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Restoring Degraded Lands

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Abstract

Land degradation continues to be an enormous challenge to human societies, reducing food security, emitting greenhouse gases and aerosols, driving the loss of biodiversity, polluting water, and undermining a wide range of ecosystem services beyond food supply and water and climate regulation. Climate change will exacerbate several degradation processes. Investment in diverse restoration efforts, including sustainable agricultural and forest land management, as well as land set aside for conservation wherever possible, will generate co-benefits for climate change mitigation and adaptation and more

broadly for human and societal well-being and the economy. This review highlights the magnitude of the degradation problem and some of the key challenges for ecological restoration. There are biophysical as well as societal limits to restoration. Better integrating policies to jointly address poverty, land degradation, and greenhouse gas emissions and removals is fundamental to reducing many existing barriers and contributing to climate-resilient sustainable development.
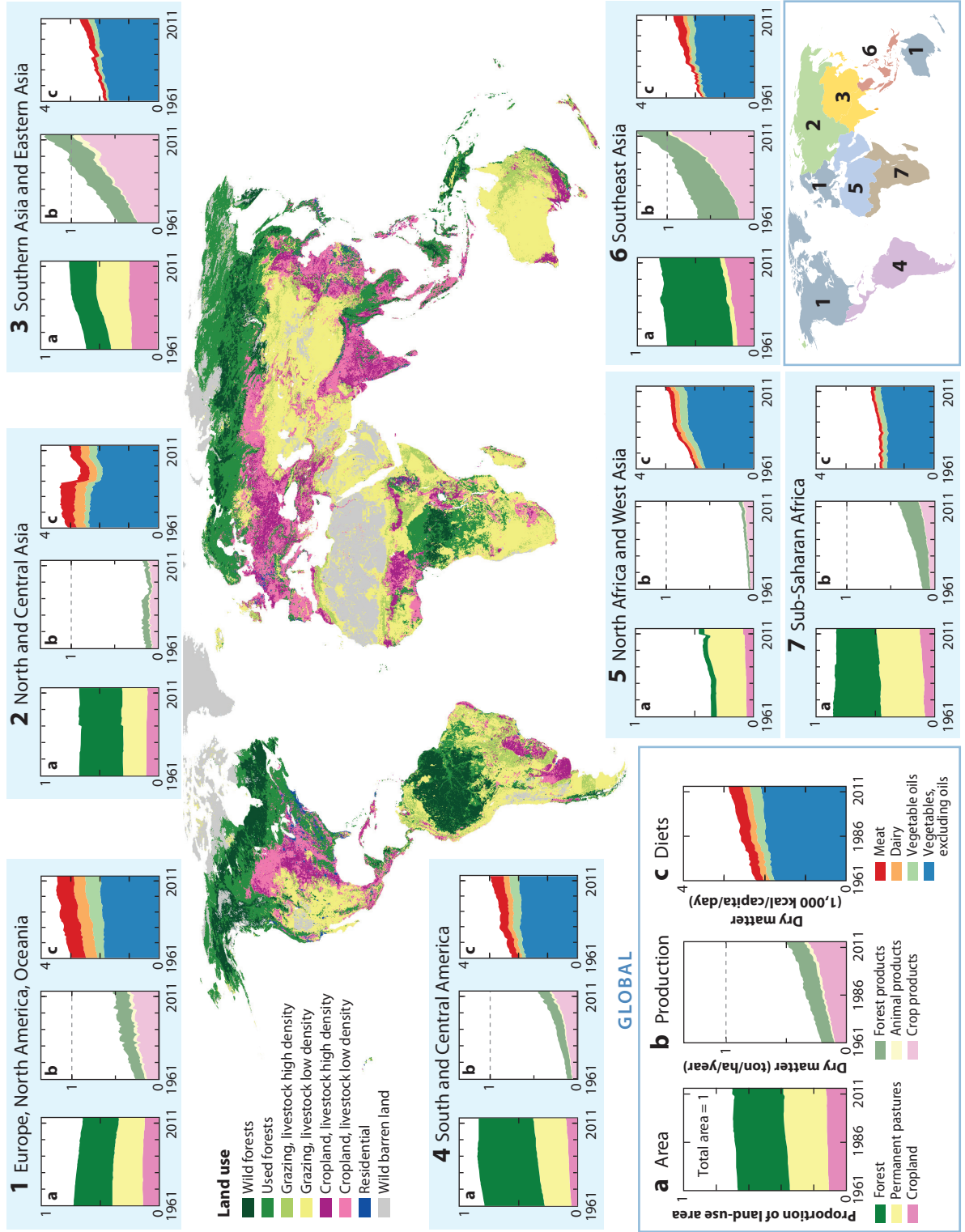
Contents

1. DEGREE AND TRENDS IN DEGRADATION

Desertification: land degradation in arid, semi-arid, and dry sub-humid areas (drylands)

The intensive use of land, with the extraction of wood, agricultural commodities, and water, has until now been the dominant driver of degradation and desertification, as well as the associated accelerating loss of terrestrial biodiversity and ecosystem functioning (1, 2). Approximately 70 to 75% of the ice-free land area is affected by human use, nearly 50% intensively so (**Figure 1**). The global forest cover today is 32–43 Mkm², whereas the prehuman forest cover has been estimated as approximately 50–55 Mkm²; approximately two-thirds of remaining forests are currently under some form of management (1). Degradation negatively impacts people's livelihoods in more than

1 Europe, North America, Oceania

2 North and Central Asia

3 Southern Asia and Eastern Asia

4 South and Central America

5 North Africa and West Asia

6 Southeast Asia

7 Sub-Saharan Africa

Land use

Wild forests
Used forests
Grazing, livestock high density
Grazing, livestock low density
Cropland, livestock high density
Cropland, livestock low density
Residential
Wild barren land

GLOBAL

a Area

Total area = 1

Proportion of land-use area

Forest
Permanent pastures
Cropland

1961   1986   2011

b Production

Dry matter (ton/ha/year)

Forest products
Animal products
Crop products

1961   1986   2011

c Diets

Dry matter (1,000 kcal/capita/day)

Meat
Dairy
Vegetable oils
Vegetables, excluding oils

1961   1986   2011

(Caption appears on following page)

Figure 1 (*Figure appears on preceding page*)

Regional and global trends in the principal land cover classes and production and diets as an example driver of land-use change. The global map shows patterns of land systems (1); livestock low/high relates to low or high livestock density, respectively. The inset graphs show (*a*) cropland, permanent pastures, and forest (used and unused) areas, standardized to total land area; (*b*) production in dry matter per year per total land area; (*c*) and per capita diets—globally and for seven world regions between 1961 and 2014 [data from FAOSTAT (**http://faostat.fao.org**)]. Figure adapted with permission from Reference 1, figure 1.3.

a quarter of the Earth's ice-free land area, with possibly up to 3.2 (1.3–3.2) billion people affected globally (3, 4). Approximately 500 (±120) million people live in or near desertification hotspots, identified by a decline in vegetation productivity between the 1980s and 2000s, extending to >9% of drylands (3, 4). Land degradation has social, political, cultural, and economic causes (3). A particular challenge in providing solutions to halt and reverse degradation arises from the majority of the people affected living in poverty in developing countries (3). However, the impacts of degradation extend beyond the local land surface and societies, affecting marine and freshwater systems, as well as people and ecosystems far away from the location of degradation. For instance, land degradation is of great concern for oceans, manifested by the now more than 500 dead coastal marine zones where excessive nutrient runoff from agriculture has contributed to the collapse of coastal marine ecosystems (5). Climate change is expected to exacerbate degradation, in particular through weather extremes (Section 3), and degradation also contributes to climate change, chiefly through emissions of greenhouse gases and by reducing the capacity of ecosystems to absorb atmospheric CO_2. Avoiding, reducing, and reversing land degradation needs to be part of climate change mitigation and adaptation strategies, with many possible co-benefits for ecosystems and human societies.

2. DRIVERS OF DEGRADATION AND IMPACTS

Land degradation: a negative trend in land condition caused by direct or indirect human-induced processes, including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity, or value to humans

Land use: the total of arrangements, activities, and inputs applied to a parcel of land; the term land use is also used for social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation, and city dwelling)

Degradation occurs as a consequence of complex and highly dynamic interactions of natural and socioeconomic drivers (3, 4). It is strongly associated with the conversion of natural into managed land and the increase of use intensity in agricultural, freshwater, and forest systems. Corresponding to changes in area under use is the rapidly increasing demand for food, feed, fiber, energy, timber, and biomass, reflecting population growth and changes in consumption patterns. Since 1961, crop production increased approximately 3.5-fold and production of animal products 2.5-fold, which was made possible by a massive increase in fertilizer inputs (+800%) and freshwater withdrawals (+100%) (1) (**Figure 2**). During the same period, population increased from 3.0 to 7.8 billion people (in 2020), while per capita calorie intake increased by 32%, and diet composition changed markedly. Per capita consumption of dairy products increased by a factor of 1.2, and meat and vegetable oil consumption more than doubled (1). Currently approximately one-quarter to one-third of the total potential net primary production on land is used by humans, i.e., of the net primary productivity (NPP) that would prevail in the absence of land use [estimated at approximately 60 GtC a^{-1} (6)] (see the IPCC Annex-I Glossary's definition of land use: **https://www.ipcc.ch/srccl/chapter/glossary/**). Approximately 50–60% of the total agricultural (cropland and grazing) biomass harvest (approximately 6 GtC a^{-1}) is consumed by livestock (7). Annual forestry harvest has continuously increased since the early 1960s, and in the first decades of the twenty-first century amounts to approximately 1 GtC a^{-1} (1, 8). In a theoretical analysis based on the complete absence of land use and with current climate, land ecosystems were estimated to store approximately twice as much as the current 450 GtC in vegetation. Land conversions (i.e., replacement of forests with cropland and pastures) and land management [i.e., harvesting of timber from managed forests or removal of herbaceous biomass through grazing (9)] almost equally cause these differences. Although changes in carbon pool
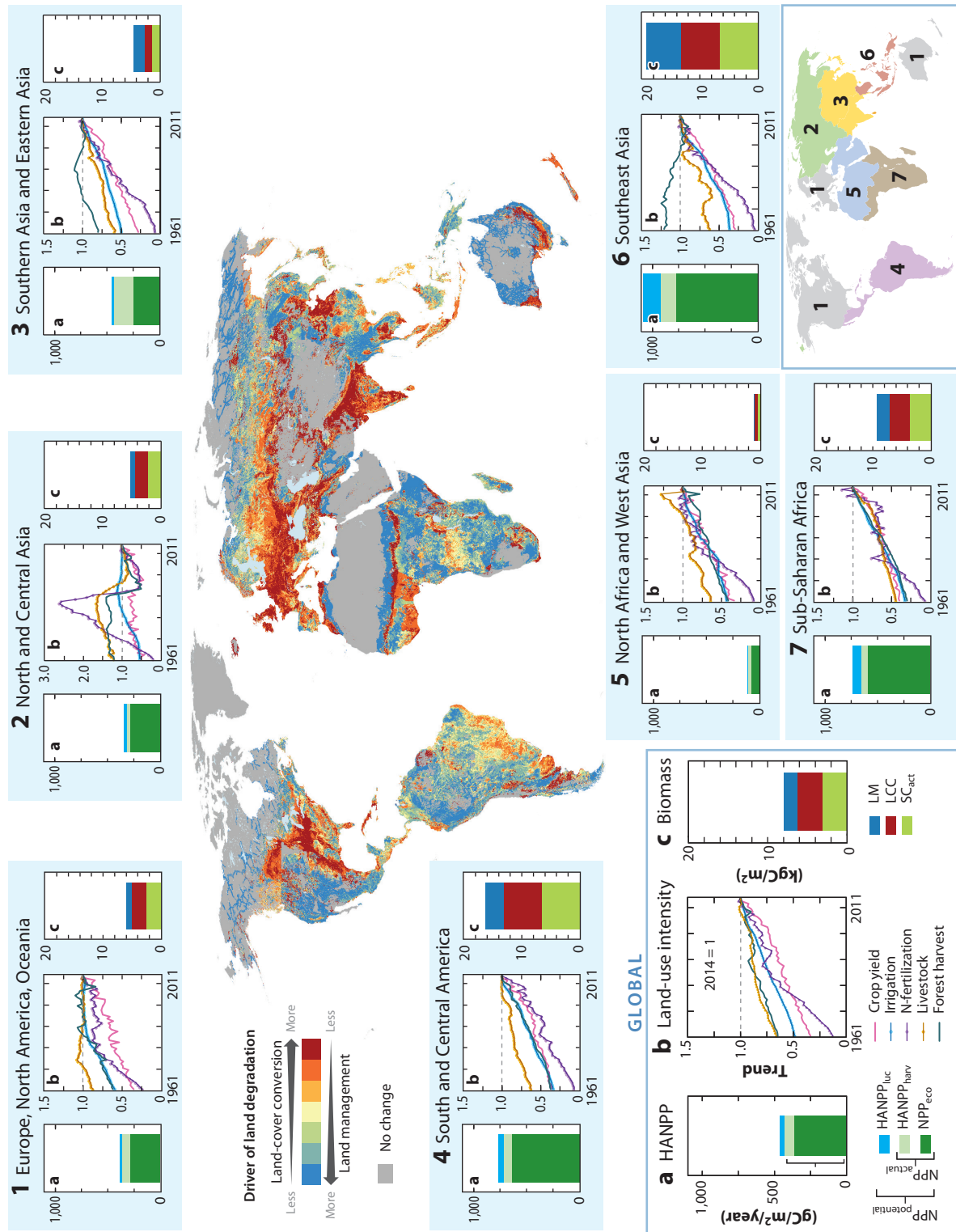
Figure 2 (*Figure appears on preceding page*)

