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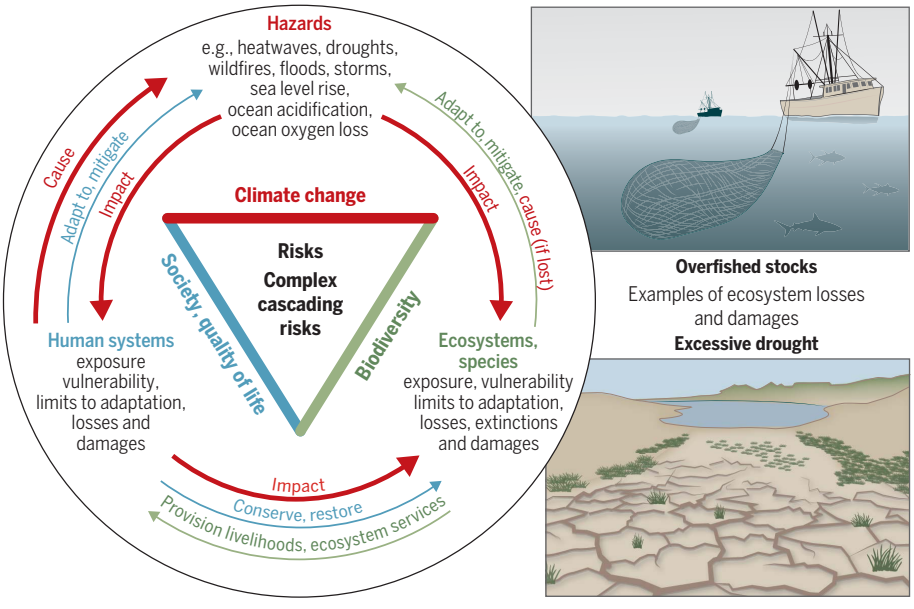
Overcoming the coupled climate and biodiversity crises and their societal impacts

H.-O. Pörtner*, R. J. Scholes†, A. Arneth, D. K. A. Barnes, M. T. Burrows, S. E. Diamond, C. M. Duarte, W. Kiessling, P. Leadley, S. Managi, P. McElwee, G. Midgley, H. T. Ngo, D. Obura, U. Pascual, M. Sankaran, Y. J. Shin, A. L. Val

BACKGROUND: Two intertwined crises threaten human well-being: Climate change—arising from human-induced greenhouse gas emissions, including those from the loss of biomass and biodiversity—is raising temperatures beyond those of the Holocene, when human civilization evolved and expanded globally. Mean warming and the increasing frequency and severity of extreme events in turn disturb ecosystem functioning, cause habitat loss to humans and biodiversity, and exacerbate the unprecedented loss of biodiversity already caused by human-induced habitat degradation, overexploitation of natural resources, and pollution. Both crises reduce nature's contributions to people, which sustain well-being, livelihoods, economies, and development prospects and also support climate change adaptation and mitigation. Failing to act will increase human vulnerability, including poverty, food insecurity, involuntary displacement, and political instability and conflict. The coupled global climate and biodiversity crises and their societal impacts concern land, freshwater, and ocean ecosystems alike but are insufficiently tackled by current actions, as identified by assessments of both the IPCC (Intergovernmental Panel on Climate Change) and IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). None of the 20 2011–2020 Aichi biodiversity targets and none of the mileposts on climate trajectories intended to limit warming to 1.5°C have been met.

ADVANCES: Climate, biodiversity, and societal challenges are intertwined but are often treated as singular problems. Solutions exist with cobenefits across sectors. In intact and functional ecosystems, nature is efficient at carbon capture (by photosynthesis) and sequestration (long-term removal from the carbon cycle), provided that warming is limited to 1.5°C or below through ambitious emissions reductions. Strengthening the biosphere on land, in freshwater, and in the ocean will support climate change mitigation, adaptation, biodiversity, human well-being, and livelihoods. Mounting scientific evidence points to the need to prioritize protection of remaining undamaged carbon- and species-rich environments and to implement targeted restoration projects, with more attention to effectively sustaining biodiversity and fairly distributed societal cobenefits. Three critical objectives for future spatial planning include a habitable climate, self-sustaining biodiversity, and sustained provisioning of nature's contributions to people to support development and a good quality of life for all. Coordinated efforts among science and policy can identify and help navigate development pathways toward climate resilience for both human society and biodiversity.

OUTLOOK: New global biodiversity, climate, and sustainability targets envisioned for 2030 and 2050 will likely fail if drivers behind climate change and biodiversity loss remain insufficiently addressed or concrete actions to meet current political agreements and goals do not increase in pace and scale. The following actions are urgently needed. (i) Ambitious emissions reduction, combined with suitable adaptation measures. (ii) Effective protection of an average of 30 to 50% of surface areas across a mosaic of interspersed and interconnected land, ocean, and freshwater "scapes." These cover a gradient, from pristine ecosystems; to spaces shared by humans and wild species and sustainably used; to spaces under intensive uses such as cities, which nonetheless can harbor substantial biodiversity in terrestrial and aquatic spaces. Efforts need to consider the specific spatial demands for healthy ecosystems. (iii) Building of development pathways and the underpinning of political, economic, and social institutions (including norms and rules) on visions such as collective responsibility, sustainable and circular uses of natural resources, avoidance of overconsumption and waste, and more equitable and participatory development regionally and globally. (iv) The enabling of just and equitable access to and benefits from natural assets across societies, groups, and individuals, securing good quality of life. Transformative action can overcome siloed approaches through institutional and individual change, achieving sustainability for nature and people, as well as human, ecosystem, and planetary health. ■



Climate, biodiversity, and human society are coupled through dynamic interactions across scales. Human-caused exploitation and climate change are increasingly threatening biodiversity and nature's contributions to people, causing losses and damages exemplified through overfished stocks and excessive drought that harm productive habitats.

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REVIEW

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Overcoming the coupled climate and biodiversity crises and their societal impacts

H.-O. Pörtner[1,2]*, R. J. Scholes[3]†, A. Arneth[4], D. K. A. Barnes[5], M. T. Burrows[6], S. E. Diamond[7], C. M. Duarte[8,9], W. Kiessling[10], P. Leadley[11], S. Managi[12], P. McElwee[13], G. Midgley[14], H. T. Ngo[15,16], D. Obura[17,18], U. Pascual[19,20,21], M. Sankaran[22], Y. J. Shin[23], A. L. Val[24]

Earth's biodiversity and human societies face pollution, overconsumption of natural resources, urbanization, demographic shifts, social and economic inequalities, and habitat loss, many of which are exacerbated by climate change. Here, we review links among climate, biodiversity, and society and develop a roadmap toward sustainability. These include limiting warming to 1.5°C and effectively conserving and restoring functional ecosystems on 30 to 50% of land, freshwater, and ocean "scapes." We envision a mosaic of interconnected protected and shared spaces, including intensively used spaces, to strengthen self-sustaining biodiversity, the capacity of people and nature to adapt to and mitigate climate change, and nature's contributions to people. Fostering interlinked human, ecosystem, and planetary health for a livable future urgently requires bold implementation of transformative policy interventions through interconnected institutions, governance, and social systems from local to global levels.

Climate change and biodiversity loss arguably represent the most substantial challenges to ecosystem health and supply of nature's contributions to people (NCP) (*1*). They also directly and indirectly affect human health and well-being and the functioning and sustainability of human societies at the global scale (*2*, *3*). Increases in greenhouse gas emissions now exceed 55 billion tonnes of carbon dioxide equivalents (Gt CO_2e) $year^{-1}$ and have resulted in warming by more than 1.1°C above preindustrial times, altered precipitation regimes, sea level rise, more extreme weather events, and oxygen depletion and acidification of aquatic environments (*4*). Climate change and other anthropogenic drivers of biodiversity loss—such as agricultural expansion and intensification, pollution, overfishing, and invasive alien species introductions—independently and together stress and disrupt ecological communities (*2*). Human activities have modified nearly 75% of Earth's land surface and 66% of its ocean area (*3*, *5*), leading to the loss of more than 80 and 50% of wild mammal and plant biomass, respectively (*6*), and threatening more species with extinction than ever before in human history (*7*). Moreover, climate change and biodiversity loss are inextricably connected, with each stressor contributing to and exacerbating the effects of the other.

Climate change is causing species shifts and biodiversity loss globally because species are confined to limited thermal performance ranges and therefore geographical ranges. Climate warming increasingly causes species to move (Fig. 1, A and C) to higher latitudes (poleward), higher altitudes (on land), or deeper water. Range shifts lead to changes in species interactions, with cascading effects on species abundances, species composition, and ecological functions. When species cannot track the changing climate or when suitable habitat shrinks, warming leads to mortality and biodiversity loss, as has been observed in the tropics (Fig. 1B). Some species in coral reefs, savannahs, rain forests, high-latitude and -altitude ecosystems, and Mediterranean systems show evidence of exceedance of tolerance and adaptation limits (*2*). Mountains and continental boundaries may become climate dead ends because climate belts shift off the top of mountains, at the ends of a continent, or on islands. Extinction risks are high for species with narrow geographic ranges or specific habitat requirements, and those in the tropics and in polar regions (*2*). Climate change surpassing species' adaptation limits constrains options to protect those species from extinction (*2*). Overall, climate change and sea level rise are projected to exacerbate the direct impacts of human activities, causing further losses in biomass, habitats, and species (*2*, *8*–*10*).

Conversely, biodiversity loss contributes to climate change through loss of wild species and biomass. This reduces carbon stocks and sink capacity in natural and managed ecosystems, increasing emissions (*2*, *4*). Habitat loss and disturbance by human activities (such as through deforestation or expansion of livestock production or pollution) are the primary cause of biodiversity loss, increasingly exacerbated by climate change. Feedbacks of biodiversity loss on climate and of climate change on biodiversity include temperature-induced changes in photosynthetic capacity and carbon storage, modified reflectivity of the land surface, altered formation of clouds and atmospheric dust, and shifted biogeochemical cycling of nutrients and carbon, which in turn influence the concentration of greenhouse gases in the atmosphere (*11*–*16*).

Biodiversity loss and climate change are thus both drivers and consequences of one another, tightly linked to human activities or demographic change and resulting in negative impacts on NCP, human health and well-being, as well as societal functioning [for example, (*17*, *18*)]. Further, the human species is also losing habitat, through sea level rise and, more widely, through prolonged exposures to lethal temperature-humidity combinations outside humans' thermal niche, especially at but not limited to the lower latitudes (*2*). Yet these interlinkages are not sufficiently recognized in policies and multilateral agreements to limit climate change and halt biodiversity loss and societal consequences, particularly as the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) have largely addressed these issues independently. Policies and actions that simultaneously address climate, biodiversity, and society (the "nexus") can help to avoid dangerous trade-offs and maximize cobenefits for humankind (*18*).

