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A Critical Review

Biodiversity Loss in a Changing World: Drivers, Ecosystem Consequences, and Pathways to Conservation and Restoration

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Abstract

Biodiversity underpins ecosystem functioning, human well-being, and resilience to environmental change, yet it is declining at rates unprecedented in human history. This critical review synthesises evidence on the extent and drivers of biodiversity loss across terrestrial, freshwater, and marine systems, the consequences of loss for ecosystem services and human societies, and the effectiveness of conservation and restoration strategies. It shows that habitat loss and degradation, overexploitation, invasive species, pollution, and climate change interact and amplify one another, producing declines in species abundance, genetic diversity, and ecosystem integrity. Monitored vertebrate populations have fallen sharply since 1970, extinction risk is rising for many groups, and ecosystem services including pollination, water purification, carbon storage, and fisheries are being eroded. The review evaluates protected areas, other effective area-based conservation measures, ecological restoration, sustainable land and sea use, and species-focused interventions, and examines the role of Indigenous and local knowledge, governance, finance, and the Kunming-Montreal Global Biodiversity Framework. It argues that conservation must move beyond isolated protected areas toward integrated, equitable, and landscape-scale approaches that address the underlying drivers of loss while supporting livelihoods. Priorities for research, monitoring, and action are identified.

Keywords: *biodiversity; extinction; ecosystem services; conservation; restoration; habitat loss; climate change; protected areas*

1. Introduction

Biodiversity, the variety of genes, species, and ecosystems, is the living fabric of the planet (Convention on Biological Diversity, 1992; Millennium Ecosystem Assessment, 2005). It provides food, medicine, clean water, pollination, climate regulation, and cultural and spiritual values, and it underpins the stability of ecosystems on which all life depends (Millennium Ecosystem Assessment, 2005; Díaz et al., 2019). Yet the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services warned that nature is declining globally at rates unprecedented in human history, with around one million species threatened with extinction, many within decades (Díaz et al., 2019; IPBES, 2019). The Living Planet Index reported an average decline of about 69 percent in monitored vertebrate populations between 1970 and 2018, with freshwater populations declining most steeply (WWF, 2022; WWF, 2024). These figures are not merely statistics about distant wildlife; they signal erosion of the ecological foundations of agriculture, fisheries, water security, and climate resilience.

Biodiversity loss is often framed as a conservation issue, separate from development, climate, and health. In reality, it is deeply connected to them (Díaz et al., 2019; Pecl et al., 2017). Land-use change that destroys forests also releases carbon, alters rainfall, and increases zoonotic disease risk (Pecl et al., 2017; IPBES, 2019). Overfishing

depletes food and livelihoods while destabilising marine food webs (Pauly et al., 2002; Worm et al., 2006). Pollution harms species and people together (Millennium Ecosystem Assessment, 2005). Understanding biodiversity loss therefore requires an integrated view that links ecology, economics, governance, culture, and human well-being.

This review has four aims. First, it describes what biodiversity is, how it is measured, and what current trends show. Second, it explains the direct and indirect drivers of loss and how they interact. Third, it evaluates consequences for ecosystem functioning, ecosystem services, and human societies. Fourth, it assesses conservation and restoration strategies, from protected areas to landscape-scale and community-led approaches, and examines policy, finance, and governance. It draws on global assessments, long-term monitoring, experimental studies, and case studies from terrestrial, freshwater, and marine systems, with emphasis on literature published between 2000 and 2025.

A central argument is that biodiversity loss is not inevitable, nor is it solved by protecting isolated patches of habitat while drivers continue elsewhere. Conservation succeeds when it addresses the causes of loss, respects the rights and knowledge of Indigenous Peoples and local communities, and integrates biodiversity into agriculture, fisheries, forestry, urban planning, and finance (Díaz et al., 2019; Jonas et al., 2014). The review therefore treats biodiversity as a whole-system challenge, not only as a matter of saving charismatic species.