Selected land-use pressures and impacts. The map shows the ratio between impacts on biomass stocks of (*red*) land-cover conversions [(LCC) i.e., land use–induced changes in vegetation cover] and of (*blue*) land management [(LM) i.e., changes that occur with land-cover types; only changes larger than 30 gC/m^2 displayed (9)], as compared to the biomass stocks of the potential vegetation (vegetation that would prevail in the absence of land use, but with current climate). Yellow indicates a state where LCC and LM are of equal importance for biomass stock changes. The inset graphs show (*a*) the global human appropriation of net primary production (HANPP) in the year 2005, in gC/m^2/year (150). The sum of the three components represents the net primary productivity (NPP) of the potential vegetation and consists of NPP$_{eco}$, i.e., the amount of NPP remaining in the ecosystem after harvest; HANPP$_{harv}$, i.e., NPP harvested or killed during harvest; and HANPP$_{luc}$, i.e., NPP foregone due to land-use change. The sum of NPP$_{eco}$ and HANPP$_{harv}$ is the NPP of the actual vegetation (6, 150). (*b*) Trajectories of land-use intensification [cropland yields, fertilization, irrigated area, forestry harvest per forest area, livestock density per agricultural area (**http://faostat.fao.org**)]. (*c*) Regional summary of the map showing standing biomass of actual vegetation [SC$_{act}$ in kgC/m^2 (*light green*)] and the impacts of LCC (*red*) and LM (*blue*). These three components sum up to the potential biomass stocks in vegetation. Figure adapted with permission from Reference 1, figure 1.3.

sizes do not necessarily imply a loss of productivity, they nonetheless indicate a loss of ecological integrity, including loss of biodiversity and altered ecosystem functioning and services (see the sidebar titled A Short Reflection on Terminology).

Drivers of degradation include very short-term events [such as rainstorms causing erosion (10)] as well as slow processes that accumulate over years and decades (such as nutrient losses or loss in biodiversity), interacting with management and land-use change (see the IPCC Annex-I Glossary's definition of land-use change: **https://www.ipcc.ch/srccl/chapter/glossary/**). Both long- and short-term drivers are altered by climate change, which impacts, e.g., productivity over weeks to decades or leads to negative impacts of extreme weather, which can become more frequent in the future. Long-term drivers also correspond to socioeconomic developments (e.g., land owner-ship, technologies, and changes in country- or regional-level wealth). As a consequence, restora-tion measures (Sections 4 and 5) work best if the short-term, often weather-driven impacts are alleviated and the long-term impacts are addressed (see Sections 2.1–2.6 and 3.1–3.3; also see Reference 11 for a discussion of the definition of restoration).

Land-use change: the change from one land-use category to another

Restoration: the process of assisting the recovery of land from a degraded state

A SHORT REFLECTION ON TERMINOLOGY

Changes in land condition resulting solely from natural processes are not considered land degradation. By defin-ing degradation as a negative trend, the baseline for the detection of degradation is the beginning of the period of interest, rather than an arbitrary historical date. The interpretation of a negative trend in land condition has to be subjective to a certain degree, especially when there is a trade-off between ecological integrity and value to humans. For example, a land-use change that reduces ecological integrity but enhances food production at a specific location is not necessarily degradation. SLM reduces the risk of land degradation and is consistent with sustainable forest management (SFM), although the definition commonly used for SFM is somewhat more complex (3). Restoration's goal is reinstating ecological integrity, whereas land rehabilitation focusses more strongly on reinstating a level of ecosystem functionality, where the goal is provision of goods and services rather than ecological restoration (125). Land restoration explicitly acknowledges the multiple links that exist between biodiversity and multiple ecosystem services and seeks to achieve an enhancement in all (148). This might be achieved by restoring natural water flow regimes, the passive regrowth of natural vegetation (which can still be used at low intensity), or actively replanting managed land with vegetation that consists of at least some of the dominant native species (148, 149). Examples of land rehabilitation include the establishment of perennial grasses to stabilize slopes on mined land, or gypsum appli-cation and subsoiling to address surface crusting and compaction in cropland. Addressing land degradation requires a combination of restoration and rehabilitation practices to deliver multiple benefits for production, environment, and sustainable development.

2.1. Forests

Drivers of forest degradation include unsustainable forest exploitation such as illegal logging; extracting high-value species and leaving behind lower-value, damaged, and diseased trees; failure to regenerate forests after harvest; conversion of natural forests to monoculture plantations; and other forms of degradation that in severe cases can culminate in deforestation (see the sidebar titled A Short Reflection on Terminology). Climate change contributes to forest degradation; e.g., drought and heat stress increase regeneration failure and tree mortality. These climate change impacts also amplify the impacts of forest mismanagement (12) (Section 3). However, climate change impacts (including also the effects of increasing atmospheric CO_2 concentration) can, in cases where other factors are not limiting, also increase forest productivity, resulting in, for example, faster tree growth (13) or elevating treelines in mountain regions (14).

The rate of deforestation has long dominated the debate about the role of forests in carbon cycling and climate regulation, although estimates of changes in global forest area vary due to differences in concepts (e.g., baselines and definitions) and methods (e.g., sampling or mapping using different data sources). Still, at least in many tropical forest regions, the area of degraded forests could well equal or even exceed the area of deforestation (15, 16); associated above-ground carbon losses have been estimated to increase estimates of gross deforestation losses by approximately 25% up to >600% (17), with additional, unknown amounts of carbon lost from soils. Globally, less than 30% of the world's forests are considered to be still intact (1), and less than 40% of forest area has been estimated to contain old-growth forest [in Reference 18, forests identified to be older than 140 years]. Different management practices, policies, and law enforcement can have large impacts on the long-term maintenance of forest carbon stocks (including below-ground). For instance, soil disturbance accompanying clear-cutting reduces soil carbon on average by approximately 10% with much larger losses in forest floor and organic soil horizons (19). Likewise, residue removal or whole-tree harvest can also cause soil disturbance, and remove root, stump, or bark biomass that would otherwise be part of soil organic matter cycling, including the formation of recalcitrant carbon pools (19). Although harvested above-ground biomass and litter carbon recovers in regrowing vegetation, the impacts of forest management on soil processes are longer term and much more difficult to quantify. Removal of deadwood as part of forest management has also been associated with reducing habitat diversity for numerous species (20). Deadwood is especially important as a living environment for insects and wood-inhabiting fungi but also affects higher trophic levels through related food webs (20). Because forest degradation involves a decline in productivity, in many regions, there is now recognition of the need for forest conservation and rehabilitation and a transition to more sustainable forest management in production forestry (21).

2.2. Grasslands and Savannahs

Grasslands are widespread natural vegetation in tropical, subtropical, and temperate regions. 30% of the approximately 46% (±0.8%) of the global land area defined as drylands are grassy ecosystems (22–24). These grasslands represent the key source of livelihoods for approximately 100 million to 200 million pastoralists around the world. Grasslands also provide essential supporting, regulating, and cultural ecosystem functions and services. For instance, tropical grassy ecosystems harbor approximately half of the vascular plant richness found in tropical forests, and species richness for mammals, birds, and amphibians is also high. Likewise, isolated trees in tropical savannahs support biodiversity in these ecosystems, as well as providing food and shelter to humans (25). The lack of formal protection, therefore, is of concern; tropical grassy biomes have a substantially lower proportion of protected areas than tropical forest, often with individual areas under protection that are far too small (26). Likewise, formerly occupying approximately

8% of the land surface, natural temperate grasslands are now reduced to a fraction of their original area and are considered one of the most endangered biomes in the world (27, 28). Less than 5% of global temperate grasslands are protected (27).

The causes of grassland degradation are numerous and complex, combining both natural and anthropogenic factors. For instance, dryland areas have high climatic variability, with periods of dry and wet climates, and corresponding cycles of greening and browning, most famously in the Sahel region (29, 30). This natural variability makes these regions vulnerable to widespread and longer-term degradation as a result of human use. The key human drivers of grassland and savannah degradation include expansion of cropped areas or conversion to intensive pasture systems (Section 2.3) (27), reduced livestock mobility and overgrazing, and—in savannahs—fuelwood extraction (4, 31). Ambiguous and insecure land tenure regimes combined with widespread poverty and frequent marginalization of pastoralist communities across many grassland areas (32) limit investment in their sustainable use and management, including access to veterinary and rural advisory services, financial and insurance markets, as well as input and output markets. Many sustainable land management (SLM) (3) practices require up-front investments that take several years to pay back (both in pasture- and cropland-related SLM; see **Tables 1** and **2**). Improved access to financial markets creates more possibilities for obtaining credit to invest in SLM measures, and insurance can reduce associated risks. Similarly, better access to input and output markets lowers the costs of applied inputs (e.g., fertilizer) and transportation (e.g., for sales), ultimately increasing profit margins, which provides greater capacity for reinvestment in SLM. These drivers of grassland degradation also limit the adaptive capacities of pastoral communities, making them severely vulnerable to climate change, degradation, and continuing marginalization in favor of crop production (4).

2.3. Intensively Managed Grazing Land

The global extent of land used for grazing is estimated to be 28–42 Mkm², the range being mainly determined by differences in definitions. The extent of permanent pastures and meadows, the key category for which global statistical data are available (**http://faostat.fao.org**; any grazing land used for more than five consecutive years), spans 28 (33) to 34 Mkm², including extensively used natural grasslands (Section 2.2), intensively managed pastures and meadows established in natural grassland areas, as well as grassland that was established after deforestation. The latter is estimated at 11.3 Mkm² in 2000 (9) and can be assumed to be under intensive management schemes. Converted grassland holds biomass stocks that are less than 10% of the potential biomass stock (9).

Grassland degradation is a widespread phenomenon, with overgrazing being a key driver, together with frequent wheel traffic, or overfertilization, all of which result in changes in sward composition, reduction in yields, and deterioration of soils. Intensively used grasslands are relatively species-poor (34); grazing systems are also particularly threatened by invasive plant species (35). Using biological productivity (e.g., NPP; see the sidebar titled A Short Reflection on Terminology) as an indicator, degradation in numerous grasslands across Europe, North America, and Asia was found to be primarily caused directly by human activities, although climate change is also a strong contributing factor (36) (Section 3).

