Reviews and syntheses: Current perspectives on biosphere research - 2024

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Abstract. This review of recent advances in biosphere research aims to provide information on selected issues related to changes in biodiversity, ecosystem functioning, social and economic interactions with ecosystems, and the impacts of climate change on the biosphere.An interdisciplinary panel of experts selected eight~~nine~~ topics from a public survey based on relevance and scientific evidence. We highlight advances on eight~~nine~~ themes that have been recently published in peer-reviewed journals that are gaining importance in the scientific community and have the potential to guide future actions as well as inspire future research questions. Our focus is on the interactions between climate, biosphere and society, and on strategies to sustain, restore or promote ecosystems and their services. While mitigating climate change is expected to reduce many risks and associated costs, rapid emission reductions are also crucial to secure various co-benefits of ecosystems, such as coastal protection or stabilization of regional hydrological cycles. In this context, conservation measures implemented in cooperation with local actors are key to efficient resource allocation. At the same time, holistic action frameworks at the global level are required to guide and support such efforts. This review emphasises the links between the various challenges and their solutions to the Earth System crisis, which is essential for making sustainable decisions.

1 Introduction

The dynamics and diversity of life on Earth as we know it and its role in the Earth system are increasingly under threat as human activity has changed and continues to change the planet in unprecedented ways.~~Life on Earth as currently organized has been under threat for decades as human activities have changed the planet drastically and without precedent in human history~~ (Watson et al., 2019; Ripple et al., 2023; Rockström et al., 2023; Crutzen, 2006; Stubbins et al., 2021; Cowie et al., 2022; Friedlingstein et al., 2023). As we are entering~~enter~~ uncharted territory, it is critical that we use scientific evidence as a foundation for decision-making, taking into account the interrelationships within the complex Earth system. The science has been~~is~~ clear for years on the need to significantly cut greenhouse gas emissions, halt biodiversity loss, reduce chemical pollution, and manage ecosystems sustainably to ensure a livable planet (Hill, 2020; Jaureguiberry et al., 2022; Meinshausen et al., 2022). The intertwined crises of climate change pollution, and biodiversity loss threatens human well-being, as theses crises~~both crises~~ impact natural~~nature~~ processes that support life quality, livelihoods, and economies , creating a comprehensive Earth system crisis (Pörtner et al., 2021b, 2023). Our economies are embedded within nature; there is growing recognition from governments and business actors that our economies need to account fully for impacts on nature and rebalance our demands within Nature's capacity to supply (Dasgupta and Treasury, 2022; TNDF, 2023). A whole-of-society approach is needed, as scholars also highlight how fair and just transformations are crucial to reach global climate and biodiversity goals for sustainability and ensuring well-being through sustainable lifestyle and resource circulation practices across food, energy, and material systems (Griggs et al., 2013; Leach et al., 2018; Martin et al., 2020; Folke et al., 2021; Pickering et al., 2022; Obura et al., 2023; McDermott et al., 2023; Schlesier et al., 2024)

The Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science and Policy Platform on Biodiversity and Ecosystem Services (IPBES) were established to summarize~~summarise~~ the state of the science on climate change, biodiversity and ecosystem services for policy makers and thus provide a basis for science-based decision-making.~~At the heart of international negotiations such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD), the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assess the scientific basis for action.~~ Through regular, comprehensive assessments of the scientific literature~~literture~~ (e.g., IPBES, 2019; IPCC, 2021, 2022a, 2023), these bodies provide grounded insights into the current state of knowledge. Their reports comprehensively inform stakeholders and decision makers about the scientific understanding of climate change and biodiversity loss, its impacts, risks and solutions, and the progress of climate action under international pledges and agreements.

Given the thematic breadth and procedural requirements, IPCC and IPBES assessments take several years to complete. For example, more than eight years elapsed between the publication of the IPCC AR5 and AR6 Synthesis Reports (Pachauri et al., 2014; Lee et al., 2023) . The first global IPBES assessment report was published in 2019 (IPBES, 2019), and the second global assessment report is scheduled to be completed in 2028. In addition, major reports provide scientific insights with a considerable time lag. For example, the AR6 Synthesis Report was published in 2023, but the cut-off date for the scientific literature reviewed by the three working groups was more than two years earlier, excluding recent publications even in the year of the report's publication. A limitation of this arrangement is therefore that negotiators and decision-makers need additional authoritative syntheses and summaries of recent scientific advances relevant to decision-making in the multi-year intervals between these major global reports.~~A limitation of this arrangement is therefore that during the multi-year intervals between these major global reports, negotiators and decision-makers lack an authoritative source for the most recent scientific advances relevant for decision-making.~~ ~~Science-policy interfaces need therefore to develop and improve workflows and mechanisms that allow for rapid deployment of the latest scientific evidence to support policy and decision-making without compromising scientific quality and rigor.~~

Reports on specific~~different~~ aspects of climate change are regularly published such as the IPCC Special Reports, and Similarly, IPBES special reports related to issues related to biodiversity and nature. Such reports summarize scientific knowledge related to that aspect often from several disciplines, but these reports are not updated after some years and hence get outdated over time. In addition to these special reports, many scientists have published summaries on a wide range of topics under the heading "Scientists' Warning".(e.g. Cavicchioli et al., 2019; Pyšek et al., 2020; Ripple et al., 2020) Additional there are regular reports like the State of the Global Climate and the Global Carbon Budget (e.g., Pörtner et al., 2019; 2024, 2024; Le Quéré et al., 2013; Friedlingstein et al., 2023) and more recently the State of Wildfires (Jones et al., 2024). Further,~~Similarly, IPBES special reports and~~ FAO publications such as the State of the World's Forests and the State of Agricultural Commodity Markets (e.g., IPBES, 2023; FAO, 2022a, b) report on biodiversity loss and ecosystem services. In addition to these reports at international level, there is also a plethora of regular national reports on various aspects of the crisis in the Earth system. These well-recognized reports update diagnostic indicators and measures familiar to those involved in or following corresponding negotiations. Due to their specific focus on certain topics and indicators, these reports sometimes lack the interdisciplinary perspective that can be observed in the above-mentioned reports. The "10 New Insights in Climate Science" reports address many of the challenges mentioned above, focusing on new findings from recent climate-related research. It is published annually and contains contributions from various disciplines (Martin et al., 2022; Bustamante et al., 2023). This strong example focused on issues related to climate change should be complemented by similar reports from other research areas related to the Earth system crisis.

Given the lack of such an integrative, annually published report focused on issues related to the biosphere, the present publication summarizes recent advances in this field of~~biosphere~~ research. Here we define the biosphere as the global ecological system that includes all living organisms and their interactions. We have also integrated social and economic links to the biosphere in this summary. In doing so, it crosses the boundaries of the established sciences to provide an interdisciplinary view of biosphere ~~research and to highlight important linkages~~. Further, it will not be about repeating well-known findings such as drastically reducing the burning of fossil fuels, the biggest lever in the fight against climate change. Instead, this international collaboration aims to inform stakeholders and decision-makers about the latest policy-relevant, peer-reviewed, biosphere-related research findings. We further hope that it may inspire scientists to develop interdisciplinary questions and holistic solutions to pressing problems linking biosphere research, which includes biodiversity issues, to climate on the one hand and social and economic research areas on the other (e.g. Mahecha et al., 2024).

Such Evidence-based solutions using all sources of knowledge are necessary to enable the transformation of socio-environmental systems to conserving ecosystems and enhancing biodiversity, building resilience in socio-ecological systems, restoring degraded ecosystems, and promoting a circular and regenerative economy (Chapin et al., 2010; Mace et al., 2018). In this process, it is key to address the main drivers and pressures of environmental degradation, including the conversion and exploitation of biodiversity and ecosystems, climate change, and pollution, as well as divestment from fossil fuels (IPBES, 2019).

Here, we present eight~~nine~~ topics with recent and significant findings from biosphere research. To be considered as “new” findings, these advances must be supported by peer-reviewed literature published after 2021 and up to the date of submission. Our topics present worrying impacts on the biosphere, strategies for maintaining vivid ecosystems or enhancing degraded ecosystems and their services to human society. In addition, we consider emerging themes and research questions that are gaining traction in the scientific community, as well as important future research questions.

B~~We find that b~~iodiversity loss, land degradation, chemical pollution, alteration of biogeochemical cycles and climate change are intricately interlinked across the biosphere . These environmental problems are shaped by and influence social and economic systems.~~and are simultaneously influenced by social and economic systems~~. For each topic, therefore, not only are the key findings presented, but the links and implications for related topics are also emphasized, contributing to a comprehensive understanding of processes in the biosphere and their interactions with human systems. With this study, we aim to raise awareness of the various challenges within the biosphere and their interconnectedness with other crises within the Earth system, provide synergistic strategies to address complex challenges, and stimulate future research questions.~~Therefore each topic not only highlights key findings within itself, but also makes connections with related topics to develop a holistic view of changes in biosphere processes and biosphere-human interactions. With this, we aim to identify synergistic approaches to address the complex challenges we are facing.~~

We note that threats to coastal habitats (Section 3.1), changes in the hydrological cycle (Section 3.2) due to changes in forest cover and shifts in fire regimes (Section 3.3) pose significant societal challenges that require transboundary cooperation for efficient and equitable resource allocation and distribution. Although climate change mitigation is expected to reduce many of these risks and associated costs, the focus should be on rapidly reducing emissions and ensuring co-benefits, as the effectiveness of natural carbon sequestration (Section 3.4) is likely to be limited by climate change. In this context, adequate conservation measures in human-altered landscapes are a key to maintain nature's contribution to humanity (Section 3.5). At the international level, interlinked and comprehensive policy packages are needed to address the drivers of environmental degradation ~~from resource extraction~~ (Section 3.6), while at the local and regional level, convivial conservation is a strategy for coexisting with biodiversity within planetary boundaries (Section 3.8). In the future, the socio-economic value of ecosystems will increase with rising real market incomes and changing ecosystem scarcity (Section 3.7). Ensuring societal support and the economic viability of solutions will therefore require a comprehensive change or development of existing nature valuation systems. ~~Finally, we provide an overview of frameworks to guide future action (Section 3.9) that promote equitable, holistic human-nature relationships and enable a sustainable, inspiring and fruitful future for both people and nature.~~

2 Method

We followed a similar methodology to that of the "10 new insights in climate change" (Martin et al., 2022). First, we set up an editorial board of experts from different fields of ecology, sociology and economics. Meanwhile, we issued an open call inviting the scientific community to submit thematic proposals for this review based on peer-reviewed publications not older than January 2022. The call for proposals (see Appendix A) was disseminated through social media, mailing lists and individual invitations. Despite our efforts to achieve global outreach, we anticipate that we may not have reached some important groups or that they may have chosen not to respond. Hence this first synthesis has to be seen as preliminary effort with caveats that can be improved in next iterations. We expect that this approach is a first step towards future annual biosphere research synthesis reports that will evolve into more substantial, comprehensive~~broader-reaching~~ assessments, with a larger pool of contributions ~~input~~ from a more diverse and globally distributed group of researchers.