Accordingly, various aspects of the "solution space" are developed in the following sections. The discussion includes (i) strategies to

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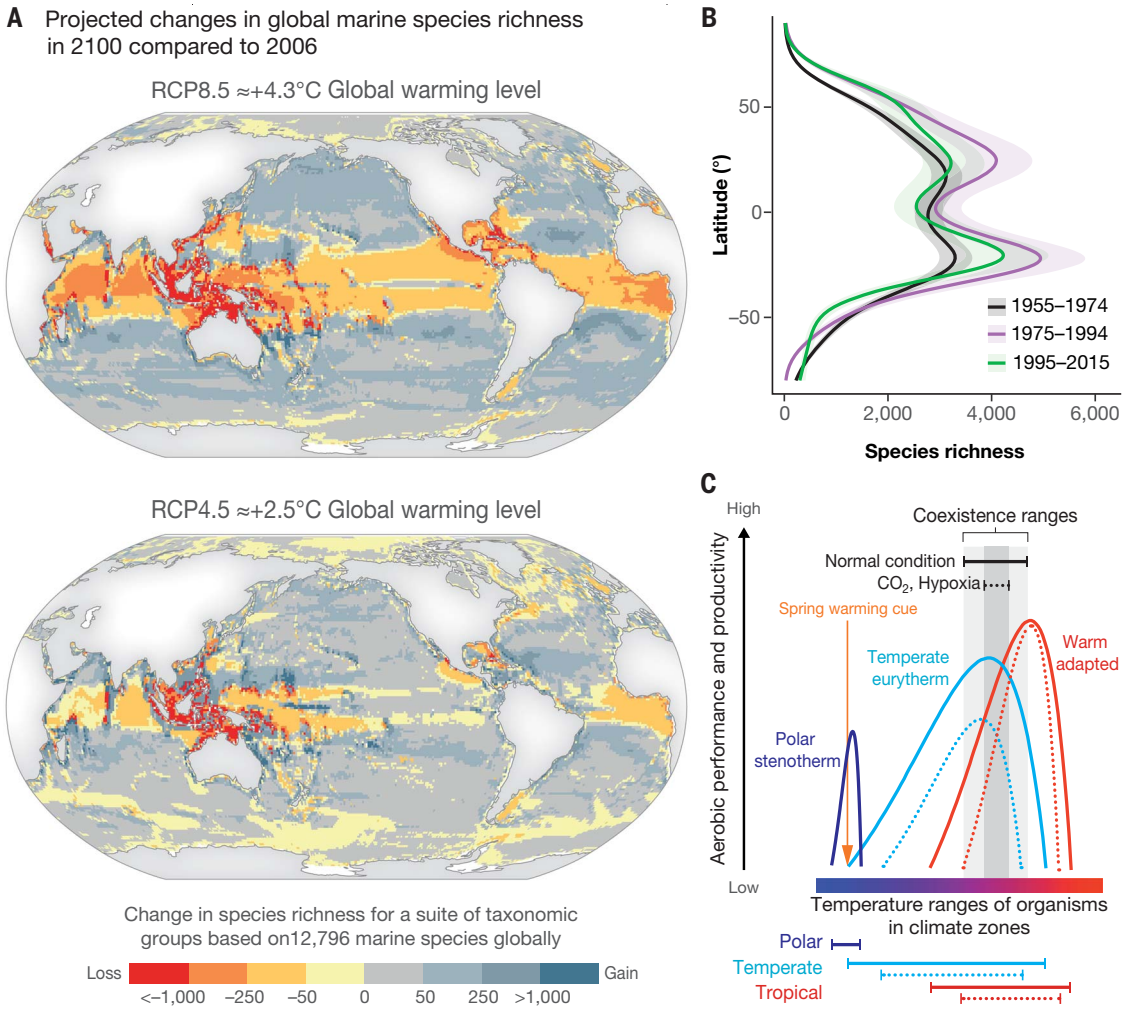


Fig. 1. Latitudinal shifts in marine species richness (12,796 species from 23 phyla) illustrate the responses of species to global warming. (**A**) Projected shifts reflect a scenario-dependent impoverishment of species richness at low latitudes. [Data are from (*10*), reproduced from (*2*).] (**B**) The projection is supported by present-day observations of reduced biodiversity at the equator compared with slightly higher Northern and Southern latitudes (48,661 marine animal species included across latitudes) [data are from (*149*)], reflecting that heat limits are already surpassed for Metazoa in warm ocean waters (*150*). Parallel phenomena are projected to occur on land (*2*). (**C**) The conceptual graph illustrates how species' thermal performance curves result from adaptation to the temperature regime of their biogeographical area. Overlapping curves define the temperature range and limits of species' coexistence and interactions. Shifts in coexistence and ecosystem dynamics would result from differential latitudinal shifts and from species-specific constraints on thermal ranges elicited by hypoxia and/or CO_2 enrichment (ocean acidification) (*8*, *18*, *151*). Surpassing such limits may trigger fatal tipping points in ecosystems and dependent societies.

address biodiversity loss and climate change, and their impacts on each other; (ii) proposed actions to address both crises together with consideration of societal needs; underpinned by (iii), the nexus between climate, biodiversity, and society, as well as the enablers and urgency of actions leading to transformative change.

Protecting biodiversity in a changing climate by multifunctional "scapes"

Conservation of biodiversity through spatial planning, conservation, and restoration is increasingly seen as an existential requirement for humankind (as addressed by CBD 2022). It is a flagship target of many conservation and restoration programs, including the Kunming-Montreal Global Biodiversity Framework of the CBD, the UN Decade on Ecosystem Restoration (2021–2030), and the Declaration on Forests and Land Use at the UNFCCC Conference of the Parties (COP) 26 (*19*). Global estimates of the average surface area required to be effectively protected for self-sustaining biodiversity and long-term ecosystem health range from 30 to 50% for land and ocean (*20*–*22*), but to integrate this target with multiple social objectives of human well-being, including equity and food security, is challenging (*23*–*26*). Further research is needed to derive biome-specific guidance and targets (*27*, *28*). For example, much higher protection, even 80%, might be needed to secure the Amazon's capacity to maintain its own regional climate regime and thereby biodiversity and global carbon sequestration capacity (*29*–*32*). For maintaining self-sustaining biodiversity in a habitable climate, the conservation of biodiversity- and carbon-rich natural ecosystems across latitudes—such as diverse forests, peatlands, and seagrass meadows—have highest priority. The conservation of spatially intact ecosystems can reduce risks to health, such as the risk of a pandemic, and implementation of some managed ecosystem types reduces climate risks to food security, such as through agroforestry (*24*, *33*–*36*). Conservation of, for example, coral reefs secures multifunctional benefits that support the UN Sustainable Development Goals (SDGs) (*37*). More encompassing conservation actions, extending beyond the historical focus on protected areas and species-based approaches, are thus required to safeguard biodiversity, support climate change mitigation and adaptation (*28*, *38*, *39*), and sustain NCP (*1*, *28*, *40*), including secure livelihoods for Indigenous Peoples and local communities (*41*). These ecosystem benefits include enhancing water and air quality; reducing soil erosion; ensuring pollination of crops; supporting food security and livelihoods; and regulating floods, regional climates, and microclimates. Climate change is already affecting access to or availability of many of these benefits (*40*). It is likely that with successful conservation and restoration efforts, human physical and mental health will also benefit (*2*).

A substantial conservation gap exists toward agreed (for example, Aichi biodiversity targets) and even more so, envisioned goals. As of 2020,

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only 15% of land was declared as protected, and only a fraction of that area was effectively protected, given threats of encroachment, loss of legal status, and shifts of biodiversity into surrounding areas that are more intensively used (*42*, *43*). Protection rates are still below 10% in the ocean, again with a smaller fraction being highly protected (*23*). Moreover, the dichotomy between protected and unprotected zones has resulted in failures to address connectivity, spatial mosaic dynamics, and human needs. This calls for complementing conservation with extensive restoration efforts.

Restoration intervenes when high degrees of ecosystem degradation prevent spontaneous recovery. Restoration of ecosystems with native species enhances climate resilience of biodiversity but, in light of shifted biogeographies under climate change, may include new species assemblages to match future climatic conditions. Restoration can involve biodiversity offsetting, which aims to mitigate the negative impacts of infrastructure development, agricultural expansion, or mining by restoring biodiversity elsewhere. In light of shifting climate zones, restoration may need to do the same under climate change. However, if biodiversity-offsetting programs limit local people's access or cause loss of services on which their livelihoods depend, this can create negative impacts on adaptation (*44*). Social-ecological trade-offs and disconnects between the loss of local and "off-stage" (distant, diffuse, and delayed) biodiversity benefits can be minimized if the scale, type, and distribution of NCP are considered in restoration and offsetting initiatives (*45*, *46*).

A new generation of conservation and restoration actions that focus on multifunctional connected "scapes" (Fig. 2) is necessary to address biodiversity and climate interactions and their nexus with human development, health, and well-being (*47*). Increasingly, biodiversity management envisages a continuum of protection requirements from highly protected areas, through shared scapes, to highly human-dominated scapes (*48*). This integrative approach aims at the maintenance of self-sustaining biodiversity that is functionally intact and resilient with respect to species composition and in providing stable ecosystem services and that also meets human socioeconomic and cultural needs, including material provisioning (such as agriculture, forestry, and fisheries), nonmaterial contributions (such as cultural identity, spirituality and inspiration, and recreation), and regulatory contributions (such as pollination, water and soil protection, and microclimate). Such multifunctional scapes would include mosaics of protected areas, climate refugia and migration corridors, spaces shared by biodiversity and humans and modified by and for human use (including lands managed by Indigenous peoples and local communities), and profoundly transformed ecosystems such as urban and intensively farmed areas (Fig. 2) (*47*, *48*). Implementing mixed-use land- and seascapes could enhance biodiversity and climate cobenefits and also generate diverse, inclusive, and equitable benefits to communities and people. In managed ecosystems, increasing crop diversity within fields (for example, by using varietal mixtures, intercropping, or agroforestry), adding temporal diversity through extended crop rotations, and diversifying agricultural practices at landscape levels dilutes risk and increases resilience to climate change (*49*, *50*). In forests, management practices that promote biodiversity such as natural regeneration, mixed species stands, and selective harvests can also increase resilience and secure livelihoods (*51*, *52*).

