half of the century, climate change is likely to become the largest driver of biodiversity loss (Newbold, 2018). Therefore, effective climate action is required to slow and reverse the loss of biodiversity (IPBES, 2019). The main response to climate change has been mitigation by enhancing the efficiency of energy use, development and uptake of renewable energy options and carbon sequestration (Paterson et al., 2008). These actions include a broad range of different measures from nature-based solutions (Nbs) or natural climate solutions (Griscom, 2017) to actions to phase out the use of fossil fuels (Anderson, 2019). Whilst these actions aim at tackling climate change, they may pose risks to biodiversity (e.g. Hof et al., 2018), and through that, to human societies. For example, tree planting may not always be appropriate if it changes the conditions of the targeted ecosystem and causes loss of native biodiversity (e.g. Bond et al., 2019). Renewable energy production may cause land use change or they might be harmful to the local biodiversity through other means (e.g. Ledec et al., 2011). Therefore, it is important to assess how different climate action measures might impact biodiversity and seek to identify ‘win-win’ solutions (CBD, 2020).

1.2 Purpose and scope of the literature review

As the government external auditors globally are increasingly conducting performance audits on climate policies, funding schemes and individual measures, there is a risk that those audits do not pay sufficient attention to potential negative impacts of climate measures on biodiversity (or vice versa) if information of potential impacts is not readily available. This might adversely impact policy coherence and value for money from a whole-of-economy perspective. Therefore, better understanding of how climate policy measures might affect biodiversity and vice versa is important.

The purpose of this literature review was to provide background on the nexus between climate change and biodiversity in order to support a project entitled Nexus area: Biodiversity and Climate of the INTOSAI WGEA Work Plan. The project aims to develop tools and criteria for government external auditors to assess the economy, efficiency, and effectiveness of the implementation of climate and biodiversity policies. This literature review was expected to shed light on how climate change and biodiversity linkages are currently considered in the implementation of respective policy measures and how climate change measures may impact biodiversity (and vice versa). By doing so, the literature review was expected to support the WGEA project in the tool and criteria development. As it is expected that climate change – biodiversity nexus -related challenges differ between regions and ecosystems globally, the literature review examined the impacts of climate change / biodiversity policy measures in four different ecosystem types; coral reefs, boreal forests, freshwater ecosystems and deserts/semi-deserts and arid/semi-arid grasslands. In terms of climate change measures, the literature review focused only on climate change mitigation. This report outlining the results of the literature review is structured according to the selected ecosystem types with key points summarized for each section separately.

1.3 Material, methods and limitations

This literature review set out to identify existing literature addressing biodiversity impacts of climate change mitigation measures and climate impacts of biodiversity protection measures in the selected ecosystem types. The search for scientific articles was first conducted in a systemic manner and the selected search terms altered to fit each ecosystem type covered in this review: boreal forests, coral reefs, freshwater ecosystems, and deserts/semi-deserts and arid/semi-arid grasslands. Further additions to the literature were made by “snowballing”, i.e., checking the references of a relevant article, or by searching for more information on a specific issue raised in one of the included articles.

We conducted the searches using two global scientific databases, Web of Science and Scopus. The search query was performed by targeting the title, key words and abstracts of peer-reviewed articles published in English. The searches were conducted using Boolean operators (i.e. AND, OR, NOT etc.) and proximity operators (i.e. WITH, NEAR). After the deletion of duplicates, all several hundred search results from Web of Science and Scopus were manually browsed through to determine whether the scientific article was truly relevant for the scope and focus of the review. Below is an example of the search terms used for deserts/semi-deserts and arid/semi-arid grasslands.

Terms related to the ecosystem in question	(tropical NEAR/5 grassland* OR savanna* OR warm NEAR/5 desert* OR semidesert* OR semi-desert* OR temperate NEAR/5 grassland* OR prairie* OR steppe OR steppes)
Terms related to the relation or impact	(conflict OR risk* OR threat* OR impact* OR interaction* OR loss* OR nexus OR trade-off*)
Terms related to biodiversity	(biodiversity OR habitat* OR "species richness" OR ecosystem*)
Terms related to climate change policies	(("climate polic*") OR (climate NEAR/5 regulat*) OR (climate NEAR/5 mitigation) OR (climate NEAR/5 goal*) OR (climate NEAR/5 activit*) OR (climate NEAR/5 target*) OR (climate NEAR/5 strateg*) OR (climate NEAR/5 conservation) OR (climate NEAR/5 action*) OR (climate NEAR/5 measure) OR (climate NEAR/5 implement*) OR (climate NEAR/5 enforcement) OR (climate NEAR/5 act))

For “grey literature” we used Google Advanced Search. The search results included reports published by national institutes from different countries, NGOs, and international scientific organisations and panels, such as IPBES. Some of these reports may present a case study or an overview of a specific issue with no references to scientific literature, while others cite their references, but may not have been peer reviewed. All results were in PDF-format. Unlike in the case of Web of Science and Scopus, the Google search does not allow for a complex search statement, such as the one presented above, so multiple searches were conducted with varying search terms for different perspectives and key words. From each of the searches, the first 30-50 results were taken into closer consideration, and the most promising ones were added to the list of potential reports or other publications to be included. Google Scholar was deliberately not used at this phase, as it targets such scientific literature which can be found through Web of Science and Scopus and would have led to more duplicates.

To be included in the review, the scientific articles and reports resulting from these searches were to, first, clearly mention biodiversity impacts on one of the ecosystem types covered in this review, and second, do so in the context of a specific climate policy or strategy, or e.g., a mitigation action. Only articles and reports published in the year 2000 or after were included. The relevant articles and reports were listed on an Excel sheet, and categorised based on the ecosystem(s) they covered, impacts they mentioned, and e.g. the country or region they focused on. The papers were then read more thoroughly by the researchers focusing on each ecosystem type. Finally, more than 200 scientific articles and reports were included in this review.

The literature search proved more challenging than expected, and there were many difficulties in finding relevant literature for the review, which leads to certain limitations in the coverage of this report. It seems the field of research for climate policy related biodiversity impacts (or vice versa) is rather small, and at best fragmented across different disciplines, which may not use the same terminology for similar concepts. The research may also be focused on very specific areas and ecosystems, described in words we did not know to include in our search terms. For example, the literature might, instead of “freshwater”, use the name of a specific river in describing potentially generalizable impacts of certain types of climate policies, and thus remain outside of our search terms. Or, likewise, not name the related policy or action as “climate” action. The use of these more general terms may have contributed to somewhat more general level material in our search results. In cases, literature lacked reference to a specific ecosystem type. For example, literature might have discussed renewable energy impacts in forests, without specifying the type of forest the findings were derived from. Furthermore, information may simply be scarce, such as in the case of coral reefs. Another important limitation is the English language: there are bound to be many exceedingly relevant regional and local reports and research papers in the corresponding local languages.

2 Boreal forests

This section first discusses the overall importance of boreal forests on biodiversity and ecosystem services. The section then moves on to examine the potential impacts of climate change mitigation measures on boreal forest biodiversity. The section closes by examining boreal forest protection and its role in climate change mitigation. Key points highlight central findings for consideration in impact assessments.

Key points derived from the reviewed literature

Climate – biodiversity synergies

- Boreal forests are vital ecosystems with unique biodiversity that cover a significant portion of the global forest area and serve as the world's largest terrestrial carbon storage.
- Bio-based products from forests help moving away from fossil-based economy.

Climate – biodiversity trade-offs

- Increasing harvest levels and collecting harvest residue for bioenergy production pose threats to forest biodiversity and carbon sequestration.
- Carbon pricing can incentivise carbon storage (by e.g., reducing harvest intensity or promoting enhanced wood biomass formation) but may influence tree species selection towards more profitable species, potentially impacting biodiversity in boreal forests.
- Clearing boreal forests for wind power development causes long-term land use change, destroys habitats and can cause direct negative impacts on forest biota.

Considerations to pay attention to:

- Harvest quantities
    - Long-term assessments on how much biomass can be sustainably extracted.
    - Long-term assessments on the greenhouse gas balance of the forests.
- Harvesting practices
    - Continuous cover forestry can have long-term positive effects on boreal forest biodiversity through maintaining structural characteristics.
    - Old growth forests and dead wood are critical elements for boreal forest biodiversity.
    - Mixed-species forests, including keystone species such as aspen are essential for boreal forest biodiversity.
- Sustainable forest management practices are essential for balancing economic utilisation and biodiversity conservation.

2.1 Importance of boreal forests for biodiversity and ecosystem services

Boreal forests form the northernmost forests on earth covering areas across Alaska, Canada, northern Europe and Russia (Frelich, 2020). According to UNECE (2021), boreal forests cover 27 % of the global forest area, making them the world's largest terrestrial carbon storage. Boreal forests grow in environments where temperatures can be below freezing annually for more than six months, and snow cover lasting for months each year (Gauthier et al., 2015). A short growing season and challenging conditions mean that in global perspective boreal forests are not biodiversity hotspots, but they are a host to many species which do not live elsewhere (Puumalainen et al., 2003). While the diversity of tree species is low (Gauthier et al., 2015), the vastness of the geographical area means that boreal forest habitats have significant heterogeneity, which has supported the evolution of a large number of specialised species adapted to specific ecological niches. For example, some species live almost exclusively on tree slash and stumps, which means that the amount of dead wood can have a direct impact on the occurrence of certain species (Hiron et al., 2017).

In addition, forest disturbances such as fires, pests and wind create significant landscape level diversity (Gauthier et al., 2015). Part of the year boreal forests are also important to migratory species as vital migration routes and breeding grounds. Approximately two thirds of boreal forest area is currently under some form of management (ibid.).

As boreal forests are a major biome in many countries situated close to the Arctic Circle, they play a regionally important role in providing a myriad of ecosystem services (UNECE, 2021). In addition to storing carbon, boreal forests play a crucial role in nutrient cycling, flood control, and the provision of valuable resources such as timber, food, and medicines (Golden et al., 2011) as well as clean water (Frelich, 2020). They also serve as social and cultural settings, as well as recreational spaces. While the forestry sector is a large employer, fields such as eco-tourism are fast-expanding, and offer employment opportunities particularly in Northern Europe (UNECE, 2021). However, whilst for example in Finland, the tree growth and the total forest area and timber volume have increased over the past century, the state of forest biodiversity in terms of both habitat and species, has continued to degrade (Mönkkönen et al., 2022). This is caused by degradation of the boreal forest qualities central to maintaining its biodiversity, namely the forest structure, proportion of deciduous trees, area of old forests and volumes of dead wood, changes which have been driven by intensive forest use (ibid.).

Boreal forests are being rapidly altered by climate change and other human induced impacts (Gauthier et al., 2015). Whilst disturbance such as fire, insects and hard winds have been a central part of natural boreal forest dynamics (Kuuluvainen and Aakala, 2011) these events are likely to increase with the changing climate (Gauthier et al., 2015). Moreover, even though vast areas of unlogged, primeval boreal forests still exist, action such as unsupervised logging, mining and oil extraction in addition to climate change pose risks (Frelich, 2020).

Monoculture forests have less biodiversity than mixed-species forests (Kivinen et al., 2020). Monoculture forests might lack “keystone species”, the importance of which is disproportional to the size of their population. For example, in northern Europe aspen is a relatively uncommon and scattered species, yet it is very important for many other species, some endangered, which inhabit it, or utilise its litter and dead trunks (Heinonen et al., 2017; Kivinen et al., 2020). The presence of aspen in boreal forests can be seen as an indicator of high biodiversity. Mixed-species forests provide ecosystem services such as enhanced pest-resilience and in some settings even higher carbon sequestration rates compared to monoculture forests (Kivinen et al., 2020).

2.2 Climate policies that can impact boreal forest biodiversity

Boreal biome is predicted to experience the greatest temperature increase of all forest biomes (Gauthier et al., 2015). Precipitation is not expected to increase in step with temperature, meaning parts of the biome could change to drier biomes such as woodland/shrubland. Forest fire regularity and intensity, severity of pest outbreaks, and drought events are all predicted to increase. One third of boreal biome rests on permafrost, the thawing of which increases the risk of drought events. The effect on ecosystem services depends on the severity and scale of changes, as well as the human response (ibid.).

Forest management

Boreal forests have a long history of being economically utilised. Some estimates state that around two-thirds of boreal forests are actively managed, ranging between 35 to 40 per cent in Canada to 90 per cent in

Fennoscandia (Gauthier et al., 2015). Therefore, the question of how much biomass can be responsibly extracted from forest sites has been a topic of interest for decades, and the issue still needs more research (Lempriere et al., 2013). Five significant environmental concerns can be identified from current research: soil, water, site productivity, forest biodiversity, and greenhouse gas balances. Research in Canada shows that some areas, such as the forested peatlands of the boreal zone are extremely vulnerable, and their natural processes easily disturbed (ibid.).