We received initially a total of 20 topic proposals. The final selection of topics was made by the editorial board on the basis of the following criteria: (i) sufficient evidence from peer-reviewed publications in the last two years; (ii) emerging general consensus; (iii) relevance to international negotiations and decision-making processes.

The editorial board decision process consisted of two steps. First, each member independently rated the proposals on a scale of 0 to 10, with 0 being 'not recommended' and 10 being 'highly recommended'. The issues were then discussed in a virtual meeting of the editorial board, starting with the highest-rated proposals. During the discussion the board members could adjusted their previous rating.~~with individual ratings adjusted on the basis of the discussion.~~ Following internal discussion and review, the Editorial Board's original recommendation was reduced from 10 topics to eight by merging them.

Each topic was written by a team of two to five experts. These topic-authors were selected by the editorial board on the basis of their scientific expertise, as evidenced by their recent scientific publications. Diversity in terms of gender, geography and

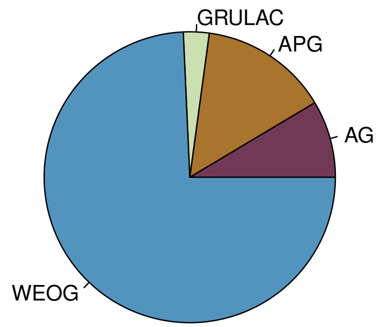

Figure 1. Origin of the authors from the geopolitical regional groups of member states of the United Nations: African Group (AG); Asia and the Pacific Group (APG), Latin American and Caribbean Group (GRULAC), Western European and Others Group (WEOG)

Table 1. Web of Science research areas represented by the authors.

research area	$\sum$	research area	$\sum$	research area	$\sum$
environmental sciences	23	biodiversity conservation	13	ecology	12
social science, interdisciplinary	9	geography	6	meteorology, atmospheric sciences	5
geosciences, multidisciplinary	4	remote sensing	4	agriculture, multidisciplinary	3
forestry	3	agricultural economics & policy	2	anthropology	2
computer science, interdis. appl.	2	economics	2	environmental studies	2
plant sciences	2	biology	1	cultural studies	1
engineering, multidisciplinary	1	ethics	1	marine & freshwater biology	1
mathematics, interdis. appl.	1	physics, applied	1	planning & development	1
political science	1	social issues	1	urban studies	1

scientific discipline was also considered (Figure 1, Table 1). We emphasize that there are differences between some perspectives and want to be open about the fact that therefore not all authors necessarily support all of them and we emphasise that this collection does not claim to be comprehensive nor absolute.

3 Insights

3.1 Innovative and inclusive solutions offer opportunities to support coastal habitats under threat

3.1.1 Background

Coastal habitats mainly refer to mangroves, saltmarshes, seagrass beds and coral reefs, which are important ecosystems that provide resilience services such as fisheries that contribute to human wellbeing (Costanza et al., 2014; Trégarot et al., 2024). Coastal habitats are important for marine biodiversity (Trégarot et al., 2024) as they function as breeding grounds for fish (Nodo et al., 2023) and shelter for water birds . They, sequester carbon at a much greater rate per area than most terrestrial ecosystems (e.g. mangroves sequester 174 gC $m^{-2}year^{-1}$ on average Alongi, 2012). Finally, they pevent~~, sequestering carbon at much greater rate than terrestrial ecosystems, and preventing~~ coastal erosion which protects human settlements.

3.1.2 Challenges

The importance of a healthy coastal habitat is well established (NOAA, 2024), yet coastal ecosystems are under threat at concerning rates from unsustainable development and climate change (IPCC, 2022c). For example, 35% of mangroves have been lost because of local drivers but 50% of mangrove ecosystems are at risk of collapse because of climate change and local factors (Hagger et al., 2022). Widespread retreat of coastal habitat is likely at warming levels above 1.5°C (Saintilan et al., 2023). 500 million people are projected to experience challenges within decades due to the likely loss and degradation of coral reefs that they currently rely on (Hoegh-Guldberg et al., 2017). Global warming of 1.5°C to 2.0°C would double the area of tidal marsh exposed to 4 mm/yr of rising sea level by the end of this century. With 3°C of warming, nearly all the world's mangrove forests and coral reef islands and almost 40% of mapped tidal marshes are estimated to be affected (Saintilan et al., 2023). Yet, each coastal habitat responds differently to climate change (Trégarot et al., 2024), making it important to consider local responses. The pressure on coastal habitats from climate change accumulates on top of other anthropogenic stressors such as overtourism, invasive species (Roy et al., 2024), land reclamation (Yamano et al., 2007), pollution (Wakwella et al., 2023), aquaculture, and development of hard infrastructure , making it a challenge to involve all relevant stakeholders.

3.1.3 Offering solutions

Research on nature-based solutions demonstrate the co-benefits of biodiversity compared to engineered solutions with hard infrastructure (Hahn et al., 2023). This potential means that investing in the space to preserve and recover coastal habitats can help restore biodiversity and mitigate and even help to adapt to climate change but also provide leisurely functions or a source of livelihood. Doing so would improve resilience to a variety of hazards and restore a healthy environment (Hahn et al., 2023). Moreover, many stakeholders already prefer nature-based over gray infrastructure (Apine and Stojanovic, 2024). While directly beneficial on the local scale, field measurements of over 370 restoration sites in various parts of the world showed that mangrove reforestation provides 60% more blue carbon benefit than afforestation on marginal tidal flats for the same area (Song et al., 2023), suggesting they play an important role for mitigation globally. Utilizing the right mangrove species for the right location may further prevent retreat of the coastal zones, reduce impacts from storms on human settlements, and positively contribute to fishing grounds among other expected co-benefits (Sunkur et al., 2023). Similarly, recent studies point to the potential of coral reef restoration, combined with coral adaptation and climate change mitigation, to hold off mass coral deterioration and enable reefs to keep up with sea level rise of low to moderate carbon emissions scenarios (Toth et al., 2023; Webb et al., 2023).

Nature-based solutions have insufficiently considered~~should be considered with~~ locally relevant species. For example, China introduced an invasive species called *Spartina alterniflora* (saltmarsh cordgrass) ~~from the USA~~ to reduce soil erosion and provide a number of other ecosystem services in 1979. While successful in fulfilling its purpose, it is occupying the niche of some local plant species (such as *Phragmites communis* and *Scirpus mariqueter*) and degrading habitat for some water bird species (Nie et al., 2023). Managing invasive species like *Spartina alterniflora* can be costly and complex. Wise use of the biomass may contribute to the local economy, prevent coastal erosion, while still benefit wildlife that depends on them. Hence, local species should be prioritized when vegetation re-establishment efforts are being planned to ensure greater co-benefits (e.g. when using mangrove or saltmarsh).

Mitigation of coastal habitat loss/degradation can be realized through management and restoration. Ensure also sustainable development upstream using a watershed approach to protect coastal habitats (e.g. preventing nutrient enrichment, coastal development, hydrologic disturbances, anchoring or sedimentation (Trégarot et al., 2024). Trade-offs and synergies between biodiversity conservation/restoration and other services such as carbon sequestration, coastal protection, water purification, aquaculture and eco-tourism should be holistically considered. For example, dedicated locations where coastal habitats serve productive purposes and contribute to biodiversity conservation may hold a solution for socio-ecological balance.

Community involvement in coastal habitat restoration can increase willingness to engage in stewardship activities, thereby improving biodiversity and climate change outcomes (Dean et al., 2024).~~Community engagement in restoration of coastal habitats can strengthen willingness to engage in stewardship activities (Dean et al. 2024) as a result improving biodiversity and climate mitigation outcomes.~~ As demonstrated by the nascent concept of "blue justice" that protests the marginalization of small-scale fishers (Isaacs, 2019), coastal stakeholders (incl. communities, Indigenous peoples, and small-scale fishers) have tended to be excluded from marine decision making (Blythe et al., 2023) yet meaningful community engagement in projects can result in equitable and resilient project outcomes (Fox et al., 2023). Better allowing space for stewardship practices by Indigenous and local communities can provide meaningful lessons for societies across borders by ensuring livelihoods and biodiversity are restored or conserved (e.g. in California USA, Sanchez et al., 2023, See also section 3.8). New practices of restoring coastal habitats with co-benefits for people and nature have also been documented (e.g. nature reserve Zwin that consists of dunes, marshes and mudflats along the Belgian and Netherlands border open to tourists and the Mai-po Wetland in Hong kong managed for the benefit of migrating birds, aquaculture and tourism (Cheung, 2011)).

Institutional mechanisms must align to enable innovative or unconventional practices. Institutional barriers to nature-based solutions are currently higher than for gray infrastructure (Jones and Pippin, 2022). Structural recognition of co-benefits of nature-based solutions (Apine and Stojanovic, 2024) could include project funding schemes that recognize the multiple benefits of restoring coastal habitats (e.g. beyond mitigating flood risks), incorporation of feedback from engaged stakeholders into the project design, and robust monitoring beyond the implementation phase (Palinkas et al., 2022). Researchers have also begun exploring the role of art in raising awareness around coastal sustainability (Matias et al., 2023). Institutional mechanisms further play an important role as to the area of jurisdiction. Coastal habitats are inseparable from upstream land-based activities. Integrated watershed management that transcend jurisdictional boundaries including through financing for long-term action can foster healthy coastal ecosystems (Wakwella et al., 2023). See also section 3.6.

3.2 Forest protection avoids worsening future droughts and keeps regional, seasonal rain patterns stable

3.2.1 Background

Climate change is altering rainfall patterns and intensity in the tropics (Field et al., 2012; Robinson et al., 2021; IPCC, 2022b, 2023) with implications for ecological and human water security. ~~Shifts towards more intense rain events, coupled with longer dry spells, potentially leading to increased incidence of both floods and droughts, have been documented~~. Also, changes in the seasonal variability in rainfall patterns across the tropics have been observed (Feng et al., 2013; Fu et al., 2013; Fu, 2015). ~~Fu et al. (2013,2015) showed a pronounced shift in dry season length and end due to climate change. TIn this context, t~~ropical forests can play a mitigating role because they are strongly coupled to the atmosphere, particularly through the water cycle (Bonan, 2008). The tropical water cycle is essential for the health of ecosystems, support biodiversity, and maintain regional rainfall.~~ The water cycle in the tropics is driven by interconnected processes, namely evapotranspiration, condensation, rainfall, and runoff. Each of these components plays a vital role in the health of tropical ecosystems, their ability to support biodiversity and their capacity to maintain regional rainfall~~ (e.g., Makarieva and Gorshkov, 2007; van der Ent et al., 2010; Spracklen et al., 2012). High rates of evapotranspiration occur across the tropics due to a combination of intense radiation, large evaporation surface (the leaves, up to 10 m^2 leaves /m^2 ground) and high temperatures and significantly contribute to atmospheric moisture. For example, several studies show that about one-third of the moisture in the Amazon Basin is recycled regionally, while about half of the moisture in the Congo Basin is recycled regionally (Sorí et al., 2017; Staal et al., 2018; Tuinenburg et al., 2020). This contributes to cloud formation and generation of rainfall patterns and other regional climatic conditions intricately linked to forest cover (e.g., Poveda and Mesa, 1997; Ellison et al., 2017). ~~The role can be illustrated by the amount of energy associated with the evaporation from the Amazon basin, which is greater than 10000 EJ per year and thus more than 10 times higher than all human energy consumption (fossil, nuclear, and other sources)~~. ~~Vegetation greening has primarily and increasingly promoted a multi-decadal increase in global ET since the 1980s (Yang et al 2023)~~. In South America, evaporated water is transported further across the continent contributing to regional rainfall (e.g., Zemp et al., 2014, 2017). In some regions, this rainfall provides a large fraction of the water needed for rainfed agriculture (e.g., Zemp et al., 2014, 2017).