The proportion and area of the different types of scapes would vary locally to meet different

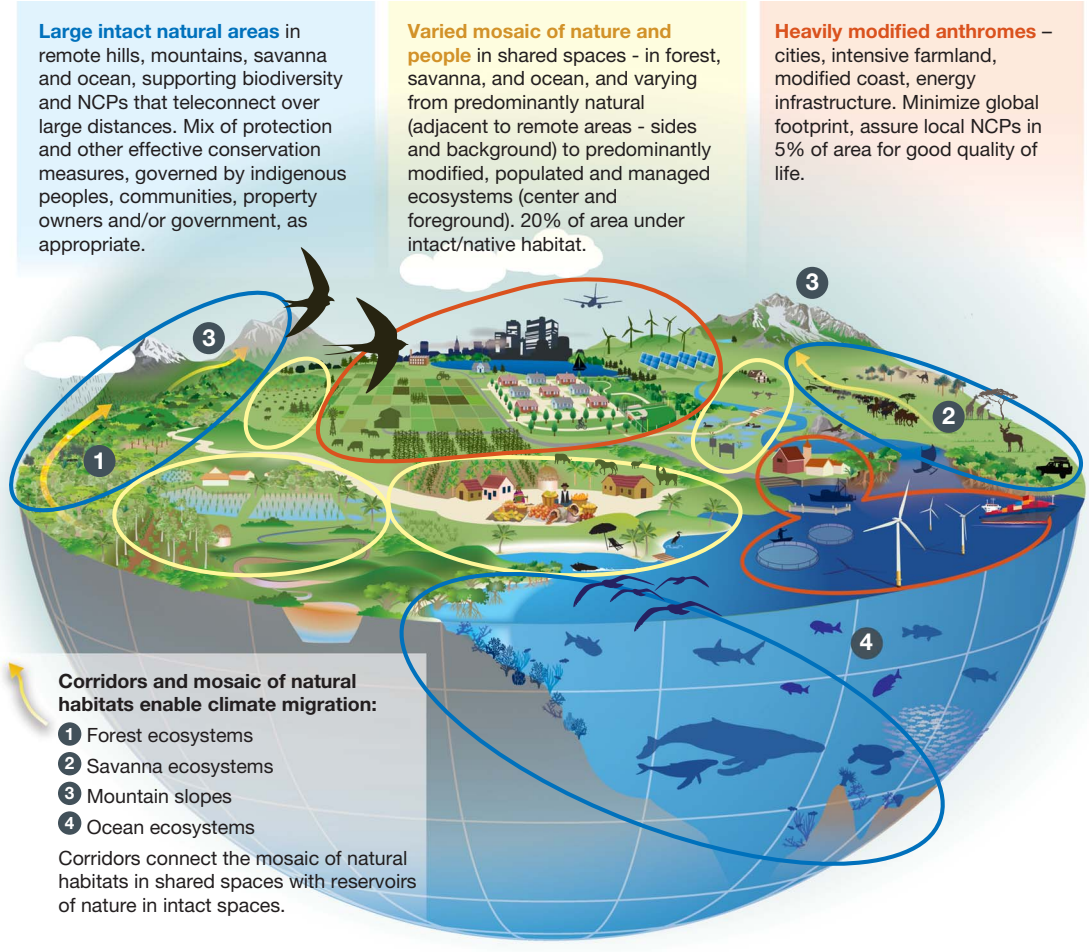


Fig. 2. Multifunctional connected and structurally and visibly distinct scapes across land, freshwater, and marine biomes. Scapes include large, intact wilderness spaces (blue circles), shared spaces (yellow circles), and anthromes (red circles). In spaces "shared" by people and biodiversity, the mosaic of intact natural habitat provides critical nature's contributions to people (NCP). Corridors of natural habitat (yellow arrows) facilitate species migration up elevational gradients. This multifunctional concept can assist integrating global and large-scale targets within local geographies (*18*).

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local-to-global objectives for biodiversity, livelihoods, and well-being, embedded in polycentric governance models that have emerged to manage cross-sectoral complexity (*48*, *53*). Critically, planning must be closely coordinated across local jurisdictions and at larger scales to jointly meet global goals and objectives (*48*). Equitable participation and leadership by Indigenous peoples and local communities is essential to these efforts, given their important and long-term role in managing biodiverse scapes and in successful conservation initiatives (*54*, *55*). Extending these conservation measures requires substantial scaling up of financial investment (*56*), connecting efforts across scapes (*57*), and seeking positive feedbacks between biodiversity conservation and social benefits and burdens (*58*).

Key ecological and social safety measures require consideration when conceiving and implementing protection and restoration programs. The mosaic scapes approach (Fig. 2) would combine protection and sustainable uses, considering human and ecosystem needs per region and ecosystem. Protection and conservation initiatives work well when they involve stakeholder engagement and support, especially at the local scale, and where recognition of values and rights and the distribution of cobenefits (and potential trade-offs and costs) are perceived as just (*2*, *26*, *39*). Involvement in and access to restored areas is critical for local communities with ecosystem-based livelihoods and can support conservation success.

Conservation and restoration activities need to be paralleled by reducing excess human consumption habits and pollution. For example, measures across sectors that reduce the demand for energy through efficiency policies can reduce current emissions by more than 50% (*59*). Sustained reductions and eventual elimination of waste and pollution can be enabled through the progressive introduction of a circular economy as part of the envisioned holistic transformation that builds on system transitions toward sustainability in land, ocean, coastal, and freshwater ecosystems; urban and rural infrastructure; energy; industry; and society (*2*, *60*). Conservation and restoration successes depend on limiting the degree of global warming, ideally to below 1.5°C (*2*).

Nature-based solutions to mitigate climate change

The protection, sustainable management, and restoration of ecosystems not only benefit biodiversity but can also aid climate change mitigation and other societal challenges (*17*, *61*). Maximizing biodiversity protection and conservation as well as contributing to climate change mitigation through nature-based solutions (with large adaptation cobenefits) entails urgently avoiding and reversing losses and degradation of ecosystems (*2*, *62*, *63*). Protection and restoration of well-connected areas are not only key strategies for halting and reversing biodiversity loss (Fig. 2) (*64*, *65*), they are also among the most rapidly implemented measures that can secure and rebuild carbon-rich ecosystems. Restoration also has long-term cobenefits—for example, water quality and poverty reduction—especially when spatial planning is optimized for such criteria (*66*). Many locations best for protecting biodiversity and nature's contributions to people are coincident with currently high carbon storage and high capacity for ongoing sequestration (*18*, *41*, *49*, *67*). Terrestrial examples include intact tropical rainforest, wetlands, peatlands, grasslands, and savannahs (*49*). In the ocean, healthy mangrove forests, salt marshes, kelp forests, and seagrass meadows are important (*41*, *67*), but so are undisturbed sediments, as well as deep water and newly colonized polar blue carbon habitats emerging from ice melt (*68*). The role, scale, and efficacy of carbon storage through nature-based solutions varies considerably with regional and local contexts (Table 1) (*23*, *69*).

Although ecosystem restoration is often more cost effective than technological mitigation measures, nature-based solutions should not be mistaken as a substitute for substantial emissions reductions from energy, transportation, agriculture, infrastructure, building, and industrial sectors (*70*). The rate at which nature-based solutions can contribute to mitigation over time is too modest compared with current emission rates (*61*, *71*). Nonetheless, because of substantial carbon storage over time (Table 1), they have an important role in long-term climate stabilization (*71*, *72*).

However, as a source of concern, the rate and effectiveness of nature-based solutions is constrained by the degree of warming. Rising temperature progressively exceeds performance optima and adaptation limits of photosynthesis and its carbon assimilation in several ecosystems (following the principles outlined in Fig. 1). Warming thus constrains the potential of nature-based solutions in terrestrial systems, exacerbated by drought (*69*, *73*–*75*), and in some ocean systems (*71*, *76*, *77*). Therefore, climate change may even turn some ecosystems from carbon sinks to carbon sources. Maintaining a high capacity of carbon storage thus depends on limiting global warming to below 1.5°C, noting that the capacity of carbon binding and storage will decline and risks to carbon stocks increase with every 0.1°C on top of current warming (*2*, *67*, *76*). Warming by 1.5°C will already weaken nature-based solutions and represents a threshold in the transition from "safe" to "dangerous" climate change (*2*, *78*). Restricting warming to 1.5°C through ambitious emissions reductions, together with reducing other and interacting pressures that drive biodiversity decline, is thus a prerequisite for the success of conservation and restoration efforts involving natural and managed ecosystems (*3*, *23*, *66*, *71*, *78*–*81*) and a guardrail for avoiding catastrophic change (*82*).

Provided emissions are successfully reduced, the effectiveness of nature-based solutions can be optimized when planned for longevity, when social equity is adequately addressed, and when solutions are not narrowly focused on rapid carbon sequestration (*83*) but also on cobenefits beyond mitigation. With careful planning and implementation, including spatial aspects and social safeguards, nature-based solutions can support multiple UN SDGs also in cities (*84*, *85*). By enhancing ecosystem adaptive capacity and resilience, they can also reduce ecosystem degradation and the associated exacerbation of climate change. Higher genetic, species, and ecosystem diversity reduces both social and ecological risks and keeps adaptation options open (*86*).

Synergies and trade-offs in climate change mitigation, adaptation, and biodiversity conservation

Biodiversity conservation and climate change mitigation actions that are well-managed and considered together tend to display more synergies than trade-offs (Fig. 3). For example, both bioenergy and reforestation projects can be implemented carefully to contribute to human development needs, alongside pronounced and rapid reductions in fossil fuel emissions (*87*, *88*). The most robust path to limiting climate change while safeguarding biodiversity depends on identifying the strongest win-win solutions by region and avoiding those with negative interactions (*89*). Management of natural or seminatural ecosystems through reintroduction of keystone species or altered wildfire frequency can strengthen biodiversity while enhancing climate mitigation and adaptation. However, although most actions to conserve biodiversity are positive or neutral for climate, some potential climate mitigation and adaptation actions will have negative effects on biodiversity unless managed well (Fig. 3). Both ecosystem protection and restoration may also interfere with food production unless carefully realized (*24*, *25*). For wetland conservation, the quantification of carbon storage and greenhouse gas flux rates is uncertain with respect to the balance between methane (CH_4) sources and CO_2 sinks (*81*, *90*), but options are available to reduce their large CH_4 emissions, such as by restoring tidal flows (*91*).

Devoting vast land areas globally to the production of biomass for bioenergy is integral to many mitigation scenarios (*49*, *78*). Yet unintended negative side effects arise from their area requirements and competition for space, especially in terrestrial ecosystems, or from afforestation of natural grasslands (*87*, *92*, *93*).

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Table 1. Examples for climate change mitigation aided through carbon uptake and storage with biodiversity cobenefits.

System and type*	Option	Mitigation potential	Biodiversity cobenefits	Data source
Forest protection	Reducing deforestation and forest degradation	0.4 to 5.8 Gt CO_2e year^{-1}	Soil and forest vegetation preserved	(*18*, *49*, *81*)
Forest restoration and reforestation	Forest expansion (for example, on less than half of degraded tropical forest area (3.69 million km^2)	1.5 to 10.1 (5.5 for tropical example by 2030) Gt CO_2e year^{-1}	Conservation of hundreds of vertebrate species	(*63*, *153*)
Land restoration	Restoring 15% of degraded land	up to 300 Gt CO_2 long term	Avoiding 60% of extinctions	(*66*)
Forest management	For example, selective logging	0.4 to 2.1 Gt CO_2e year^{-1} globally	Improved regeneration, protected forest soils	(*49*)
Agroforestry	Strengthening resilience, reducing soil tillage, and maintaining plant cover	0.1 to 5.7 Gt CO_2e year^{-1}	Resilience building, healthy soils	(*154*, *155*)
Peatland restoration	Protecting and growing carbon stores	0.15 to 0.81 Gt CO_2e year^{-1} up to 2050	Distinct biodiversity regained	(*81*, *156*, *157*)
Grassland and savannah restoration and management	Restoration of degraded grassland, rotational and light grazing	Reducing wildfires, strengthens soil carbon, 2.3 to 8 Gt CO_2e year^{-1}	Protection of megafauna, increase of grass-species and soil biodiversity	(*16*, *158*, *159*)
Total land management	Sustainably managed lands†	≈5 Gt CO_2e year^{-1} or higher by 2030	Global-scale synergies	(*18*)
Urban management	Green and blue spaces	Small contribution	Biodiversity refugia in cities	(*48*, *160*)
Marine protection	Blue carbon habitats (coastal marine)§	0.14 to 0.46 Gt CO_2e year^{-1}	Avoidance of coastal habitat loss	(*41*)
Marine restoration	Blue carbon habitats (coastal marine)§	0.62 to 1.06 Gt CO_2e year^{-1}	Expansion of coastal habitat	(*41*)
Protection of sediments and rebuilding marine species stocks	Protecting large sediment carbon stores, carbon export by abundant species stocks plankton to whales	Strengthening natural pathways of carbon export, large long-term potential	Restoring natural species stocks, enhanced nutrient cycling	(*23*, *161*, *162*)
Expanding ecosystems	High latitude retreat of ice opens new habitat	New biomass through colonization	Expansion of natural coastal habitat	(*71*, *163*)
Sustainably managed cultures	Seaweed use and farming	≈1500 tons CO_2e km^{-2} year^{-1}, up to 0.24 Gt CO_2e year^{-1} by 2050	Creating protected habitat	(*164*, *165*)

*Four types of nature-based solutions: (i) protection, (ii) restoration, (iii) management, or (iv) expansion of ecosystems in and around cities or across the wider landscape. †Release of methane can offset carbon sequestration. ‡Emissions reductions supported by plant-based human diets and reduced methane emissions from livestock, such as by adding farmed red seaweed to ruminant diets, and from rice paddies and reduced nitrous oxide (N_2O) from fertilizer application (*49*, *81*, *164*, *166*). §Blue carbon encompasses all biologically driven carbon fluxes and storage in marine systems that are amenable to management (*167*).