As described above, intensive use of boreal forests has led to changes in forest structure towards favouring certain tree species over others (Mönkkönen et al., 2022). A recent study found that tree species diversity in Canadian boreal forest was associated with higher soil carbon and nitrogen accumulation, indicating that higher tree diversity provides better carbon storage potential compared to tree species poor forests (Chen et al., 2023).

Approximately two-thirds of the total boreal forest area worldwide is actively managed, primarily for wood production (Gauthier et al., 2015). While protected forest areas are important for biodiversity, maintaining biodiversity in commercial forests is crucial as a large proportion of boreal forests are under economic management (Tikkanen et al., 2012). There are a number of certifications widely in use. For example, FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification) aim to promote responsible and sustainable use of forests. Both have criteria regarding biodiversity and reconciling the needs of the forestry sector with other ecological and social goals.

In the Fennoscandian boreal region, covering Finland, Norway, Sweden and north-western parts of Russia along the Finnish and Norwegian borders, only a small percentage of forests are protected (Gauthier et al., 2015). This highlights the importance of maintaining functional connectivity between protected areas that helps preserve biodiversity (Määttänen et al., 2022). For example, data from Finland shows that the loss of habitats outside protected areas indirectly reduces biodiversity in protected areas as well due to decreased functional connectivity, as wildlife is unable to travel along green corridors between habitats (ibid.). This is particularly relevant for highly specialised species, some of which are not able to move long distances between suitable habitats.

Carbon pricing can serve as a mechanism to reward forest landowners for their efforts in increasing carbon storage (Salzman et al., 2018). It is expected to play an increasing role in influencing forest management in the future (Hashida et al., 2020). The literature review found some research pieces regarding carbon pricing and boreal forests. Typically, carbon pricing involves implementing practices such as reduced harvest intensity or adopting other management techniques that enhance wood biomass within the forest, which has a positive impact on biodiversity, meaning there are potential synergies between carbon pricing and biodiversity conservation (Hashida et al., 2020). However, as carbon pricing prioritises carbon storage above other ecosystem services, it can influence the selection of tree species for replanting after harvesting (ibid.). As climate change is likely to favour some tree species over others (Crookston et al., 2010), this might determine which species are most profitable in terms of carbon pricing since the profitability of carbon pricing depends on the carbon sequestration rates of different tree species (Hashida et al., 2020). As Gauthier et al. (2015) predict, in some regions climate change is expected to favour hardwood tree species over coniferous species such as Douglas fir due to drying of the soil and rising temperatures. In such locations, for example in the Northwest coast of the United States, simulations show that carbon pricing may potentially incentivise the planting of hardwoods (Hashida et al., 2020). That is due to slowing fir growth as a result of more challenging conditions, which makes hardwood species more profitable for carbon pricing, but also as a timber source (ibid.). Consequently, this could diminish the availability of suitable habitat for numerous species, thereby impacting biodiversity in those areas (ibid.) However, the magnitude of the impact remains uncertain since the effects will depend on the behaviour of forest landowners (ibid.).

There is also indication that particularly clear cutting can negatively affect ectomycorrhizal fungi, which live in symbiosis with living tree roots (Dinesen et al., 2021). Fungi are responsible for storing carbon to the soil as they exchange nutrients with trees. A case study in Sweden indicated that between 50 to 70 % of carbon stored in the boreal forest soil was derived from tree roots and root-associated fungi (Clemmensen et al., 2013). Since many species of fungi form symbiosis only with living trees, repeated cycles of clear cutting can reduce the soil biodiversity, and in the long term even slow down tree growth and increase the need for fertilisation due to reduced nutrient transfer from fungi to trees (Dinesen et al., 2021). Sustainable forest management practices such as tree retention, where some trees are left standing, have been shown to protect fungal biodiversity, although the evidence indicates that the amount of tree retention required by most common sustainable forest management certifications is not nearly enough to protect mycorrhizal diversity (ibid.).

Bioenergy and building materials from forests

Forests as a renewable resource are a central element not only in energy policy but also in manufacturing wood-based products, which act as a carbon storage (Camia et al., 2021; Blattert et al., 2023). Therefore, forests are the foundation of many bioeconomy strategies, and the greater utilisation of bio-based products is a key instrument in moving away from fossil-based economy (Eyvindson et al., 2018). However, more research is needed to understand the effects of practices such as removal of fine and coarse harvest residues on biodiversity (Riffell et al., 2011). For example, in Finland the climate change impacts of bioeconomy have been actively under debate but less attention has been given to the bioeconomy impacts on biodiversity (and citizens) (Mustalahti, 2018). Recent evidence suggests that in Fennoscandian forests, increase in harvests has already happened, and is due to boreal forests having several different and sometimes conflicting priorities in bioeconomy policies (Blattert et al., 2023).

The harvesting of forest bioenergy has trade-offs with other climate policies such as carbon sequestration as well as biodiversity conservation (Repo et al., 2020). If harvest levels were to increase, it would pose a threat to biodiversity as intensive forestry practices negatively impact the characteristics, resources, and variations that are vital for forest species (Eyvindson, 2018). If the harvest levels rise towards the maximum economically sustainable level due to increased demand of wood-based products, it can negatively affect not only forest biodiversity but also carbon sequestration (ibid.). If the demand for bioenergy and bio-based construction materials increases, fulfilling both the sequestration targets and bio-based product targets is impossible (Blattert et al., 2023). Increased harvest levels mean that affected forest habitats are less suitable for certain species, and their ability to provide ecosystem services diminishes.

A large number of species is specialised on living on dead wood, and removing stumps and slash for bioenergy also removes important habitats, negatively affecting forest biodiversity (Hiron et al., 2017). Some species have actually adapted to living in sun-exposed locations on clear-cut stumps and dead residue on forest floor (Bouget et al., 2012). A simulation in Sweden showed that extracting woody residues such as stumps is detrimental to rare species in particular, while generalist species were less affected (Johansson et al., 2015). The effect was observed already at low stump harvest rates, highlighting the trade-off between increased use of bioenergy and conserving biodiversity. Scenario analysis by Heinonen et al. (2017) concluded that the amount of dead wood, including dead wood of deciduous species deceased considerably when harvesting levels were high.

Wood used in construction acts as a carbon storage for the duration of the building use phase (Sikkema et al., 2023). It can also replace fossil-intensive materials such as concrete, which reduces the overall greenhouse gas emissions. Simulations done in the Finnish context show that lower harvest levels increase the amount of deadwood, old-growth forests and keystone species such as aspen (Heinonen et al., 2017). Therefore, depending on harvest levels, synergies between wood construction and biodiversity conservation in boreal forests exist. But if increased wood construction leads to higher harvest levels there is a risk that it could negatively impact biodiversity. The impact of wood construction on harvest rates depends on many factors, so the actual effect remains uncertain and varies between locations (Seppälä et al., 2019), but the use of wood in construction is projected to increase (Sikkema et al., 2023).

Wind energy production

Forested countries such as Finland have seen an increase in wind energy development in recent years, and there is policy support to facilitate the development (Gaultier et al., 2023). Due to the large forest cover particularly in the European boreal region, wind turbines are being built on boreal forests (Gaultier et al., 2020). This often requires not only clearing the site, but also building necessary infrastructure such as roads and power lines. While the forest areas in question might not be large by size of the area, the land use changes from forests to wind energy development are long-lasting and impact a host of different species (ibid.). However, more research is needed for a more holistic understanding (ibid.).

The literature review found research articles that had examined the effects of wind power on bats in boreal regions. For example, the operational phase of wind turbines seems to negatively affect migrating bats, which are important for the biodiversity of boreal forests (Gaultier et al., 2020, 2023). Besides habitat destruction occurring during the construction phase, the operation phase can also cause bat deaths when bats collide with turbines. Turbines also have a deterrent effect: depending on the species, the radius at which bats avoid wind turbines could be greater than one kilometre. It is not known whether bats avoid the turbines itself, or the surrounding area, which has been altered by turbine construction. In any case, the avoidance has cascading effects, because sites where bats are not present might have a larger amount of pest insects, which bats would eat in normal circumstances.

Literature review also found research articles regarding how some bird species, for example capercaillie (Tetrao urogallus), an indicator species of high biodiversity in boreal forests, is affected by wind turbines (Coppes et al., 2020). The birds are more likely to stay at least 650 metres away from turbines, and avoid areas affected by noise emissions from turbines, as well as areas which are in the turbine’s shadow for parts of the year (ibid.). The effect was observed also in areas which would otherwise be suitable for capercaillie in terms of environmental characteristics.

Skarin et al. (2018) examined the effects of wind power construction and operation on reindeers in the boreal forest landscape in northern Sweden. The research found that both, construction and operation had adverse effects on reindeer habitat use including selection of calving sites and home ranges, the impacts being more significant during the continuous disturbance caused by operation.

Gartman et al. (2016) have proposed a framework for mitigating the wildlife impact of wind power. It is not specific to any ecosystem but rather acts as a set of guiding principles for minimising the impacts on wildlife, covering planning and siting, construction and operation phase, and decommissioning. Integrating needs of the wildlife with optimal siting in terms of wind and other conditions is challenging, since different species would require different measures.

2.3 Potential impacts of boreal forest biodiversity policies on climate

Mature forests act as significant carbon storages, and clear-cutting creates a long-lasting “carbon debt” (Smith, 2020). In addition, boreal forest soils have an important role in global carbon sequestration (Chen et al., 2023). In Canadian simulations, logging has reduced carbon stocks between 33 and 50 % compared to naturally occurring fire cycles (Malcolm et al., 2020). Simulations show that when replacing fossil fuels with wood-based biofuels, recovering the carbon sequestering properties and the carbon which was stored before logging can in some circumstances take centuries (Holtsmark, 2012; Malcolm et al., 2020), which underscores the long-term implications of logging activities on carbon dynamics and the importance of sustainable forest management practices. Therefore, if biodiversity policies affect the amount of mature forests being replaced with younger, faster growing forests, it can impact carbon storages and carbon sequestration.

Continuous cover forestry is a practice that involves selective tree cutting and the establishment of uneven-aged forests, preserving the natural structural characteristics of the ecosystem (Savilaakso et al., 2018). This practice is primarily aimed at maintaining biodiversity within forest ecosystems. However, it is important to consider that mature forests generally sequester carbon at a slower rate compared to young forests, although this variation in sequestration rates is influenced by numerous factors (Smith, 2020). As a result, policies focused on boreal forest biodiversity, such as extending the harvest cycle or transitioning to continuous cover forestry, can have positive implications for climate by affecting carbon sequestration dynamics.

Practices reducing the amount of deadwood such as harvesting stumps for bioenergy reduce the forest carbon stock and conservation capacity of the landscape (Repo et al., 2020). In some cases, the reduction of carbon stocks due to bioenergy harvesting can half the emissions savings achieved from the use of bioenergy. If stump and other dead wood harvesting would be reduced as a result of biodiversity policies, it might impact the production of bioenergy. (ibid.).

Forest management strategies that increase the proportion of broad-leaf tree species in the boreal zone can support both climate change mitigation (Astrup et al., 2018) and biodiversity (Kivinen et al., 2020). A higher proportion of broad-leaf species reduce the risk of forest fires that can accelerate global warming (Bernier et al., 2016) as well as enhance surface albedo (Bright et al., 2017).

3 Coral reefs

This section of the report focuses on warm-water coral reefs (later referred to as "coral reefs"). It first discusses the overall importance of coral reefs on biodiversity and ecosystem services. The section then moves on to examine the potential impacts of climate change mitigation measures on coral reef biodiversity. The section closes by examining coral reef protection and its role in climate change mitigation. Key points highlight central findings for consideration in impact assessments.

Key points derived from the reviewed literature

Climate – biodiversity synergies

- As coral reefs are highly sensitive to the effects of climate change, actions that mitigate global climate change are beneficial to coral reefs in long term.
- Marine protected areas and sustainable use of marine and coastal ecosystems support the high carbon sequestration potential of the blue carbon system. Healthy coral reefs play an important role in the blue carbon system by providing protection from wave damage and erosion.

Climate – biodiversity trade-offs

- Some proposed ocean-based mitigation actions such as mineral mining and geoengineering can have significant negative impacts on coral reefs and the ocean ecosystems at large.
- Marine renewable energy production may jeopardise the integrity and connectivity of coastal and marine ecosystems.
- Renewable energy projects that generate heat may negatively impact coral reefs.
- Projects that alter nutrient cycles or cultivate algae for biomass may foster algae growth with significant negative impacts on coral reefs.
- carbon storage in seabed can help mitigate climate change but may impact ocean chemistry with negative impacts on coral reefs.