3.2.2 Challenges

Despite efforts to curb deforestation, tropical forest loss has accelerated over the last two decades (Feng et al., 2022). Several lines of research suggest that deforestation reduces regional and downwind rainfall, highlighting again the role of forests in sustaining regional hydrological cycles (Spracklen and Garcia-Carreras, 2015; Leite-Filho et al., 2021; Staal et al., 2023). Loss of forest cover disrupts transpiration and reduces precipitation, leading to a drier climate, reduced agricultural productivity and increased stream flow in large watersheds (Zhang et al., 2017; Zhang and Wei, 2021). In the Amazon basin, this has led to a measurable decrease in precipitation across South America (Lawrence and Vandecar, 2015). Across the whole tropics, a 1% reduction in forest cover is thought to have reduced precipitation by an average of 0.25 ± 0.1 mm per month over the past two decades (Smith et al., 2023). Deforestation in South America might delay the onset of the rainy season by 30-40 days compared to historical periods up to mid-century (Commar et al., 2023; Bochow and Boers, 2023). Modelling studies indicate that future deforestation in the Congo can reduce local precipitation by 8–10% in 2100 (Smith et al., 2023).C, and current Earth system models are known to underestimate water recycling in the tropical forests, especially in the Amazon (Baker and Spracklen, 2022). In this context, recent studies showevidence is mounting that the coupling between the water cycle and vegetation is tightening in many regions across the globe such that LAI affects ET more strongly over time (Forzieri et al., 2020), and LAI gets more sensitive to soil moisture availability (Li et al., 2022). However, such an increase instronger water-vegetation coupling is not reportedobserved in the tropics so far. This suggests that tropical forests may be key elements to buffer changes which are already observed elsewhere.

Also links between drought and deforestation have been established (Staal et al., 2020). Here it is assumed that droughts may be intensified during heatwaves and propagate via teleconnections (Miralles et al., 2019). Droughts have recently more frequently been observed in many tropical regions. In the Amazon, severe and exceptional droughts occurred in 2005, 2010, 2015 and 2023 (z. B. Jiménez-Muñoz et al., 2016; Papastefanou et al., 2022) with impacts on human well-being in the affected regions. Also, tropical rainforests were affected (Phillips et al., 2009; Lewis et al., 2011; Tao et al., 2022), which could in turn lead to forest loss and with this to a reduction in precipitation (Zemp et al., 2017; Bochow und Boers, 2023).

Droughts during heatwaves appear be intensified by deforestation and can spread via teleconnections (Miralles et al., 2019; Staal et al., 2020). Droughts have recently increased in many tropical regions. For example, severe and exceptional droughts occurred in the Amazon region in 2005, 2010, 2015 and 2023 (e.g., Jiménez-Muñoz et al., 2016; Papastefanou et al., 2022). Other tropical rainforests were also affected (Phillips et al., 2009; Lewis et al., 2011; Tao et al., 2022). Droughts can also lead to forest loss and thus cause a positive feedback with decreasing precipitation (Zemp et al., 2017; Bochow and Boers, 2023).

Uncertainty in analyzing tropical water-vegetation interactions result from limited soil data and the challenges to estimate evapotranspiration using remote sensing techniques, due to dense vegetation. A related challenge is the uncertainty of both observation- and model-based analyses of water and vegetation interactions in the tropics. This arises from the scarcity of soil observations in these regions and the inefficacy of estimating soil moisture or evapotranspiration using remote sensing techniques, due to dense vegetation. Therefore, hydrological datasets derived with machine learing technicsTherefore, also machine learning derived hydrological datasets which extrapolate water variables in space are limited in the tropics (O. and Orth, 2021; Nelson et al., 2024). In summary, human activities, particularly anthropogenic climate change and deforestation for agriculture and urban development, have profound impacts on the tropical water cycle. Due to these uncertainties, itIt is not yet clear when the tipping point will be reached at which the rainforest turns into a dryland or grassland due to reduced moisture as a result of deforestation, but ita tipping point will be reached as a result of deforestation, which would lead to severe dieback due to a drier climate (Lovejoy and Nobre, 2018), and~~but~~ the consequences for the water and carbon cycle would be severe (Lenton et al., 2019).

3.2.3 Offering solutions

Increased efforts are needed to halt deforestation as well as forest degradation~~conserve~~ and accelerate their restoration~~restore forests and other terrestrial ecosystems~~ by 2030, as pledged in the New York Declaration on Forests and the Glasgow Leaders' Declaration on Forests and Land Use (Gasser et al., 2022). Particularly in areas with high deforestation rates (Feng et al., 2022; Lapola et al., 2023; Partners, 2023).

Protecting forests is essential to mitigating future droughts and maintaining stable seasonal rainfall patterns. Evidence indicates that deforestation arises from activities such as speculative land clearing, land tenure conflicts, transient agricultural practices, abandoned farmland, and agriculture-related fires encroaching on adjacent forests (Pendrill et al., 2022). Effective measures to curb deforestation require sustainable economic alternatives for intact forests (e.g. Griscom et al., 2020, see sections 3.8, 3.7), the establishment of protected areas, enforcement of substantial penalties for illegal logging (e.g. Brancalion et al., 2018, see also section 3.5), and broader improvements in land governance and rural development (e.g. Latawiec et al., 2017; Bastos Lima and Persson, 2020). International supply chain interventions can help reduce tropical deforestation, but will be most effective if they target high-risk areas with initiatives that promote sustainable rural development and strengthen territorial governance (Pendrill et al., 2022). Indigenous peoples are also crucial to forest conservation, as their traditional land management practices have proven exceptionally effective in conserving forest ecosystems (Fa et al., 2020). Empowering indigenous communities and legally securing their land rights are therefore critical to long-term conservation success.

Restoring degraded and deforested areas worldwide can increase precipitation and thus mitigate the reduction caused by forest loss (Hoek van Dijke et al., 2022, see also section 3.6). ~~But this depends on the regional climate and vegetation characteristics.~~ An increase of forest cover increases both precipitation and evapotranspiration. ~~; moisture tracking models can reveal the balance between the two in order to infer the local net effect. In the tropics and particularly the Amazon area this effect is clearly positive, i.e. increased forest cover would lead to increased soil water storage which can then buffer droughts and fires.~~ For instance, i~~Reforestation has the greatest effect in the following areas: I~~n the southern and eastern Amazon, reforestation could increase precipitation, which is critical given the risk of climate change-induced drying and a possible tipping point at which a forest transitions to a dryland or grassland due to decreased moisture (Zhao et al., 2017). Similarly, reforestation in middle America and SEA (including south China) could largely offset projected drying, and Mediterranean Europe would also benefit from regional reforestation efforts. Further, due to moisture-recycling of forests, reforestation in the south eastern Amazon would increase gross primary productivity (Staal et al., 2023).

Yet, afforestation for carbon capture in savannahs and other naturally tree-poor ecosystems can disrupt local water balances and biodiversity (Veldman et al., 2015; Fernandes et al., 2016). Trees often use more water than grasslands, which can lower the water table and reduce the availability of water for other plants and animals native to these areas. This change can lead to the drying up of wetlands and lesser water flows in streams and rivers (Farley et al., 2005; Lalonde et al., 2024), impacting species that are adapted to specific water regimes. Moreover, planting non-native tree species can alter soil properties and inhibit the growth of native vegetation, which relies on fire and open sunlight conditions to thrive (see section 3.3). These ecological shifts can diminish the natural resilience of these ecosystems, making them less adaptable to climatic changes and more susceptible to invasive species. Therefore, while afforestation in certain contexts can be beneficial for carbon sequestration and local societies, it requires careful planning and management to avoid unintended ecological consequences (Farley et al., 2005).

More and more accurate data on tropical vegetation and water could be collected through (i) more standardized and regionally distributed ground-based measurements and monitoring, as often water-related perspective and country or regional level analysis is missing to understand regional-specific feasibility. Furtherand (ii) future satellite missions using longer wavelengths such as SAR L-band (Lal et al., 2023) or p-band missions (Garrison et al., 2024), although the use of the latter is restricted by the military in many areas. This can provide a basis for more accurate observation-based analysis, and better constrain state-of-the-art models to better quantify the large-scale pan-tropical effect of afforestation or deforestation on the hydrological cycle (see also Doelman et al., 2020; Koch and Kaplan, 2022; Yu et al., 2022). Consequently, this can also contribute to a more accurate understanding and estimation of the Amazon tipping point.

3.3 Delayed climate change mitigation likely to increase fire risks in many regions

3.3.1 Background

Fire is a natural phenomenon that has shaped many ecosystem types around the world and contributed to their biodiversity (Bond and Keeley, 2005; Pausas and Keeley, 2009; Bowman et al., 2011; He et al., 2019). Humans have altered fire regimes by utilizing fire and changing the landscape, and also suppressing fires to avoid its destructive consequences (Bowman et al., 2011). However, unprecedented record wildfires have recently affected different parts of the world, such as the 18 million ha burn in Canada in 2023 Copernicus (2023), bringing to the fore concerns over future fire dynamics.

Many factors affect fire regimes but recent research suggests that two major factors - human activities (including land use change) and meteorological fire danger - are pulling in opposite directions. On the one hand, human factors (in particular agricultural expansion and intensification in African savannas and grasslands (Andela et al., 2017) have caused a decrease in burned area over the last two decades (Andela et al., 2017; Jones et al., 2022; Chen et al., 2023). On the other hand, increasing fire weather and decreased snow cover have increased burned area and fire intensity in high-latitude regions, e.g. boreal and forests of eastern Siberia and western Canada albeit with large regional variability (Bedia et al., 2015; Jones et al., 2022; Chen et al., 2023; Cunningham et al., 2024; Hessilt et al., 2024). Across the globe the two factors may change individually or in conjunction. So against a backdrop of globally decreasing fire occurrence burned area, some areas are experiencing increasing extreme fire seasons (Brown et al., 2023; Cunningham et al., 2024) and so-called ‘megafires’ which are large, intense and difficult to control (San-Miguel-Ayanz et al., 2013; Collins et al., 2021). These megafires exceed natural fire regimes and are extremely detrimental to biodiversity (Leeuwen et al., 2023), carbon stocks (Clarke et al., 2022; Copernicus, 2023; Zheng et al., 2023), human infrastructure and air quality (Xu et al., 2023).