Projected CO_2 uptake rates through bioenergy or monoculture forest regrowth by 2050, which are similar in magnitude to double today's existing terrestrial carbon sink (*49*, *94*), are unrealistic. Further, relying on tree biomass for long-term carbon sequestration is risky, particularly in monocultures with high vulnerability to heat, drought, storms, fire, or pest outbreak (*95*). Trade-offs of bioenergy crops or afforestation at large scales by using monoculture or nonindigenous species (*96*) cause displacement of other land uses locally or elsewhere. Associated risks include carbon and biodiversity losses, negative impacts on food security, as well as dispossession of local access to land and to a wide range of NCP (*97*–*101*).

Deployment of renewable energy infrastructure can substantially contribute to mitigation, but hydropower, solar and wind energy, and storage for these intermittent sources of energy can also have negative impacts on biodiversity if their scale and design are not carefully implemented (*102*). For example, nearly 4000 major dam projects are currently underway or planned for energy production, irrigation, or flood control (*103*), but large dams generally have detrimental impacts on freshwater biodiversity (*104*) unless reduced through sustainable management (*105*). Likewise, the negative impacts of wind turbines on bats and birds, and of solar energy on the terrestrial or aquatic areas they cover, can be reduced through careful placement and operation (*106*, *107*). Technological mitigation measures can also exert harm to the environment and to biodiversity through the vast amount of materials required, such as metals or toxic waste products (*108*), which argues for strong environmental and social sustainability criteria. As one safe alternative, placing solar panels on half of the world's roofs could meet humankind's entire (as of 2018) electricity demand (*109*). Expanding circular economies will reduce the net use of materials, enable reuse, and avoid waste (*110*). Enhanced energy savings and efficiency also reduce the extent to which infrastructure needs to be deployed.

Climate adaptation policies can also incur large biodiversity impacts. For example, building sea walls to limit impacts of sea level rise on coastal infrastructure, adding irrigation capacity to reduce climate change impacts on agriculture, or introducing exotic tree species in anticipation of increasing climatic stress on forests impose substantial risks of large aggregate losses of biodiversity from these actions (*86*, *111*). As such, there is an urgent need

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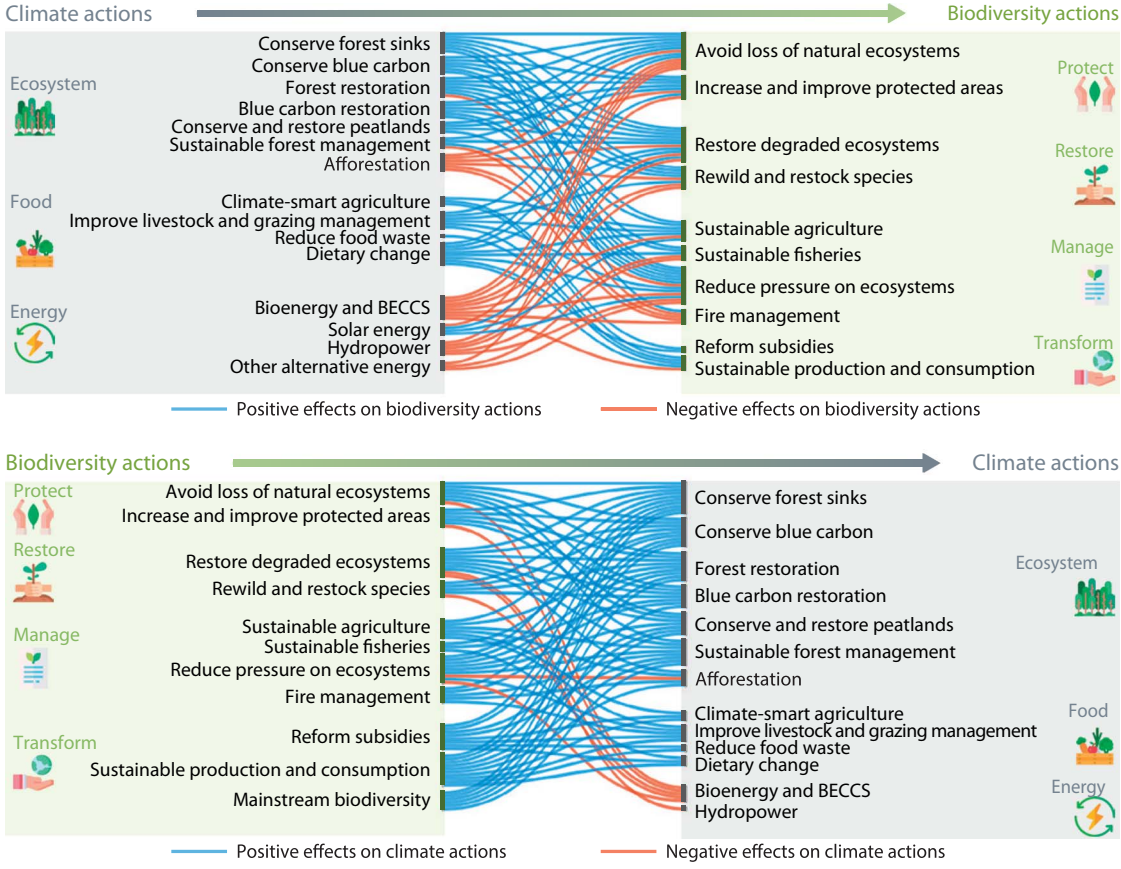


Fig. 3. Positive and negative effects (Top) of actions to mitigate climate change on actions to reduce biodiversity loss and (Bottom) of actions reducing biodiversity loss on those mitigating climate change. Orange lines indicate potential negative effects, and blue lines indicate potential positive effects. Interactions may shift over time and may surpass thresholds that trigger unforeseen consequences, positive or negative [after (*18*)].

to assess the cumulative impacts of these adaptation (and maladaptation) measures on biodiversity, evaluate more positive alternatives (for example, those that rely on nature-based solutions), and plan deployment with biodiversity impacts explicitly accounted for (*2*, *86*).

In both land and ocean systems, options exist to manage trade-offs by combining nature-based solutions and technology-based measures for climate change mitigation and adaptation, while sustaining biodiversity (*112*). For example, solar panel fields integrated with cropping or grazing systems can create multiple benefits: Grazing underneath solar panels can enhance soil carbon, and positive spillover effects into neighboring fields have been observed when habitat for pollinators is created underneath solar panels (*108*). Solar power generation on land is more efficient on an area basis than production of bioenergy crops and could thus contribute to reducing competition for land (*113*). Photovoltaic cells on the surface of water bodies can reduce evaporation, which could be beneficial to hydroelectric reservoirs in arid regions, considering that floating photovoltaics may also affect the water body's physical, chemical, and biological properties, particularly air exchange and thus oxygen supply (*114*). Offshore wind in combination with hydrogen generation can be powerful for both mitigation and biodiversity conservation if negative impacts on mobile species (such as birds) can be minimized (*115*); offshore turbines can create artificial substrate, with beneficial effects on marine biodiversity (*106*).

Implementing a nexus approach

Lack of appropriate governance mechanisms to anticipate and address the nexus between climate, biodiversity, and society can lead to the surpassing of biodiversity and climate tipping points with dire consequences for nature and society (*2*, *71*, *78*, *81*). Cascading effects, such as from melting of the polar ice sheets or forest dieback, can lead to breaching of socially acceptable limits and thresholds, especially regarding already vulnerable and marginalized societies (*116*). For example, reduced stability of crop yields may trigger food crises and subsequently lead to political instability, mass migration, and other crises (*2*, *81*). The uncertainty in the projections of tipping point timing and locations suggests that the best approach to avoid them is to stay far away from even the lowest thresholds that would trigger irreversible change (*117*) and implement quantified safety margins toward "safe and just" futures (*118*). These considerations emphasize the need for rapid progress in emissions reductions and biodiversity protection (*2*), paralleled by rapid transformative action in all systems (*2*).

Given the complexity of the nexus, there is thus a need for effective governance approaches that are appropriate for implementing and meeting protection and restoration goals, including multifunctional land, freshwater, and ocean scapes and providing equitable benefits that avoid trade-offs (*18*, *119*). This requires a "nexus approach" to governance, which at a minimum would involve mainstreaming of biodiversity into climate policy and vice versa, and of both into initiatives to advance human development and good quality of life. Such an approach would also benefit from socioecological systems perspectives, which identify interacting subsystems involving resources, users, and governance at multiple scales. Three key insights should inform related decisions and their implementation: first, all climate-biodiversity interactions have social considerations, with implications for both intra- and intergenerational equity and justice (*120*); second, telecoupling challenges abound, in which

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off-stage effects also manifest far from the location of the intervention on different time scales (*46*, *121*); and third, trade-offs and feedbacks among system components, as well as threshold effects and nonlinear outcomes for biodiversity, climate, and societal relationships are the norm rather than the exception (*119*).

Taking a nexus approach can help guide policy interventions that have the potential to generate double or triple wins and avoid unintended consequences while facilitating more deep and rapid transformative change (*119*, *122*). Assessing the range of viable solutions requires recognition of differences in both environmental conditions and social and cultural situations and their vulnerabilities. For example, when defining suitable conditions for human society, ecosystems, their biodiversity, and the planet, the interrelationships between systems and between human, ecosystem, and planetary health need to be considered (*2*). Shifts in planetary functioning due to climate change (for example, responses of ocean currents and atmospheric streams) influence regional and local climate regimes, which in turn set environmental conditions for human well-being as well as ecosystem functioning, on which human health and well-being depends (*118*). Cascading unfavorable outcomes (such as habitat loss) can affect all levels and systems (species, ecosystems, and humans), requiring in turn multiscalar action (*2*).

Just as environmental characteristics differ from place to place and requirements for biodiversity differ across biomes, motivations, interests, preferences, and values embedded in institutions, societies, and cultures are also highly diverse (*58*, *123*). Biodiversity conservation interventions that take into account this diversity, such as those that deliberately include Indigenous peoples and local communities, have better outcomes on both human well-being and biological indicators (*54*). This observation calls for robust and transparent governance mechanisms aimed at inclusion that are able to overcome unequal power relations among stakeholders. A shift toward coordinated bottom-up pathways may enable both the local granularity and the global coherence needed to address nexus challenges across scales (*37*, *48*, *124*). Thus, it is crucial to identify interventions that are universal in terms of intent but sufficiently flexible and adaptive to different socioecological contexts, including historically and culturally embedded institutional and political governance structures (*125*, *126*). Some promising governance initiatives are already emerging, including jurisdictional approaches, experimental policy mixes, and rights-based approaches (*127*, *128*).