Grasslands can act as carbon sinks, transferring carbon below-ground via their expansive root systems. However, grazing impacts are complex. A meta-analysis of studies found that heavy grazing decreases soil organic carbon content in grassland dominated by vegetation of the C3 photosynthetic pathway and increased soil organic carbon content in mixed and C4 photosynthetic-type grasslands (37). Others have argued that carbon sinks or sources in grasslands depend heavily on the previous land use, climate, and/or time since conversion (38). Additionally, intensively used

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Sustainable land management (SLM): the stewardship and use of land resources to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions

Table 1   Overview of key sustainable land management practices that contribute strongly to halting and reversing degradation and with notable co-benefits for climate change mitigation and/or adaptation. Sources: see References 3, 4, 62, 67, 96, 147

Practice	Definition/example activities	(Co-) Benefit	Estimate potential		Barriers
			Mitigation[a]	Adaptation[b]	
Agroforestry	Mixed cropping or pasture systems with trees	Income diversification: cash crops (e.g., fruit trees) and staple crops; shade from heat extremes; enhance carbon storage; habitat for biodiversity	0.1–5.7	2,300	Knowledge, outreach, required up-front investment together with time lag before payback
Improved cropland, livestock, grazing management	For example, improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, agricultural biotechnology; optimized fertilizer application rate, type, timing; reduced tillage intensity and residue retention; adjust animal stocking density, feeding management, manure management	Enhance carbon storage; reduce erosion, pollution; enhance fertility; reduce greenhouse gas emissions	3–6.5	1 to larger than 25	Knowledge, outreach, access to land, finance, and technology; adequate rural advisory services
Agricultural diversification	Mixed crop-livestock systems, mixed annual and perennial systems, mixed cereal and legume rotations	Income diversification; habitat for biodiversity	Unknown	>25	Knowledge, outreach, access to land, finance, and technology; adequate rural advisory services
Increased food productivity, especially in areas of large yield gaps	Sustainably closing existing yield gaps[c], breeding of drought or heat-tolerant crop varieties	Free land for restoration: food demand to be met with less land and/or fewer animals, reduced greenhouse gas emissions	>13	3,000	Access to finance, technology, and markets
Integrated water management	Increase irrigation efficiency	Reduce competition for drinking water; reduce water pollution; reduce pressure on freshwater biodiversity	0.1–0.72	250	Access to finance, technology
Reduced deforestation/ degradation	Stop conversion of forests and savannahs into agricultural systems	Maintain carbon stocks and uptake potential; flood control; habitat for biodiversity	0.5–5.8	1–25	Government regulation; land-use zoning and planning; alternative income opportunities to forest-dependent communities; weak law enforcement to protect forests and dependent communities
Improved forest management	For example, improved tree varieties, mixed forests, reduced disturbance when harvesting, selective logging	Enhance forest carbon content; reduced risks from insects/pathogens; habitat for biodiversity	0.4–2.1	>25	Access to knowledge, technology

(Continued)

Table 1 (*Continued*)

Practice	Definition/example activities	(Co-) Benefit	Estimate potential		Barriers
			Mitigation[a]	Adaptation[b]	
Reforestation/ restoration	Foster natural forest regrowth or planting of mixed-species forests on former cropland or pastures that are naturally forested	Enhance forest carbon content; reduced risks from insects/pathogens; habitat for biodiversity	1.5–10.1	>25	Access to knowledge, finance and technology
Restoration/ reduced conversion of inland wetlands and peatlands	Remove drainage systems in former peatlands; create/ maintain natural dams	Enhance net carbon content (balance of CO_2 uptake and CH_4 emissions); flood regulation; habitat for biodiversity	0.6–2	Unknown	Government regulation, restoration requirements; alternative income opportunities to wetland-dependent communities; weak law enforcement to protect wetland and dependent communities
Fire management	Foster controlled burning; minimize risks of extreme wildfires	Reduce risk of large-scale forest (and property) loss and fire-related ecosystem shifts; maintain ecological role of fire	0.5–8.1	>6	Government regulation, restoration requirements
Biodiversity conservation	Protected area networks, habitat diversification	Contribute to carbon uptake and storage; provide niche for pollinators and predators/ natural pest control; contribute to flood control	0.9	Unknown	Government regulation, restoration requirements; conservation law enforcement is often weak and missing compensation to affected communities
Biochar addition	Add biochar to agricultural soils	Enhanced soil structure, water- and nutrient-holding capacity and enhance long-term carbon storage. Mitigation estimate is net across supply chain from feedstock production to soil application, including avoided emissions and carbon sequestered.	0.03–6.6 (Plausible to technical potential) 0.5–2 (Sustainable potential)	Up to 3,200 unless arable land would be used for biochar feedstock production	Access to knowledge and technology

Co-benefits for: Mitigation   Adaptation   Food security   Biodiversity

[a]Estimated mitigation potential in Gt CO_2-equivalent a^{-1}
[b]Estimated adaptation potential in million people affected
[c]The difference between yield potential and average farmers' yield. Can be reduced by changes in land management (such as irrigation, fertilization, pest control) but care must be taken to minimize environmental or societal side effects (e.g., pollution, water availability).

grasslands are sources of ruminant methane (CH_4) emissions as well as nitrous oxide (N_2O) emissions from excreta or fertilized pastures. Intensively managed grazing land is thus likely to be a net greenhouse gas source.

2.4. Croplands

It is axiomatic that modern conventional agriculture is a driver of terrestrial and marine ecosystem degradation as well as emissions of greenhouse gases. Since the Neolithic Revolution some 12,000 years ago, the upper 2 m of soils are estimated to have lost almost 116 GtC, of which 37 GtC have been attributed to croplands and associated vegetation cover classes (39). The replacement

Table 2 Barriers that prevent governments, farmers, or foresters from adopting restoration/sustainable land management practices

Barriers	Relates to category	Agent	Importance	Action
Perverse subsidies	Institutional	Government	High	Redirect to act on environmental concerns
Diverse lobby groups	Institutional	Government	High	Dialog with lobbyists transparent to public
Reliance on imports, trade agreements	Institutional	Government	High	Include environmental standards in trade agreements
Lack of political incentives	Institutional	Government	High	Targeted political measures, redirection of subsidies
Actual or perceived effects on performance of restoration/sustainable land management practices	Human/social	Farmer/forester	High	Communication and education; rural advisory services
Actual or perceived lack of financial benefit	Economic	Farmer/forester	High	Communication and education, financial incentives
Costs of adoption/lack of access to credit	Economic	Farmer/forester	Moderate	Investment support
Lack of access to input and output markets	Economic	Farmer/forester; government	Moderate	Financial incentives, transportation infrastructure, labeling
Hidden and transaction costs	Economic/institutional	Farmer/forester	Moderate	Simplification of regulations
Lack of infrastructure	Technological/economic	Farmer/forester	Moderate/locally contextual	Investment support
Uncertain land tenure	Institutional	Government; farmer/forester	Moderate/locally contextual	Appropriate regulations and engagement with stakeholders
Lack of adequate spatial planning	Institutional	Government; farmer/forester	Moderate/locally contextual	Appropriate regulations and engagement with stakeholders
Traditions, practices	Human	Farmer/forester	Moderate/high	Communication and engagement

Table adapted from Reference 141.

of natural vegetation, dominated by deep-rooted mixed perennial plants, with shallow-rooted annual crops in monocultures, in combination with frequent disturbance of the soil profile through tillage, is responsible for this massive loss of soil carbon. The proportion of soil carbon lost from agricultural soils varies from approximately 20% to more than 60% (3). It is not known how much of this carbon has been lost to the atmosphere rather than being redistributed to other parts of a landscape via wind and water erosion (which could lead to burial and hence long-term carbon storage). However, the large historic loss of soil carbon implies that agricultural systems have a significant capacity to take up CO_2 from the atmosphere and to store it in the form of soil carbon with a wide range of co-benefits in addition to climate change mitigation (40).

Agricultural soils and practices are also a major source of CH_4 and N_2O. Within the agricultural and forestry sector, annual emissions of CH_4 and N_2O together are similar (in CO_2-equivalents) to emissions of CO_2 from net deforestation. Whereas ruminant livestock are the main source of CH_4 from the agricultural sector, rice cultivation is the most important source of CH_4 from agricultural soils (41). Crop management and soil moisture are also important determinants of emissions whereby waterlogging and soil compaction generally are associated with high CH_4 emissions (42). N_2O emissions are generally associated with increased use of (mostly mineral) fertilizer, which (on an expanding area of cropland) has been estimated to have contributed >80% of the N_2O emission increase since the 1860s (43).

2.5. Wetlands and Peatlands

Wetlands play a vital role for a range of ecosystem services, such as flood control, water purification, groundwater replenishment, and nutrient retention, and they are often hotspots of biodiversity. The total amount of carbon stored in wetlands and peatlands has been estimated at approximately 1,500 GtC, approximately 30–40% of the global terrestrial carbon stock (44, 45). Estimates of the current and recent areal extent of wetlands vary substantially, from under 2% to over 20% of the global land area (46). This large variation is due to the lack of an accepted definition of wetlands and difficulties in linking definitions with data sources. Despite their importance, wetlands are under severe stress and subject to degradation. Historical data on their areal extent are highly uncertain, but an estimated 87% of the world's wetlands were lost in the past 300 years, 54% since 1900 (47), and 35% since 1970 (48).

The most important human drivers of wetland decline are urbanization, drainage for agricultural expansion, and increasing use of irrigation in agriculture causing wetlands to dry (48). Climate change is projected to exacerbate the degradation of wetlands due to increasing evaporation and increasing demand for irrigation, as well as enhancing fire risks (49) (Section 3). The large amount of carbon stored in wetlands makes them exceptionally important in terms of future climate change, and so preventing further degradation is an important priority for mitigation. Wetland degradation can result in emissions of both CO_2 and CH_4 (3). Global CH_4 emissions have risen rapidly since 2007, with a further acceleration after 2014 (50). Approximately half of the rise since 2007 comes from the increasing number of ruminant livestock, whereas the other half has uncertain origins. One cause might be the high global temperatures since 2014, which have accelerated emissions of CH_4 from low-latitude wetlands (51), whereas emissions responses from high-latitude wetlands are more uncertain (52). Restoring already degraded wetlands can sequester carbon on a century scale, albeit at an often relatively slow pace and possibly at the expense of increased CH_4 emissions (53), but with large potential to improve conditions for biodiversity (54).

2.6. Rivers

On the basis of estimated global blue water runoff (approximately 42,000 km^3 a^{-1}), a sustainable level of human use may be 1,200–8,300 km^3 a^{-1} (55), depending on the chosen criteria. Given that at present humans withdraw approximately 2,500–3,200 km^3 a^{-1}, these numbers paint at first sight a relatively encouraging picture. However, global averages hide the very large regional and intra-annual variation in river runoff. Freshwater extraction typically takes place in regions where freshwater is much scarcer than the global average (56). Only 37% of rivers longer than 1,000 km remain free-flowing over their entire length, often in very remote regions (57). The building of dams alters habitats and results in biodiversity loss putting pressure on freshwater megafauna by blocking fish migration, range contraction, and population decline. Changes in river flow regimes, but also pollution inflow from agricultural fields, can increase algal biomass; reduce invertebrate richness, abundance, and density; and alter organic matter decomposition (58). The availability and quality of freshwater is projected to continue to decline in the future due to extraction for irrigation, drinking water, and energy, pollution, and increased shipping, with dam building for irrigation expected to disproportionately impact South America, south and east Asia, and the Balkan region (59).

3. DIRECT AND INDIRECT IMPACTS OF CLIMATE CHANGE

Although climate change has until now had relatively minor impacts on degradation, it is expected to become more important for degradation in the future (3, 4), exacerbating the effects of

land-use change. Analyses of remotely sensed vegetation greenness (and vegetation browning) as well as model-based studies found that climate change has contributed to degradation chiefly in regions located around 15–45°S, although studies disagree regarding the exact region of impact (36, 60, 61). Model-based estimates of NPP indicate that climate change is an important driver of degradation in approximately 35–45% of the world's degraded grasslands (36, 61). Attribution of climate change as a driver of degradation is made more difficult by concurrent increases in atmospheric CO_2 and the large regional variability in observed and projected climate trends. In many regions, for example, leaf-area index and land ecosystem carbon uptake have increased over recent decades, partly due to the CO_2 fertilization effect (60, 62). Future climate change is expected to accelerate degradation most strongly through weather extremes (heatwaves, drought, floods) and associated episodic events such as wildfire and insect outbreaks (12), given that these extremes override the positive impacts that might arise from trends in temperature, precipitation, or CO_2. The impacts of climate change are expected to be most negative in regions that are already under degradation pressures (11), but a substantial change in frequency and magnitude of extremes can also trigger processes of degradation in currently intact ecosystems (3, 4). Moreover, indirect climate change–related drivers, such as large-scale mitigation efforts on land, have also raised concerns with respect to increasing degradation (1, 63).