3.3.2 Challenges

Analyses of fire trends and future projections show strong climate-change-induced increases in fire weather severity across most of the world (Abatzoglou et al., 2019; Jones et al., 2022; Jain et al., 2022). This poses a significant challenge for society, particularly forestry and civil protection. However, the problem is highly heterogeneous, with already fire prone areas experiencing increased risk of extreme weather conditions (Scholten et al., 2021; Brown et al., 2023; Cunningham et al., 2024) but also fire prone conditions emerging in relatively cooler and wetter areas that have been little affected by fire so far, e.g. boreal and temperate zones and mountains (de Groot et al., 2013; Jones et al., 2022; Hetzer et al., 2024).

These challenges are heightened by local factors relating to ignitions, vegetation and land cover that can play a major role in increasing fire danger. In some regions, land cover is characterized by highly flammable species such as pine, spruce and eucalypt, and planted in large and homogeneous stands which can promote fire spread. For one of the largest wildfires in central Europe, where Norway spruce monocultures suffer heavily from bark beetle attacks since the exceptional drought in 2018, it has been shown that burn severity was highest in dead spruce stands (Beetz et al., 2024). For fire risk assessments, both climatic and non-climatic factors need, thus, to be considered (European Environment Agency, 2024).

Changing fire regimes also threaten large stores of carbon but with regionally unique consequences. In the humid tropics, intact forest and peatlands are threatened by deforestation fires (Andela et al., 2022; Chen et al., 2023) and wildfires exacerbated by climate and land use change (Turetsky et al., 2015; Harrison et al., 2020). High-latitude peatlands in remote areas are vulnerable to large, long lasting fires burning through deep peat layers (Scholten et al., 2021; Nelson et al., 2021) which are not actively controlled and lead to large carbon losses (Turetsky et al., 2015). Future stocks from potential 'nature-based solutions' may also be vulnerable to wildfires, undermining climate mitigation efforts. However long-term predictions of fire risk that could be incorporated into planning still include large uncertainties at local scale (Hantson et al., 2020). See also Section 3.2 and 3.4.

3.3.3 Offering solutions

Decreasing trends in burned area in regions where the fire weather has become more severe, such as non-Mediterranean Europe (Jones et al., 2022) clearly show that fire risks can be mitigated, although at increasing cost (Bayham et al., 2022). The costs of fire mitigation are, however, surpassed by losses, especially for extreme fire seasons (Bayham et al., 2022) and comparable to other climate change mitigation costs (Phillips et al., 2022). Several studies emphasize that the burned area is negatively related to the Human Development Index at both global (Chuvieco et al., 2021; Teixeira et al., 2023) and continental scale (Forrest et al., 2024). This demonstrates that more economically developed societies ~~are less likely to be severely affected by fires~~ tend to reduce their burnt area, either due to effective fire prevention measures or because of rapid and successful firefighting (see also Section 3.6). Whilst this broad picture is encouraging, it is important that this view is tempered with knowledge that relying on fire suppression as a sole strategy is risky and potentially counterproductive, as it can increase fuel accumulation and therefore fire severity (Kreider et al., 2024). A clear example of this is the forests of the United States where, despite a high level of economic development, burnt area is increasing (Iglesias et al., 2022; Chen et al., 2023).Whilst climate change plays a large role in this trend (Iglesias et al., 2022; Burton et al., 2024), a very effective strategy of fire suppression over the 20th century (Magerl et al., 2023) without a sufficient fuel reduction strategy has led to current levels of very high fuel accumulation. These high fuel loads are contributing to the current crisis, a phenomenon that was anticipated over 50 years ago (Dodge, 1972).

Strategies should be developed targeting risks at local, national, and regional levels (Chuvieco et al., 2023). Locally, fire suppression can be aided by introducing fire breaks and access points, particularly roads (Haas et al., 2022), however this solution should be applied with caution as land fragmentation also negatively affects species richness (Willmer et al., 2022). Fuel reduction techniques might also be considered, including mechanical or grazing, but prescribed burning might also provide a more natural solution also useful for maintaining fire-dependent vegetation types and biodiversity (Neidermeier et al., 2023). Moreover, fire suppression should be limited in areas where regular low-intensity fires play a vital role in naturally clearing fuels. There, maintaining fires as a part of the ecosystem can reduce the risk of more severe fires from excessive fuel accumulation. National strategies should promote biodiversity because this also promotes fire resilience by avoiding monocultures of highly flammable species. Furthermore, studies have shown that cross-border collaborations are necessary and effective for allocating resources efficiently and minimizing risk (Bloem et al., 2022). International cooperations can benefit from comprehensive 'fire-smart' solutions, such as those recently targeted in the EU Green Deal (Ascoli et al., 2023; Regos et al., 2023). A number of cases document the value of incorporating Indigenous knowledge and governance into fire management strategies in Latin America (Oliveira et al., 2022), Africa (Croker et al., 2023), North America (Connor et al., 2022), and Australia (Legge et al., 2023). See also Sections 3.6, 3.8.

3.4 Nature-based CDR implementation risks

3.4.1 Background

A key intersection point between ecology and climate change research is role of land ecosystems in exchanging carbon between terrestrial and atmospheric carbon pools. ~~the ability of terrestrial ecosystems to remove carbon from the atmosphere and store it in above and below-ground carbon stocks. Terrestrial ecosystems currently absorb about a third of total anthropogenic (fossil fuel + land-use) CO_2 emissions, mostly as a result of CO_2 fertilization of vegetation growth~~ Human activities are affecting these carbon exchanges directly via deforestation and other land-use activities, as well as indirectly via the response of terrestrial ecosystems to elevated CO_2 and resulting changing climate conditions (Friedlingstein et al., 2023; IPCC, 2021). Direct effects (including deforestation, forest regrowth and other land-use activities), currently produce net emissions to the atmosphere of about 4 billion tonnes of CO_2 per year (about 10% of global fossil fuel emissions), which includes an estimated removal flux from reforestation activities of 2 billion tonnes of CO_2 per year. Indirect carbon fluxes resulting from processes like CO_2 fertilization and changing growing season length, currently absorb about 12 billion tonnes of CO_2 per year; this indirect carbon sink shows interannual variability, though has consistently represented an absorption of close one third of annual fossil fuel co_2 emissions over the past several decades ~~In addition, regrowth of previously deforested land accounts for an additional~~

removal of CO2 from the atmosphere; this regrowth is equivalent to about a third of gross land-use-related CO2 emissions (Friedlingstein et al., 2023; IPCC, 2022a).

3.4.2 Challenges

Given the current role ofkey role of the terrestrial biosphere as a net carbon sink (the net of direct emissions and indirect uptake), there is considerable interest in pursuing strategies to enhance nature-based carbon dioxide removal (CDR) as a contribution to climate mitigation efforts. Many studies have highlighted the potential of nature-based CDR (Griscom et al., 2017; Fuhrman et al., 2023) as a key component of a range of potential CDR options. Reforestation and afforestation are typically seen as the largest potential contributors, though nature-based CDRsolutions also include strategies such as biochar and other agricultural management practices to increase soil carbon sequestration. Many concerns about nature-based carbon removal have also been raised in recent literature however, including whether a focus on CDR in research and policy discussion could lead to delays in fossil fuel emissions reductions (Carton et al., 2023), as well as whether nature-based CDR has a large enough potential to be a meaningful contribution to climate mitigation goals (Roebroek et al., 2023). Parr et al. (2024) also highlight an important concern that reforestation with non-native tree plantation species could lead to loss of native ecosystems that may negate any carbon-related gains, supporting previous findings that more biodiverse forests are better at capturing and storing carbon (Liu et al., 2018b). These and other concerns highlight a growing understanding that nature-based CDR must be undertaken with attention to local ecosystems and community needs (Seddon, 2022), and that nature-based CDR should in all cases be treated as a complement (and not an alternative) to fossil fuel CO_2 emissions reductions Matthews et al. (2022).

Nature-based CDR, particularly in the case of its use as an offset for fossil fuel CO_2 emissions faces a number of known and well-understood challenges. These challenges include: (i) accounting: accurate measurement of forest carbon accounting inclduding removal and storage; (ii) additionality: an assessment of whether the removal would have occurred in the absence of offset financing; (iii) leakage: an analysis, which examines whether the intervention displaces land-use activities, resulting in emissions elsewhere; (iv) durability: the risk of reversal analysis, which considers the longevity of carbon storage; (v) environmental justice: which examine whether the carbon removal efforts amplify existing inequalities and injustices; (vi) and finally non-climate effects: for instance changes in albedo or other biophysical effects. (Carton et al., 2021; Haya et al., 2023; Groom and Venmans, 2023; Hasler et al., 2024).

The durabilityA key challenge associated with nature-based carbon storage is that land carbon pools are vulnerable to disturbances, either from natural processes (such as fire) or human pressures (such as deforestation) has been of particular concern in recent years owing to increases in natural disturbances (as discussed in Section 3.3). Climate-driven changes to wildfire and other natural disturbance regimes have considerable potential to lead to increased future vulnerability of land-based carbon stocks with continuing climate change (Anderegg et al., 2020). Furthermore, the permanence of land carbon storage can also be compromised by changing human disturbance pressures, including those emerging from potential uses of biomass as an energy sources in climate mitigation strategies is that land carbon pools are vulnerable to disturbances, either from natural processes (such as fire) or human pressures (such as deforestation). Furthermore, climate-driven changes to wildfire and other natural disturbance regimes have the potential to lead to increased vulnerability of land-based carbon stocks

~~with continuing climate change~~ (Anderegg et al., 2020). The potential for land-based carbon storage to be temporary evokes a particular~~n~~ accounting challenge when used as an offset for fossil fuel CO_2 emissions which represent a permanent transfer of new carbon from a geologic reservoir to the atmosphere-land-ocean carbon system. Concerns of impermanence (~~also referred to as durability concerns~~ or risks of reversal) are a key concern associated with the application of nature-based carbon storage as a contributor to climate mitigation efforts (Zickfeld et al., 2023). However, even temporary carbon storage does have climate value, and in particular has been shown to decrease peak warming if coupled with ambitious fossil fuel emissions reductions (Matthews et al., 2022).