Considerations to pay attention to:

- Marine ecosystems are closely interlinked and therefore changes in different marine ecosystems can affect coral reefs through complex ecosystem interactions. When assessing impacts of different climate change mitigation actions, the interconnectedness of marine ecosystems needs to be taken into account.
- We do not yet fully understand the complex ecosystem interlinkages in oceans.
- Impacts of a given climate mitigation measure should be assessed together with other prevalent stressors from human activities.
- Coral reefs are critical habitats that should be particularly taken into consideration when assessing ocean-based climate change mitigation measures.

3.1 Importance of coral reefs for biodiversity and ecosystem services

Corals are important ecosystem engineers and providers of different critical ecosystem services. Coral reefs create habitat structure, modify environments, provide food and have a central role in supporting ocean biodiversity (IBPES-IPCC, 2021). Coral reef biodiversity is at least an order of magnitude higher than anywhere else in the ocean ecosystem (Reaka-Kudla, 1997) and they host 91,000 described species of reef taxa (IPCC, 2002). Corals also host reef-associated fish assemblages and thus provide an important source of food and income for coastal communities (Ainsworth and Mumby, 2015). Moreover, coral reefs provide coastal protection from the rising sea levels and storm surges (IPBES-IPCC, 2021). Coral reefs are therefore also highly important for coastal communities (e.g., Ainsworth and Mumby, 2015) and they support tourism as an income source (IPBES-IPCC, 2021). Together with mangroves and seagrasses, coral reefs form an important ecosystem and contribute significantly to the economic resources of many small island countries (IPCC, 2002).

However, coral reef ecosystems are currently being affected by multiple anthropogenic factors and climate change (UN Environment, 2019). Currently, less than 13 % of the global ocean area remain free from substantial human impacts and approximately half of coral reef areas have been lost (IPBES, 2019). For example, the Great Barrier Reef is facing increasing pollution and turbidity of coastal waters caused by fertilizers, pesticides, herbicides and sediment loading (IPCC, 2002). Increasing clustering of cities along the coast has also resulted in contracting of different coastal ecosystems, such as coral reefs (Cooley, 2022) threatening their biodiversity and ecosystem services (IPBES-IPCC, 2021). Land-sourced marine litter pollution is increasingly affecting coral reefs (Santodomingo et al., 2021). Coral reefs are also being degraded by overfishing and destructive fishing (Abelson, 2020). Moreover, anthropogenic climate change poses additional and substantial threats to coral reefs as species, such as coral, living close to their upper thermal limits and ecosystems that are geographically restricted are at particular risk (IPCC, 2002; Hoegh-Guldberg and Bruno, 2010; Hughes et al., 2019;).

Coral reefs face high extinction risks due to climate change (e.g., Campbell et al., 2009; IPBES-IPCC, 2021). Under the current climate situation (1°C warming), particularly warm-water coral reefs are at high risk (IPBES-IPCC, 2021). If sea surface temperature increases more than 1°C above the seasonal maximum, coral reefs will be impacted detrimentally (IPCC, 2002). It has been estimated that a 1-2°C rise in temperature can result in widespread bleaching of coral reefs (Donner et al., 2005). Bleaching has been reported to cause declines of up to 90 % in coral populations in some regions and to result in changes in species composition (Graham et al., 2015). Corals will also be impacted by diseases promoted by warming sea water (Campbell et al., 2009) and climate change will reduce coral calcification rates (IPCC, 2002; Simard et al., 2016). These together can lead to the loss of many reef-associated species and communities (IPCC, 2002; Campbell et al., 2009). For instance, several zooxanthellate reef-building coral species are threatened with extinction due to coral bleaching, and diseases driven by sea surface rise (Carpenter et al., 2008). Coupled with climate change, also increasing nutrient and chemical inputs to coastal waters result in the expansion of dead zones in the coastal areas causing compounding stress and coral mortality (Altieri et al., 2017).

The decline in reef-building corals will have considerable implications for the vast biological communities that coral reefs support, including coral reef fish (e.g., Pratchett et al., 2008). Mass mortality of corals can rapidly tip ecosystems by causing loss of foundation species (Wernberg et al., 2013). The destruction of coral reefs will be associated with negative impacts on the ecosystem services that they provide such as fisheries, coastal protection, building materials, new biochemical compounds and tourism (Hoegh-Guldberg et al., 2007) and will have long-term implications for coastal zone protection, ecosystem integrity, biodiversity, and productivity of the tropical seas and fisheries (World Bank, 2008).

3.2 Potential impacts of climate policies on coral reef biodiversity

Oceans hold significant potential to support climate change mitigation action by reducing or sequestering and storing emissions (Hoegh-Guldberg et al., 2019). The role of coastal and marine ecosystems in mitigation was also explicitly included in the Katowice Climate Package (UNFCCC, 2018). These ocean-based mitigation possibilities include (i) ocean-based renewable energy, such as offshore wind, wave and tidal power (ii) ocean-based transport, including freight and passenger shipping; (iii) coastal and marine ecosystems, including mangroves, tidal marshes, and seagrass beds; and (iv) increasing GHG efficiency in fisheries and aquaculture and opportunities for shifting diets away from emission-intensive land based protein and towards low-carbon, ocean-based protein (Hoegh-Guldberg et al., 2019). The next sections include findings from reports and research articles which have identified direct or indirect impacts of climate change policies on coral reefs.

Renewable energy production

Marine renewable energy aims to contribute to the reduction of GHG emissions. It generally refers to wind turbines and tidal wave technologies utilized to harness the energy generated by marine tides, currents and winds (UNFCCC, 2022). It has been noted that the impacts of marine renewable energy on marine ecosystems should be assessed as they may jeopardise the integrity and connectivity of coastal and marine ecosystems (UNFCCC, 2022). The Ocean Climate Platform has emphasized that the development of marine renewable energy needs to consider the protection of seascapes and marine species.

The isolated stress caused by any given ocean energy installation does not determine the environmental impact of a project, but impact should be assessed together with other prevalent stressors from human activities and taking into consideration for instance the interactions within the marine food web (Hammar, 2014). Whilst current understanding of cumulative effects is not complete it is still important to be aware of possible cumulative effects and consider best practice.

As highlighted by for example the Renewables Grid Initiative, renewable energy projects, including offshore wind energy development should pay particular attention to critical habitats as also outlined in the international World Bank and IFC standards (Stephenson, 2022). In the marine ecosystem, those critical habitats include coral reefs, mangroves, seagrass beds and mammal and bird migratory corridors. The literature review found very little information regarding direct marine renewable energy impacts on coral reefs. However, the review found literature regarding how marine renewable energy production may affect marine ecosystems in broader terms. As different coastal ecosystems are closely interlinked, these findings have been included, due to their potential indirect effects on coral reefs.

OFFSHORE WIND POWER

Offshore wind turbines have the potential to influence different coastal habitat types, such as salt marshes, oyster beds, wetlands, sandbanks, coral reefs, seagrasses and mangroves (Bennun et al., 2021). As described above these habitats provide important ecosystem services but are also sensitive to degradation. Therefore, attention needs to be paid to planning and site selection in order to avoid adverse impacts on these sensitive habitats. In addition to the turbines, also positioning of the export cable is an important consideration as the cable may need to traverse long distances from the turbines to land (Bennun et al., 2021). The cable route should avoid sensitive ecosystems, such as reefs and the installation method should reduce potential negative impacts such as sediment plumes (Bennun et al., 2021).

Several potential mechanisms through which offshore wind power may impact marine biodiversity either adversely or positively have been reported. The installation and operation of wind turbines can lead to habitat loss, collision risk, noise and electromagnetic fields that can interfere with the communication and navigation of marine life (e.g., Madsen et al., 2006; Inger et al., 2009). The acoustic impacts of wind turbines on marine mammals in ocean ecosystems have been assessed as mild during operation but can be significant during the construction phase (Madsen et al., 2006). Offshore turbines have been found to affect benthic flora and fauna by e.g., altering the distribution of fish (Soukissian et al., 2017).

Some potential impacts of offshore wind power on marine life have been little studied, such as effects of electric fields around cables connecting them to the land (IPBES-IPCC, 2021). However, as offshore wind farms create an exclusion zone for fishing, they can act as de facto marine protected areas for marine life (Ledec et al., 2011). As in the case of terrestrial wind power plants (see chapter 2.2.3), wind turbines have been reported to cause bird and bat mortality also at sea, as the animals collide with the turbine blades (ibid.). Therefore, particular attention should be paid to wind power installation plans particularly near bird or bat migration pathways or nesting colonies, such as small islands (ibid.).

It has been reported that offshore turbines may create so called “artificial reefs” (i.e. hard structures provided by turbine installations on the ocean floor that can be used as colonization structures by benthic organisms) that may have both beneficial and negative impacts on biodiversity (Soukissian et al., 2017). These artificial reefs can create additional habitats, attract marine life and offer an area protected from fishing (Inger et al., 2009). However, artificial reefs can also support invasive alien species (Dafforn et al., 2009). Some research has found that invasive species are able to take advantage of these artificial structures more effectively compared to native species (Dafforn et al., 2009) and that species assemblages differ between artificial and natural reef structures (Clynick et al., 2008). Considering the potential impacts of artificial reefs is particularly important in areas where they may impact mangrove and coral reef ecosystems that provide nursery grounds for fish (Campbell et al., 2009). The need for more research on the potential impacts of renewable energy on marine ecosystems has been identified (Inger et al., 2009).

TIDAL ENERGY

The literature found no cases where the impacts of wave or tidal power on coral reefs would have been examined directly. However, as the ocean ecosystems are interconnected as described above, the review also presents findings regarding the potential impacts of wave and tidal energy on ocean ecosystems.

Tidal or marine current turbines operate in a similar manner to wind turbines as they generate electrical power from strong horizontal tidal currents (Meletiou et al., 2019). Tidal power involves movement of water either through turbines or tidal barrages (Campbell et al., 2009). Tidal power plants can generate both positive and negative environmental impacts (Morris, 2013). Tidal power can impact biodiversity through changes in flow, fish mortality, changes in salinity and sediment deposition, underwater noise, impacts on migration corridors and physical disturbance (e.g., Boehlert 2008 after Campbell et al., 2009). Negative impacts have been reported at least regarding birds (Frid et al., 2012) and fish reproduction and feeding (Henderson et al., 2010) which can cause broader ecosystem-wide effects and contribute to the decrease of aquatic species (Hooper et al., 2013). Water circulation modification is likely to have significant impacts on the benthic habitat (Boehlert 2008 after Campbell et al., 2009). Therefore, an environmental impact assessment of tidal power plants has been regarded as important (Progênio et al., 2021). According to current understanding, wave power and small-scale tidal current devices are less likely to have significant negative environmental impacts while the harmfulness of larger scale tidal and ocean current power will be dependent on their design and local ecological conditions (Hammar, 2014).

OCEAN THERMAL ENERGY CONVERSION (OTEC)

Ocean thermal energy conversion utilise the vertical heat difference of tropical seas to produce power as well as desalinated water (Hammar, 2014). Due to the water intake process, high quantities of organisms may be carried into and impinged by the system. The harmful impacts may be substantial for e.g. planktonic eggs, larvae and other small organisms. OTEC might also alter hydrological conditions, such as temperature, acidity and salinity and increase nutrient load of surface waters. The increase in nutrients can cause eutrophication, increase the growth of algae which could then outcompete corals and seagrass beds and eventually lead to detrimental impacts on sensitive ecosystems such as coral reefs and seagrass beds, altering, possibly irreversibly the ecosystem (Hammar, 2014).

NUCLEAR POWER

Elevated sea surface temperatures are one of the major stressors causing coral bleaching (Hoegh-Guldberg, 1999). Research has noted that as thermal discharge from nuclear plants has gained consideration, it would be necessary to monitor the reefs to gain some basic knowledge of the potential impacts (Govindaraju et al., 2011).

Nuclear power plant cooling water and the subsequent thermal discharge and change of water temperature may affect the ambient biota in the power plant impact zone (Jan et al., 2001). Bleaching of coral located near nuclear plant outlet has been reported (Wilkinson, 1998).

Hung et al. (1998) found seawater temperature increases especially in the vicinity of a nuclear power plant canal outlet in Taiwan and concluded that it caused coral bleaching (Hung et al., 1998). The research also found fish body anomalies caused by the thermal discharges along the power plant outlets (ibid.). However, also Jan et al. (2001) examined long-term effects of nuclear power plant on coral reef communities in the same area. The research concluded that changes in water temperature measured at sub-tidal stations were minor, as were other changes such as chlorine release and fish impingement (ibid.). Observed changes in the fish communities were assessed to be largely related to other than nuclear power plant induced factors (ibid.).