3.1. Drought

The term drought describes a broad range of climatic situations characterized by low precipitation, low soil moisture, low levels of water in streams and lakes, or a shortage of water for society at large. Droughts usually evolve relatively slowly, posing difficulties in identifying their onset and end (64), although the rapid onset of flash droughts is also possible (65). Occurrence of droughts does not automatically lead to land degradation, as the land productivity may recover completely after the end of a drought event (4). Furthermore, drought impacts can be alleviated by SLM practices, such as use of cover crops and mulching, supplementary irrigation if surface or groundwater sources are available, or the selection of drought-tolerant crop and forest species (66). However, if droughts increase in numbers and intensity, this can disrupt the ability of vegetation to recover (47), leading to degradation, particularly when coupled with unsustainable land management. Climate change is projected to increase the frequency and severity of droughts in many areas of the world (67, 68). In drylands, the land area annually experiencing droughts has already increased by approximately 50% since 1961 (69). Moreover, in many dryland areas, droughts together with unsustainable land management can amplify degradation, including increasing dust-storm activity. Projections show that under the Shared Socioeconomic Pathway (SSP) SSP2 (a "middle of the road" scenario), by 2050 approximately 1,152 million people in dryland areas alone will be exposed to higher drought intensity and water stress at 2°C warming, whereas this number would be reduced to 974 million people under SSP1 ("sustainable" scenario) and increased to 1,267 million people in an SSP3 ("fragmented world") projection by 2050 (70, 71). Increasing droughts will cause stress to coastal and inland wetlands. Groundwater recharge is expected to respond to climate change with increases during wet, winter periods and declines during dry, summer periods; overall declines are expected in more arid locations (72). Higher temperature increases result in higher projected numbers of people exposed to, and vulnerable to, water scarcity and droughts (70, 71). The projected increases in drought severity can also increase the incidence and extent of wildfires (73, 74). Responding to droughts proactively by increasing the resilience of societies and ecosystems was found to be more efficient in limiting drought impacts than reactive drought relief efforts, which are still widely practiced across the world (4).

3.2. Wildfire

Vegetation fires are an important ecological feature of most land ecosystems and are used as a management tool but also often negatively affect human societies through, e.g., losses of properties and lives and local and long-range air pollution (75). Ignition sources, vegetation characteristics, land use, fire management, and climate all play a role in determining the frequency, severity, and spread of wildfires. Although wildfires that have coevolved with an ecosystem are not a degrading feature, there is concern that a change in fire regimes caused by climate change could negatively interfere with the integrity of an ecosystem, lead to changes in biome type, and cause increased risk to the human populations living in fire-prone environments. The extreme fires in parts of Australia during 2019–2020, which were associated with unprecedented drought and heat, were estimated to impact >30% of the habitat area of 21 animal species threatened with extinction (76). Wildfires in boreal regions, which have experienced overproportional warming, can accelerate permafrost thaw and cause large carbon losses from vegetation and organic soils. Changes in fire regimes can also contribute to a shift in vegetation composition, as more frequent fires, especially those coinciding with drought or insect outbreaks, suppress seedling regeneration and push, for example, closed forests toward more open forest-steppe systems (77, 78). Climate change–related forest decline is observed in many regions, e.g., in the US Northwest and British Columbia, in which drought and increasing fire frequency interact with additional stressors such as insect infestation (79). Frequently burned sites across continents were found to have up to tenfold less soil organic matter decomposing extracellular enzyme activity and up to 185% lower soil carbon and nitrogen concentrations due to reduced biomass inputs and reduced tree abundance (80).

In a warmer, drier climate, fire risk will increase. Whether this will translate into larger areas burnt or more intense fires depends greatly on location and on active (suppression, extinction) and passive (landscape fragmentation, fuel reduction) management (81). Although investment in adopting fire management practices under climate change can reduce wildfire impacts in populated regions, it seems unlikely that impacts from changes in fires on remote ecosystems can be prevented.

3.3. Rainfall Extremes and Flood

Future changes in precipitation are generally more challenging to project than temperature increase. But the intensification of the hydrological cycle as a result of warming of the atmosphere is well understood, and the effect has been detected in climatic time series for several decades. Theoretically, the intensification is assumed to be at least linearly linked to warming at a rate of 6–7% per degree K (the Clausius-Clapeyron response), but empirical evidence and model studies indicate a steeper increase in precipitation intensity, particularly in dry regions (82, 83).

Rainfall-induced impacts operate at many spatial scales, from a single furrow in a field to an entire region, and temporal scales, from a few minutes to multiple years. The impacts are also seen both on-site, i.e., the rainfall and its impacts are at the same location, and off-site, where the impacts happen downstream (3). Under current climatic conditions, erosion and nutrient leakage from agricultural land is substantial and an important cause of deterioration of marine and terrestrial aquatic ecosystems (84, 85). Erosion from agricultural fields under conventional tillage is often 2–3 orders of magnitude larger than the rate of soil formation. The increasing intensity of rainfall expected from climate change will lead to increased erosion and nutrient loss from croplands unless SLM practices are widely implemented (86).

The overall frequency of tropical cyclones may not change, or may even decrease with continued climate change, but high intensity cyclones are expected to increase in number and intensity as well as the amount and intensity of rainfall (87, 88). The combined effect of sea-level

rise and more intensive hurricane activity is projected to increase flood damage dramatically (89). In mountainous regions, landslides and other impacts of intensive rainfall are often the major cause of climate-related loss of life and damage to property (90).

3.4. Bioenergy

Bioenergy refers to a range of energy products (electricity, liquid fuels, gas) derived from a diverse range of biomass sources, such as crop and forest residues, dedicated energy crops, wood fuel, greenwaste, and biosolids. Unsustainable harvesting of fuelwood for domestic use is a major cause of land degradation, especially in tropical and dryland regions. Demand for bioenergy is anticipated to grow along with demand for other renewables, especially bioenergy linked with carbon capture and storage (BECCS), which emerges in future scenarios as one of the few technologies that can deliver carbon dioxide removal at required scales. Because most scenarios illustrating pathways to meet a 1.5 or 2° temperature goal show heavy reliance on BECCS (91), bioenergy could become an indirect climate change–related cause of degradation. Expansion of purpose-grown energy crops such as canola, soy, miscanthus, or oil palm causes loss of carbon stocks in biomass and soil, loss of soil fertility, and loss of biodiversity if it leads, directly or indirectly, to the conversion of grassland or natural forest to cropland or plantations and/or to further environmentally detrimental intensification of cropland management. Over an 80-year perspective, a recent study (92) estimated for different forms of BECCS and a range of annual bioenergy production potentials a land area requirement between 22 and 46 Mkm^2, with the upper end similar in magnitude to the entire remaining global forest area. Likewise, removal of residues that would otherwise be retained on the soil surface increases the risk of soil erosion and depletes soil organic matter (93, 94). For strong climate change mitigation scenarios, the required expansion of land area for bioenergy crops was found to have similarly negative impacts on terrestrial biodiversity as had unmitigated climate change (95) due to the reduction in species' ranges and pressure on protected areas.

4. CLIMATE CHANGE MITIGATION AND ADAPTATION CO-BENEFITS ARISING FROM AVOIDING FURTHER DEGRADATION AND INCREASING RESTORATION

Socioeconomic drivers of degradation such as population growth and increasing per capita demand for ecosystem services are projected to continue into the future. Acting immediately and simultaneously with regionally adjusted measures would enhance food, fiber, and water security, help to curb loss of biodiversity, as well as alleviate and reverse land degradation, without compromising the nonmaterial or regulating benefits from land ecosystems. Given the rapidly increasing rate of climate change, drastically reducing net emissions of greenhouse gases and other climate forcers is urgently required, while also adapting to unavoidable climate change. Measures to achieve mitigation in land ecosystems with immediate positive synergies with conservation and adaptation are foremost a reduction in the conversion of forest and nonforest (semi)natural ecosystems into intensively managed ecosystems, together with the restoration of ecosystems with large carbon sequestration potential. Mitigating climate change by utilizing vast land areas globally for the production of bioenergy (Section 3.3) or reforestation and afforestation (Section 4.2), which is at present still integral to many climate change scenarios, is unsustainable (1, 63, 96; also see the IPCC Annex-I Glossary's definition of reforestation and afforestation: **https://www.ipcc.ch/srccl/chapter/glossary/**). However, numerous different analyses have begun to highlight the large co-benefits that emerge when multiple societal and environmental targets are considered simultaneously (97–99), as discussed below.

Reforestation: conversion to forest of land that has previously contained forests but that has been converted to some other use

Afforestation: conversion to forest of land that historically has not contained forests

These analyses demonstrate that regionally adapted restoration activities have large potential to support climate change mitigation while simultaneously reducing climate change impacts on ecosystems and people, with added benefits for multiple ecosystem services. Suitable actions include, for example, a global reduction in the consumption of animal protein, with a more equitable share between rich and poor countries; a reduction in the approximately 30% of food that is annually lost and wasted; and lake and wetland restoration to assist with flood control and provide water for supply, irrigation, fisheries, and tourism (100). Measuring and monitoring the success of combined mitigation-adaptation approaches is nontrivial; multiple and very different indicators need to be used that are cognizant of the agreements made in international conventions as well as capturing local consequences (101). For instance, reductions in net greenhouse gas emissions or atmospherically reactive precursors of climate forcers are in principle measurable, but these measurements are often technically complex and expensive and require large investment in human power and instrumental infrastructure. Likewise, the reduction of negative impacts, which reflects successful adaptation, could be quantified, e.g., in terms of enhanced assets and livelihoods; in resources (food, water) security, health, cultural, or spiritual well-being; or in conservation and biodiversity (101, 102). These categories span wide-ranging values, from monetary profits to nontangible benefits. These are difficult to gauge and difficult to compare, which often prevents the assessment of co-benefits or trade-offs (101, 103).

In both cases, the effectiveness of measures may only become evident years or even decades after implementation, such as the carbon uptake of a restored forest (including the fate of wood products or carbon losses through fire or insects) or the net carbon budget (CO_2 versus CH_4) and catchment water balance in restored wetlands, which may take decades to centuries to semi-equilibrate. Likewise, the benefits to biodiversity or the avoided damage to human societies, especially from extreme weather events (101), will accrue only over a long-term time period. There is also increasing recognition that restoration and management of restored ecosystems will need to be dynamically adopted in response to ongoing and unavoidable changes (101–103). When faced with climate change, restoration will be about managing change, with a return to historical states hard or impossible to achieve.

4.1. Principles of Sustainable Land Management and Contribution to Restoration/Rehabilitation

Numerous options exist to create synergies between the management of agriculture and forest vegetation and soils with the objective to reverse degradation (**Table 1**). SLM practices include reduced tillage, residue retention, use of nitrogen-fixing cover crops or intercropping (e.g., alternating rows of cereals and legumes in the same field), managing mixed-species and uneven-aged forests, practices that aim to halt erosion, such as avoiding clear-cutting of forests, or the use of organic amendments in agriculture such as mulches, compost, and biochar to increase soil carbon and nutrient content (3). As a co-benefit, these practices also enhance ecosystem carbon sinks and food security as well as deliver multiple other co-benefits (63), with positive changes in areas totaling globally greater than 10 Mkm² (63).