3.4.3 Offering Solutions

One solution to the~~this~~ challenge of the durability of land carbon storage may be to treat all nature-based carbon removal and storage as a temporary quantity and to explicitly account for the amount of time the carbon remains in storage as part of its climate value. Matthews et al. (2023) proposed a new application of tonne-year accounting to measure the~~showed that carbon storage measured in tonne-years (which represent~~ the time-integral of land carbon removal and storage as a way of tracking the climate benefit of temporary storage~~is proportional to degree-years of avoided warming (the time-integral of avoided warming)~~. Previous applications of tonne-year accounting have focused on trying to equate temporary and permanent storage, leading to strategies such as vertical stacking of offset credits to claim that some amount of temporary storage is equivalent to an unit of permanent storage~~, leading to strategies such as vertical stacking of offset credits to claim that some amount of temporary storage is equivalent to an unit of permanent storage~~ (Haya et al., 2023). This previous use of tonne-year accounting has been widehowever, tly critiqued in the literature given that it is not grounded in any physical climate science relationship, and leads to a false equivalency of temporary and permanent storage that could further disconnect carbon offset calculations from the scientific understanding of carbon stocks and flows in natural systems (Levasseur et al., 2012; Brander and Broekhoff, 2023). However, Matthews et al. (2023) showed that a~~if~~ reimagined approach to tonne-years could effectively ~~as a metric to simply~~ track nature-based carbon storage over time. Furthermore, they showed that~~,~~ tonne-years of temporary carbon storage are proportional to degree-years of avoided warming (i.e. the time integral of the temperature change caused by temporary storage), providing an approach~~accounting has the potential~~ to measure the climate effect of temporary carbon storage in a way that is coherent with scientific understanding (Matthews et al., 2023). Measuring and quantifying the time dimension of nature-based carbon storage and treating carbon offset as a time-share rather than a single purchase (e.g. by using horizontal stacking to guard against loss over time) could be an important improvement to~~would require a substantial rethink of~~ current carbon offset protocols ~~, which currently struggle with how to use carbon buffer amounts to guard against loss from disturbane~~(Haya et al., 2023). ~~An accounting framework based on tonne-year as a proxy for degree-years of avoided warming has the potential to robustly measure the climate value of temporary carbon storage.~~

3.5 Sustaining Nature's Contributions to People in human-modified landscapes requires at least 20%–25% (semi-)natural habitat per square kilometer

3.5.1 Background

Biodiversity is declining faster than ever despite decades of increased conservation investment to bend the curve of biodiversity decline (Leclère et al., 2020). This decline is mainly driven by land and sea use change, resource overexploitation, pollution, exotic species invasions, and climate change (IPBES, 2019). Such decline is also associated with the expansion of global systems of extractivism in recent centuries, contrasting sharply with earlier patterns of stewardship (Ojeda et al., 2022; Molnár et al., 2024, see also Section 3.8). Converting natural habitats has provided benefits by creating more space for agriculture, housing and industry, but at a significant cost to biodiversity, jeopardizing valuable ecosystem functions and beneficial contributions, such as healthy and sustainable food production, clean air and water, and recreational spaces among others. These contributions, known as ecosystem services or Nature's Contributions to People (NCP), directly or indirectly contribute to human well-being, economic stability, and overall quality of life (Díaz et al., 2018, see also Section 3.1 and 3.2).

3.5.2 Challenges

Biodiversity has multiple dimensions making it challenging to define synthetic policy objectives and metrics or track progress (Díaz et al., 2020). Most conservation efforts focus on halting the conversion of remaining intact natural ecosystems, and safeguarding their unique species as articulated in Goal A of the Kunming-Montreal Global Biodiversity Framework (Watson et al., 2018; Allan et al., 2022). However, human-modified lands and waters, covering about half of the global Earth surface (IPBES, 2019), including highly managed agricultural fields and urban green spaces in mixed mosaic landscapes where natural functions are limited to small patches of habitat, are often overlooked in conservation policies and global target setting (Pollock et al., 2020), despite their critical roles in maintaining and supporting human well being and sustainable food production (Goodness et al., 2016; Díaz et al., 2018). The close proximity and relationship of people with biodiversity in these areas makes their contributions to human well-being even more important. Identifying metrics to ensure continuous contributions of such nature to human well-being is challenging due to the highly context-specific conditions under which biodiversity supports ecosystem functions (e.g. Section 3.2). Yet, few proposals for the post-2020 Global Biodiversity Framework (GBF), address human-modified lands explicitly or the role of functional biodiversity in maintaining a good quality of life for all people (Rounsevell et al., 2020; Maron et al., 2021; Hammoud et al., 2024).

NCP provisioning in human-modified landscapes relies on the amount, quality, and spatial arrangement of habitat fragments and their accessibility to beneficiaries (Garibaldi et al., 2021; Priyadarshana et al., 2024). These landscape components serve as proxy measures of ecosystem functional integrity (Rockström et al., 2023; Mohamed et al., 2024). Evidence suggests that many NCP can be maintained by habitat within highly human-modified landscapes as long as a minimum level, quality, and distance to biodiversity is present, and/or the functional integrity is retained or rebuilt (Martin et al., 2019; Eeraerts, 2023; Mohamed et al., 2024). The required habitat levels for NCP provisioning vary depending on the context, the NCP, demand for it, landscape type and taxa involved making it difficult to assess direct relationships (Garibaldi et al., 2011; Cariveau et al., 2020). Nonetheless, below a certain threshold nature can no longer provide a majority of benefits (Rockström et al., 2023).

A recent systematic review of 154 studies found that the capacity of human-modified lands to pollinate crops, regulate pests and diseases, maintain clear water, limit soil erosion, and maintain recreation spaces for people significantly declines and often disappears when habitat area falls below 20%–25% per km2 and nearly disappeared below 10% habitat per km^2 (Mohamed et al., 2024). Alarmingly, only one-third of global human-modified lands are above the 20%-25% per km^2 level to sustain NCP provisioning, emphasizing the urgent need for policy interventions to restore and regenerate ecosystem functions and their benefits in the remaining two-thirds of global human-modified lands (Mohamed et al., 2024).

The proposed minimum habitat levels can serve as a general guide to identify priority locations for conservation and restoration to support sustainable NCP provisions. However, uncertainties remain on the successful implementation of these minimum habitat levels in practice due to factors such as climate change, habitat loss, unsustainable agriculture, and human settlements expansion which complicates the implementation and may create trade-offs. General estimates and targets for land management are important, but often oversimplify the complexities of local conditions and can misrepresent the needs of local communities due to the inherent biases in ecological research that may not account for all biomes or ecosystem functions (Martin et al., 2012; Manning, 2024). Additionally, these metrics often overlook finer-scale NCP, e.g., NCP provided by soil biodiversity, and ignore the important role of complementary agricultural practices such as no-till farming, cover cropping, and leguminous rotations which can reduce erosion, nutrient loss and maintain biodiversity (Blanco-Canqui et al., 2015; Skaalsveen et al., 2019; Guinet et al., 2020; Rakotomalala et al., 2023). Current remote-sensing technologies also struggle to detect small and linear habitat elements or differentiate complex landscape types, likely leading to underestimations of the current state of (semi-)natural habitats globally (Lechner et al., 2009; Jurkus et al., 2022). Therefore, allocating 20-25% of each square kilometer~~areas~~ to (semi-)natural habitat within human-modified lands using general estimates, without proper management and consideration of local socio-economic priorities and ecological needs~~conditions~~ can lead to significant social and economic challenges. These include high restoration costs, land tenure issues, policy constraints, lack of expertise and knowledge, and potential conflict with the provisioning of material NCP which~~and~~ might compete with food production ambitions and local community needs (e.g., housing), ~~which~~ is negatively affecting the well-being of local people relying on those NCP (Mohamed et al., 2024).

3.5.3 Offering solutions

The implementation of such strategies effectively necessitates adapting and adopting practices that are suited best to local context and conditions, rather than prescribing a single practice to be applied globally. Restoration could, for instance, prioritize areas where habitat additions align with community needs and minimize trade-offs with food production. Countless context-specific strategies exist to enhance NCP provisioning and can be implemented in ways that create more synergies than trade-offs and support food security, livelihood and overall human well-being without compromising local resources (Jones et al., 2023; Rakotomalala et al., 2023). For example, modern agroecological practices and nature-based solutions including diverse crop rotations (Shah et al., 2021; Ewert et al., 2023) and mixed cropping systems (Lichtenberg et al., 2017; Tscharntke et al., 2024) maintain habitat heterogeneity and promote ecosystem resilience. Agroforestry systems enhance soil health, water retention, and global carbon sequestration (Zomer et al., 2022; Fahad et al., 2022). Strategically incorporating habitats such as hedgerows, no-mow zones around field margins or other practices (M'Gonigle et al., 2015; Marja et al., 2022; Maskell et al., 2023) combined with innovations such as precision agriculture practices can maintain species diversity (Arroyo-Rodríguez et al., 2020; Knapp et al., 2023) while optimizing agricultural productivity (Balafoutis et al., 2017). Protecting green spaces and parks in cities can enhance physical and mental well-being (Konijnendijk, 2023) and placing vegetation buffers along waterways can capture sediment and pollutants, among many other tools (Luke et al., 2019).

To implement this approach, it is essential to enhance tools and methodologies for identifying and quantifying key NCPs at the landscape scale. This includes determining the locally specific quantity (20–25% per km^2), composition, and spatial configuration of habitat elements required for effective NCP provisioning. To avoid conflicts, partnerships with diverse stakeholders - such as indigenous peoples, local communities, scientists and NGOs - should be prioritized in decision-making. These groups offer valuable, practical solutions for halting and reversing the loss of NCPs and promoting sustainable conservation efforts. In addition, resources must be reallocated to promote innovations in agriculture, production systems and urban planning that prioritize biodiversity.

The 25% high-functioning nature in every square kilometer offers a key policy tool since it is the first widely applicable measurement of the minimum level of human-modified land that needs to be in a (semi-)natural state across several NCP and a wide range of landscapes. This proposed habitat level is the minimum level, not the optimal level required to meet adequate NCP demand (Mohamed et al., 2024). This habitat threshold reflects an approach that harmonizes human activities with ecosystem integrity, focusing on integration rather than strict separation between human and nature. It serves as a general guideline synergizing with existing policy targets (e.g., UN Decade on Restoration) for prioritizing conservation initiatives and formulating adaptive, scalable policies beyond natural areas. See also Section 3.6, 3.8.

3.6 Interconnect and deliver comprehensive policy packages to address the root causes of degradation and revitalized, just human-nature relationships

3.6.1 Background

Today's dominant production and consumption patterns are far from achieving the CBD 2050 vision of "living in harmony with nature," even under the "most sustainable" climate scenarios (SSP1, RCP 2.6 - Pereira et al., 2020b, 2024). While global efforts focus heavily on achieving climate targets, this emphasis undermines our shared life-support systems and overlooks opportunities to synergize human-nature relationships and reverse alarming biodiversity trends while addressing climate impacts (Obura et al., 2023; Kim et al., 2023). Addressing these challenges requires a paradigm shift toward sustainable practices, emphasizing conservation, ecosystem rehabilitation, and regeneration (Meli et al., 2017; Chazdon et al., 2020). The growing momentum around "nature-positive" business practices highlights the importance of circular economy principles, which aim to minimize waste and promote resource reuse. This systemic approach aligns business activities with sustainability goals, reduces ecological footprints, and fosters resilience against environmental degradation and climate change (Bocken et al., 2019; Korhonen et al., 2018; Lüdeke-Freund et al., 2019). Integrated policy frameworks and international cooperation are essential to mitigate the impact of environmental degradation and incentivize balanced economic growth while supporting ecosystem recovery (Leal Filho et al., 2019; IPCC, 2023; Rockström et al., 2017; Steffen et al., 2018).