BIOMASS PRODUCTION

Large scale cultivation of algae for biofuels to replace fossil fuels can provide large amounts of biomass but the biofuel algal species can become invasive in shallow coastal ecosystems such as coral reefs, bringing significant risk to coastal biodiversity (Phalan, 2009).

Moreover, pesticides and fertilizers utilized in large scale bioenergy crop production on land may negatively affect adjacent marine ecosystems (Maxwell et al., 2016) (see chapter 4.2.1.3 for more discussion on biofuel production in the context of grasslands, and 5.2.1. for freshwater ecosystems).

Mineral mining

The transition to renewable energies to replace fossil fuels in the effort to mitigate climate change has increased the demand for critical raw materials (EEB, 2022). Deep ocean mining of sulphide deposits, ocean-floor polymetallic nodules or cobalt crust has raised concerns regarding its impacts on biodiversity and ecosystems (Jones et al., 2018; Orcutt et al., 2020). Deep sea mining simulations have discovered significant negative biodiversity and ecosystem impacts (Simon-Lledó et al., 2019) and can lead to contamination of coral reefs and other aquatic systems (EEB, 2022). Seabed mining will also remobilize carbon with unknown consequences for the ocean carbon dynamics (Thurber et al., 2014). The European Environment Bureau has alerted that deep seabed mining can have “massive, yet largely unknown effects on marine biodiversity” and has called for an international moratorium to the deployment of this industrial activity and emphasized the move towards circular economy (EEB, 2022).

Geo-engineering

Geoengineering refers to actions that aim at carbon dioxide removal (CDR) or solar radiation modification (SRM). Carbon dioxide removal in ocean ecosystems can take place by ocean fertilization in order to increase primary production and the delivery of carbon into the deep sea (e.g. Minx et al., 2018), by increasing seawater alkalinity to sequester carbon (e.g. Fuss et al., 2018) or by electrochemical splitting of water into hydrogen (H+) and hydroxide ions (OH-) to capture carbon or to increase alkalinity of seawater (IPBES-IPCC, 2021).

These techniques have generated some interest. However, the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters and its London Protocol defines marine geoengineering as “a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe”. The Convention further notes that marine geoengineering should not be considered as a substitute for measures to reduce greenhouse gas emissions (IMO). For example, the London Convention (LC-LP.1 (2008)) states that ocean fertilization for other than legitimate scientific research should not be allowed.

As geoengineering techniques are not based on natural processes, the rationales behind them are theoretical and their impacts to the marine ecosystems are not known (Hoegh-Guldberg et al., 2019). For example, ocean fertilization might have significant risks in relation to its impacts on biodiversity (Glibert et al., 2008). In relation to coral reefs, fertilization by nitrogen loading could result in corals being overgrown by algae which would lead to community shifts towards algal overgrowth and disruption of the entire coral reef ecosystems (McCook et al., 2001). Biodiversity rich reefs have been deemed inappropriate candidates for ocean fertilization experiments (Gilbert et al., 2008).

Ocean enrichment experiments have been conducted to understand how oceans respond to limiting nutrients (Gilbert et al., 2008). For example, experiments have included adding iron in areas with high macronutrient but low micro-nutrient availability in order to stimulate phytoplankton growth (Buesseler et al., 2008) or enriching oceans with nitrogen (Gilbert et al., 2008). Since these technologies may support carbon sequestration, these experiments have led some to propose that ocean fertilization could serve to support climate change mitigation action (Gilbert et al., 2008). However, research stresses that the biogeochemical and ecological impacts of ocean fertilization are unknown and thus the experiments bear risks of alteration of ocean ecosystems and unforeseen consequences (Buesseler et al., 2008). Ocean fertilization is likely to change species composition with serious implications on food web dynamics (e.g., Shepherd et al., 2007; Gilbert et al., 2008). Nitrogen fertilization has for example been proposed at the Sulu Sea, Philippines, which hosts high biodiversity, including corals (Gilbert et al., 2008). Research concluded that the enrichment is not likely to produce the phytoplankton assemblages desired but instead it would lead to increased production of harmful algae (Gilbert et al., 2008). The research further stressed that once algae become established, they would continue to proliferate causing ecosystem-level alterations.

Carbon capture and storage

Carbon capture and storage (CCS) involves the capture, liquefaction, and injection of CO2 into geological formations or the ocean (Lal, 2008). Research and technology for CCS has been increasing (Figueroa et al., 2008) and it has been perceived as a promising technology for climate change mitigation (Campbell et al., 2009). By supporting climate change mitigation, CCS together with other successful mitigation action can have a positive overall impact for marine ecosystems, including corals (Campbell et al., 2009). The biological and chemical implications of carbon dioxide injection are, however, largely unknown (Damen et al., 2006; Shepherd et al., 2007). Injection of carbon into the deep-sea will alter ocean chemistry and could have significant adverse impacts on deep sea ecosystems and marine organisms (Thistle et al., 2007; Lal, 2008; Campbell et al., 2009; CBD, 2009). In addition, carbon leakage from the storage could increase ocean acidification, which can have negative effects of marine ecosystems, including coral reefs.

3.3 Potential impacts of coral reef biodiversity policies on climate

Nature-based solutions - blue carbon

Ocean based Nature-based Solutions (NbS) can play an important role in climate change mitigation (e.g., Hoegh-Guldberg et al., 2019; Jacquemont et al., 2022). It has been estimated that nature-based solutions have the potential of providing 21 % of the total GHG emission reductions per year needed to achieve the 1.5 °C target by 2050 (Hoegh-Guldberg et al., 2019).

Seagrass beds, mangroves and salt marshes are generally referred to as “blue carbon” as they are highly productive ecosystems which can act as hotspots for carbon storage (Nelleman et al., 2009). Their carbon sequestration rates per hectare have been estimated to be ten times higher compared to terrestrial ecosystems (McLeod et al., 2011). If these ecosystems are degraded, for example if mangroves are converted to aquaculture, the carbon they have stored in their biomass and soils is emitted to the atmosphere (Hoegh-Guldberg et al., 2019). Thus, sustainably using, protecting and restoring these blue carbon ecosystems is understood as essential to maintain the carbon sequestration benefits in addition to many other ecosystem services they provide, including fisheries and coastal protection (Howard et al., 2017).

Even though corals are significant carbon conduits, they are not considered at present to represent long-term carbon sinks to be included under existing climate mitigation policies (Simard et al., 2016) (in contrast to boreal forests, see chapter 2.3.). Generally, high biodiversity areas deliver high levels of carbon sequestration, but this is not the case for coral reefs (IPBES-IPCC, 2021). In coral reefs, the level of primary production and the build-up of organic carbon over time is low (Reaka-Kudla, 1997). However, the ocean ecosystems such as coral reefs, mangroves and seagrass beds are intrinsically interlinked (Carlson et al., 2021). Therefore, even though coral reefs do not have significant carbon sequestration potential (Howard et al., 2017), they still play a vital role in the functioning of the blue carbon ecosystem due to ecosystem connectivity (Guerra-Vargas et al., 2020). Coral reefs function to protect and mitigate effects of wind and waves on seagrass meadows and lagoons (Gillis et al., 2014; Guannel et al., 2016). Coral reefs can prevent wave damage and erosion in blue carbon ecosystems (Guannel et al., 2016). For example, the degradation of coral reefs could increase wave heights within lagoons and this in turn could result in losses of seagrass or mangroves that would suffer from the waves and sea level rise (Saunders et al., 2014). Coral reefs have been estimated to reduce wave energy by an average of 97 % (Ferrario et al., 2014).

For instance, it was found that in seagrass beds sheltered by coral reefs, the level of organic carbon in sediments was 144 Mg ha^{-1} compared to 91 Mg ha^{-1} of unsheltered reefs (Guerra-Vargas et al., 2020). Therefore, the protection of coral reefs as an integral coastal defense system is important to support coastal blue carbon ecosystems (Hoegh-Guldberg et al., 2019). There are three broad management approaches through which blue carbon ecosystems can support climate change mitigation, namely preservation, restoration and creation (Froehlich et al., 2019; Macreadie et al., 2019). For example, marine protected areas offer a relatively simple nature-based solution (Roberts et al., 2017). Marine protected areas can support ocean-based climate change mitigation by ensuring intact, complex, high diversity ecosystems that maintain carbon sequestration and storage processes and prevent the loss of stored carbon (Roberts et al., 2017).

An example from the Indian Ocean Chagos Marine Protected Area evidenced that reefs free from many human stresses and disturbance can recover from degradation (Perry et al., 2015). The research reported that regardless of higher than 90 % coral mortality during the 1998 bleaching event, communities within a marine reserve recovered rapidly, with coral cover restored to the levels in 1996 by 2010, and in 2015 the average carbonate production recorded in Chagos was 28 % higher than in post-disturbance sites across the Caribbean. There are however some controversial results reported as some research has shown that corals within protected areas have succeeded as poorly or even worse during bleaching events compared to corals outside of protected areas (Graham et al., 2008). This might be caused by protected areas hosting a higher fraction of sensitive species (Graham et al., 2008) or lower genetic diversity (Selkoe et al., 2016).

4 Deserts/semi-deserts and arid/semi-arid grasslands

This section of the report focuses on arid and semi-arid open ecosystems in tropical and temperate regions. These ecosystems include deserts and semideserts and grasslands, including savanna, cerrado and steppe ecosystems. This section discusses also grasslands used for grazing. However, it does not cover agricultural lands, but refers briefly to some research on restoring degraded agricultural lands to grasslands. Therefore, agricultural management actions influencing carbon balance, such as conservation agriculture or agroforestry systems, have not been discussed. The section first discusses the overall importance of the identified areas on biodiversity and ecosystem services. The section then moves on to examine the potential impacts of climate policy measures on biodiversity. The section closes by examining biodiversity policies in desert and grassland ecosystems and their role in climate change mitigation. Key points highlight central findings for consideration in impact assessments.

Key points derived from the reviewed literature

Climate – biodiversity synergies

- Since grasslands hold high carbon sequestration potential, sustainable management of grasslands, grassland protection and restoration can yield both climate and biodiversity benefits.
- It may be possible to actively manage grasslands for biomass production whilst protecting native biodiversity.

Climate – biodiversity trade-offs

- Solar and wind power development help shifting away from fossil-based energy but may come with adverse biodiversity impacts:
  - Vegetation removal at solar power installations can cause erosion which negatively impacts dryland biodiversity and carbon sequestration.
  - Solar and wind power installations may restrict animal movement by e.g. blocking migration corridors or acting as a deterrent on otherwise suitable habitat.
  - Solar and wind power installations can cause direct animal mortality.
- Biofuels may offer an alternative to fossil-fuels, but cultivation of biofuels can cause land-use change with adverse effects on native biodiversity and ecosystem services as well as potentially to carbon sequestration.
- Afforestation of native grasslands may have significant negative impacts on local biodiversity and its use as a climate change mitigation measure should be carefully considered.

Considerations to pay attention to:

- Drylands are often mistaken as degraded land and hence may become targets for biofuel production or afforestation.
- Desert plant species are particularly vulnerable to disturbance and their disappearance can have cascading adverse effects on wildlife.
- There are many uncertainties regarding how different grassland management measures affect its carbon cycles. Therefore, climate change mitigation focused grassland management should be adjusted to local conditions.

4.1 Importance of desert and grassland ecosystems for biodiversity and ecosystem services

Deserts cover 17 % of the global terrestrial area and against common perceptions, harbour high biodiversity, including endangered species (MEA, 2005). Moreover, approximately 6 % of the global human population, including some of the most vulnerable and marginalized groups, habitat desert ecosystems

(Mortimore et al., 2009). Desert ecosystems are also important for the global carbon cycle, harboring nearly one-third of terrestrial carbon stocks (Trumper et al., 2008). Climate change has adverse impacts also on desert ecosystems (IPCC-IPBES, 2021).

In addition, also grasslands play an important role in the global carbon cycle (Campbell et al., 2009; McSherry and Ritchie, 2013). They can store large amounts of carbon primarily in the soil and grassland degradation can result in carbon loss (Campbell et al., 2009). Whilst the literature reviewed for this report concur that grasslands store significant amounts of carbon, the estimates of the magnitude vary (e.g., White et al., 2000; Lehman and Parr, 2016; Eze et al., 2018). In addition to supporting climate mitigation, grasslands provide also several other ecosystem services (Eze et al., 2018).