In managed ecosystems, soils have received particular attention because of their crucial role in regulating nutrient and water flows and fertility and because soil carbon can, in principle, have long residence times. Proven and cost-effective methods exist that can be implemented now to increase the soil carbon content of agricultural soils without compromising productivity and food security (40). The shift from conventional agriculture, characterized by frequent tillage and complete removal of vegetation for parts of the season, to regenerative (or conservation) agriculture is particularly promising and universally applicable (104). Regenerative agriculture

applies three principles: avoidance of soil disturbance, the use of cover crops or mulch to avoid leaving the soil exposed, and diversification through complex/long crop rotations or inter-cropping. Regenerative agriculture increased from 7.5% to 15% of global croplands between 2008/2009 and 2015/2016 (105). It now covers more than 70% of the cropland in the Southern Common Market (MERCOSUR) region and 34% in North America, but only approximately 5% in Europe (106). In addition, on heavily contaminated or saline soils, energy crops such as perennial grasses and short-rotation woody species including poplar and mallee can be strategi-cally planted to improve soil conditions and contribute to phytoremediation (107, 108). Likewise, perennial woody or herbaceous energy crops (e.g., grasses such as switchgrass or *Miscanthus* species) can be grown where topsoil has been lost, as they are able to grow, albeit slowly, on low fertility soils. Energy crops can enhance the biodiversity of degraded lands, especially if native species are included and/or if perennial grasses and woody crops enhance habitat diversity in what are otherwise large cropland monocultures (109).

Agroforestry, characterized by growing woody perennials with agricultural crops, animal graz-ing, or a combination of both, has also been shown to enhance soil carbon content signifi-cantly compared with more conventional agricultural systems, especially in the upper soil layers (>30 cm), in which an overall increase of approximately 25% was detected in a meta-analysis of field studies (110). This effect may be caused by changes in the quality and amount of litter in-puts, root litter input into deeper soil layers, or changed microclimate (shade, windbreak). Yields in agroforestry areas also tend to be higher when compared to the yields obtained if crops and woody perennials were grown separately (111). This may arise from the reduced risks of complete failure, complementary strategies in which growth periods of woody versus annual crops overlap only a little, or from the shelter to crops provided by trees (111). Given that trees, shrubs, or hedges provide very different habitat to agricultural crops or pure pasture, agroforestry is also beneficial to conservation and enhancement of biodiversity—which in turn can be beneficial to production by enhancing pollinator presence or biological pest control (111).

4.2. Reforestation/Afforestation Are Not Necessarily the Same as Restoration

Recent decades have seen reforestation in temperate regions while tropical deforestation contin-ues unbated. Globally, the estimated forest carbon sink for 2001–2010 was approximately 40% in intact old-growth forests and 60% in regrowing forests (18). Afforestation and reforestation are considered relatively cost-effective climate change mitigation options (96). In addition to the car-bon removal during tree growth, Churkina et al. (112) recently estimated a large potential for using timber in construction, which decreases carbon emissions from concrete and steel production and provides long-term carbon storage in wood. Yet international activities such as the Bonn Chal-lenge (**http://www.bonnchallenge.org**), which aims to restore 3.5 Mkm^2 of forested landscapes by 2030, have also been criticized for potentially leading to wasteful usage of planted forests as sources of bioenergy, further biodiversity loss, being detrimental to existing systems' carbon stor-age, and challenging food production if local environmental constraints or societal concerns are not considered (96, 113). Forests planted in savannahs or other ecosystems with low tree cover will critically damage these often highly species-diverse and carbon-rich ecosystems (113, 114). Hence, replacing these ecosystems with forest will severely limit the intended climate change mitigation benefits. Exotic monoculture plantations have little or no benefit for biodiversity, or they can even be detrimental if the planted species becomes invasive (115). Furthermore, relying on forests for long-term carbon sequestration is a risk, particularly for monocultures with high vulnerability to storms, fire, or pest outbreaks (12, 116). Carbon sinks decline in all forests as they mature. Biophysical surface exchange processes in tropical forests, with often large evapotranspiration

rates, cause local cooling as a climate co-benefit. Reforestation in the boreal region must consider the net climate effects of increased carbon storage, increased surface warming where evergreen conifer foliage absorbs solar radiation (116), and cooling due to the formation of secondary organic aerosols.

As with agricultural ecosystems, restoring forests from a multiple ecosystem service perspective rather than climate change mitigation alone is a more promising approach, which requires consideration of multiple species and above- and below-ground functional diversity (117). Successful examples of reversing forest degradation exist. In South Korea, for instance, as a consequence of reforestation, total forest volume increased more than tenfold between 1973 and 2016, with significant co-benefits such as a 43% simulated increase in downstream water yields across catchments and an 87% reduction in soil losses (3). Biodiversity and productivity in forests are positively correlated globally (118). A global meta-analysis found that forest restoration can increase biodiversity (mammals, birds, herpetofauna, invertebrates, and plants) by 15–84% and vegetation structure (biomass, cover, stem density, and height or amount of leaf litter) by 36–77% above degraded ecosystems—although values remained below those found in old-growth forests (119). As with the beneficial aspect of different crop production systems, when combined with a strong restoration focus (i.e., regrowth of natural vegetation and limited management), large co-benefits exist from both an economic and nature conservation perspective (98, 116).

4.3. Role of Wild Animals

Discussions about restoration or renovation of ecosystems focus on vegetation type and habitat structure, assuming that whole species assemblages would follow and with it a return to healthy ecosystem functioning, especially where dominant natural species are replanted or natural regrowth takes place (120, 121). These discussions mostly neglect the role of animals, despite their essential role in shaping habitat structure, ecosystem productivity, and nutrient cycling (122). "Soil engineers" such as earthworms and termites are well known for their role in decomposition of litter and soil organic matter and nutrient turnover. Inoculating such types of soil animals into degraded soils, or stimulating them through indirect measures (such as compost), has been found to enhance important soil physical and chemical properties, especially related to restoring land for crop production (121).

Furthermore, the presence or absence of large carnivores impacts type and density of prey animals, including the abundance of herbivores and the type and amount of consumed green leaf area. Large herbivores also influence ecosystem structure and function through physical impacts such as trampling or pushing over trees (122). And animals have carbon to nitrogen ratios that are lower than plant material; hence, the return of nutrients to soil in the form of animal feces has quite different decomposition rates than plant litter. The overall impact on productivity (as an important degradation measure) will likely differ between regions and ecosystem types.

Reintroducing large carnivores has so far mostly been viewed in terms of restoring natural food webs and biodiversity. Wolves preying on moose in Northern American boreal forests were also estimated to enhance NPP and net ecosystem carbon uptake by up to 30% via increased growth of deciduous trees (which, as the preferred fodder of moose, are suppressed in their presence) and enhanced tree leaf area index. Tree cover was observed to increase in the Serengeti National Park following the recovery of the wildebeest population after the eradication of rinderpest (122). However, predicting the trophic response (and hence its interaction with functioning) of restoring carnivores (or large mammals) to ecosystems has been shown to be challenging (123), and assumptions about ecosystems simply returning to a historical state seem too simplistic given interactions with climate change and episodic events such as fire.

4.4. Economic Aspects

SLM and restoring and rehabilitating degraded lands are high-return actions from not only an environmental but also an economic and social perspective. Practices that enhance soil carbon and nutrients in principle should deliver the same yields with less input and hence be more economically viable. A suite of case studies conducted in various settings across the world (124) showed that each dollar invested into land restoration activities could yield between US$3 and $6 of societal economic returns, through both provisioning and nonprovisioning ecosystem services, over a 30-year period (124). Sustainable cultivation of lignocellulosic energy crops provides a financial return, while at the same time supporting the rehabilitation of degraded lands and restoring productivity (125). Agroforestry not only reduces risks (having at least partial production if one crop fails) but also delivers cash crops such as fruits and nuts; however, potentially higher costs of harvest, storage, and transport need to be considered (111). Giger et al.'s (126) analysis of the costs and benefits of individual SLM technologies showed that most of the SLM technologies analyzed became profitable within three to ten years after continued application. Overall, an increasing set of studies indicate that farming practices exist that reverse degradation while still producing sufficient food for a growing human population.

Despite this strong economic justification, the adoption of SLM technologies and the initiation of land restoration and rehabilitation activities remains insufficient to address the ongoing land degradation around the world (4). There are numerous reasons for this. Firstly, an important share of the economic benefits of restoration is in the form of nonprovisioning ecosystem services, which benefit society as a whole, but individual land users cannot fully monetize these benefits. This reduces the incentive to invest in land restoration. Secondly, even when the value of private goods can be realized by land users, the benefits may accrue only after a long period of time, while up-front costs may be prohibitively high, especially for the poor without access to credit. Furthermore, continuing institutional barriers such as land tenure insecurity and lack of access to rural advisory services, i.e., to the information and know-how about SLM and land restoration technologies, pose formidable barriers to the wider adoption of SLM practices and technologies. Establishing financial mechanisms for compensating land users for SLM and improved delivery of ecosystem services, e.g., through payments for ecosystem services, could provide a much-needed incentive for increased investment into land restoration and rehabilitation (111, 127, 128). In this context, redirection of misdirected subsidies is a crucial approach. For instance, the European Court of Auditors highlighted that €66 billion spent within the common agricultural policy between 2014 and 2020 did not achieve its goal of stopping agricultural biodiversity loss (**https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=53892**), a result supported by Scown et al. (129), who estimated that subsidies in the CAP (common agricultural policy) supported high-pollution practices in agriculture and low nature-value farmland, as well as increasing income inequality.

4.5. Lack of Restoration Scenarios for Climate Change/Biodiversity Projections

Scenario analysis is used to explore the future potential directions of uncertain drivers by combining qualitative storylines of alternative, socioeconomic development trajectories with models to quantify projections of individual environmental indicators (1). Although scenario analysis is used widely across the environmental sciences, there are very few examples of large-scale scenarios of restoring degraded land. Wolff et al. (130) explored the consequences of achieving global land restoration targets outlined in the United Nations Sustainable Development Goals (SDGs) and by several multinational environmental agreements [the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), and the

United Nations Convention to Combat Desertification (UNCCD)]. They found that meeting these targets would require an increase in global tree cover of 4 million km² that would increase forest carbon stocks by 50 Gt and protect 28% of the terrestrial surface with high biodiversity and carbon values. However, increasing forest areas also led to the contraction and further intensification of cropland and pastureland, in some scenarios causing negative impacts on many carbon and biodiversity hotspots in the Americas, India, and Indonesia due to land-use displacement (Section 4.2). This highlighted the importance of targeted land-management measures that are consistent with policy targets of global restoration. Metzger et al. (131) provided guidelines on how best to use the scenario method in support of restoration planning. They highlight (*a*) the need for participatory approaches in defining targeted restoration outcomes with key actors and promoting capacity building, (*b*) defining scenario methods according to multiple desired outcomes and iteratively improving restoration interventions, (*c*) considering interactions among variables using dynamic, and spatially explicit, multicriteria approaches, and (*d*) highlighting the trade-offs and synergies between different restoration outcomes by identifying scenarios that maximize benefits and minimize costs.

5. GOVERNANCE, POLICY, AND THE LIMITS TO RESTORATION

Governance is key in fostering restoration because of its social function in steering collective behavior toward desired outcomes and decision-making by individuals, households, markets, organizations, and government (132). Effective main-streaming of mitigation and adaptation in sustainable land and forest management needs to combine the advantages of centralized governance (notably coordination, stability, compliance) with those of more horizontal structures (that allow flexibility, autonomy for local decision-making, multistakeholder engagement, co-management) (133). At the local level, integrated landscape planning aims to take a balanced approach to property rights, wildlife and forest conservation, encroachment of settlements, and agricultural production. Sustainable, bottom-up and place-based solutions build on existing governance arrangements (134). Continuous, collaborative problem solving of multiscale decision-making that employs experimentation and conflict resolution has been shown to build capacity for resource self-management (135). Global leadership could advance such local initiatives.

5.1. Restoration and International Policy Targets and Objectives

Many synergies exist between restoration and key international policy areas that relate to nature-based solutions for climate change mitigation and adaptation (UNFCCC), avoiding and reducing degradation and restoring degraded land (UNCCD), and the CBD and its Aichi Biodiversity Targets. These measures also contribute to many SDGs, including 15 (through restored landscapes and protected forests and biodiversity), 13 (through carbon capture and storage and enhanced ecosystem resilience), and 1 (by increasing income from forest and agriculture sector). Land degradation neutrality,[1] target 15.3 of the SDGs, provides an incentive and framework that encourages strategic actions to restore and rehabilitate degraded land, within the context of integrated landscape planning and management, aimed at delivering multiple environmental and development objectives (136). More than 120 countries have already committed to set

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[1]The Parties to the UN Convention to Combat Desertification provide the following definition of land degradation neutrality: "a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems" (**https://www.unccd.int/actions/achieving-land-degradation-neutrality**).

land degradation neutrality targets (**https://www.unccd.int/actions/ldn-target-setting-programme**). Commitments under the Bonn Challenge and other voluntary restoration targets in 2019 resulted in the aim of restoring a total of 230 million hectares of forest (137). However, the commitments of approximately a quarter of countries are larger than the existing forest or agricultural areas in those countries, which implies the need for enormous transformation in current land-use practices and agricultural and forest economies (137; see also Section 4.2).