3.6.2 Challenge

Current global trade structures often exacerbate environmental and social inequalities, disproportionately affecting developing countries with weaker regulations (Newell and Taylor, 2022). Industrial agricultural practices and resource extraction have a devastating impact on the biosphere that exceeds even the direct effects of climate change, while social displacement at the local level contrasts with economic benefits disproportionately enjoyed elsewhere. (Barlow et al., 2018; Köhler et al., 2019; Hickel, 2020; Sánchez-Bayo and Wyckhuys, 2019; Jaureguiberry et al., 2022, see also section 3.4, 3.5). This phenomenon, known as ’telecoupling’, highlights the interconnectedness of distant economic activities and their environmental impacts (Liu et al., 2018a).Several studies demonstrate this telecoupling: For example, Meijaard et al. (2020) assesses the global demand for palm oil, while Northey et al. (2017); Mancini et al. (2021) analyses mining in Africa. In this context, it should be noted that while lithium extraction raises environmental concerns such as water depletion and landscape disruption, it is generally less harmful than large-scale extraction of fossil fuels such as coal and oil, which have more severe and widespread environmental impacts and contribute significantly to climate change (Vikström et al., 2013; Krishnan and Gopan, 2024).Improving the recycling of lithium from spent batteries can therefore reduce the need for new lithium mining, thereby reducing its environmental impact (Geissdoerfer et al., 2017). Effective biodiversity governance faces significant challenges, including the lack of platforms to set norms, address injustices and enforce accountability. These problems are often rooted in exploitative practices and colonial legacies (REF?). Revitalising the relationship between people and nature and fostering collective action are essential to halting biodiversity loss and restoring ecosystems.

Therefore, understanding global trade networks and their impacts is crucial to develop fair and sustainable integrated policies and international cooperation to mitigate harmful environmental and social impacts and to adopt circular economy principles (Wiedmann and Lenzen, 2018; Wiedmann et al., 2020; Leal Filho et al., 2019; IPCC, 2023; Meli et al., 2017; Chazdon et al., 2020; Geissdoerfer et al., 2017). Solutions: Integrated policy packages should integrate environmental, economic and social policies to address the root causes of biosphere degradation and pollution and to mitigate climate change, while promoting sustainable practices such as the promotion of renewable energy and the enhancement of carbon sinks and conservation of ecosystems (Litvinenko et al., 2022; Ikram et al., 2022; Tedesco et al., 2022; UNEP, 2022; Ostrom, 2009, e.g, see also section 3.5). Measures include stricter regulations on resource extraction, the adoption of cleaner technologies and incentives to restore ecosystems. Policies such as the European Green Deal are examples of comprehensive frameworks that align climate action with economic and social objectives (Commission, 2019). International cooperation is also crucial to harmonise efforts across borders and prevent environmental damage from being displaced. For example, the Paris Agreement demonstrates the potential of global commitments to reduce carbon emissions and promote sustainability (UNFCCC, 2018; Steffen et al., 2018). International environmental agreements with improved compliance mechanisms and accountability are crucial for strengthening global environmental agreements. Lessons learnt from international human rights agreements, such as the integration of accountability measures, can improve compliance with biodiversity commitments such as the Convention on Biological Diversity (CBD) Koh et al. (2022). Sustainable trade policies should be enforced through certification schemes such as the Forest Stewardship Council (FSC), the Marine Stewardship Council (MSC) or Fair Trade International for goods. Control mechanisms such as the EU Deforestation Regulation (EUDR), which aims to reduce illegal deforestation, are another lever. Incentives such as tax breaks or subsidies should also encourage companies to adopt sustainable practices, minimise waste, conserve resources and reduce emissions (OECD, 2020). Transnational conservation collaborations such as the Amazon Cooperation Treaty Organisation (ACTO) and Africa's Great Green Wall project demonstrate the value of multinational approaches to conservation. These initiatives focus on combating deforestation and wildlife trafficking, restoring degraded lands and supporting local communities. Such projects show how regional cooperation can protect critical ecosystems and promote sustainable livelihoods (UNCCD, 2016; Fernandes et al., 2024). Although there are several promising policies packages, like those presented above, they have to be developed further and applied from international to local scale: Such future policies should adopt frameworks that integrate multiple values of biodiversity, promote cross-sectoral actions, and ensure stakeholder participation. Locally tailored solutions and scalable approaches are necessary to restore ecosystems and foster positive outcomes for nature and people. Progress should be tracked through innovative biodiversity monitoring and adaptive management that incorporates Indigenous and local knowledge systems. The following framework by Perino et al. (2022) promises to improve future action reversing current trends of degeneration of the biosphere: (i) The identification process for locally suitable actions and the promotion of stakeholder ownership must recognise the multiple values of biodiversity (Pascual et al., 2023; Martin et al., 2024) and account for remote responsibility. (ii) Cross-sectoral implementation and mainstreaming of biodiversity considerations need scalable and multifunctional approaches to restoring ecosystems and aim for positive futures for nature and people. (iii) Assessment of progress and adaptive management needs to be informed by novel biodiversity monitoring and modeling approaches that address the multidimensionality of biodiversity change, including the incorporation of Indigenous and local knowledge (as e.g. in Gielen et al., 2024). The Nature Futures Framework (NFF) supports collaborative decision-making by recognizing diverse values of nature and exploring shared pathways toward sustainable futures (Pereira et al., 2020a; Kim et al., 2023; IPBES, 2023). It emphasizes adaptive management and scenario analysis to plan for positive synergies between biodiversity conservation and climate action. Immediate actions include: (i) Integrating plural values and engaging diverse stakeholders in decision-making processes. (ii) Mainstreaming biodiversity conservation into all sectors. (iii) Using nexus approaches to address interlinkages, co-benefits, and trade-offs. (iv) Improving policy coherence and integration. (v) Applying best practices in ecosystem restoration and management (see also Pörtner et al., 2021a, Section 7). The implementation of global environmental policy packages requires an equity lens and a rights-based approach, as projects that are aligned with local people's preferences and through inclusive governance are likely to have more effective social and environmental outcomes (Obura et al., 2023; Löfqvist et al., 2023; McDermott et al., 2023). In addition, unpacking elements of social and environmental justice, including procedural, recognitional and distributive dimensions, is needed to support long-term transformation towards sustainability (Leach et al., 2018; Pereira et al., 2023). Indigenous peoples and local communities are leading by example by managing the biosphere in ways that support ecological integrity and thus biodiversity conservation (Garnett et al., 2018; Dawson et al., 2024; Seebens et al., 2024; Massarella et al., 2021, see also section), see also section 3.6 and 3.8).

Integrating biodiversity into global trade policy ensures that efforts to protect the environment are coordinated and effective across borders. These interlinked actions provide a way to address the twin crises of climate change and biodiversity loss, and promote a healthier planet for people and nature.

3.7 The social-economic value of ecosystems will increase in proportion to rising real market incomes and the changing scarcities of ecosystems

3.7.1 Background

People derive various benefits from nature, such as through biodiversity, ecosystems or ecosystem functioning. These benefits can manifest as tangible outputs, such as water and food, but also include cultural, recreational, and spiritual interactions that directly or indirectly influence human well-being (e.g., Pascual et al., 2023).

Although assigning monetary values to the benefits humans derived from ecosystem services involves numerous philosophical and practical challenges, as emphasized in the next section, the alternative is often to consider no value at all in governmental planning processes such as benefit-cost-analyses, leading to an underinvestment in ecosystems (Dasgupta and Treasury, 2022). Thus, already in 2010, at the 10th Conference of the Convention on Biological Diversity in Japan, the international community agreed that the values of biodiversity needed to be integrated into planning processes (Aichi Target 2). In the Kunming-Montreal Global Biodiversity Framework it is reflected in Target 14: Integrate Biodiversity in Decision-Making at Every Level.

One quickly realizable way to conceptualize these ecosystem service benefits is through the notion of ecosystem services that include both use and non-use values of nature. The values in this category are anthropocentric, encompassing both instrumental and relational values (IPBES, 2019). The continuous loss of animal and plant species and their respective habitats leads to the loss of the services they provide. To be better able to reflect these ecosystem services in benefit-cost analyses, environmental-economic national accounting or damage litigation processes, governments convert ecosystem services into monetary values (Bishop et al., 2017). ~~Although assigning monetary values to ecosystem services involves numerous philosophical and practical challenges, the alternative is often to consider no value at all, leading to an underinvestment in ecosystems. Thus, already in 2010, at the 10th Conference of the Convention on Biological Diversity in Japan, the international community agreed that the values of biodiversity needed to be integrated into planning processes (Aichi Target 2). In the Kunming-Montreal Global Biodiversity Framework it is reflected in Target 14: Integrate Biodiversity in Decision-Making at Every Level.~~

3.7.2 Challenges

Governments around the world are currently looking for new approaches to appropriately assess the benefits from scarce ecosystems and their economic value. This is intended to assist in making the consequences of the destruction or the benefits of the conservation of nature more visible in analyses that underpin political decision-making processes and help with an economically efficient and environmentally effective allocation of tight governmental budgets.

For now, calculation methods of nature's values incorporate—if at all—solely the monetary value of ecosystem services as determined under current conditions (Drupp et al., 2024), meaning that nature becomes relatively less valuable over time compared to other goods and services whose value increases with the expected rise in global economic prosperity. In fact also our appreciation of nature increases over time as we get wealthier and ecosystems scarcer. Two factors play a key role in this changing value of scarce ecosystems over time. The prosperity of the world's population is expected to rise—by an estimated inflation-adjusted two percent per year (Müller et al., 2022)—and as household incomes increase, people will be willing to pay more to conserve nature and enjoy its services in the future. In addition, as the services provided by ecosystems become scarcer, this will further increase their value to society. The fact that scarce goods become more expensive is a fundamental principle in economics, and it also applies to nature's values.

3.7.3 Offering solutions

Drupp et al. (2024) provide governments with a ready to use formula to estimate the future economic values of scarce ecosystem services that can be used in decision-making processes. The formula scrutinizes up-to-date evidence on the so-called relative price change of non-market environmental goods (e.g., Hoel and Sterner, 2007; Sterner and Persson, 2008; Drupp and Hänsel, 2021) and recommends considering nature's values to increase proportionally with real market income. This is in line with what governmental bodies use for valuing reductions in mortality risk or travel time. As a result, if only the expected increases in income over the next 100 years were taken into account, the value of global ecosystems would have to increase by more than 130%. This holds for stagnating ecosystems. If ecosystems are projected to decline or degrade further, the value adjustment needs to be higher still. In the case of endangered species as captured in the prominent Red List Index, for instance, the value adjustment would amount to more than 180%. Accounting for these effects would thus increase the likelihood of projects that conserve ecosystem services to pass a benefit-cost test.