However, grassland ecosystems face several pressures. For example, the African savannas are under high land-use change pressure and approximately 50 % of Brazilian cerrado has been transformed for agricultural use (ibid.). Asian (e.g., Kumar et al., 2020) and African (e.g., Pfeiffer et al., 2020) savannas are also facing risks of conversion from grassland to woodland dominated systems contributed partly to increased carbon dioxide levels of climate change. In fact, remnant native grasslands have been identified as one of the ecosystems most vulnerable to climate change (along with e.g., coral reefs, mangroves, high mountain ecosystems and permafrost ecosystems) (CBD, 2003). Temperate grasslands, once covering approximately 8 % of the land surface, are now considered to be one of the most endangered biomes globally with less than 5 % of the area currently under protection (Carbutt et al., 2017). In Asia, nearly two-thirds of the domestic livestock are supported by grasslands/rangelands, from which however 10 % has been classified as having soil constraints (IPCC, 2002). Nearly 70 % of Mongolian pastures face degradation (ibid). In China, degradation of grasslands is said to account for the highest loss of carbon in the country (Xie et al., 2007).

4.2 Potential impacts of climate policies on grassland and desert biodiversity

Renewable energy production

Open, barren desert lands are often ideal for renewable energy installations due to their high wind resources and ample sunlight (Bennun et al., 2021).

SOLAR POWER DEVELOPMENT

Arid areas can support unique ecosystems and species, making it crucial to carefully evaluate the ecological consequences of renewable energy projects. The alteration of a landscape through the removal of vegetation and the construction of structures can increase animal mortality and change the characteristics of the environment in a way that affects wildlife (Lovich and Ennen, 2011). For example, facilities can cause habitat fragmentation leading to barriers to gene flow. Construction increases exposure to eroded soils and dust suppressants and impacts biodiversity together with direct mortality caused by construction (Pimentel Da Silva and Branco, 2018). Direct mortality is a result of for example polarised light reflected from solar panels attracting insects and birds, potentially creating an ecological trap (O'Leary et al., 2017) (the same effect has been reported on floating solar PV, see chapter 5.2.1). Concentrated solar light energy on the other hand can also harm bird feathers and burn flying birds or insects.

Large-scale solar development could result in significant loss of ecologically valuable lands (e.g., Cameron et al., 2012). For example, in the Mojave Desert, studies estimate this loss to range from over 250,000 hectares (<1 %) to 1.6 million hectares (<5 %) (ibid.). Such loss would hinder the achievement of ecoregional conservation goals, particularly for biodiversity targets such as mesquite upland scrub, greasewood flats, blackbrush shrubland, and mixed salt desert scrub (ibid.). Additionally, habitats suitable for species like the desert tortoise and desert bighorn sheep would be affected, leading to habitat fragmentation and the loss of connectivity between existing conservation areas (ibid.). Drainage channels in arid lands are important ecological features that can be disrupted by large solar facilities, impacting nutrient transport and wildlife habitats. Ground-mounted facilities require management strategies to control invasive species, manage altered hydrology, and mitigate for the loss of ecological features (ibid.).

Solar facilities have the potential to modify microclimate conditions in deserts, semi-arid regions, and grasslands (e.g., Lovich and Ennen, 2011). The research by Lovich and Ennen (2011) suggests that concentrating solar facilities can increase the albedo of desert environments by 30 % to 56 %. This change in surface reflectivity can influence local temperature and precipitation patterns by altering wind speed and evapotranspiration processes. Moreover, depending on their design, large concentrations of solar facilities can generate significant amounts of unused heat. This excess heat may be carried downwind into adjacent wildlife habitats, potentially leading to localized drought conditions.

Moreover, grassland ecosystems are vulnerable to the impacts of solar energy development. The removal of vegetation to make way for solar facilities can disrupt carbon cycling, potentially converting grasslands from carbon sinks to carbon sources (O’Leary et al., 2017). This alteration in carbon dynamics can disturb the natural balance of grassland ecosystems and impact the species that rely on them (ibid.). Moreover, solar facilities located in grassland areas can affect riparian systems, critical habitats for numerous wildlife species (ibid.). In southern Europe, grasslands and steppic habitats are considered desirable locations for solar energy development, while harbouring populations of protected birds already suffering due to habitat conversion (Lammerant et al., 2020). Studies have demonstrated that ground-mounted solar facilities can cause avian mortality, with estimates of bird deaths ranging from 16,200 to 59,400 per year in southern California alone (ibid.). These negative impacts on wildlife and disruption of essential ecological processes emphasize the importance of careful planning and mitigation measures when siting solar energy projects in grassland areas.

Water scarcity in arid regions can limit the types of cooling systems used, potentially impacting water resources (O’Leary et al., 2017). Water consumption is a significant environmental consideration for solar energy development, particularly in arid and semi-arid habitats (Gitay et al., 2002). The use of water for cooling systems, cleaning solar panels, and dust control can alter the availability of surface and groundwater sources, affecting riparian vegetation and groundwater-dependent habitats (Bennun et al., 2021). The drying and fragmentation of ephemeral water bodies and desert washes can adversely affect aquatic ecosystems (Jager et al., 2021) (see also chapter 5.2.1). In grasslands, solar energy development can disturb infiltration, increase runoff due to soil compaction, and reduce water quality (Lammerant et al., 2020).

Ground-mounted solar energy development can negatively affect desert plant communities and the ecosystem services they provide (Grodsky and Hernandez, 2020). Desert plants, such as cacti and Mojave yucca, are particularly vulnerable to disturbance caused by solar development, leading to reduced plant cover and structure. This reduction can have a significant impact on biodiversity, cultural services, provisioning, and regulating ecosystem services provided by desert plants. The loss of desert plant species, such as cacti and Mojave yucca, can have cascading effects on wildlife, including ants, birds, and cactophilic invertebrates. The promotion of invasive grasses further exacerbates biodiversity loss and can contribute to wildfires (ibid.).

Remote sensing and modelling studies alone may inaccurately estimate the loss of biodiversity and species-specific ecosystem service values, highlighting the need for field-based studies to complement remote sensing data and provide a more holistic understanding of the impacts of solar energy development on desert vegetation (Grodsky and Hernandez, 2020). For example, data from the southwestern USA and Sahara is inconclusive about the effects on vegetation (ibid.). More data is therefore needed to conduct a more rigorous assessment (Lovich and Ennen, 2011).

In grasslands, solar facilities pose similar risks to local animal and plant communities (Bennun et al., 2021). Provisions for protecting native habitat in developing solar facilities include designing green corridors, avoiding sensitive areas and controlling invasive species, which can reduce the impact on biodiversity (ibid.). Such measures can also contribute towards pollinator biodiversity (IPBES-IPCC, 2021). Compared to arid regions, where restoration of habitats is challenging due to extreme climates, slow soil formation, and herbivory, disturbed grasslands hold greater potential for responding to restoration attempts (O’Leary et al., 2017).

WIND POWER DEVELOPMENT

Locations such as the Great Plains in the USA are renowned for their abundant wind resources and have been identified as crucial for expanding the country's wind energy capacity (Bennun et al., 2021). The Great Plains are also home to some of the few remaining grassland habitats in the USA, which support unique biodiversity, including bison, pronghorn antelope, deer, and prairie chickens. Open desert lands with low bird and bat densities are generally considered suitable for wind power development, except in areas with freshwater oases or near coastlines where bird numbers can be higher (Ledec et al., 2011).

Wind farms can have both direct and indirect effects on desert biodiversity. Direct impacts include habitat loss and fragmentation due to the establishment of wind turbines and the construction of associated infrastructure (Kati et al., 2021; Ledec et al., 2011). Windfarms need less land than other renewables in terms of power production per square meter (Kati et al., 2021). However, their land take footprint extends to building roads and on-site construction. In particular, mountain ridge-top forests and semi-arid ecosystems are vulnerable to degradation caused by wind farm development (Ledec et al., 2011). Moreover, the construction and operation of wind farms can lead to displacement of certain bird species and large mammals from their otherwise suitable habitat (Campbell, 2009; Ledec et al., 2011).

Bird electrocutions primarily occur when medium to large birds perch on power lines or poles and complete a circuit by touching live wires (Ledec et al., 2011). Large raptors, including eagles, hawks, and vultures, are particularly vulnerable to such electrocutions. Similar concerns have been raised regarding threatened species such as Spanish Imperial Eagles and Bonelli's Eagles in Europe, as well as Cape Griffons and African White-backed Vultures in South Africa. However, at least in the USA studies show that windmills located on grasslands reduce bat mortality, one reason being that grasslands are a less suitable habitat for bats (Thompson et al., 2023). Therefore, placing windmills in open areas means bats are less likely to collide with them compared to placing them in forested areas.

Wind farm development and operation can have indirect effects on wildlife as well (Ledec et al., 2011). Displacement from otherwise suitable habitat is a significant concern for some bird species (Shaffer and Bulh, 2016). Certain birds inhabiting open, naturally treeless habitats, such as prairie grouse in North America or bustards in Europe, may abandon extensive areas of suitable habitat around wind turbines due to their instinctive avoidance of tall structures (Ledec et al., 2011.). Similarly, large mammals relying on migration corridors may be impacted by the presence of wind farm employees and vehicles during construction and operation (ibid.).

BIOFUEL PRODUCTION

Biofuel production is a common component of climate change mitigation strategies, but biofuel crops vary in their impacts on local biodiversity and provision of ecosystem services (Helms et al., 2020). Land-use change appears to be the main driver of biodiversity loss associated with bioenergy production (Immerzeel et al., 2014). Also, alterations in species richness and abundance and biological homogenization have been reported (Immerzeel et al., 2014). There is no clear distinction between degraded, marginal or low-intensity pasture or grassland (Immerzeel et al., 2014). Since such areas might be valuable for biodiversity, conversion of such areas to bioenergy production can result in negative biodiversity impacts (Felton et al., 2010).

For example, Brazilian Cerrado is facing conversion to sugarcane and soybean plantation whilst the grasslands in the United States are being converted to corn production (Fargione et al., 2008). Bioenergy production, together with other human induced land-use change pressures, have been also noted to constitute a direct threat to biodiversity and the provisioning of ecosystem services in the African savanna biome (Aleman et al., 2016; Sala et al., 2016).

A study by Lark et al. (2015) found that biofuel crop expansion resulted in substantial landscape transformation, including conversion of grasslands in the United States. In North America, the predominant biofuel crop is corn (Zea mays) which is used to produce ethanol (Helms et al., 2020). The spread of corn production has been noted to result in loss of biodiversity and the effects on associated ecosystem services are partly unknown (ibid.). For example, when corn production areas were compared with areas of native perennial biofuel crops, the native crops supported up to 185 % more ant species, including seed dispersing species, potentially higher ant diversity, provided up to 55 % more natural pest suppression and provided more associated ecosystem services compared to the corn production site (ibid.). The intensive cultivation of corn as mono-cultures is associated with reduced plant and animal biodiversity and diminished ecosystem functions and services (Hoekman and Broch, 2018). Corn-ethanol production has also been associated with adverse impacts on water quality and availability, and on soils and ecosystems (Hoekman et al., 2018) with indirect negative impacts on biodiversity. Intensive cultivation can result in soil erosion, which reduces ecosystem productivity and negatively influences biodiversity.

A study by Landis et al., 2018 argue that switching from corn to native perennial fuel crops could yield lower ethanol quantities but outperform corn in the provision of other ecosystem services. Similarly, Fargione et al. (2008) have noted that producing biofuels by clearing carbon rich habitats, such as Cerrado and native grasslands can in fact increase CO2 emissions. It has been noted that native grassland perennial species can provide a greater climate change mitigation potential, provide higher bioenergy yields (238 % greater compared to monoculture yields after a decade) compared to corn ethanol or soybean biodiesel whilst having biodiversity benefits (Tilman et al., 2006). Restoring corn production sites to native prairie grassland vegetation has been proposed as a means to support climate change mitigation whilst resulting in biodiversity benefits (Helms et al., 2020). A study by Werling et al. (2013) suggested that it is possible to actively manage grasslands for biomass production whilst maintaining ecosystem services, but the research emphasizes the importance of site-level management decisions.

Perennial grassland fertilization in the attempt to enhance biomass production may increase biomass yields but negatively impact biodiversity and provision of ecosystem services (Werling et al., 2014). For example, research has noted that nitrogen fertilization should not be considered as a nature-based solution (Reise et al., 2022). Fertilization can negatively impact grassland plant biodiversity (Bai et al., 2010).

Biofuels grown on degraded croplands and produced from waste biomass minimize the related habitat destruction and yield climate benefits (Fargione et al., 2008). Bioenergy plantations that do not replace natural vegetation but are founded on degraded land such as degraded cropland or plantations may improve soil structure and fertility (CBD, 2003).