Restoration is also part of the CBD's post-2020 biodiversity targets that are expected to be agreed upon at the next UN CBD Conference of the Parties (COP) in China (which will take place in 2021), and restoration measures could also be aligned with the goals of the Paris Agreement. At least 66% of Paris Agreement signatories were found to include nature-based solutions in some form in their Nationally Determined Contributions (NDCs). Approximately 30% of government pledges in the NDCs are predicated on land-based measures to help achieve their climate change mitigation and/or adaptation goals, but many of the measures are not yet clearly defined (138). Although there is climate change mitigation potential in restoring forests (and avoiding further deforestation), if done poorly, both land-based climate change mitigation measures and restoration measures could backfire. As indicated in Sections 3.3 and 4.2, large-scale deployment of bioenergy and afforestation/reforestation would have major negative impacts on biodiversity and land degradation, if they were to lead to the conversion of natural vegetation. Impacts could cascade through SDGs due to trade-offs between land for climate mitigation versus food production, or between forest biomass-based livelihoods versus global carbon storage with impacts on poverty alleviation. There is also, however, large scope for the restoration of grasslands, drylands, coastal ecosystems (e.g., mangroves), and wetlands to contribute to climate change mitigation and biodiversity, if the climate change risks to carbon uptake (Section 3) are minimized (63). Enhancing synergies and reducing trade-offs can be achieved by (*a*) policy decisions and implementation that consider cross-disciplinary scientific knowledge on natural, economic, and societal aspects and (*b*) mapping and quantification of stakeholder choices in relation to various ecosystem service choices (139).

5.2. Limits to Restoration

Soft barriers to restoration include human (cognitive and behavioral obstacles), social (undermined participation in decision-making and inequity), economic (market failures, perverse incentives, lack of domestic funds), institutional (mal-coordination of policies, government failures, path-dependent institutions and a lack of cross-sectoral policy making), and technological (140). Barriers specific to restoration may include a perceived lack of financial benefit, insufficient information or education, prohibitive costs of adoption, lack of access to credit, systems of uncertain land tenure, and lack of infrastructure or appropriate spatial planning (141) (**Table 2**). Many of these barriers can be addressed. In principle, two strategies apply (141): the revision of policies that impede restoration objectives and the introduction of targeted initiatives that could directly help remove the key barriers. As one example, for the Brazilian Atlantic Forest, Strassburg et al. (98) showed that a spatial prioritization of restoration efforts could deliver large co-benefits for biodiversity conservation and carbon storage, at drastically lower costs compared to a nonsystematic baseline approach. Nevertheless, the required efforts of coordination and societal and policy coherence are massive.

However, even though nature and society have significant capacities, given the degree and rate of environmental change some hard limits to restoration have been clearly identified in ecosystems, such as species already committed to extinction, habitat loss due to sea-level rise even under low levels of climate warming, or where tipping points may be unavoidable (e.g., climate-driven

desertification or permafrost collapse). Successful restoration will, therefore, be much more about managing change, with a return to a pristine historical ecosystem state in some places difficult or impossible to achieve. In these cases, societal or institutional resistance to change has been too large to enact necessary and forward-looking responses to a rapid environmental change (such as climate change). Governance of ecosystems can be a hard limit to adaptation or restoration, unless radical changes can be achieved (142, 143).

5.3. Dealing With Uncertain Futures

Given large uncertainties about the future (and a general lack of restoration scenarios) static goals and policies that aim to achieve restoration (and sustainable development more generally) are likely to fail. An example of this are the nature conservation measures that rely on the implementation of a fixed percentage and placement of protected areas. Future climate change will cause shifts in species distributions and ranges that may go beyond the boundaries of static protected areas and/or increase the number and frequency of episodic, forest stand-destroying events such as wildfire or insect and pest outbreaks (12). However, the need for dynamic conservation strategies was not considered in the Aichi Biodiversity Targets, nor is it being considered in the current draft of the post-Aichi objectives (144). Rather than making fixed and irreversible decisions now, alternative climate change mitigation and restoration pathways could explore the future outcomes of decision-making when accounting for climate or socioeconomic developments, new knowledge or technologies, and changing societal values (145). Coupled global-scale, socio-ecological models are emerging as tools to account for a full range of human decision-making processes, beyond economic factors alone (146). These new models could be used to identify the environmental and societal co-benefits of considering multiple ecosystem services as part of human agency. Such models could also be linked to novel scenarios to illustrate alternative futures (Section 4.5). The SSPs currently widely used in the global environmental change research community vary in their challenges to climate change adaptation and mitigation, but do not specify challenges to nature conservation, nor many of the critical drivers of ecosystem change. Projected outcomes of agricultural or forest land-use change do not, therefore, capture whether crops, pastures, or forests are managed sustainably. Given the challenges at hand, but also the multiple co-benefits from restoration, applying new modeling methods to novel scenario frameworks would help to identify plausible pathways that achieve multiple societal and political visions, while concurrently avoiding further degradation.

6. CONCLUSION

Land degradation is a ubiquitous challenge to human societies, driven mostly by socioeconomic factors. Climate change is expected to exacerbate degradation processes in many regions, while degradation-related greenhouse gas emissions and the loss of carbon sink capacity in turn contribute to climate change. Land-based solutions aimed only at greenhouse gas mitigation, such as large-scale afforestation or bioenergy plantations, are at risk of contributing to land degradation and can have other negative, unintended societal and environmental consequences. However, multiple strands of evidence show that degradation can be halted and reversed with appropriate land management practices, which would deliver co-benefits for a range of sustainable development objectives. Removing the existing barriers to their adaptation (such as financial incentives and the redirection of perverse subsidies, access to knowledge and technology, enforcement of environmental policies, appropriate spatial planning) requires multilevel governance supported by cross-disciplinary scientific knowledge of natural, economic, and societal drivers and impacts. Carefully

implemented and monitored over sufficient areas and in collaboration with local stakeholders, land restoration measures should form the backbone of any global climate change mitigation and sustainable development strategy.

SUMMARY POINTS

1. Land degradation exacerbates food insecurity; emits greenhouse gases and aerosols; drives the loss of biodiversity; and undermines wide-ranging ecosystem services, including access to clean drinking water and the regulation of air quality.

2. Climate change is expected to increase in importance as a driver of degradation in the future, exacerbating the effects of land use and management.

3. Investment in diverse restoration efforts, and land set aside for conservation, can generate co-benefits for climate change mitigation and adaptation, economically and more broadly for human and societal well-being.

4. Acting immediately and simultaneously with regionally adjusted measures to alleviate and reverse land degradation would enhance food, fiber, and water security and help to curb loss of biodiversity, without compromising the nonmaterial or regulating benefits from land.

5. The highest priority is the reduction of deforestation and prevention of the loss of non-forest (semi)natural ecosystems.

6. If done poorly, both land-based climate change mitigation measures and restoration measures could backfire as a result of trade-offs between land for climate mitigation versus food or conservation, or between forest biomass-based livelihoods versus global carbon storage.

7. Restoration efforts can be strengthened by (*a*) enhancing policy decisions and implementation with cross-disciplinary scientific knowledge of natural, economic, and societal drivers and impacts and (*b*) acknowledging stakeholder perspectives in relation to various ecosystem service choices.

8. Governance is key to fostering successful restoration if it supports the identification and integration of the interests of all actors, but the degree of extant environmental change commitments and the rate of change can pose hard environmental and social limits.

FUTURE ISSUES

1. Enhanced adoption of SLM technologies and the initiation of land restoration and rehabilitation activities will require overcoming numerous societal and economic barriers to provide the necessary incentive for increased investments in land restoration.

2. Given uncertain futures, and the often long time periods until fruition of restoration measures, more targeted restoration scenarios are required that can be used jointly with improved global-scale socio-ecological models to explore the co-benefits and negative side effects of different options for restoration.

5. Altieri AH, Harrison SB, Seemann J, Collin R, Diaz RJ, Knowlton N. 2017. Tropical dead zones and mass mortalities on coral reefs. *PNAS* 114:3660–65

6. Haberl H, Erb K-H, Krausmann F. 2014. Human appropriation of net primary production: patterns, trends, and planetary boundaries. *Annu. Rev. Environ. Resour.* 39:363–91

7. Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber PJ. 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Glob. Food Secur.* 14:1–8

8. FAO. (United Nations Food and Agric. Organ.) 2020. *Global Forest Resources Assessment 2020: Main report.* Rome. Rep., FAO. **https://doi.org/10.4060/ca9825en**

9. Erb K-H, Kastner T, Plutzar C, Bais ALS, Carvalhais N, et al. 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* 553:73–76

10. Marzen M, Iserloh T, de Lima J, Fister W, Ries JB. 2017. Impact of severe rain storms on soil erosion: experimental evaluation of wind-driven rain and its implications for natural hazard management. *Sci. Total Environ.* 590:502–13

11. IPBES (Intergov. Sci.-Policy Platf. Biodivers. Ecosyst. Serv.). 2018. *The IPBES Assessment Report on Land Degradation and Restoration.* Bonn, Ger.: IPBES Secr.

12. Anderegg WRL, Trugman AT, Badgley G, Anderson CM, Bartuska A, et al. 2020. Climate-driven risks to the climate mitigation potential of forests. *Science* 368:eaaz7005

13. Hember RA, Kurz WA, Girardin MP. 2019. Tree ring reconstructions of stemwood biomass indicate increases in the growth rate of black spruce trees across boreal forests of Canada. *J. Geophys. Res. Biogeosci.* 124:2460–80

14. Trant A, Higgs E, Starzomski BM. 2020. A century of high elevation ecosystem change in the Canadian Rocky Mountains. *Sci. Rep.* 10:9698

15. Bullock EL, Woodcock CE, Souza C, Olofsson P. 2020. Satellite-based estimates reveal widespread forest degradation in the Amazon. *Glob. Change Biol.* 26:2956–69

16. Matricardi EAT, Skole DL, Costa OB, Pedlowski MA, Samek JH, Miguel EP. 2020. Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science* 369:1378–82

17. Maxwell SL, Evans T, Watson JEM, Morel A, Grantham H, et al. 2019. Degradation and forgone removals increase the carbon impact of intact forest loss by 626%. *Sci. Adv.* 5:eaax2546

18. Pugh TAM, Lindeskog M, Smith B, Poulter B, Arneth A, et al. 2019. Role of forest regrowth in global carbon sink dynamics. *PNAS* 116:4382–87

19. Mayer M, Prescott CE, Abaker WEA, Augusto L, Cecillon L, et al. 2020. Tamm Review: Influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. *Forest Ecol. Manag.* 466:118127

20. Thorn S, Seibold S, Leverkus AB, Michler T, Müller J, et al. 2020. The living dead: acknowledging life after tree death to stop forest degradation. *Front. Ecol. Environ.* 18:505–12

21. Meyfroidt P, Lambin EF. 2011. Global forest transition: prospects for an end to deforestation. *Annu. Rev. Environ. Resour.* 36:343–71

22. Koutroulis A. 2018. Dryland changes under different levels of global warming. *Sci. Total Environ.* 655:482–511

23. Prăvălie R. 2016. Drylands extent and environmental issues. A global approach. *Earth-Sci. Rev.* 161:259–78

24. FAO (United Nations Food Agric. Organ.). 2016. *Trees, Forests and Land Use in Drylands: The First Global Assessment—Preliminary Findings.* Rome: FAO

25. Brandt M, Tucker CJ, Kariryaa A, Rasmussen K, Abel C, et al. 2020. An unexpectedly large count of trees in the West African Sahara and Sahel. *Nature* 587:78–82