Drupp and Hänsel (2021) apply the formula to the evaluation of global climate policy. Economists typically use integrated climate-economy assessment models, such as the DICE model developed by Nobel Laureate William Nordhaus, to evaluate the trade-offs between mitigation costs and avoided damages from climate change and to estimate required CO2-prices (Nordhaus, 2019). A key criticism leveled at these models is that they do not appropriately capture the loss of nature's services and thus underestimate climate damages. Drupp and Hänsel (2021) disentangle how non-market goods and services, such as environmental amenities, are captured within these models and explicitly account for this based on an empirical analysis of fundamental drivers of the relative price effect of non-market goods. They find that the social costs of climate change increase by more than 50%, suggesting substantially higher economically optimal CO2-prices (see also Section 3.6). The increase in the economically optimal global mean temperature change is accordingly reduced by half a degree Celsius, which highlights the importance of accounting for the scarcity of nature when evaluating climate policy.

3.8 Convivial conservation's principles

3.8.1 Background

~~By integrating a diversity of knowledge systems and considering relational values in conservation efforts, we can develop more holistic and sustainable approaches to safeguarding biodiversity (see also Section 3.5, 3.6).~~

Convivial conservation is a new “vision, a politics and a set of governance principles for the future of conservation” (Büscher and Fletcher, 2019, p.284). Through its focus on ‘living with’ biodiversity within planetary boundaries, it aligns with transformative action for climate change (Pörtner et al., 2021b). Grounded in political ecology, it foregrounds the political economy as a significant constraint to transformative conservation. Political ecology is inherently cross-scalar, charting connections from global to local, while emphasising the importance of history and power relations (Watts, 2017). Furthermore, convivial conservation allies with social and environmental movements (e.g., Indigenous and decolonial). It proposes a long-term, holistic, “post-capitalist approach to conservation that promotes radical equity, structural transformation, and environmental justice and thus contributes to an overarching movement to create a more equal and sustainable world” (Büscher and Fletcher, 2019, p.283).

3.8.2 Challenges

Convivial conservation responds to two dominant conservation agendas ~~, presented here as ‘strong’ versions to help differentiate the contribution it is making~~. First, ‘new conservation’, which breaks with a long-standing fixation on ‘pristine wilderness’ seen as separate from humans, and instead promotes integration ~~“rambunctious gardens"~~ () into human development (Sullivan, 2006; Buscher and Fletcher, 2020; Kareiva et al., 2011; Marris, 2013) ~~as cultural land and seascapes. New conservationists propose that nature should be integrated~~ but do not address the harmful capitalist model of economic development that underpins biodiversity loss (e.g., tourism or payments for ecosystem services). The second approach, neoprotectionism, tries to completely separate nature from human development, calling for an expansion of conventional ’fortress’-style protected areas and therefore reinforces the dichotomies between nature and culture (Hutton et al., 2005; Wuerthner et al., 2015; Buscher and Fletcher, 2020). Although new conservation moves beyond these dualisms, it looks to market mechanisms to fund and save nature (e.g., Payments for Ecosystem Services, ecotourism) , creating other social and environmental problems~~thereby producing other contradictions~~. Convivial conservation proposes that both approaches have limitations, as inherited from philosophies and global development models that drive the intertwined biodiversity and climate crises.

3.8.3 Offering solutions

The specific contribution of long-term convivial conservation is that it aims to produce integrated nature-culture spaces within postcapitalist conservation strategies. At its core, it investigates and challenges dominant global political-economic structures, assumptions, beliefs, and knowledge production systems, “including those that are the foundation of paradigms of economic growth and adaptation without limits” (O’Brien and Barnett, 2013, p.385).

~~Today,~~ Convivial conservation is gaining traction in research, policy and practice (Massarella et al., 2023; Ochieng et al., 2023): “There is widespread agreement that our current reality of global, human-induced ecosystemic and climatic change presents stark challenges for conservation ~~. It is concern for this dynamic that has led to the radical proposals now on the table~~” (Büscher and Fletcher, 2019, p.285). At the same time, breaking through the hegemony of protectionist neoliberal conservation

(Fletcher, 2023) is also the greatest challenge of convivial conservation. To further address this challenge, a manifesto was developed that outlines 10 core principles of convivial conservation. We summarise key elements of these principles here; for a complete overview of all 10 principles, we refer to the manifesto website (Centre, 2024).

~~Integrated landscapes:~~ Humans have always shaped the ecosystems in which they live, co-producing diverse landscapes that in turn shaped and supported people. However,~~Yet~~ mainstream conservation interventions often separate people from ~~the~~ surrounding ecosystems based on the unfounded assumption that local communities threaten biodiversity (Brockington et al., 2012). ~~This assumption is undermined by growing evidence that humans, especially Indigenous peoples, have actively managed and used what are today erroneously considered 'wild' areas throughout the world~~ The ~~re is a need to promote landscapes that integrate people and nonhuman species: the~~ question is not *whether* people should live with the rest of nature, but *how* ~~we do~~ (see Section 3.5).

~~Direct democratic and equitable governance:~~ International and regional inequality contributes to the destruction of ~~the~~ global commons necessitating equitable stewardship of ecosystems, centred on those who live within them. Nurturing extra-local commons institutions and economies based on values of ~~responsibility and~~ care would help cross-generational and cross-scale conviviality. Convivial conservation challenges dominant top-down forms of political power and advocat es~~ing~~ for inclusive ~~deliberation and~~ decision-making processes,~~processes~~ in particular for those ~~in proximity and~~ dependent on the ecosystems in question (Lanjouw, 2021). ~~This is based on the principle of subsidiarity, which means that~~ All decisions that can be reached effectively~~effectively be reached~~ at the local level should be, with higher-level processes that support~~supporting~~ local autonomy and only intervene~~intervening~~ when necessary (e.g., Gokkon, 2018, see also Section 3.6).

~~Non-market, redistributive funding and valuation based on intrinsic/spiritual significance:~~Emphasizing only the monetary valuation of biodiversity can be counterproductive. Instruments like 'payments for environmental services', REDD+, and carbon credits use the logic of the problem (capitalist accumulation through the use of natural resources~~natural resource use~~ as the logic of the solution (Fletcher, 2023). This~~Monetary valuation also~~ conflicts with convivial co-existence between humans and non-humans, and can undermine~~s~~ other non-monetary ways of valuing nature. It is crucial to~~Delinking conservation from global capitalism could~~ support existing~~traditional~~ livelihoods rather than (further) forcing locals into exploitative external markets. Moreover, mechanisms to redistribute existing wealth and resources would preclude the need to finance~~fund~~conservation through environmentally harmful economic growth (Moranta et al., 2022).

~~mbracing diverse forms of knowing:~~ Protected areas have usually relied on paradigms based on~~depended on~~ positivist ~~Western~~ scientific knowledge ~~paradigms~~ at the expense of rich local and Indigenous philosophies, histories, and practices. However, many different~~Yet many diverse~~ other ways of knowing and practical ways of being in relation to the world such as Ubuntu~~with the world like Ubuntu~~ (Mabele et al., 2022), Buen Vivir, and Eco-Swaraj promote life through mutual care~~caring~~ and sharing between humans and non-humans,~~and among humans and nonhumans,~~ discouraging individualism and unsustainable extraction (Dickson-Hoyle et al., 2022). ~~Local knowledge held by stewards of landscapes and place based communities are also invaluable and often overlooked in technocratic decision makin~~ This ~~full range of~~ diversitye knowledge must be valued (Orlove et al., 2023).

~~Challenging broader political-economic forces: Although Indigenous Peoples and local communities should be supported and have their rights recognized, they should not be made solely responsible for conserving nature~~ Too often, those who live ~~living~~ in or close to conservation areas are expected to change their behavior the most (Brockington et al., 2012; Merino and Gustafsson, 2021). However,~~But~~ large industrial extractive practices and ~~the elites'~~ high consumerist lifestyles~~m~~ drive disproportionate loss of biodiversity. However, these people and organisations are not perceived as causative agents~~perceived as such~~ because they are far from conservation spaces or~~and appear~~ too powerful ~~and intractable~~ to influence (Wiedmann et al., 2020). Conservationists should~~must avoid appeasing and overlooking the impacts of these forces, and instead~~ challenge both the regimes that indulge in human rights violations and displacement in the name of biodiversity, and the rights of global or national elites to control or hinder conservation efforts (see also Section 3.6).

4 synthesis

The eight~~nine~~ themes introduced above~~presented here~~ highlight ~~the~~ complex interrelationships within the biosphere and their connections to social and economic systems, and as well as to the Earth system~~how these are entangled with climate change~~. It is evident that various vicious cycles exist.~~We are trapped in various vicious cycle.~~ For example, changes in temperature and precipitation patterns as a result of climate change and deforestation can lead to lower agricultural yields and increased fires. This increases pressure on ecosystems and local people, who~~, human communities, which~~ depend on nature~~them~~, and face challenges in maintaining their livelihoods and meeting the demand for~~which are under pressure to provide~~ resources and products in the global market. The provision of various commodities under current trading paradigms and subsidy schemes further fuels climate change, ecosystem degradation and deforestation. In addition to identifying interdependence between these challenges, our eight~~nine~~ themes offer four key~~some~~ insights into escape hatches from such ~~this~~ cycles.

4.1 1. Improve mechanisms of inclusive decision making

The involvement of diverse stakeholders, including civil society, Indigenous people and local communities and private sector actors, enriches decision-making by incorporating a variety of perspectives and fostering support for innovative solutions (section 3.6). For example, the concept of 'blue justice' advocates for the rights and recognition of small-scale fishers, challenging their marginalisation and empowering them within the regions they inhabit, fostering ecosystem stewardship (section 3.1). Similarly, the integration of indigenous knowledge and governance has proven valuable in improving fire management strategies and promoting biodiversity and fire resilient ecosystems (section 3.3). Such approaches promote equitable and resilient outcomes that align conservation efforts with sustainable development goals (section 3.6). In addition, decision-makers from adjacent ecosystems should sometimes be involved, as, for example, upstream land-based activities have significant impacts on coastal ecosystems (section 3.1).

Raising **public awareness through education** campaigns and **fostering collaboration** enables a holistic approach to environmental challenges (sections 3.1, 3.3. 3.8). Various knowledge systems, such as Ubuntu, Buen Vivir and Eco-Swaraj, emphasise mutual care and sustainable relationships between humans and non-humans. These frameworks discourage individualism and over-exploitation while promoting sustainable living. Incorporating such worldviews into decision-making processes is essential for sustainable and effective governance (section 3.8).

Comprehensive policy packages need to integrate environmental, economic and social dimensions to address the root causes of environmental degradation and to promote sustainability (sections3.6). These packages should encourage the adoption of cleaner technologies and provide incentives for the conservation and restoration of ecosystems. Initiatives such as the European Green Deal underline the importance of integrating climate and biosphere protection with economic and social objectives. International cooperation is essential to ensure coherent policies across borders and to drive meaningful progress (sections3.6).

4.2 2. Establish incentives for sustainability

Institutional mechanisms need to be adapted **to support innovative and unconventional practices**, enabling transformative approaches to environmental challenges (section 3.1). Recognising the structural co-benefits of nature-based solutions, such as the reduction of flood risk and the provision of additional ecosystem services that come from the protection of coastal wetlands, is crucial for integrated policy and planning (section 3.1).