A review by Immerzeel et al. (2014) identified important gaps in relation to understanding the effects of bioenergy crop production on biodiversity. The study found that biodiversity impacts of ‘second generation’ bioenergy crops tend to be less negative compared to the ‘first generation’ ones and may even be positive as showcased by some examples from tropical region (ibid.). Another study noted that the potential biodiversity effects of so called ‘second generation’ biofuels are largely unknown (Campbell et al., 2009). Some studies have questioned their biodiversity impacts as all biomass is removed for fuel potentially impacting soil fertility and as the plants do not produce beneficial co-products (Eickhout et al., 2008).

Afforestation

Deforestation and forest degradation account for substantial greenhouse gas emissions (IPCC, 2014). Afforestation (i.e. introducing a forest in an area without recent tree cover) is promoted as supporting climate change mitigation by enhancing carbon sequestration (Bastin et al., 2019). In addition to climate benefits, afforestation activities can yield biodiversity benefits if they convert degraded areas, include native trees, result in diverse, multi-strata canopies, prevent invasive species, result in minimal disturbance and support ecosystem connectivity (CBD, 2003).

Whilst reforestation of degraded forest ecosystems provide both biodiversity and climate benefits, concerns have been raised over climate mitigation activities that aim at afforesting naturally treeless ecosystems (Veldman et al., 2015b). Afforestation activities may be based on the wrong assumption that open ecosystems are degraded forests (Ratnam et al., 2016; Bond et al., 2019) and they may omit the potential negative effects of such activities on biodiversity (Bond et al., 2019; Kumar et al., 2020). These open iconic ecosystems of tropical Africa, South America and Australasia have been maintained for millennia by wildfire and browsing dynamics (IPCC-IPBES, 2021). This landscape supports for example the high value nature-based tourism in Africa (ibid.). A substantial portion of these ecosystems have been targeted by afforestation programs, creating a conflict between climate change mitigation and biodiversity protection, with implications for water (IPCC-IPBES, 2021). For example, in South Asia it has been estimated that misclassifying grassy savannas as areas suitable for afforestation could result in 35-40 % loss of these unique ecosystems (Kumar et al., 2020). According to Bond et al. (2019) 1 million km2, mostly of grassy biomes in Africa have been targeted for “restoration” by 2030. Research has called for an urgent need to correct misinterpretations regarding savannas and other grasslands as potential sites for afforestation (e.g., Kumar et al., 2020).

The carbon sequestration benefits of afforestation are determined largely by the previous land use of the afforested site (Campbell et al., 2009). Afforestation of grasslands can increase above-ground carbon stocks but can result in substantial losses of belowground carbon (Dass et al., 2018). For example, afforestation of grassland in one region of China had a net positive impact (Hu et al., 2008), whereas a study in Africa found that afforestation in savanna ecosystems had negative impacts on the carbon budget one year after plantation due to soil disturbances (Nouvellon et al., 2008). The assumption that planted forest would always sequester more carbon than open areas has been challenged (e.g., Veldman et al., 2015a).

For example, plantations typically alter nutrient cycles which can reduce soil carbon storage (e.g. Berthrong et al., 2012). These are sometimes overlooked when estimating potential carbon gains (ibid.). It has also been emphasized that afforestation activities should consider the fire-proneness of dry grassland ecosystems and that carbon stocks belowground are less vulnerable to disturbance from fire than those above ground (Veldman et al., 2015b). The carbon stored in grasslands is mostly belowground where it is protected from fire (Dass et al., 2018). The increased levels of biomass resulting from afforestation can change fire regimes towards hotter fires and associated higher losses of carbon (Bennett and Kruger, 2015). Eucalyptus and pine plantations are especially vulnerable to fire (Bond et al., 2019). For example, Dass et al. (2018) concluded that in the absence of effective forest fire management, the grasslands in California store more carbon for a longer time period compared to forests. Grassy biomes targeted for afforestation may be better at conserving carbon compared to forests that are more fire prone (Dass et al., 2018).

Afforestation of non-forested, high biodiversity value landscapes such as natural grasslands and savannas could lead to significant loss of biodiversity (CBD, 2003; CBD, 2009). Biodiversity loss could be accrued through reduction in the availability of sunlight (Veldman et al., 2015a), habitat loss, fragmentation and introduction of invasive alien species (CBD, 2009). Afforested trees can cause resource competition which can then result in the loss of herbaceous and endemic savanna species (Brooks et al., 2010). Afforestation activities have also been reported to have introduced invasive alien species such as Lantana camara and Prosopis juliflora (Hiremath and Sundaram, 2013).

For example, afforestation of shrublands and natural grasslands was found to result in approximately 30 % decrease in plan species richness and the decrease was particularly high for endemic and native species, which were found to decline in richness by 38 % in the shrublands and 47 % in the grasslands (Bremer and Farley, 2010). Afforestation, together with the increased tree growth caused by climate change is leading to a conversion of these ecosystems into areas of bush encroachment (Stevens et al., 2017). For example, in Africa reforestation of dryland ecosystems (including grasslands, savanna and forests) by non-native Acacia species, has lead to bush encroachment and negative biodiversity impacts (including impacts on vultures, cheetahs and grassland birds) as well as reduction in ecosystem services (such as water availability and fuelwood) (IPBES-IPCC, 2021). Mbaabu et al. (2020) examined the impacts of Prosopis juliflora encroachment in semi-arid region in Kenya and found that the encroachment increased carbon stocks. However, other research has found that Prosopis encroachment threatens biodiversity across multiple trophic levels (Linders et al., 2019).

Afforestation can also affect stream flow and water quality (Farley et al., 2005). For example, planting of fast-growing species in semi-arid regions or replacing natural grasslands with forest plantations can increase evapotranspiration and divert soil water resources from groundwater recharge (Silveira et al., 2016). Impacts of afforestation vary depending on the tree species but may be more pronounced with non-native species (Epple et al., 2016; IPCC-IPBES, 2021). For example, Farley et al. (2005) estimated an annual reduction in runoff of about 44 % and 31 % when grasslands and shrublands were afforested respectively. However, it is important to note that forest restoration can also improve water filtration and groundwater recharge (Ellison et al., 2017). (See chapter 5.2.3 for the impacts of afforestation on freshwater ecosystems.)

A clear distinction has been called for to distinguish between reforestation of deforested lands and afforesting historically non-forest lands to forests or tree plantations (Putz and Redford, 2009). Afforestation of grassy biomes can have considerable negative biodiversity effects and compromise ecosystem services (Bremer and Farley, 2010) such as hydrology (Jackson et al., 2005) and soil nutrient cycles (Berthrong et al., 2009). Afforestation activities may raise conflicts of interest between various stakeholder groups who emphasize economic benefits from plantations, carbon sequestration efforts or protection of biodiversity (Bond et al., 2019).

Afforestation plans should be assessed carefully and the potential benefits (e.g. erosion control and access to timber) should be weighed against the potential risks and potential landscape scale impacts (Epple et al., 2016). Due to the negative impacts of afforestation of natural grassland ecosystems is not considered as a Nature based Solution and is not generally recommended (Reise et al., 2022).

Carbon sequestration and management strategies

Due to the carbon sequestration potential of grasslands, grassland management has importance for climate change mitigation as it can affect the levels of carbon stored in grasslands (e.g., Conant and Paustian, 2002; Eze et al., 2018). However, the effects of the management activities on carbon stocks are not altogether clear (ibid.). Research has been called for to estimate the changes in grassland soil carbon stocks caused by grassland management (Conant and Paustian, 2002).

As concluded also by Campbell et al. (2009), literature found regarding carbon sequestration in grasslands focuses mainly on the management of grazing lands rather than unmanaged grasslands. As referred to in Campbell et al., (2009), these management strategies include supporting biomass production (see also Eze et al., 2018), humification of biomass returned to the soil, facilitating carbon transfer into subsoil by root system development and the formation of organomineral complexes (Lal, 2004). Management practices such as adjusting the intensity of grazing (Gerber et al., 2013), rotational grazing and management of nutrients (Khan et al., 2007) as well as fire management have been found to increase soil carbon stocks (Lal, 2004; Gerber et al., 2013). Also avoiding conversion to croplands and restoration of degraded grasslands have been identified as a climate mitigation approach in grasslands (Gerber et al., 2013). Also, management of species that may increase primary production have been adopted (Campbell et al., 2019).

Climate change mitigation actions on grasslands can have both positive and negative impacts on biodiversity (Epple et al., 2016). Grassland management, including management of grazing, protection and fire management, can enhance carbon storage in soils and biomass while simultaneously conserving biodiversity (CBD, 2003). From biodiversity perspective, avoiding conversion and degradation of grasslands and grassland restoration (particularly by natural regeneration) are desirable (MEA, 2005). The biodiversity impacts of fire regulation depend on natural fire regimes of the region to which species are adapted to and the used regulation practices (ibid.). Mitigation action that can yield negative biodiversity impacts include activities that affect wild herbivore populations, that involve intensive grassland management and the use of fertilizers, irrigation and re-seeding with high performance grasses (Berry et al., 2008). Negative biodiversity impacts can also accrue from afforestation activities that are wrongly directed towards natural grassland ecosystems (Veldman et al., 2015b).

WILDFIRE MANAGEMENT

Forest encroachment may be contributed partly to fire suppression and the increased tree growth caused by climate change (Buitenwerf et al., 2012; Abreu et al., 2017). Fire suppression might offer a way to enhance carbon stocks in mixed tree/grass ecosystems. In Brazilian Cerrado, fire suppression increased carbon stocks but resulted in loss of biodiversity where one quarter of plant and one third of ant species were lost (Abreu et al., 2017). Forest encroachment into open savanna can result in increase in tree species richness but lead to decreases in the diversity of shrubs and herbaceous plants – the species that are most prevalent for grassland ecosystems (Abreu et al., 2017). A study from Brazilian Cerrado reported that if forest encroachment is not interrupted, the savanna ecosystems from the particular study area were expected to be lost with severe impacts on biodiversity. The study notes that reintroducing natural fire would reverse the forest encroachment process but highlights that this needs to be done before the canopy becomes dense and causes substantial impacts on the herbaceous layer (Abreu et al., 2017). If the diversity of herbaceous plants is lost, it is unlikely to readily recover after canopy is opened as the area may become dominated by aggressive non-native grasses that prevent the recovery of native herbaceous vegetation (Veldman and Putz, 2011). Strategic burning that leads to more frequent but less intensive fires has been successful in some regions in reducing carbon emissions (Fitzsimons et al., 2012).

GRAZING MANAGEMENT

Globally, approximately 41 % of land surface area is classified as rangelands (MEA, 2005) and due to their global extent, these areas have been identified as important carbon sinks (IPCC, 2007; McDermot and Elavarthi, 2014). These grassy ecosystems are used as natural ecosystems for livestock grazing as well as conserving wildlife (Allen et al., 2011). The Millennium Ecosystem Assessment (MEA, 2005) included rangelands with drylands. According to some studies, rangelands can store up to 10-30 % of global soil organic carbon (Derner and Schuman, 2007) and act as important carbon sequester (Lal, 2004). It is still unclear, how grazing affects soil organic carbon despite decades of research (McSherry and Ritchie, 2013). Research has found both positive and negative effects of grazing on soil organic carbon (ibid.). For example, research has found that grazing in semi-arid grasslands causes grassland degradation and loss of soil organic carbon in Northern China (He et al., 2011) and America (Neff et al., 2005) and increased soil organic carbon after introduction of grazing management has been reported from different parts of the world (Conant et al., 2001).

Grassland soils offer a potentially large carbon sink due to the extent of degradation that has already occurred (Conant, 2010). According to one estimate, full rehabilitation of the overgrazed grasslands by better distribution of livestock and adopting more moderate levels of grazing could sequester approximately 45 million tons of carbon per year (Conant and Paustrian, 2002). The optimal level of grazing to achieve best results for carbon sequestration depend on climate, and the type of soil and vegetation (ibid.). Whilst moderate grazing has been found to yield best results in some grasslands, even moderate levels of grazing have been found to lead to losses of soil carbon in others (ibid.).

Some research has recommended that due to the heavy grazing in tropical grasslands, future tropical grassland management policies should focus on reducing the intensity of grazing in order to support carbon sequestration (Eze et al., 2018). For example, Mgalula et al. (2021) found that in Eastern African rangelands, it is possible to enhance carbon sequestration by moderate grazing, restoration and enclosures (Mgalula et al., 2021). However, the research emphasizes that more information on the emission sources and carbon sequestration potential for Eastern Africa rangelands is vital to develop mitigation strategies (ibid.). Similarly, Manaye et al. (2019) found that grazing exclosures supported by enrichment planting of trees on previously degraded semi-arid grazing lands in Ethiopia enhanced the regeneration of naturally generated woody species diversity, composition and structure as well as increased the total biomass and soil carbon stock. The study concluded that enrichment planting and grazing exclosures on such degraded dryland areas could provide a viable carbon sequestration strategy (ibid.). Degradation caused by overgrazing has also been reported from Mongolian steppe and grazing management has been a common strategy to combat this (Chang et al., 2015). Results by Chang et al. (2015) showed that the reduction of grazing pressure offered a solution for pairing livestock production with soil organic carbon recovery.