These approaches often stress the need for integrated and multifunctional interventions from toolboxes of adaptive solutions instead of single silver bullets. More innovative and flexible governance approaches can also give room to local autonomy to choose between alternative pathways to transformative change (*129*). Yet there is currently insufficient cross-sectoral policy coherence and integration, as seen in separate UN conventions such as UNFCCC and CBD, which often debate the interests of national governments who in turn have their own siloed approaches. Overall, although integrated solutions for the nexus exist that have cobenefits in terms of sustainable development and meeting basic needs of the poor and vulnerable (*130*), designing and financing these approaches faces numerous barriers because they require the cooperation of multiple actors across scales (*119*, *129*, *131*).

Enabling urgent action for transformative change

Limiting warming to 1.5°C or even to below 2°C and halting biodiversity loss require rapid action, which entails transformative change through transformative governance. This includes drawing on collaborative solutions across integrated systems, involves a broad range of actors and diversity of values about nature, engages different knowledge systems through more equitable approaches, and adaptively manages complex interactions (*119*, *132*, *133*). Transformative change implies deep shifts away from current ways of governing and decision-making that are often made on the basis of single-issue, short-term priorities. For example, current pledges of net zero emissions by companies and countries run the risk of exacerbating inequitable outcomes if they push nature-based solutions that are inappropriate (such as tree planting in natural grasslands), have few social benefits or increase vulnerability, or fail to be accompanied by simultaneous fossil fuel emissions reductions (*61*). Previous experiences from REDD+ programs (set up by UNFCCC to initiate "reduced emissions from deforestation and degradation" of forests) show that interventions need to be codesigned across stakeholders to create fair compensation mechanisms for equitable distribution of benefits and costs and to avoid risks to the most vulnerable, otherwise the effectiveness can be compromised (*21*, *49*).

Part of the move to transformative governance entails better harnessing of positive social tipping points that, when reached and exceeded, can accelerate transformative change toward desirable biodiversity-climate interactions and help navigate through strong and often unavoidable trade-offs within the nexus (Fig. 4) (*134*). Social tipping dynamics require synergizing technological, political, and behavioral processes toward structural reorganization, leading to targeted and "contagious" interventions with positive impacts on climate, biodiversity and human well-being (*116*, *135*). Such interventions depend on social contexts, cultural or behavioral specificities, and political as well as institutional systems (such as norms and regulations) (*119*). Ideally, goals for social tipping points should focus on structural reorganization through targeted interventions across institutions, technology, and behavior with positive impacts on climate, biodiversity, and human well-being (*116*, *135*). Some examples include the spread of carbon-neutrality pledges across businesses and cities, rapid adoption of new technologies such as electric vehicles, or the strengthening of climate and biodiversity education and civil society engagement (*119*, *136*–*138*). Because the locations of tipping points are moving targets, owing partly to the interconnectedness of the climate-biodiversity-social system, social tipping interventions need to be flexible and adaptive (*119*, *134*). Activating such social tipping interventions necessarily involves a shift of individual and collectively shared social values away from individualism and materialism to principles such as responsibility, stewardship, and justice (*59*, *123*). Such shifts in values will require structural actions as well, such as eliminating subsidies that presently support fossil fuel uses (*139*) or activities that harm biodiversity such as deforestation (*140*–*142*) or overfishing (*143*); such subsidies currently prevent the take-off of alternative approaches and technologies that would immediately aid climate change mitigation by avoiding further emissions. Transformative governance would also entail creating coalitions of support to confront recalcitrant and powerful interest groups (such as economic actors benefiting from fossil fuel subsidies) whose goal is keeping economic privileges and the political status quo and who lobby against transformative agendas (*144*).

Transformative change requires the use of levers and decision points that have the potential to alter future social-ecological trajectories (Fig. 4) (*59*). "Deep" leverage points (decision points that are harder to act on but have stronger potential effects) include moving away from valuing nature in narrow (market-based instrumental) ways and exploring alternative collective visions of development and good quality of life, while empowering individuals to enhance a sense of collective responsibility, especially toward more vulnerable natural systems and people (*123*). Interventions that activate deep leverage points could include (i) reconceptualizing economic development away from aggregate value of market flows (such as gross domestic product) to others that recognize a more inclusive understanding of changes in wealth (*145*) as well as the multiple values of nature (*123*) for a good quality of life within climate, biodiversity, and social limits; (ii) establishing deliberative governance instruments to empower civil society to take decisions by emphasizing their role as citizens as opposed to consumers (*123*, *146*); and (iii) recognition of Indigenous peoples' and community conserved

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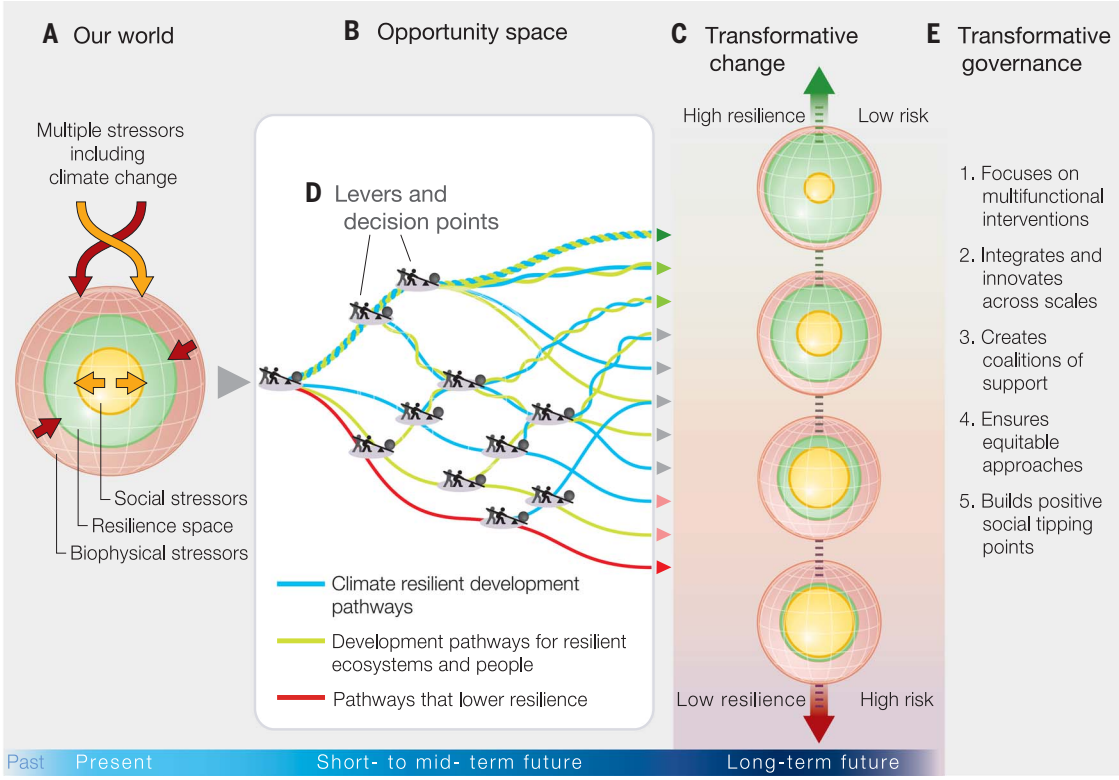


Fig. 4. Biodiversity-climate interactions in social-ecological systems with an explicit depiction of resilience outcomes for alternative pathways. (**A**) Alternative pathways start from the present world and cross the opportunity space (**B**), reaching different levels of resilience depending on the success of transformative change (**C**). It is assumed that high resilience for biodiversity and ecosystems and human society is paralleled by low risk as a condition for social stability and human well-being. (**D**) Decision points reached over time and associated levers relating to governance and policy interventions have the potential to keep the system on desired trajectories toward cobenefits and high resilience. (**E**) These transitions are enabled by transformative governance that triggers adaptive and inclusive decision-making at relevant time points, including positive social tipping interventions that can help shift toward positive biodiversity-climate interactions and associated social outcomes (*2*). [Figure adapted from (*152*).]

territories and areas, initiated, designed, and governed by local communities, along with full development of "other effective area-based conservation measures" (*147*) that can lead to the conservation of natural and modified ecosystems and their biodiversity and associated benefits, including climate benefits (*69*).

Conclusions

Achieving the scale and scope of transformative change needed to concurrently meet the goals of the UNFCCC, the CBD, and the UN Agenda 2030 and its SDGs will rely on far-reaching mobilization and transformation actions of a type never before attempted, within a rapidly closing time window as required to keep global warming below 1.5°C and to secure a livable future (*2*). Healthy ecosystems and a healthy planet are preconditions for flourishing life on Earth. Strengthening biodiversity in all systems will also support long-term climate stabilization. Securing human, ecosystem, and planetary health and societal well-being is facilitated through implementation of multifunctional connected scapes and other integrated actions across the climate-biodiversity nexus, building on an analysis of critical assets (*148*) and their protection and expansion through restoration. Securing a livable future will require rapid action and commitment not only from countries through actions in their national territories but also from emergent coalitions and governance models at all levels. Addressing conventions in concert with one another, such as the Paris Agreement of the UNFCCC (alongside SDG 13) and the Kunming-Montreal Global Biodiversity Framework (together with SDGs 14 and 15), will put society on the pathway to a positive vision of good quality of life in harmony with nature (*37*). Engaging in deeper transformative change will require effective incentives and social tipping points, capacity building with broad education and outreach initiatives, institutional change and improved cooperation across sectors and jurisdictions, and shifts in values to support intergenerational justice as well as equity more broadly. This vision of inclusive, integrative, and adaptive decision-making can overcome societal and political inertia (*2*, *3*) and thereby help society to avoid crossing biophysical tipping points and their worst impacts, as well as help build a more just and sustainable world (*2*).