Strengthening financial support, such as tax breaks, subsidies or grants, for actions that adopt sustainable practices can reduce emissions, water use and waste production (section 3.6). For example, strengthening firefighting resources - through increased funding for equipment, personnel and surveillance - improves fire prevention and response capacity. This investment is critical as the costs of fire suppression are consistently outweighed by the losses from unmanaged fires (section 3.3). Further, future benefits derived from ecosystems should be uplifted proportionally with increasing real market incomes and changing real scarcities of ecosystems (section 3.7).

An exclusive focus on monetary incentives for biodiversity protection undermines its **intrinsic, relational and cultural values**, which are equally important for promoting respect for nature and long-term sustainability (section 3.8). Addressing these dimensions holistically is essential for effective and equitable environmental governance.

4.3 3. Measure and share regional features

Strengthening monitoring capacity is essential for effective environmental management and conservation (section 3.5). For example, increased field measurements in tropical regions are critical to fill gaps in water-related perspectives and to enable country or region-specific analyses to assess the feasibility and cost-benefit trade-offs of different reforestation strategies (section 3.2).

Similarly, fire **risk assessments and forecasts** need to consider regional factors beyond fire weather, including landscape and vegetation characteristics, management practices, ignition sources and socio-economic drivers of vulnerability and exposure (section 3.3).

Environmental certification of imports and exports is essential to maintain high environmental standards. The expansion of existing schemes and the creation of new sector-specific certifications, coupled with regular reviews, transparent reporting and mandatory disclosure of progress, can hold stakeholders accountable to clear benchmarks and timelines (section 3.6). For example, tonne-year accounting provides a scientifically robust method for measuring the climate impact of temporary carbon storage, bringing carbon accounting practices into line with current scientific understanding (section 3.4).

4.4 4. Adopt long lasting holistic landscape management strategies

Humans have always shaped the ecosystems in which they live, co-producing **diverse landscapes** that in turn shaped and supported people (section 3.8). Restoring degraded landscapes worldwide can boost precipitation and mitigate losses from forest degradation (section 3.2). For instance, coastal habitat restoration in Belgium and Hong Kong highlights the co-benefits of nature-based solutions (section 3.1) awhile national strategies that prioritize biodiversity helps to promote fire resilience by avoiding mono-cultures of highly flammable species (section 3.3). Maintaining or restoring 20-25% of (semi-)natural habitat per square kilometre in human-modified landscapes is crucial for maintaining severa of nature's contributions to people (NCPs), particularly in agricultural and urban areas. Incorporating habitats such as hedgerows and no-mow zones alongside precision agriculture can balance biodiversity with optimised productivity, making the 25% target a valuable policy tool (section 3.5).

Consider trade-offs carefully: Land fragmentation for fire suppression can reduce species richness, whereas controlled burning may offer a more natural solution, supporting fire-dependent vegetation and biodiversity (section 3.3). Similarly, while afforestation can enhance carbon sequestration and benefit local communities, it requires meticulous planning to avoid unintended ecological consequences (section 3.2). To optimize outcomes, trade-offs and synergies between biodiversity conservation and services like carbon sequestration, coastal protection, water purification, aquaculture, and eco-tourism must be holistically evaluated (section 3.1).

Ecosystem governance should prioritize the people who live within them, empowering Indigenous people and local communities to restore and conserve both livelihoods and biodiversity (section 3.1). Supporting extra-local commons and economies based on values of care contributes to intergenerational and inter-scale sustainability (section 3.8). At the same time, increased transnational cooperation, as exemplified by the Amazon Cooperation Treaty Organization, is essential to combat illegal deforestation and wildlife trafficking and promote more effective conservation strategies (section 3.6).

We note that these four insights align closely. More effective mechanisms of inclusive decision-making are fundamental to promoting the collective effort and will needed to bring transformations of existing structures. Such mechanisms will enable decision-makers to respond to incentives for sustainability and to draw on improved metrics. These, in turn, will support the adoption of long-lasting landscape management strategies.

~~As **climate change** alters weather patterns, disrupts hydrological cycles, and increases the frequency of extreme events, it undermines ecosystems' capacity to provide essential services such as water purification, pollination, and soil fertility (IPBES 2019). To mitigate these impacts, it is crucial to stop greenhouse gas emissions **and** stay close to, or even below, the 1.5°C target. Exceeding this threshold, for example, is expected to cause widespread mangrove retreat (Section 3.1) and increase the severity of fire weather across most of the world (Section 3.3). Regions that are not adapted to fire regimes may experience increased vulnerability, with adaptation efforts driving up costs (Section 3.3). Beyond stopping greenhouse gas emissions, it is essential to reduce **anthropogenic stressors** such as overexploitation, resource extraction, pollution, and unsustainable~~

management, which threaten the ability of ecosystems to directly or indirectly support human well-being, economic stability, and overall quality of life (Sections 3.1, 3.2, 3.4, 3.5,3.6).

Nature-based solutions to climate change have demonstrated **co-benefits** for biodiversity and hydrological cycles (Section 3.1, 3.2). However, afforestation, for example, requires careful planning and management to avoid unintended ecological consequences (Section 3.2, Section 3.3). Controlled burning is a natural fire management solution that can maintain fire-dependent vegetation types and biodiversity and is cost-effective, compared to other engineered solutions (Section 3.3). Quantifying the co-benefits of dynamic ecosystems over time and across spatial scales for decision making remains a challenge. One approach to accounting for dynamic carbon storage is to measure it in tonne-years, which are proportional to degree-years of avoided warming (Section 3.4). To maintain and/or restore various **ecosystem services**, at least 20-25% per square kilometer of (semi-)natural habitats should be present in human-modified landscapes, including agricultural and urban areas (Section 3.5). Given the benefits of nature-based solutions that go beyond climate change mitigation, future efforts need to focus on improving metrics to monitor and quantify progress as well as analysing and sharing successful management practices (Section 3.2, 3.3, 3.5, 3.6, 3.9).

Global trade is a major contributor to ecosystem vulnerability, degradation and social inequalities in regions far from where products are consumed, resulting in uneven environmental impacts and exacerbating socio-economic disparities (Section 3.6). To address these issues, it is essential to adopt circular economy principles and **international** comprehensive **policy frameworks** that recognise the multiple benefits of nature-based solutions and integrate climate action with economic and social objectives (Sections 3.6, 3.7, 3.9). For example, the value of ecosystem services should be adjusted in proportion to rising real market incomes and changing ecosystem scarcities (Section 3.7). Such policy frameworks and economic measures can create synergies that enhance ecosystem resilience, support sustainable development and improve the health of human-nature relationships (Sections 3.6, 3.8, 3.9).

While international cooperation is essential to coordinate policy frameworks, **local implementation** strategies need to be tailored to local circumstances and conditions, taking into account all available knowledge (Section 3.8). For example, man-made changes in species composition (through resource management or introduction of new species) needs to take into account changes in biogeochemical cycles and impacts on local biodiversity 3.1, 3.2, 3.3). The development of adaptation strategies to fire, especially in previously unaffected regions, is crucial as fires can lead to significant carbon losses and the assessment of future fire risks remains uncertain (Section 3.3). It is important to explicitly consider temporal dynamics and spatial heterogeneity in decision-making processes (Sections 3.4 and 3.5, 3.8). Indigenous peoples and local communities are often an example of effective stewardship of the biosphere and support ecological integrity and biodiversity conservation (Section 3.9). Implementation decisions should therefore be taken at the local level where possible, with higher level processes supporting local autonomy and governance (Sections 3.6, 3.8, 3.9). However, governance from national to local scales tends to be influenced by the geographical context, resource availability, time horizon and socio-political dimensions (e.g. Nilsson et al.2018). Therefore, more local studies and effective knowledge sharing, together with advances in the ecological theory of transient ecosystems, will help to develop future proactive solutions.

5 Conclusions

Taken together, these eight~~nine~~ themes , described in section 3, illustrate the importance of considering the impact of human activities on surrounding ~~neighbouring~~ areas when analysing, evaluating or developing policies or economic measures. Focusing exclusively on a single problem, question or objective is not enough. Overly siloed approaches can overlook or even ~~worse~~ exacerbate, existing problems in other areas (Fanning et al., 2022). As different aspects of the Earth system crisis are typically addressed by different research disciplines, closer collaboration between scientists of diverse fields~~different research disciplines~~ is essential to develop a holistic understanding and ~~to~~ effectively tackle~~address~~ complex and~~,~~ critical issues even in smaller research projects. This interdisciplinary approach is already practiced in the major reports such as those by~~of e.g.~~ IPBES and IPCC.

Our study offers a sample of the active, growing body of work on biosphere research from the perspective of different research domains, provides recommendations and reasserts the value of interdisciplinary research. Nevertheless, this collection of pressing ecological issues does not claim to be exhaustive, and the compilation may be superficial on some topics that require more in-depth discussion. In the future, we need to encourage greater contributions from scientists in other regions of the world, particularly the Global South, to incorporate their knowledge and perspectives. Their insights~~input~~ can help identify new targets and research questions that may have been overlooked so far.

Despite receiving less public attention than other currently dominant issues, the Earth System crisis - including climate change, biodiversity loss, pollution and land-use change - remains the major challenge of this century. While many ecosystems around the world are suffering from these threats, functioning ecosystems also offer significant potential for addressing many aspects of Earth system crises.

In conclusion, we curated this list of pressing environmental issues and recommendations to underscore that we are not limited by how much we know about the problem or how much we know about how to act. The obstacles are structural, cultural and political in nature. They prevent the necessary pace and scale of implementation needed to achieve ~~the~~ various international commitments and the goals of the Paris Agreement and the Kunming-Montreal Global Biodiversity Framework in a fair and equitable manner. E~~Instead, an e~~ffective implementation of these eight themes helpt to can promote a flourishing biosphere that facilitates economic, cultural, and spiritual interactions essential to human well-being

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Appendix A: Questionnaire

A1 Disclaimer:

We welcome contributions from all active researchers in all disciplines working on issues related to ecosystems and human interactions with these systems worldwide. Please tell us what you think are the 1-3 most important discoveries or advances in your field of research since 1 January 2022, and the key articles and reports that highlight these findings. In order to cover a specific topic, the editorial team requests at least two articles published after 1 January 2022. Each response must meet the following criteria:

- sufficient evidence from peer-reviewed publications in the last two years;
- no ongoing critical debate on the issue;
- relevance to international negotiations.

A2 Questions

- What is an important recent advance in biosphere research related to climate change and other anthropogenic stressors? Please add up to 5 publications published since 1-1-2022 that support your claim. (if possible weblinks or library references)
- What is an important recent advance in biosphere research related to adaptation and mitigation potentials? Please add up to 5 publications published since 1-1-2022 that support your claim. (if possible weblinks or library references)
- What is an important recent advance in biosphere research related to the identification of efficient policy making and economics concepts? Please add up to 5 publications published since 1-1-2022 that support your claim. (if possible weblinks or library references)