26. Murphy BP, Andersen AN, Parr CL. 2016. The underestimated biodiversity of tropical grassy biomes. *Philos. Trans. R. Soc. B* 371:20150319

27. Carbutt C, Henwood WD, Gilfedder LA. 2017. Global plight of native temperate grasslands: going, going, gone? *Biodivers. Conserv.* 26:2911–32

28. van Oijen M, Bellocchi G, Hoglind M. 2018. Effects of climate change on grassland biodiversity and productivity: the need for a diversity of models. *Agronomy* 8:14

29. Brandt M, Mbow C, Diouf A, Verger A, Samimi C, Fensholt R. 2014. Ground and satellite-based evidence of the biophysical mechanisms behind the greening Sahel. *Glob. Change Biol.* 21:1610–20

30. Rishmawi K, Prince S. 2016. Environmental and anthropogenic degradation of vegetation in the Sahel from 1982 to 2006. *Remote Sens.* 8:948

31. Lehman CER, Parr CL. 2016. Tropical grassy biomes: linking ecology, human use and conservation. *Philos. Trans. R. Soc. B* 371:20160329

32. Morton J. 2010. Why should governmentality matter for the study of pastoral development? *Nomad. Peoples* 14:6–30

33. Ramankutty N, Evan AT, Monfreda C, Foley JA. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Glob. Biogeochem. Cycles* 22:GB1003

34. Gossner MM, Lewinsohn TM, Kahl T, Grassein F, Boch S, et al. 2016. Land-use intensification causes multitrophic homogenization of grassland communities. *Nature* 540:266–69

35. Shin Y-J, Arneth A, Roy-Chaudhury R, Midgley G, Boafo Y, et al. 2019. Plausible futures of nature, its contributions to people and their good quality of life. In *The IPBES Global Assessment on Biodiversity and Ecosystem Services*, ed. IPBES (Intergov. Sci.-Policy Platf. Biodivers. Ecosyst. Serv.), Bonn, Ger.: IPBES Secr. **https://ipbes.net/sites/default/files/ipbes_global_assessment_chapter_4_unedited_31may.pdf**

36. Gang C, Zhou W, Chen Y, Wang Z, Sun Z, et al. 2014. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. *Environ. Earth Sci.* 72:4273–82

37. McSherry ME, Ritchie ME. 2013. Effects of grazing on grassland soil carbon: a global review. *Glob. Change Biol.* 19:1347–57

38. Smith P. 2014. Do grasslands act as a perpetual sink for carbon? *Glob. Change Biol.* 20:2708–11

39. Sanderman J, Hengl T, Fiske GJ. 2017. Soil carbon debt of 12,000 years of human land use. *PNAS* 114:9575–80

40. Bossio DA, Cook-Patton SC, Ellis PW, Fargione J, Sanderman J, et al. 2020. The role of soil carbon in natural climate solutions. *Nat. Sustain.* 3:391–98

41. Humphreys J, Brye KR, Rector C, Gbur EE. 2019. Methane emissions from rice across a soil organic matter gradient in Alfisols of Arkansas, USA. *Geoderma Reg.* 16:e00200

42. da Silva Cardoso A, Quintana BG, Janusckiewicz ER, de Figueiredo Brito L, da Silva Morgado E, et al. 2019. How do methane rates vary with soil moisture and compaction, N compound and rate, and dung addition in a tropical soil? *Int. J. Biometeorol.* 63:1533–40

43. Tian H, Yang J, Xu R, Lu C, Canadell JG, et al. 2019. Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: magnitude, attribution, and uncertainty. *Glob. Change Biol.* 25:640–59

44. Kayranli B, Scholz M, Mustafa A, Hedmark Å. 2010. Carbon storage and fluxes within freshwater wetlands: a critical review. *Wetlands* 30:111–24

45. Page SE, Baird AJ. 2016. Peatlands and global change: response and resilience. *Annu. Rev. Environ. Resour.* 41:35–57

46. Tootchi A, Jost A, Ducharne A. 2019. Multi-source global wetland maps combining surface water imagery and groundwater constraints. *Earth Syst. Sci. Data* 11:189–220

47. Prince S, Von Maltitz G, Zhang F, Byrne K, Driscoll C, et al. 2018. Status and trends of land degradation and restoration and associated changes in biodiversity and ecosystem functions. In *The IPBES Assessment Report on Land Degradation and Restoration*, ed. IPBES (Intergov. Sci.-Policy Platf. Biodivers. Ecosyst. Serv.), pp. 315–426. Bonn, Ger.: IPBES Secr.

48. Darrah SE, Shennan-Farpón Y, Loh J, Davidson NC, Finlayson CM, et al. 2019. Improvements to the Wetland Extent Trends (WET) index as a tool for monitoring natural and human-made wetlands. *Ecol. Indic.* 99:294–98

49. Colloff MJ, Lavorel S, Wise RM, Dunlop M, Overton IC, Williams KJ. 2016. Adaptation services of floodplains and wetlands under transformational climate change. *Ecol. Appl.* 26:1003–17

50. Nisbet EG, Manning MR, Dlugokencky EJ, Fisher RE, Lowry D, et al. 2019. Very strong atmospheric methane growth in the 4 years 2014–2017: implications for the Paris Agreement. *Glob. Biogeochem. Cycles* 33:318–42

51. Mikaloff Fletcher SE, Schaefer H. 2019. Rising methane: a new climate challenge. *Science* 364:932–33

52. Oh Y, Zhuang Q, Liu L, Welp LR, Lau MCY, et al. 2020. Reduced net methane emissions due to microbial methane oxidation in a warmer Arctic. *Nat. Clim. Change* 10:317–21

53. Hemes KS, Chamberlain SD, Eichelmann E, Anthony T, Valach A, et al. 2019. Assessing the carbon and climate benefit of restoring degraded agricultural peat soils to managed wetlands. *Agric. Forest Meteorol.* 268:202–14

54. Meli P, Benayas J, Balvanera P, Martinez-Ramos M. 2014. Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: a meta-analysis. *PLOS ONE* 9:e93507

55. Hogeboom RJ, de Bruin D, Schyns JF, Krol MS, Hoekstra AY. 2020. Capping human water footprints in the world's river basins. *Earths Future* 8:e2019EF001363

56. Bogardi JJ, Fekete BM, Vorosmarty CJ. 2013. Planetary boundaries revisited: a view through the 'water lens'. *Curr. Opin. Environ. Sustain.* 5:581–89

57. Grill G, Lehner B, Thieme M, Geenen B, Tickner D, et al. 2019. Mapping the world's free-flowing rivers. *Nature* 569:215–21

58. Sabater S, Bregoli F, Acuna V, Barcelo D, Elosegi A, et al. 2018. Effects of human-driven water stress on river ecosystems: a meta-analysis. *Sci. Rep.* 8:11462

59. Zarfl C, Berlekamp J, He F, Jähnig SC, Darwall W, Tockner K. 2019. Future large hydropower dams impact global freshwater megafauna. *Sci. Rep.* 9:18531

60. Zhu ZC, Piao SL, Myneni RB, Huang MT, Zeng ZZ, et al. 2016. Greening of the Earth and its drivers. *Nat. Clim. Change* 6:791–95

61. Liu YY, Yang Y, Wang Q, Khalifa M, Zhang ZY, et al. 2019. Assessing the dynamics of grassland net primary productivity in response to climate change at the global scale. *Chinese Geogr. Sci.* 29:725–40

62. Le Quéré C, Andrew RM, Friedlingstein P, Sitch S, Hauck J, et al. 2018. Global carbon budget 2018. *Earth Syst. Sci. Data* 10:2141–94

63. Smith P, Calvin K, Nkem J, Campbell D, Cherubini F, et al. 2019. Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Glob. Change Biol.* 26:1532–75

64. Wilhite D, Pulwarty RS. 2017. *Drought and Water Crises, Integrating Science, Management, and Policy*. Boca Raton: CRC Press

65. Mo K, Lettenmaier D. 2015. Heat wave flash droughts in decline. *Geophys. Res. Lett.* 42:2823–29

66. Stroosnijder L. 2009. Modifying land management in order to improve efficiency of rainwater use in the African highlands. *Soil Tillage Res.* 103:247–56

67. Jia G, Shevliakova E, Artaxo P, De Noblet-Ducoudré N, Houghton R, et al. 2019. Land–climate interactions. 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*, ed. PR Shukla, J Skea, E Calvo Buendia, V Masson-Delmotte, HO Pörtner, et al., pp. 131–247. Geneva: Intergov. Panel Clim. Change

68. Zheng J, Yingzhuo Y, Zhang X, Hao Z. 2018. Variation of extreme drought and flood in North China revealed by document-based seasonal precipitation reconstruction for the past 300 years. *Clim. Past* 14:1135–45

69. Ziese M, Schneider U, Meyer-Christoffer A, Schamm K, Vido J, et al. 2014. The GPCC Drought Index—a new, combined and gridded global drought index. *Earth Syst. Sci. Data* 6:285–95

70. Byers E, Gidden M, Leclère D, Balkovič J, Burek P, et al. 2018. Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environ. Res. Lett.* 13:5

71. Hurlbert M, Krishnaswamy J, Davin E, Johnson FX, Mena CF, et al. 2019. Risk management and decision-making in relation to sustainable development. 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*, ed. PR Shukla, J Skea, E Calvo Buendia, V Masson-Delmotte, HO Pörtner, et al., pp. 673–800. Geneva: Intergov. Panel Clim. Change

72. Shrestha S, Hoang NAT, Shrestha PK, Bhatta B. 2018. Climate change impact on groundwater recharge and suggested adaptation strategies for selected Asian cities. *APN Sci. Bull.* 8(1). **https://doi.org/10.30852/sb.2018.499**

73. Clarke H, Evans JP. 2018. Exploring the future change space for fire weather in southeast Australia. *Theor. Appl. Climatol.* 136:513–27

74. Williams AP, Allen CD, Millar CI, Swetnam TW, Michaelsen J, et al. 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *PNAS* 107:21289–94

75. McLauchlan KK, Higuera PE, Miesel J, Rogers BM, Schweitzer J, et al. 2020. Fire as a fundamental ecological process: research advances and frontiers. *J. Ecol.* 108:2047–69

76. Ward M, Tulloch AIT, Radford JQ, Williams BA, Reside AE, et al. 2020. Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nat. Ecol. Evol.* 4:1321–26

77. Halofsky JE, Peterson DL, Harvey BJ. 2020. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecol.* 16:4

78. Kukavskaya EA, Buryak LV, Shvetsov EG, Conard SG, Kalenskaya OP. 2016. The impact of increasing fire frequency on forest transformations in southern Siberia. *Forest Ecol. Manag.* 382:225–35

79. Seidl R, Thom D, Kautz M, Martin-Benito D, Peltoniemi M, et al. 2017. Forest disturbances under climate change. *Nat. Clim. Change* 7:395–402

80. Pellegrini AFA, Hobbie SE, Reich PB, Jumpponen A, Brookshire ENJ, et al. 2020. Repeated fire shifts carbon and nitrogen cycling by changing plant inputs and soil decomposition across ecosystems. *Ecol. Monogr.* 90:e01409

81. Knorr K, Jiang L, Arneth A. 2016. Climate, CO_2, and demographic impacts on global wildfire emissions. *Biogeosciences* 13:267–82

82. Donat MG, Lowry AL, Alexander LV, O'Gorman PA, Maher N. 2016. More extreme precipitation in the world's dry and wet regions. *Nat. Clim. Change* 6:508–13

83. Van Der Bolt B, Van Nes EH, Bathiany S, Vollebregt ME, Scheffer M. 2018. Climate reddening increases the chance of critical transitions. *Nat. Clim. Change* 8:478–84

84. Wang Z-H, Li S-X. 2019. Nitrate N loss by leaching and surface runoff in agricultural land: a global issue (a review). In *Advances in Agronomy*, Vol. 156, ed. DL Sparks, pp. 159–217. Amsterdam: Elsevier

85. Withers P, Neal C, Jarvie H, Doody D. 2014. Agriculture and eutrophication: Where do we go from here? *Sustainability* 6:5853–75