REFERENCES AND NOTES

1. S. Díaz *et al.*, Assessing nature's contributions to people. *Science* **359**, 270–272 (2018). doi: 10.1126/science.aap8826; pmid: 29348221
2. Intergovernmental Panel on Climate Change, "Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" in, H.-O. Pörtner *et al.*, Eds. (Cambridge Univ. Press., 2022), p. 3056.
3. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), "Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services," E. S. Brondizio, J. Settele, S. Díaz, H. T. Ngo, Eds. (IPBES, 2019); https://doi.org/10.5281/zenodo.3831674.
4. Intergovernmental Panel on Climate Change, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," V. Masson-Delmotte *et al.*, Eds. (Cambridge Univ. Press, 2021).
5. J. E. M. Watson *et al.*, Protect the last of the wild. *Nature* **563**, 27–30 (2018). doi: 10.1038/d41586-018-07183-6; pmid: 30382225
6. Y. M. Bar-On, R. Phillips, R. Milo, The biomass distribution on Earth. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 6506–6511 (2018). doi: 10.1073/pnas.1711842115; pmid: 29784790
7. S. Díaz *et al.*, Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **366**, eaax3100 (2019). doi: 10.1126/science.aax3100; pmid: 31831642
8. H. O. Pörtner *et al.*, Ocean systems in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth*

Downloaded from https://www.science.org at University of Nevada Reno on September 26, 2026

Assessment Report of the Intergovernmental Panel on Climate Change, C. B. Field *et al*., Eds. (Cambridge Univ. Press, 2014), pp. 411–484; https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap6_FINAL.pdf.
9. R. Warren, J. Price, E. Graham, N. Forstenhaeusler, J. VanDerWal, The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science* **360**, 791–795 (2018). doi: 10.1126/science.aar3646; pmid: 29773751
10. J. García Molinos *et al*., Climate velocity and the future global redistribution of marine biodiversity. *Nat. Clim. Chang.* **6**, 83–88 (2016). doi: 10.1038/nclimate2769
11. D. F. Zhao *et al*., Environmental conditions regulate the impact of plants on cloud formation. *Nat. Commun.* **8**, 14067 (2017). doi: 10.1038/ncomms14067; pmid: 28218253
12. S. Chen *et al*., Plant diversity enhances productivity and soil carbon storage. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 4027–4032 (2018). doi: 10.1073/pnas.1700298114; pmid: 29666315
13. S. Wang, M. Maltrud, S. Elliott, P. Cameron-Smith, A. Jonko, Influence of dimethyl sulfide on the carbon cycle and biological production. *Biogeochemistry* **138**, 49–68 (2018). doi: 10.1007/s10533-018-0430-5
14. T. W. Crowther *et al*., The global soil community and its influence on biogeochemistry. *Science* **365**, eaav0550 (2019). doi: 10.1126/science.aav0550; pmid: 31439761
15. S. Xu *et al*., Species richness promotes ecosystem carbon storage: Evidence from biodiversity-ecosystem functioning experiments. *Proc. Biol. Sci.* **287**, 20202063 (2020). doi: 10.1098/rspb.2020.2063; pmid: 33234078
16. O. J. Schmitz *et al*., Animals and the zoogeochemistry of the carbon cycle. *Science* **362**, eaar3213 (2018). doi: 10.1126/science.aar3213; pmid: 30523083
17. E. Cohen-Shacham, C. Janzen, S. Maginnis, G. Walters, *Nature-Based Solutions to Address Global Societal Challenges* (IUCN, 2016); https://portals.iucn.org/library/node/46191.
18. H.-O. Pörtner *et al*., "Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change" (IPBES Secretariat, 2021); doi: 10.5281/zenodo.5031995.
19. UK Government, "Policy paper – World leaders summit on 'Action on forests and land use'" (2021); https://www.gov.uk/government/publications/cop26-world-leaders-summit-on-action-on-forests-and-land-use-2-november-2021/world-leaders-summit-on-action-on-forests-and-land-use.
20. E. Wilson, *Half-Earth: Our Planet's Fight for Life* (Liveright, 2016).
21. E. Dinerstein *et al*., An ecoregion-based approach to protecting half the terrestrial realm. *Bioscience* **67**, 534–545 (2017). doi: 10.1093/biosci/bix014; pmid: 28608869
22. J. E. M. Watson *et al*., Set a global target for ecosystems. *Nature* **578**, 360–362 (2020). doi: 10.1038/d41586-020-00446-1; pmid: 32071453
23. E. Sala *et al*., Protecting the global ocean for biodiversity, food and climate. *Nature* **592**, 397–402 (2021). doi: 10.1038/s41586-021-03371-z; pmid: 33731930
24. Z. Mehrabi, E. C. Ellis, N. Ramankutty, The challenge of feeding the world while conserving half the planet. *Nat. Sustain.* **1**, 409–412 (2018). doi: 10.1038/s41893-018-0119-8
25. J. Schleicher *et al*., Protecting half of the planet could directly affect over one billion people. *Nat. Sustain.* **2**, 1094–1096 (2019). doi: 10.1038/s41893-019-0423-y
26. N. Zafra-Calvo *et al*., Progress toward equitably managed protected areas in Aichi Target 11: A global survey. *Bioscience* **69**, 191–197 (2019). doi: 10.1093/biosci/biy143; pmid: 30914829
27. C. A. Soto-Navarro *et al*., Towards a multidimensional biodiversity index for national application. *Nat. Sustain.* **4**, 933–942 (2021). doi: 10.1038/s41893-021-00753-z
28. S. Díaz *et al*., Set ambitious goals for biodiversity and sustainability. *Science* **370**, 411–413 (2020). doi: 10.1126/science.abe1530; pmid: 33093100
29. D. M. Lapola *et al*., Pervasive transition of the Brazilian land-use system. *Nat. Clim. Chang.* **4**, 27–35 (2014). doi: 10.1038/nclimate2056
30. T. E. Lovejoy, C. Nobre, Amazon tipping point. *Sci. Adv.* **4**, eaat2340 (2018). doi: 10.1126/sciadv.aat2340; pmid: 29492460
31. O. L. Phillips, R. J. W. Brienen; RAINFOR collaboration, Carbon uptake by mature Amazon forests has mitigated Amazon nations' carbon emissions. *Carbon Balance Manag.* **12**, 1 (2017). doi: 10.1186/s13021-016-0069-2; pmid: 28413845
32. A. Antonelli *et al*., Amazonia is the primary source of Neotropical biodiversity. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 6034–6039 (2018). doi: 10.1073/pnas.1713819115; pmid: 29760058
33. IPBES, "Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)," in P. Daszak *et al*., Eds. (IPBES Secretariat, 2020; doi: 10.5281/zenodo.4147317.
34. A. L. Val, Biodiversity—The hidden risks. *An. Acad. Bras. Cienc.* **92**, e20200699 (2020). doi: 10.1590/0001-3765202020200699; pmid: 32428091
35. R. K. F. Unsworth, L. M. Nordlund, L. C. Cullen-Unsworth, Seagrass meadows support global fisheries production. *Conserv. Lett.* **12**, e12566 (2019). doi: 10.1111/conl.12566
36. F. A. Ascioti, M. C. Mangano, C. Marcianò, G. Sarà, The sanitation service of seagrasses – Dependencies and implications for the estimation of avoided costs. *Ecosyst. Serv.* **54**, 101418 (2022). doi: 10.1016/j.ecoser.2022.101418
37. D. O. Obura, Getting to 2030—Scaling effort to ambition through a narrative model of the SDGs. *Mar. Policy* **117**, 103973 (2020). doi: 10.1016/j.marpol.2020.103973
38. G. G. Gurney, S. Mangubhai, M. Fox, M. Kiatkoski Kim, A. Agrawal, Equity in environmental governance: Perceived fairness of distributional justice principles in marine co-management. *Environ. Sci. Policy* **124**, 23–32 (2021). doi: 10.1016/j.envsci.2021.05.022
39. H. D. Jonas *et al*., Equitable and effective area-based conservation: Towards the conserved areas paradigm. *Parks* **27**, 71–84 (2021). doi: 10.2305/IUCN.CH.2021.PARKS-27-1HJ.en
40. R. Chaplin-Kramer *et al*., Global modeling of nature's contributions to people. *Science* **366**, 255–258 (2019). doi: 10.1126/science.aaw3372; pmid: 31601772
41. P. I. Macreadie *et al*., Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* **2**, 826–839 (2021). doi: 10.1038/s43017-021-00224-1
42. Secretariat of the Convention on Biological Diversity, "Global Biodiversity Outlook 5" (SCBD, Montreal, Canada, 2020).
43. R. E. Golden Kroner *et al*., The uncertain future of protected lands and waters. *Science* **364**, 881–886 (2019). doi: 10.1126/science.aau5525; pmid: 31147519
44. J. P. G. Jones *et al*., Net gain: Seeking better outcomes for local people when mitigating biodiversity loss from development. *One Earth* **1**, 195–201 (2019). doi: 10.1016/j.oneear.2019.09.007
45. J. T. Erbaugh, J. A. Oldekop, Forest landscape restoration for livelihoods and well-being. *Curr. Opin. Environ. Sustain.* **32**, 76–83 (2018). doi: 10.1016/j.cosust.2018.05.007
46. U. Pascual *et al*., Off-stage ecosystem service burdens: A blind spot for global sustainability. *Environ. Res. Lett.* **12**, 075001 (2017). doi: 10.1088/1748-9326/aa7392
47. H. Locke *et al*., Three global conditions for biodiversity conservation and sustainable use: An implementation framework. *Natl. Sci. Rev.* **6**, 1080–1082 (2019). doi: 10.1093/nsr/nwz136; pmid: 34691979
48. D. O. Obura *et al*., Integrate biodiversity targets from local to global levels. *Science* **373**, 746–748 (2021). doi: 10.1126/science.abh2234; pmid: 34385386
49. P. Smith *et al*., Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Glob. Chang. Biol.* **26**, 1532–1575 (2020). doi: 10.1111/gcb.14878; pmid: 31637793
50. FAO, *The State of the World's Biodiversity for Food and Agriculture* (FAO Commission on Genetic Resources for Food and Agriculture Assessments, 2019); http://www.fao.org/3/CA3129EN/CA3129EN.pdf.
51. W. R. L. Anderegg *et al*., Hydraulic diversity of forests regulates ecosystem resilience during drought. *Nature* **561**, 538–541 (2018). doi: 10.1038/s41586-018-0539-7; pmid: 30232452
52. F. Bussotti, M. Pollastrini, V. Holland, W. Brüggemann, Functional traits and adaptive capacity of European forests to climate change. *Environ. Exp. Bot.* **111**, 91–113 (2015). doi: 10.1016/j.envexpbot.2014.11.006
53. K. Carlisle, R. L. Gruby, Polycentric systems of governance: A theoretical model for the commons. *Policy Stud. J.* **47**, 927–952 (2019). doi: 10.1111/psj.12212
54. N. M. Dawson *et al*., The role of Indigenous peoples and local communities in effective and equitable conservation. *Ecol. Soc.* **26**, art19 (2021). doi: 10.5751/ES-12625-260319
55. S. T. Garnett *et al*., A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.* **1**, 369–374 (2018). doi: 10.1038/s41893-018-0100-6
56. A. Seidl, K. Mulungu, M. Arlaud, O. van den Heuvel, M. Riva, The effectiveness of national biodiversity investments to protect the wealth of nature. *Nat. Ecol. Evol.* **5**, 530–539 (2021). doi: 10.1038/s41559-020-01372-1; pmid: 33462490
57. M. Ward *et al*., Just ten percent of the global terrestrial protected area network is structurally connected via intact land. *Nat. Commun.* **11**, 4563 (2020). doi: 10.1038/s41467-020-18457-x; pmid: 32917882
58. U. Pascual *et al*., Biodiversity and the challenge of pluralism. *Nat. Sustain.* **4**, 567–572 (2021). doi: 10.1038/s41893-021-00694-7
59. K. M. A. Chan *et al*., Levers and leverage points for pathways to sustainability. *People Nat.* **2**, 693–717 (2020). doi: 10.1002/pan3.10124
60. E. H. Arruda, R. A. P. B. Melatto, W. Levy, D. de Melo Conti, Circular economy: A brief literature review (2015–2020). *Sustain. Oper. Comput.* **2**, 79–86 (2021). doi: 10.1016/j.susoc.2021.05.001
61. N. Seddon, Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science* **376**, 1410–1416 (2022). doi: 10.1126/science.abn9668; pmid: 35737796
62. P. Smith *et al*., How do we best synergize climate mitigation actions to co-benefit biodiversity? *Glob. Chang. Biol.* **28**, 2555–2577 (2022). doi: 10.1111/gcb.16056; pmid: 34951743
63. Y.-J. Shin *et al*., Actions to halt biodiversity loss generally benefit the climate. *Glob. Chang. Biol.* **28**, 2846–2874 (2022). doi: 10.1111/gcb.16109; pmid: 35098619
64. R. A. Magris *et al*., Biologically representative and well-connected marine reserves enhance biodiversity persistence in conservation planning. *Conserv. Lett.* **11**, e12439 (2018). doi: 10.1111/conl.12439
65. S. L. Maxwell *et al*., Area-based conservation in the twenty-first century. *Nature* **586**, 217–227 (2020). doi: 10.1038/s41586-020-2773-z; pmid: 33028996
66. B. B. N. Strassburg *et al*., Global priority areas for ecosystem restoration. *Nature* **586**, 724–729 (2020). doi: 10.1038/s41586-020-2784-9; pmid: 33057198
67. O. Hoegh-Guldberg *et al*., The human imperative of stabilizing global climate change at 1.5°C. *Science* **365**, eaaw6974 (2019). doi: 10.1126/science.aaw6974; pmid: 31604209
68. N. Bax *et al*., Perspective: Increasing blue carbon around Antarctica is an ecosystem service of considerable societal and economic value worth protecting. *Glob. Chang. Biol.* **27**, 5–12 (2021). doi: 10.1111/gcb.15392; pmid: 33064891
69. M. L. Noon *et al*., Mapping the irrecoverable carbon in Earth's ecosystems. *Nat. Sustain.* **5**, 37–46 (2021). doi: 10.1038/s41893-021-00803-6
70. N. Seddon *et al*., Getting the message right on nature-based solutions to climate change. *Glob. Chang. Biol.* **27**, 1518–1546 (2021). doi: 10.1111/gcb.15513; pmid: 33522071
71. Intergovernmental Panel on Climate Change (IPCC), "IPCC Special Report on the Ocean and Cryosphere in a Changing Climate," H. O. Pörtner *et al*., Eds. (Cambridge Univ. Press, 2019). doi: 10.1017/9781009157964
72. German Advisory Council on Global Change (WBGU), "Beyond Climate Neutrality. Policy Paper 12," policy paper (WBGU, 2021); https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/politikpapiere/pp12_2021/pdf_und_ebook/wbgu_pp12_navi_en.pdf.
73. K. A. Duffy *et al*., How close are we to the temperature tipping point of the terrestrial biosphere? *Sci. Adv.* **7**, eaay1052 (2021). doi: 10.1126/sciadv.aay1052; pmid: 33523891
74. D. Gampe *et al*., Increasing impact of warm droughts on northern ecosystem productivity over recent decades. *Nat. Clim. Chang.* **11**, 772–779 (2021). doi: 10.1038/s41558-021-01112-8
75. L. V. Gatti *et al*., Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021). doi: 10.1038/s41586-021-03629-6; pmid: 34262208
76. H.-G. Hoppe, K. Gocke, R. Koppe, C. Begler, Bacterial growth and primary production along a north-south transect of the Atlantic Ocean. *Nature* **416**, 168–171 (2002). doi: 10.1038/416168a; pmid: 11894092
77. L. Kwiatkowski *et al*., Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences* **17**, 3439–3470 (2020). doi: 10.5194/bg-17-3439-2020
78. Intergovernmental Panel on Climate Change, "Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty", V. Masson-Delmotte *et al*., Eds. (Cambridge Univ. Press, 2018). doi: 10.1017/9781009157940