RE-VEGETATION

Re-vegetation refers to supporting the establishment of vegetation that does not meet the definitions for afforestation or reforestation (Campbell et al., 2019). The purpose generally is to control erosion on degrade lands. Information regarding the potential of re-vegetation to support climate change mitigation is scarce (CBD, 2003). The biodiversity impacts of re-vegetation are generally positive as it targets degraded lands, but impacts may vary if non-native species are used (ibid.).

SOIL MANAGEMENT

Due to the role of grassland soils in climate change mitigation, the role of soil management should be emphasized (Campbell et al., 2019). As soil degradation also has negative biodiversity impacts through the loss of productivity and reduction in water quality, soil management also comes with biodiversity benefits (ibid.).

4.3 Potential impacts of grassland / desert biodiversity policies on climate

Grassland conservation and avoided conversion

Degradation of semi-arid ecosystems leads to considerable carbon emissions caused by soil erosion and degradation (Chappell et al., 2019). Soil is the largest terrestrial carbon reservoir, but rapid losses of soil carbon stocks have been reported for example for tropical savannas due to intensive livestock grazing, agriculture and changes in fire regimes (Reid et al., 2004).

Carbon stocks have been shown to decline up to 60 % following conversion of grasslands to cropland (Guo and Gifford, 2002). Therefore, avoided conversion has been said to offer the largest possible carbon savings per hectare (ibid.). The conversion from cropland back to grassland offer generally more moderate carbon benefits but can lead to approximately 20 % increases in soil carbon over several decades (ibid.). Due to the decline in carbon stocks following grassland conversion, impacts of climate change mitigation activities that involve grassland conversion for cultivation of biofuels or afforestation should be carefully assessed (ibid).

Conservation of open-canopy ecosystems can enhance soil carbon storage and carbon sequestration, whilst providing species protection (Bremer and Farley, 2010). Preventing grassland conversion to cropland can save soil organic carbon and avoid emissions from the conversion (Reise et al., 2022). According to one estimate, avoided emissions from halting grassland conversions (1.7 Mha/yr) have been estimated at 0.12 GtCO2e/yr in the top 30 cm of the soil for temperate, tropical and subtropical grasslands (Griscom et al., 2017).

Nature based Solutions in grasslands should therefore focus on protecting natural and semi-natural grasslands and avoid their conversion (Reise et al., 2022). Protecting grasslands from conversion and hence protecting the carbon they store can meaningfully contribute to reducing global greenhouse gas emissions (Ahlering et al., 2016).

Grassland restoration

Restoration of abandoned cropland to permanent grassland can increase primary production (Reynolds et al., 2012) and soil carbon while providing grassland-related ecosystem services (Conant et al., 2017). For example, Lu et al. (2018) found that ecological restoration in forest, grassland and shrubland ecosystems in China contributed substantially to CO2 mitigation. Restoration of degraded grasslands with native species can also yield positive biodiversity impacts (Campbell et al., 2019). The climate change mitigation benefits of grassland restoration are said to be even larger if biomass is harvested and used to replace fossil fuels (Oates et al., 2016). The research however points out, that there are many other potential uses for such land such as reforestation or biodiversity conservation (Yang et al., 2018).

Research in Kenya found that total soil organic carbon in degraded grasslands was 37 % lower compared to that of pristine grasslands (Mbaabu et al., 2020). Thirty years after restoration, soil organic carbon of degraded semi-arid grasslands had increased nearly to the level of pristine grassland (ibid.). Restoration also increased the availability of fodder, but 30 years was not sufficient to restore plant species richness (ibid.). The research notes that recovery of plant species requires more time and/or targeted grassland management interventions, since the speed of recovery may be limited for example by depleted soil seed bank (ibid.).

Thus, rebuilding of the soil and plant carbon stocks of semi-arid regions can offer potentially significant contributions to climate change mitigation due to the vast areas these ecosystems occupy (Lal, 2004; Ahlström, 2015). For example, in semi-arid rangelands of Sudan it was concluded that regardless that the carbon sequestration levels in the semi-arid rangelands is low compared to some other ecosystems, the potential for carbon storage is high due to the significant area of land (CBD, 2003). However, this view has also been contested (e.g. Yusuf et al., 2015) as has been the efficacy of restoring degraded semi-arid systems (Gosnell et al., 2020). Carbon dynamics in savanna ecosystems are complex and poorly understood as the impacts of land use, climate and soils vary spatially and temporally (Yusuf et al., 2015).

5 Freshwater ecosystems

This final section of the report focuses on freshwater ecosystems and related biodiversity impacts of climate policies. The section focuses on lakes and rivers when specified, and does not cover wetland ecosystems, such as bogs, swamps and marshes. It is worth noting that the cited literature does not often specify the exact form or location of the “freshwater” it refers to, and many cited publications speak in general terms. The section begins with an overview of the importance of freshwater ecosystems for global biodiversity and moves on to detail the potential impacts different climate actions have on these types of ecosystems. The bulk of related literature focuses on renewable energy, especially hydropower.i

Key points derived from the reviewed literature

Climate – biodiversity synergies

- Floating solar photovoltaic (PV) panels may reduce evaporation in arid areas and provide a solution for poorly managed water sites.
- Agricultural erosion control practices related to biofuel farming can improve water quality, reduce emissions, reduce flood risks, and increase biodiversity in aquatic systems.
- Climate change serves as an additional incentive to improve the management of inland waters and the efforts to slow down deforestation; they offer both financial and conservation benefits.
- Sustainable water management can help avoid or reduce emissions.
- Protecting and restoring ecosystems helps to protect functioning water cycles which in turn supports terrestrial ecosystems in carbon sequestration.

Climate – biodiversity trade-offs

- Climate change mitigation measures can negatively affect freshwater resources, leading to ecosystem degradation.
- Energy production is water intensive and therefore impacts on water should be assessed carefully when designing low-carbon energy projects.
- Hydropower dams alter the water flow and fragment river habitats; they prevent fish migration and spawning.
- Solar energy production may contribute to water pollution, habitat fragmentation, and disturb birds and insects.
- Intensified forest management and associated fertilization can increase nitrogen emissions and potentially have negative impacts on aquatic biodiversity.

Considerations to pay attention to:

- Consider the area of the whole watershed: disruptions on the water flow may have far reaching consequences.
- Hydropower plants can be constructed to have less or no negative impacts on biodiversity:
    - construction and use of run-of-the-river, small scale, closed-loop systems and technologies such as fish ladders.
    - consider the dam’s biodiversity impacts from construction to decommission.
- Little is still known about the biodiversity impacts of energy sources on aquatic ecosystems, for example in the case of solar panels and photovoltaic (especially their potential chemical runoff), and shale development (especially in relation to ground and surface water contamination).

5.1 Importance of freshwater ecosystems for biodiversity and ecosystem services

Freshwater ecosystems, such as rivers, lakes, wetlands, and streams, are crucial for supporting global biodiversity. These ecosystems are home to a wide variety of plants, insects, fish, amphibians, reptiles, birds, and mammals, many of which are specially adapted to these aquatic environments. Despite covering less than 1 % of the Earth's surface, freshwater ecosystems contain a disproportionately high percentage of the world's species and a vast amount of genetic diversity (Strayer and Dudgeon, 2010). This high species diversity is due to the diverse range of habitats and ecological niches found in freshwater systems. They offer breeding grounds, nesting sites, feeding areas, and shelter for a vast number of species, contributing to their survival and reproduction. Protecting and maintaining healthy freshwater habitats is also essential for ensuring the survival of many migratory species throughout their journeys.

Freshwater ecosystems also act as natural water filtration systems (CBD, 2003). They remove pollutants, sediments, and excess nutrients from water, improving its quality. This purification function is not only important for maintaining the health of freshwater ecosystems but also for providing clean and safe water for human communities. Freshwater ecosystems provide numerous other ecosystem services that benefit human societies: they regulate the water cycle, regulate floods and droughts, recharge groundwater, and help in maintaining stable water supplies (Juffe-Bignoli et al., 2012). Additionally, these ecosystems support recreational activities like fishing, boating, and birdwatching, contributing to local economies and human well-being. The effects of disturbing these aquatic ecosystems, especially in tropical areas, may in turn lead to increased pathogens and an increase in human diseases such as malaria, schistosomiasis, filariasis, and yellow fever (CBD, 2003).

Human impacts have, however, altered freshwater ecosystems (CBD, 2003). Agricultural runoff, pollution and sedimentation degrade freshwater habitats on their way to the world’s oceans, where they continue to erode coastal and marine ecosystems (ibid.). Groundwater systems are also affected through the accumulation of nitrogen from fertilizers (ibid.). Freshwater is a finite resource that is already being over-exploited in many places and climate change is further increasing the pressure (Ingemarsson et al., 2022). Only a fraction of the world’s freshwater resources, especially rivers, remain outside of human influence (Vörösmarty et al., 2010).

According to CBD (2003), climate change is expected to impact freshwater ecosystems through changes in water cycle, and through changes in the nearby terrestrial ecosystems. It is important to consider the area of the whole watershed, including especially the coastal zone, in adaptation planning. The vulnerability of freshwater biodiversity to climate change is increased by the fact that many rivers are blocked by dams and embankments. This limits the adaptational capability of river biota, which is otherwise reasonably fast to react to natural changes in environmental conditions and poses an obstacle in implementing new climate adaptation strategies. (CBD, 2003).

Furthermore, the global climate system and water cycles are intrinsically intertwined (Ingemarsson et al., 2022). Water is an essential element in climate mitigation action. On the other hand, climate change mitigation actions can negatively affect freshwater resources. Mitigation actions can affect water cycles and balances, leading to reduction in water quantities, pollution and ecosystem degradation. Conflicts may arise between biodiversity and energy policies, particularly concerning the protection of designated areas and the expansion of renewable energy projects. For example, the European Union’s Water Framework Directive plays a crucial role in ecological protection, aiming to achieve a "good" status for all water bodies and prevent their deterioration (Water Framework Directive, Article 4(1)). To address these conflicts, it is suggested that biodiversity concerns be integrated into the Renewable Energy Directive framework, developing sustainability criteria tailored to each renewable energy source. Additionally, the biodiversity protection directives should establish standards for assessing the impacts of renewable energy projects within their scope, supported by continued and enhanced monitoring of environmental parameters during project construction and operation (Dulluri and Rat, 2019). Since energy production requires considerable amounts of water, particularly the energy sector should account for the availability of freshwater when planning for the low-carbon transition (Ingemarsson et al., 2022).

5.2 Potential impacts of climate policies on freshwater biodiversity

Renewable energy production

Energy production, including renewable energy, is highly water intensive (Ingemarsson et al., 2022). This includes for example hydropower, bioenergy, solar power, geothermal power and nuclear power. It has been emphasized, that a comprehensive analysis of water availability, estimated water usage and competing water demands, including those at the ecosystem level, is required when assessing energy alternatives. On the other hand, availability of water can greatly influence renewable energy production capacity, particularly of hydropower.

HYDROPOWER

Dams are constructed for various purposes, such as irrigation, and about 21 % of dams are designed for power generation. However, deliberate impoundment of water as a result of dams leads to significant modifications to the physical conditions of a river and causes effects on both aquatic and terrestrial ecosystems throughout the river system (Chen et al., 2015). According to the EKLIPSE Project (Meletiou et al., 2019), there is a risk that increasing investment in hydropower may trigger rapid dam construction and projects, which do not consider the environmental and social implications and can damage river ecology (Meletiou et al., 2019). Dams have various negative effects on water flow, as they disrupt the natural seasonal flow of river, and cause frequent changes in river depths and widths (EEB, 2022). The transformation of a river into an artificial reservoir alters water depth, temperature, chemical composition, dissolved oxygen levels, and sediment loading, leading to unsuitable conditions for some aquatic plants and wildlife (Meletiou et al., 2019).

One of the most cited and researched negative impacts dams have for biodiversity is how it challenges fish migration. Migration is crucial for the life cycle of many fish species and the construction of dams can lead to the reduction of aquatic and terrestrial biodiversity by altering water timing, flow, flood pulses, and oxygen and sediment content (IPCC, 2002). Dams fragment river habitats through installations and ancillary infrastructure (Gasparatos et al., 2021) and pose risks to fish by turbine entrainment and the inability to move upstream (Jager et al., 2021). Flow modifications can disrupt spawning, which is triggered by pulse flows, and the proximity of multiple dams can threaten lotic species with vulnerable life histories (ibid.). The prevention of fish migration caused by dams not only disrupts ecosystems but also damages fishing resources and affects local populations relying on them (CBD, 2003). As a case in point, currently only four Finnish rivers sustaining natural reproduction of salmon remain, as a consequence of nearly complete loss of spawning habitats from large-scale damming of rivers for hydropower generation (Similä et al., 2021).