86. Eekhout JP, De Vente J. 2020. How soil erosion model conceptualization affects soil loss projections under climate change. *Prog. Phys. Geogr. Earth Environ.* 44:212–32

87. Lee C-Y, Camargo SJ, Sobel AH, Tippett MK. 2020. Statistical–dynamical downscaling projections of tropical cyclone activity in a warming climate: two diverging genesis scenarios. *J. Clim.* 33:4815–34

88. Patricola CM, Wehner MF. 2018. Anthropogenic influences on major tropical cyclone events. *Nature* 563:339–46

89. Marsooli R, Lin N, Emanuel K, Feng K. 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. *Nat. Commun.* 10:3785

90. Aksha SK, Juran L, Resler LM. 2018. Spatial and temporal analysis of natural hazard mortality in Nepal. *Environ. Hazards* 17:163–79

91. IPCC (Intergov. Panel Clim. Change). 2018. *Global Warming of 1.5°C*. Geneva: IPCC

92. Hanssen SV, Daioglou V, Steinmann ZJN, Doelman JC, Van Vuuren DP, Huijbregts MAJ. 2020. The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change* 10:1023–29

93. Gregg JS, Izaurralde RC. 2010. Effect of crop residue harvest on long-term crop yield, soil erosion and nutrient balance: trade-offs for a sustainable bioenergy feedstock. *Biofuels* 1:69–83

94. Liska AJ, Yang H, Milner M, Goddard S, Blanco-Canqui H, et al. 2014. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. *Nat. Clim. Change* 4:398–401

95. Hof C, Voskamp A, Biber MF, Böhning-Gaese K, Engelhardt EK, et al. 2018. Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. *PNAS* 115:13294–99

96. Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, et al. 2018. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* 13:063002

97. Girardello M, Santangeli A, Mori E, Chapman A, Fattorini S, et al. 2019. Global synergies and trade-offs between multiple dimensions of biodiversity and ecosystem services. *Sci. Rep.* 9:5636

98. Strassburg BBN, Beyer HL, Crouzeilles R, Iribarrem A, Barros P, et al. 2019. Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. *Nat. Ecol. Evol.* 3:62–70

99. Palomo I, Dujardin Y, Midler E, Robin M, Sanz MJ, Pascual U. 2019. Modeling trade-offs across carbon sequestration, biodiversity conservation, and equity in the distribution of global REDD plus funds. *PNAS* 116:22645–50

100. Nilsson C, Riis T, Sarneel J, Svavarsdóttir K. 2018. Ecological restoration as a means of managing inland flood hazards. *BioScience* 68:89–99

101. Morecroft MD, Duffield S, Harley M, Pearce-Higgins JW, Stevens N, et al. 2019. Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science* 366:eaaw9256

102. Donatti CI, Harvey CA, Hole D, Panfil SN, Schurman H. 2020. Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. *Clim. Change* 158:413–33

103. Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, Turner B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B* 375:20190120

104. Rhodes CJ. 2017. The imperative for regenerative agriculture. *Sci. Prog.* 100:80–129

105. Montgomery DR. 2017. *Growing a Revolution: Bringing Our Soil Back to Life*. New York: WW Norton & Co.

106. Kassam A, Friedrich T, Derpsch R. 2019. Global spread of conservation agriculture. *Int. J. Environ. Stud.* 76:29–51

107. Davis SC, Boddey RM, Alves BJR, Cowie AL, George BH, et al. 2013. Management swing potential for bioenergy crops. *GCB Bioenergy* 5:623–38

108. Witters N, Van Slycken S, Ruttens A, Adriaensen K, Meers E, et al. 2009. Short-rotation coppice of willow for phytoremediation of a metal-contaminated agricultural area: a sustainability assessment. *BioEnergy Res.* 2:144–52

109. Immerzeel DJ, Verweij PA, van der Hilst F, Faaij APC. 2014. Biodiversity impacts of bioenergy crop production: a state-of-the-art review. *GCB Bioenergy* 6:189–209

110. De Stefano A, Jacobson MG. 2018. Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Syst.* 92:285–99

111. Wilson MH, Lovell ST. 2016. Agroforestry—the next step in sustainable and resilient agriculture. *Sustainability* 8:574

112. Churkina G, Organschi A, Reyer CPO, Ruff A, Vinke K, et al. 2020. Buildings as a global carbon sink. *Nat. Sustain.* 3:269–76

113. Veldman JW, Overbeck GE, Negreiros D, Mahy G, Le Stradic S, et al. 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *Bioscience* 65:1011–18

114. Abreu RCR, Hoffmann WA, Vasconcelos HL, Pilon NA, Rossatto DR, Durigan G. 2017. The biodiversity cost of carbon sequestration in tropical savanna. *Sci. Adv.* 3:e1701284

115. Brundu G, Richardson DM. 2016. Planted forests and invasive alien trees in Europe: a code for managing existing and future plantings to mitigate the risk of negative impacts from invasions. *NeoBiota* 30:5–47

116. Wilson SJ, Schelhas J, Grau R, Nanni AS, Sloan S. 2017. Forest ecosystem-service transitions: the ecological dimensions of the forest transition. *Ecol. Soc.* 22:38

117. Aerts R, Honnay O. 2011. Forest restoration, biodiversity and ecosystem functioning. *BMC Ecol.* 11:29

118. Liang JJ, Crowther TW, Picard N, Wiser S, Zhou M, et al. 2016. Positive biodiversity-productivity relationship predominant in global forests. *Science* 354:aaf8957

119. Crouzeilles R, Curran M, Ferreira MS, Lindenmayer DB, Grelle CEV, Benayas JMR. 2016. A global meta-analysis on the ecological drivers of forest restoration success. *Nat. Commun.* 7:11666

120. Cross SL, Bateman PW, Cross AT. 2020. Restoration goals: Why are fauna still overlooked in the process of recovering functioning ecosystems and what can be done about it? *Ecol. Manag. Restor.* 21:4–8

121. Jouquet P, Blanchart E, Capowiez Y. 2014. Utilization of earthworms and termites for the restoration of ecosystem functioning. *Appl. Soil Ecol.* 73:34–40

122. Schmitz OJ, Wilmers CC, Leroux SJ, Doughty CE, Atwood TB, et al. 2018. Animals and the zoogeochemistry of the carbon cycle. *Science* 362:eaar3213

123. Kimmerer R. 2011. Restoration and reciprocity: the contributions of traditional ecological knowledge. In *Human Dimensions of Ecological Restoration. Society for Ecological Restoration*, ed. D Egan, EE Hjerpe, J Abrams, pp. 257–76. Washington, DC: Island Press

124. Nkonya E, Mirzabaev A, von Braun J. 2016. Economics of land degradation and improvement: an introduction and overview. In *Economics of Land Degradation and Improvement—A Global Assessment for Sustainable Development*, ed. E Nkonya, A Mirzabaev, J von Braun, pp. 1–14. Cham, Switz.: Springer Int. Publ.

125. Mentis M. 2020. Environmental rehabilitation of damaged land. *Forest Ecosyst.* 7:19

126. Giger M, Liniger H, Sauter C, Schwilch G. 2018. Economic benefits and costs of sustainable land management technologies: an analysis of WOCAT's global data. *Land Degrad. Dev.* 29:962–74

127. Lambin E, Meyfroidt P, Rueda X, Blackman A, Börner J, et al. 2014. Effectiveness and synergies of policy instruments for land use governance in tropical regions. *Glob. Environ. Change* 28:129–40

128. Reed MS, Stringer LC, Dougill AJ, Perkins JS, Atlhopheng JR, et al. 2015. Reorienting land degradation towards sustainable land management: linking sustainable livelihoods with ecosystem services in rangeland systems. *J. Environ. Manag.* 151:472–85

129. Scown MW, Brady MV, Nicholas KA. 2020. Billions in misspent EU agricultural subsidies could support the Sustainable Development Goals. *One Earth* 3:237–50

130. Wolff S, Schrammeijer EA, Schulp C, Verburg PH. 2018. Meeting global land restoration and protection targets: What would the world look like in 2050? *Glob. Environ. Change* 52:259–72

131. Metzger JP, Esler K, Krug C, Arias M, Tambosi L, et al. 2017. Best practice for the use of scenarios for restoration planning. *Curr. Opin. Environ. Sustain.* 29:14–25

132. Folke C. 2016. Resilience (Republished). *Ecol. Soc.* 21:44

133. Acosta LA, Virk A, Kumar R, Sharma S, Ikeda T, et al. 2018. Options for governance and decision-making across scales and sectors. In *The IPBES Regional Assessment Report on Biodiversity and Ecosystem Services for Asia and the Pacific*, ed. M Karki, SS Sellamuttu, W Suzuki, S Okayasu, pp. 429–536. Bonn, Ger.: IPBES Secr.

134. George C, Reed MG. 2015. Operationalising just sustainability: towards a model for place-based governance. *Local Environ.* 22:1105–23

135. Parlee CE, Wiber MG. 2018. Using conflict over risk management in the marine environment to strengthen measures of governance. *Ecol. Soc.* 23:5

136. Cowie AL, Orr BJ, Castillo Sanchez VM, Chasek P, Crossman ND, et al. 2018. Land in balance: the scientific conceptual framework for land degradation neutrality. *Environ. Sci. Policy* 79:25–35

137. Fagan ME, Reid JL, Holland MB, Drew JG, Zahawi RA. 2020. How feasible are global forest restoration commitments? *Conserv. Lett.* 13:e12700

138. Seddon N, Sengupta S, García-Espinosa M, Hauler I, Herr D, Rizvi AR. 2019. *Nature-Based Solutions in Nationally Determined Contributions: Synthesis and Recommendations for Enhancing Climate Ambition and Action by 2020*. Gland, Switz./Oxford: Int. Union Conserv. Nat., Univ. Oxford

139. Metzger MJ, Dick J, Gardner A, Bellamy C, Blackstock K, et al. 2019. Knowledge sharing, problem solving and professional development in a Scottish Ecosystem Services Community of Practice. *Reg. Environ. Change* 19:2275–86

140. Eakin H, York A, Aggarwal R, Waters S, Welch J, et al. 2016. Cognitive and institutional influences on farmers' adaptive capacity: insights into barriers and opportunities for transformative change in central Arizona. *Reg. Environ. Change* 16:801–14

141. Wreford A, Ignaciuk A, Gruere G. 2017. *Overcoming barriers to the adoption of climate-friendly practices in agriculture*. Pap. 101, Food, Agric. Fish., Org. Econ. Co-op. Dev., Paris

142. Barnett J, Evans LS, Gross C, Kiem AS, Kingsford RT, et al. 2015. From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecol. Soc.* 20:5

143. Dow K, Berkhout F, Preston BL, Klein RJT, Midgley G, Shaw MR. 2013. Limits to adaptation. *Nat. Clim. Change* 3:305–7

144. Arneth A, Shin Y-J, Leadley P, Rondinini C, Bukvareva E, et al. 2020. Post-2020 biodiversity targets need to embrace climate change. *PNAS* 117:30882–91

145. Kwakkel JH, Haasnoot M, Walker WE. 2016. Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environ. Model. Software* 86:168–83

146. Otto IM, Wiedermann M, Cremades R, Donges JF, Auer C, Lucht W. 2020. Human agency in the Anthropocene. *Ecol. Econ.* 167:106463

147. Pörtner HO, Scholes RJ, Agard J, Archer E, Arneth A, et al. 2021. *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change*. Rep., IPBES (Intergov. Sci.-Policy Platf. Biodivers. Ecosyst. Serv.), Bonn, Ger. **http://doi.org/10.5281/zenodo.4659158**

148. Bullock JM, Aronson J, Newton AC, Pywell RF, Rey-Benayas JM. 2011. Restoration of ecosystem services and biodiversity: conflicts and opportunities. *Trends Ecol. Evol.* 26:541–49

149. Kollmann J, Meyer ST, Bateman R, Conradi T, Gossner MM, et al. 2016. Integrating ecosystem functions into restoration ecology—recent advances and future directions. *Restor. Ecol.* 24:722–30

150. Krausmann F, Erb K-H, Gingrich S, Haberl H, Bondeau A, et al. 2013. Global human appropriation of net primary production doubled in the 20th century. *PNAS* 110:10324–29

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V. Methods and Indicators