Downloaded from https://www.science.org at University of Nevada Reno on September 26, 2026

79. M. Jung *et al*., Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nat. Ecol. Evol.* **5**, 1499–1509 (2021). doi: 10.1038/s41559-021-01528-7; pmid: 34429536
80. D. Leclère *et al*., Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020). doi: 10.1038/s41586-020-2705-y; pmid: 32908312
81. Intergovernmental Panel on Climate Change, "Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems", P. R. Shukla *et al*., Eds. (Cambridge Univ. Press, 2019). doi: 10.1017/9781009157988
82. L. Kemp *et al*., Climate Endgame: Exploring catastrophic climate change scenarios. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2108146119 (2022). doi: 10.1073/pnas.2108146119; pmid: 35914185
83. C. A. J. Girardin *et al*., Nature-based solutions can help cool the planet - if we act now. *Nature* **593**, 191–194 (2021). doi: 10.1038/d41586-021-01241-2; pmid: 33981055
84. I. Palomo *et al*., Assessing nature-based solutions for transformative change. *One Earth* **4**, 730–741 (2021). doi: 10.1016/j.oneear.2021.04.013
85. S. Goodwin, M. Olazabal, A. J. Castro, U. Pascual, Global mapping of urban nature-based solutions for climate change adaptation. *Nat. Sustain.* (2023). doi: 10.1038/s41893-022-01036-x
86. M. D. Morecroft *et al*., Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science* **366**, eaaw9256 (2019). doi: 10.1126/science.aaw9256; pmid: 31831643
87. S. Fuss *et al*., Negative emissions-Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018). doi: 10.1088/1748-9326/aabf9f
88. S. Roe *et al*., Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang.* **9**, 817–828 (2019). doi: 10.1038/s41558-019-0591-9
89. P. McElwee *et al*., The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. *Glob. Chang. Biol.* **26**, 4691–4721 (2020). doi: 10.1111/gcb.15219; pmid: 32531815
90. T. Spencer *et al*., Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. *Global Planet. Change* **139**, 15–30 (2016). doi: 10.1016/j.gloplacha.2015.12.018
91. J. A. Rosentreter *et al*., Half of global methane emissions come from highly variable aquatic ecosystem sources. *Nat. Geosci.* **14**, 225–230 (2021). doi: 10.1038/s41561-021-00715-2
92. R. C. R. Abreu *et al*., The biodiversity cost of carbon sequestration in tropical savanna. *Sci. Adv.* **3**, e1701284 (2017). doi: 10.1126/sciadv.1701284; pmid: 28875172
93. K. D. Holl, P. H. S. Brancalion, Tree planting is not a simple solution. *Science* **368**, 580–581 (2020). doi: 10.1126/science.aba8232; pmid: 32381704
94. J. Rogelj *et al*., Scenarios towards limiting global mean temperature increase below 1.5°C. *Nat. Clim. Chang.* **8**, 325–332 (2018). doi: 10.1038/s41558-018-0091-3
95. W. R. L. Anderegg *et al*., Climate-driven risks to the climate mitigation potential of forests. *Science* **368**, eaaz7005 (2020). doi: 10.1126/science.aaz7005; pmid: 32554569
96. S. Lewis, C. Wheeler, E. Mitchard, A. Koch, Restoring natural forests is the best way to remove atmospheric carbon. *Nature* **568**, 25–28 (2019). doi: 10.1038/d41586-019-01026-8; pmid: 30940972
97. K. Dooley, S. Kartha, Land-based negative emissions: Risks for climate mitigation and impacts on sustainable development. *Int. Environ. Agreement Polit. Law Econ.* **18**, 79–98 (2018). doi: 10.1007/s10784-017-9382-9
98. F. Humpenöder *et al*., Large-scale bioenergy production: How to resolve sustainability trade-offs? *Environ. Res. Lett.* **13**, 024011 (2018). doi: 10.1088/1748-9326/aa9e3b
99. A. Arneth *et al*., "Chapter 1: Framing and Context" in *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, P. R. Shukla *et al*., Eds. (IPCC, 2019); https://www.ipcc.ch/site/assets/uploads/sites/4/2019/12/04_Chapter-1.pdf.
100. O. Reisman-Berman, T. Keasar, N. Tel-Zur, Native and non-native species for dryland afforestation: Bridging ecosystem integrity and livelihood support. *Ann. For. Sci.* **76**, 114 (2019). doi: 10.1007/s13595-019-0903-2
101. B. A. Polidoro *et al*., The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLOS ONE* **5**, e10095 (2010). doi: 10.1371/journal.pone.0010095; pmid: 20386710
102. J. M. Pérez-García *et al*., Priority areas for conservation alone are not a good proxy for predicting the impact of renewable energy expansion. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2204505119 (2022). doi: 10.1073/pnas.2204505119; pmid: 35878057
103. J. Boulange, N. Hanasaki, D. Yamazaki, Y. Pokhrel, Role of dams in reducing global flood exposure under climate change. *Nat. Commun.* **12**, 417 (2021). doi: 10.1038/s41467-020-20704-0; pmid: 33462241
104. H. Wu *et al*., Effects of dam construction on biodiversity: A review. *J. Clean. Prod.* **221**, 480–489 (2019). doi: 10.1016/j.jclepro.2019.03.001
105. J. Best, Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* **12**, 7–21 (2019). doi: 10.1038/s41561-018-0262-x
106. T. H. Soukissian *et al*., Marine renewable energy in the Mediterranean Sea: Status and perspectives. *Energies* **10**, 1512 (2017). doi: 10.3390/en10101512
107. K. Dai, A. Bergot, C. Liang, W.-N. Xiang, Z. Huang, Environmental issues associated with wind energy—A review. *Renew. Energy* **75**, 911–921 (2015). doi: 10.1016/j.renene.2014.10.074
108. A. Dhar, M. A. Naeth, P. D. Jennings, M. Gamal El-Din, Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. *Sci. Total Environ.* **718**, 134602 (2020). doi: 10.1016/j.scitotenv.2019.134602; pmid: 31843306
109. S. Joshi *et al*., High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. *Nat. Commun.* **12**, 5738 (2021). doi: 10.1038/s41467-021-25720-2; pmid: 34611151
110. OECD, "Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences" (OECD Publishing, 2018); https://dx.doi.org/10.1787/9789264307452-en.
111. P. M. Berry *et al*., Cross-sectoral interactions of adaptation and mitigation measures. *Clim. Change* **128**, 381–393 (2014). doi: 10.1007/s10584-014-1214-0
112. R. R. Hernandez *et al*., Techno-ecological synergies of solar energy for global sustainability. *Nat. Sustain.* **2**, 560–568 (2019). doi: 10.1038/s41893-019-0309-z
113. T. D. Searchinger, T. Beringer, A. Strong, Does the world have low-carbon bioenergy potential from the dedicated use of land? *Energy Policy* **110**, 434–446 (2017). doi: 10.1016/j.enpol.2017.08.016
114. A. Armstrong, T. Page, S. J. Thackeray, R. R. Hernandez, I. D. Jones, Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees. *Environ. Res. Lett.* **15**, 114055 (2020). doi: 10.1088/1748-9326/abbf7b
115. M. Agha, J. E. Lovich, J. R. Ennen, B. D. Todd, Wind, sun, and wildlife: Do wind and solar energy development "short-circuit" conservation in the western United States? *Environ. Res. Lett.* **15**, 075004 (2020). doi: 10.1088/1748-9326/ab8846
116. M. Milkoreit *et al*., Defining tipping points for social-ecological systems scholarship—An interdisciplinary literature review. *Environ. Res. Lett.* **13**, 033005 (2018). doi: 10.1088/1748-9326/aaaa75
117. D. M. Bergstrom *et al*., Combating ecosystem collapse from the tropics to the Antarctic. *Glob. Chang. Biol.* **27**, 1692–1703 (2021). doi: 10.1111/gcb.15539; pmid: 33629799
118. J. Rockström *et al*., Identifying a safe and just corridor for people and the planet. *Earths Futur.* **9**, (2021). doi: 10.1029/2020EF001866
119. U. Pascual *et al*., Governing for transformative change across the biodiversity-climate-society nexus. *Bioscience* **72**, 684–704 (2022). doi: 10.1093/biosci/biac031
120. M. Leach *et al*., Equity and sustainability in the Anthropocene: A social–ecological systems perspective on their intertwined futures. *Glob. Sustain.* **1**, e13 (2018). doi: 10.1017/sus.2018.12
121. L. R. Carrasco, J. Chan, F. L. McGrath, L. T. P. Nghiem, Biodiversity conservation in a telecoupled world. *Ecol. Soc.* **22**, art24 (2017). doi: 10.5751/ES-09448-220324
122. Y. Takahashi *et al*., Enhancing synergies in nature's contributions to people in socio-ecological production landscapes and seascapes: Lessons learnt from ten site-based projects in biodiversity hotspots. *Sustain. Sci.* **17**, 823–836 (2021). doi: 10.1007/s11625-021-00927-w
123. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, "Methodological assessment of the diverse values and valuation of nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services," P. Balvanera, U. Pascual, M. Christie, B. Baptiste, D. González-Jiménez, Eds. (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2022); https://doi.org/10.5281/zenodo.6522523.
124. D. Obura, Bringing the Sustainable Development Goals to life through stories. *Current Conservation* 20 June 2021; https://www.currentconservation.org/bringing-the-sustainable-development-goals-to-life-through-stories.
125. C. Folke, T. Hahn, P. Olsson, J. Norberg, Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.* **30**, 441–473 (2005). doi: 10.1146/annurev.energy.30.050504.144511
126. C. Wyborn, Co-productive governance: A relational framework for adaptive governance. *Glob. Environ. Change* **30**, 56–67 (2015). doi: 10.1016/j.gloenvcha.2014.10.009
127. J. Ensor, E. Hoddy, Securing the social foundation: A rights-based approach to planetary boundaries. *Earth Syst. Govern.* **7**, 100086 (2020). doi: 10.1016/j.esg.2020.100086
128. M. von Essen, E. F. Lambin, Jurisdictional approaches to sustainable resource use. *Front. Ecol. Environ.* **19**, 159–167 (2021). doi: 10.1002/fee.2299
129. X. Bai, R. R. McAllister, R. M. Beaty, B. Taylor, Urban policy and governance in a global environment: Complex systems, scale mismatches and public participation. *Curr. Opin. Environ. Sustain.* **2**, 129–135 (2010). doi: 10.1016/j.cosust.2010.05.008
130. E. G. King, D. R. Nelson, J. R. McGreevy, Advancing the integration of ecosystem services and livelihood adaptation. *Environ. Res. Lett.* **14**, 124057 (2019). doi: 10.1088/1748-9326/ab5519
131. E. Cohen-Shacham *et al*., Core principles for successfully implementing and upscaling nature-based solutions. *Environ. Sci. Policy* **98**, 20–29 (2019). doi: 10.1016/j.envsci.2019.04.014
132. M. Di Gregorio *et al*., Multi-level governance and power in climate change policy networks. *Glob. Environ. Change* **54**, 64–77 (2019). doi: 10.1016/j.gloenvcha.2018.10.003
133. I. J. Visseren-Hamakers *et al*., Transformative governance of biodiversity: Insights for sustainable development. *Curr. Opin. Environ. Sustain.* **53**, 20–28 (2021). doi: 10.1016/j.cosust.2021.06.002
134. I. M. Otto *et al*., Social tipping dynamics for stabilizing Earth's climate by 2050. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 2354–2365 (2020). doi: 10.1073/pnas.1900577117; pmid: 31964839
135. S. Sharpe, T. M. Lenton, Upward-scaling tipping cascades to meet climate goals: Plausible grounds for hope. *Clim. Policy* **21**, 421–433 (2021). doi: 10.1080/14693062.2020.1870097
136. X. Bai *et al*., Defining and advancing a systems approach for sustainable cities. *Curr. Opin. Environ. Sustain.* **23**, 69–78 (2016). doi: 10.1016/j.cosust.2016.11.010
137. X. Bai *et al*., Plausible and desirable futures in the Anthropocene: A new research agenda. *Glob. Environ. Change* **39**, 351–362 (2016). doi: 10.1016/j.gloenvcha.2015.09.017
138. C. Folke *et al*., Transnational corporations and the challenge of biosphere stewardship. *Nat. Ecol. Evol.* **3**, 1396–1403 (2019). doi: 10.1038/s41559-019-0978-z; pmid: 31527729
139. J. Timperley, Why fossil fuel subsidies are so hard to kill. *Nature* **598**, 403–405 (2021). doi: 10.1038/d41586-021-02847-2; pmid: 34671143
140. J. Alroy, Effects of habitat disturbance on tropical forest biodiversity. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 6056–6061 (2017). doi: 10.1073/pnas.1611855114; pmid: 28461482
141. R. Fuchs, C. Brown, M. Rounsevell, Europe's Green Deal offshores environmental damage to other nations. *Nature* **586**, 671–673 (2020). doi: 10.1038/d41586-020-02991-1; pmid: 33106645
142. M. Verhoeven, W. Magrath, A. Robbins, E. Kallaur, *Mobilizing and Managing Public Forestry Revenue* (World Bank, 2019); https://elibrary.worldbank.org/doi/abs/10.1596/33086.
143. U. R. Sumaila *et al*., WTO must ban harmful fisheries subsidies. *Science* **374**, 544–544 (2021). doi: 10.1126/science.abm1680; pmid: 34709891
144. J. C. V. Pezzey, The influence of lobbying on climate policies; or, why the world might fail. *Environ. Dev. Econ.* **19**, 329–332 (2014). doi: 10.1017/S1355770X14000345
145. P. Dasgupta, *Economics of Biodiversity: The Dasgupta Review* (Great Britain Treasury, 2021).
146. OECD, *Innovative Citizen Participation and New Democratic Institutions* (OECD, 2020); https://www.oecd-ilibrary.org/content/publication/339306da-en.