Technologies such as fish ladders, fish bypasses, and fish-friendly turbines have been developed to mitigate these impacts (Meletiou et al., 2019). The trapping of sediments by dams affects downstream physical processes and can lead to negative environmental effects such as eutrophication and biodiversity loss (ibid.). However, there are cases where hydropower plants have had negligible effects on water quality or where initial negative effects stabilized over time (). The alteration of water parameters by hydropower projects can have cumulative negative effects on specialized aquatic and semi-aquatic species, emphasizing the need for proper design and operation of reservoirs and dams (ibid.). Additionally, the location of dams within a river system plays a significant role, and dams near tributary headwaters have fewer impacts compared to mainstream dams that affect the entire watershed (CBD, 2003; Jager et al., 2021).

Small-scale hydropower schemes, such as run-of-the-river hydropower and micro dams, generally have fewer negative impacts on biodiversity compared to large dams, although the cumulative effects of multiple small units should be considered (CBD, 2003). Large-scale hydropower development, on the other hand, can have significant environmental and social costs, leading to serious impacts on aquatic and riparian ecosystems, causing deforestation, loss of habitats, and disrupting downstream floodplains and wetlands (CBD, 2003; Campbell et al., 2009). Large dams can also alter hydrological patterns, lower groundwater levels, and impact freshwater species and migration, making careful planning crucial (Dulluri and Rat, 2019). According to Dulluri and Rat (2019) a big part of the ecological and social impacts of hydropower projects occur during the construction phase, which involves laying roads, erecting dams, reservoirs, and connecting transmission lines. However, the effects during whole life cycle of a hydropower installation must be considered, from its initial construction to its renovation, decommissioning or their day-to-day operation and management (EU, 2018). Dam reservoirs result in loss of land, which may also lead to the loss of local terrestrial biodiversity (IPCC, 2002; CBD, 2003). While some efforts have been made to decentralize power supply and reduce environmental impact through smaller dam projects, they can still lead to habitat fragmentation and degradation, requiring appropriate infrastructure, basin-scale perspectives, and ecological assessments (Smith et al., 2021).

Mitigation options exist to address diurnal variability in flows and temperatures caused by hydropower plants operating in peaking mode, e.g. providing cover for fish and benthic organisms in tailwaters and exploring alternatives like battery storage instead of fluctuating flows (Jager et al., 2021). Closed-loop pumped storage systems can be used to provide storage for renewables by storing water until electricity is needed. Closed-loop systems also reduce the risk of fish entrainment compared to open-loop systems (ibid.).

Hydropower projects generally have relatively low greenhouse gas emissions, except for large shallow lakes in heavily vegetated tropical areas where there may be emissions from decaying vegetation (IPCC, 2002; Meletiou et al., 2019); the filling of reservoirs and decomposition of submerged organic matter can lead to significant emissions of carbon dioxide and methane. The quantities of greenhouse gas emissions from hydropower plants depend on for example, nutrient loading and organic content, water temperature and levels of primary production (Ingemarsson et al., 2022). Nonetheless, some recent studies suggest that overall greenhouse gas emissions from hydropower may be lower than initially anticipated (Meletiou et al., 2019).

SOLAR ENERGY

Concentrated solar power (CSP) plants require significant amounts of water for cooling and cleaning, although water usage can be reduced through methods like manual dry brushing (Bennuin et al., 2021). Water-intensive cleaning of dust from photovoltaic (PV) panels can also impact surface and groundwater sources, particularly in arid regions, affecting riparian vegetation and habitats. Construction and operation of solar plants can contribute to water pollution, such as thermal pollution from releasing cooling water and the risk of contaminating water bodies with hazardous chemicals. (ibid.).

The negative effects of floating PV plants on biodiversity and aquatic ecosystems are not well understood (Bennuin et al., 2021). Operational floating solar PV can block sunlight penetration into water, inhibiting algal growth and potentially impacting water quality. Birds and insects may mistake the flat surfaces of PV panels for water bodies, posing a risk of injury and disturbance to certain bird species that rely on water for take-off (ibid.1) (similar effect has been reported on solar panels on land, see chapter 4.2.1). The drying and fragmentation of ephemeral water bodies and desert washes can have adverse effects on aquatic ecosystems in arid regions (Jager et al., 2021) (see chapter 4.2.1). Still, little is understood of the impacts of photovoltaics on the hosting water body's physical, chemical and biological properties (Smith et al., 2021).

On the other hand, floating PV offers the advantage of reducing algae proliferation, and it can be applied adaptively according to site-specific parameters and weather constraints (SolarPower Europe, 2022). Floating PV have also been demonstrated to reduce evaporation from the water bodies and according to Smith et al. (2021) are being discussed as promising options especially when applied to hydroelectric reservoirs in arid regions. Solar PV can also be deployed on poorly managed water sites, providing a potential solution for utilizing underutilized areas for solar PV projects (SolarPower Europe, 2022).

BIOFUEL PRODUCTION

The increased biofuel production can have significant impacts on regional and local water resources, posing risks to aquatic ecosystem health and human water uses (Meletiou et al., 2019). The selection of crop species, location, quantity of production and production techniques can have potentially significant impacts on water availability and water cycles (Ingemarsson et al., 2022). The water quality and ecosystem impact of cultivating conventional crops for biofuel are similar to those of other farm crops, including intensive fertilizer use, pesticide application, and other agricultural practices that may be detrimental (Meletiou et al., 2019). The careless use of chemical inputs and irrigation water, as well as the increased use of nitrogen fertilizers, can have adverse effects on soil and water quality, leading to increased energy use and potential emissions of N2O (IPCC, 2002). Nitrogen fertilization can cause eutrophication in freshwater and coastal areas, harmful algal blooms, and dead zones (Smith et al., 2021). The magnitude of runoff and increased water withdrawals for irrigation of bioenergy crops, can also impact freshwater ecosystems (Smith et al., 2021). Moreover, irrigation can deplete local water resources which then negatively affects the ability of local vegetation to sequester carbon (Ingemarsson et al., 2022). The introduction of pollinators or pest control measures can inadvertently result in new pest issues, and the use of pesticides can further contribute to soil and water pollution by leaching into surface waters and groundwater, which can have negative impacts on both aquatic biodiversity and human health (IPCC 2002; CBD, 2003). (See chapter 3.2.1 for impacts of biofuel farming on coral reefs, and 4.2.1 on arid and semi-arid areas.)

However, the agricultural practices aimed at increasing production can also have benefits for biodiversity and fisheries (IPCC, 2002,). For example, erosion control practices, such as water conservation structures, vegetative strips, and agroforestry shelterbelts can increase productivity, improve water quality, reduce fertilizer use, decrease siltation of waterways, reduce CH4 emissions, reduce flood risks, and increase biodiversity in aquatic systems (CBD, 2003).

NATURAL GAS

The replacement of old coal plants with natural gas plants is considered as a potentially fast way to reduce emissions. However, relying solely on this transition may not be sufficient to meet long-term climate targets, highlighting the need for a swift transition to renewable energy sources. (Jager et al., 2021). While natural gas has a smaller land footprint compared to certain renewables, it still imposes significant costs on terrestrial and aquatic ecosystems (ibid.). Despite the global growth of renewable energy and shale gas extraction, the trade-offs between protection of local biodiversity and global biodiversity conservation have not been extensively quantified (Popescu et al., 2020). According to Popescu et al. (2020) significant knowledge gaps exist regarding the impacts of shale development on biodiversity, particularly in relation to ground and surface water contamination, terrestrial fragmentation from infrastructure, and cumulative impacts.

Water management

According to CBD (2009) the river flood defence systems are similar to those used in coastal defence. The structures used to prevent flooding, e.g., river breakwaters, dikes, dams, levees, and floodgates can have significant negative environmental impacts. Adverse effects to biodiversity of such larger structures may include loss of natural vegetation along riverbanks, reduced connectivity between lakes, rivers, and riparian zones, and reduced sediment flows (ibid.). Also the removal of river vegetation to improve river flow can have a negative impact on biodiversity, as it disconnects wetlands from water sources (Campbell et al., 2009).

According to CBD (2003), efforts to manage inland water ecosystems in a way that promotes natural hydrological function can, however, have significant benefits for biodiversity conservation. Modern approaches to river management emphasize the importance of sustaining "environmental flows" as a management target, considering climate change and its potential impact on extreme weather events like droughts and floods. Climate change serves as an additional incentive to improve the management of inland waters and offers both financial and conservation benefits. Preserving natural river form and ecosystem processes can also yield advantages for coastal regions (ibid.).

Deforestation and afforestation

The efforts to slow down deforestation and forest degradation can have benefits for biodiversity conservation, in addition to mitigating emissions and preserving ecosystem services. The protection of forests from degradation can help slow soil erosion, protect water resources, and conserve biodiversity in the watershed (CBD, 2003). On the other hand, afforestation, the process of establishing forests in areas that were previously non-forested, may lead to increased water use and reductions in streamflow, as the expansion of forested areas may compete with land used for food production and can reduce freshwater availability in rivers (Smith et al., 2021; IPCC, 2022). Furthermore, intensified forest management and associated fertilization, while enhancing productivity, can increase N2O emissions and potentially have negative impacts on overall forest and aquatic biodiversity (Smith et al., 2021). However, in the context of dam protection from siltation, measures such as reforestation or afforestation within the watershed can encourage biodiversity conservation (CBD, 2003; see also guidelines for water and energy planning: World Commission on Dams 2000). (See chapter 4.2.2. for the impacts of afforestation on arid and semi-arid areas.)

5.3 Potential impacts of freshwater biodiversity policies on climate

Nature-based Solutions, including protecting, restoring and sustainably managing ecosystems such as freshwater, can support the achievement of climate mitigation targets (Ingemarsson et al., 2022). Availability of water and functioning water cycles are essential in supporting terrestrial ecosystems in their carbon sequestration since reduction in the soil moisture can limit the ability of plants to store carbon. On the other hand, water stress can for example, result in carbon release from degraded forests. Avoiding ecosystem degradation helps to protect water cycles and promote nature-based solutions for climate change mitigation (ibid.).

Moreover, healthy freshwater bodies can act as greenhouse gas sinks, but for example, nutrient loading can result in freshwater bodies becoming greenhouse gas emitters (Ingemarsson et al., 2022). Also sustainable water management, such as urban water and waste water management, can lead to avoided or reduced emissions of carbon, methane and nitrous oxide (ibid.).

6 Conclusions

Climate change mitigation is crucial for limiting the significant negative impacts of climate change. However, designing mitigation measures should pay attention to their potential negative effects on biodiversity. This literature review affirmed the assumption that climate change mitigation measures may carry adverse biodiversity impacts. However, ecosystem-based mitigation measures were found to benefit both climate and biodiversity targets. The review further found examples of biodiversity policies positively affecting climate but found no examples of biodiversity policies with negative climate impacts.

The development of renewable energy (such as solar, wind, hydro and tidal/wave power) seems to affect all of the selected ecosystem types. Whilst renewable energy development is central for the transition away from fossil-based energy, these measures may also come with adverse biodiversity impacts related to habitat loss and fragmentation and direct animal disturbances or even mortality such as in cases of collision with solar panels/wind rotors and turbines of hydro/tidal/wave power.

Biofuels are also used to support energy transition, but their production can negatively affect terrestrial, freshwater and marine ecosystems. Biofuel production in boreal forests can increase logging and contribute to changes in the forest characteristics critical for forest biodiversity, such as old trees and dead wood. Biofuel production in grassland ecosystems can result in habitat loss and negative impacts on local biodiversity. Biofuel production can also negatively impact freshwater biodiversity through nutrient and pesticide runoff.

In addition, this review found few examples of ocean-based biomass production, which can pose risks to coastal biodiversity as biomass plants can become invasive and displace native biodiversity, including that related to coral reefs.

Finally, this review found several positive examples of nature-based climate change mitigation solutions. Boreal forests, grasslands, and coastal and freshwater ecosystems were all found to play an important role in the global carbon cycles. The climate change mitigation potential of these ecosystems can be supported with appropriate management practices and by avoiding the conversion of natural ecosystems.

As emphasized in this report, climate change and biodiversity loss are major global threats and due to their interconnectedness, they must be addressed together. This literature review found that climate change mitigation measures can either support or harm biodiversity whereas biodiversity measures were generally found to support climate change mitigation. The findings of this review therefore further emphasize the importance of seeking win-win solutions when designing climate change mitigation measures.

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