Downloaded from https://www.science.org at University of Nevada Reno on September 26, 2026

147. G. G. Gurney *et al*., Biodiversity needs every tool in the box: Use OECMs. *Nature* **595**, 646–649 (2021). doi: 10.1038/d41586-021-02041-4; pmid: 34312552
148. R. Chaplin-Kramer *et al*., Mapping the planet's critical natural assets. *Nat. Ecol. Evol.* **7**, 51–61 (2023). doi: 10.1038/s41559-022-01934-5; pmid: 36443466
149. C. Chaudhary, A. J. Richardson, D. S. Schoeman, M. J. Costello, Global warming is causing a more pronounced dip in marine species richness around the equator. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2015094118 (2021). doi: 10.1073/pnas.2015094118; pmid: 33876750
150. D. Storch, L. Menzel, S. Frickenhaus, H.-O. Pörtner, Climate sensitivity across marine domains of life: Limits to evolutionary adaptation shape species interactions. *Glob. Chang. Biol.* **20**, 3059–3067 (2014). doi: 10.1111/gcb.12645; pmid: 24890266
151. A. Åkesson *et al*., The importance of species interactions in eco-evolutionary community dynamics under climate change. *Nat. Commun.* **12**, 4759 (2021). doi: 10.1038/s41467-021-24977-x; pmid: 34362916
152. V. R. Burkett *et al*., Point of departure, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al*., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 169–194.
153. K. M. S. Kemppinen *et al*., Global reforestation and biodiversity conservation. *Conserv. Biol.* **34**, 1221–1228 (2020). doi: 10.1111/cobi.13478; pmid: 32017194
154. FAO, ITPS, GSBI, CBD, EC, "State of knowledge of soil biodiversity - Status, challenges and potentialities, Report 2020" (FAO, 2020); https://doi.org/10.4060/cb1928en.
155. A. Wurz *et al*., Win-win opportunities combining high yields with high multi-taxa biodiversity in tropical agroforestry. *Nat. Commun.* **13**, 4127 (2022). doi: 10.1038/s41467-022-30866-8; pmid: 35882849
156. J. Couwenberg, R. Dommain, H. Joosten, Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Glob. Change Biol.* **16**, 1715–1732 (2009). doi: 10.1111/j.1365-2486.2009.02016.x
157. B. W. Griscom *et al*., Natural climate solutions. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017). doi: 10.1073/pnas.1710465114; pmid: 29078344
158. A. Dobson *et al*., Savannas are vital but overlooked carbon sinks. *Science* **375**, 392–392 (2022). doi: 10.1126/science.abn4482; pmid: 35084954
159. Y. Bai, M. F. Cotrufo, Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science* **377**, 603–608 (2022). doi: 10.1126/science.abo2380; pmid: 35926033
160. V. Enzi, B. Cameron, P. Dezsényi, D. Gedge, G. Mann, U. Pitha, "Nature-Based Solutions and Buildings – The Power of Surfaces to Help Cities Adapt to Climate Change and to Deliver Biodiversity" in *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages Between Science, Policy and Practice*, Theory and Practice of Urban Sustainability Transitions, N. Kabisch, H. Korn, J. Stadler, A. Bonn, Eds. (Springer, 2017), pp. 159–183; https://doi.org/10.1007/978-3-319-56091-5_10.
161. D. Bianchi, D. A. Carozza, E. D. Galbraith, J. Guiet, T. DeVries, Estimating global biomass and biogeochemical cycling of marine fish with and without fishing. *Sci. Adv.* **7**, eabd7554 (2021). doi: 10.1126/sciadv.abd7554; pmid: 34623923
162. O. J. Schmitz *et al*., Animating the Carbon Cycle. *Ecosystems* **17**, 344–359 (2014). doi: 10.1007/s10021-013-9715-7
163. N. Zwerschke *et al*., Quantification of blue carbon pathways contributing to negative feedback on climate change following glacier retreat in West Antarctic fjords. *Glob. Chang. Biol.* **28**, 8–20 (2022). doi: 10.1111/gcb.15898; pmid: 34658117
164. C. M. Duarte, A. Bruhn, D. Krause-Jensen, A seaweed aquaculture imperative to meet global sustainability targets. *Nat. Sustain.* **5**, 185–193 (2021). doi: 10.1038/s41893-021-00773-9
165. C. M. Duarte, J. Wu, X. Xiao, A. Bruhn, D. Krause-Jensen, Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* **4**, (2017). doi: 10.3389/fmars.2017.00100
166. J. A. Gephart *et al*., Environmental performance of blue foods. *Nature* **597**, 360–365 (2021). doi: 10.1038/s41586-021-03889-2; pmid: 34526707
167. N. Hilmi *et al*., The role of blue carbon in climate change mitigation and carbon stock conservation. *Front. Clim.* **3**, 710546 (2021). doi: 10.3389/fclim.2021.710546

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Overcoming the coupled climate and biodiversity crises and their societal impacts

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Facing coupled environmental crises
Humanity is facing major social and ecological impacts from climate change and biodiversity loss. These two crises are intertwined, with common causes and effects on one another. Pörtner *et al*. review the results of a joint meeting of members of the International Panels on Climate Change and Biodiversity and Ecosystem Services. They discuss the connections between biodiversity loss and climate change and propose potential solutions for addressing them as interconnected problems. Drastic reductions in greenhouse gas emissions, protection of multiuse landscapes and seascapes, and policies for providing equitable access to natural resources can help to ensure future ecological function and human well-being. —BEL

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