2. What Is Biodiversity and How Is It Measured?

Biodiversity is commonly understood at three levels: genetic diversity within species, species diversity, and ecosystem diversity (Convention on Biological Diversity, 1992; Millennium Ecosystem Assessment, 2005). Genetic diversity allows populations to adapt to changing conditions, resist disease, and maintain productivity in crops and livestock (Frankham et al., 2010). Species diversity shapes interactions such as predation, competition, pollination, and seed dispersal, which in turn shape ecosystem functioning (Hooper et al., 2005; Cardinale et al., 2012). Ecosystem diversity refers to the variety of habitats, from forests and grasslands to wetlands, coral reefs, and deep-sea systems, each with distinct communities and processes (Millennium Ecosystem Assessment, 2005). Functional diversity, the variety of traits and ecological roles, is increasingly recognised as critical, because two ecosystems with the same number of species can function very differently if one lacks pollinators, predators, or decomposers (Hooper et al., 2005; Cardinale et al., 2012).

Measurement remains challenging. Species richness is easy to count but says little about abundance, evenness, or function (Magurran, 2004). The Living Planet Index tracks trends in population abundance, the Red List Index tracks changes in extinction risk, and the Biodiversity Intactness Index estimates how much of an original community remains (WWF, 2022; IUCN, 2023). Remote sensing, environmental DNA, acoustic monitoring, and citizen science are expanding coverage, but tropical forests, deep oceans, soil, and freshwater systems remain under-sampled (IPBES, 2019; Díaz et al., 2019). A decline in abundance often precedes extinction, so population trends are early warnings, not only outcomes (WWF, 2022). Figure 2 illustrates the pattern of decline in monitored vertebrate populations, which is steepest for freshwater species and for tropical regions (WWF, 2024).

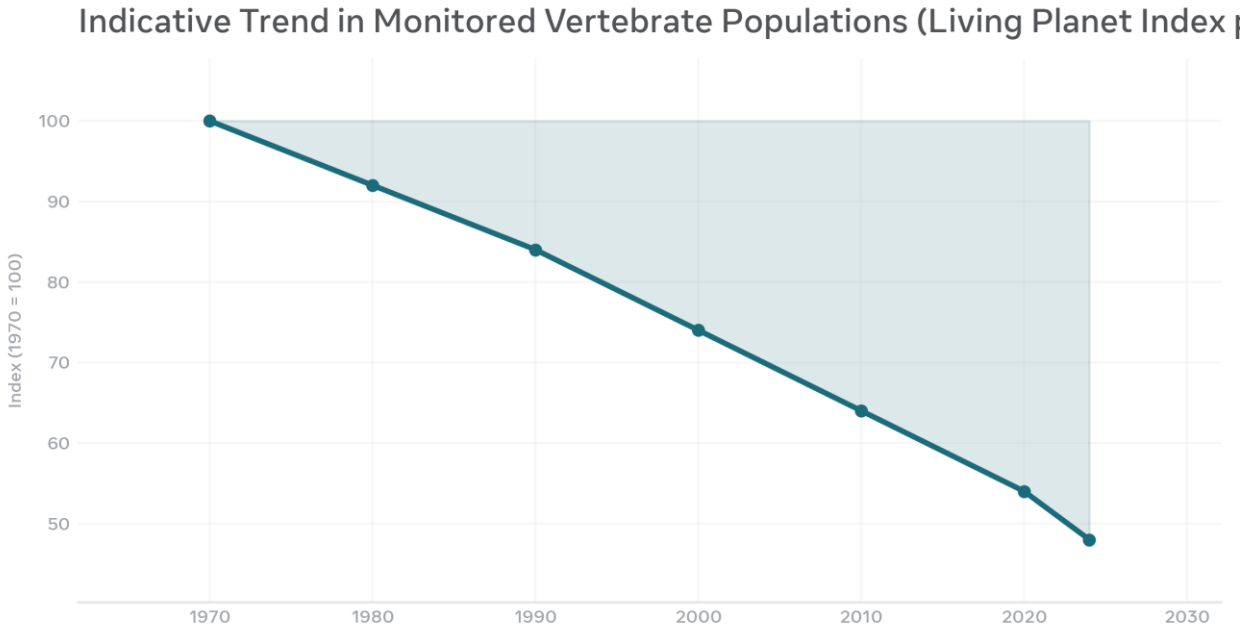

Figure 2. Indicative trend in monitored vertebrate populations, following the pattern reported by the Living Planet Index (WWF, 2022; WWF, 2024). Freshwater populations have declined most steeply.

Extinction risk is assessed by the International Union for Conservation of Nature Red List, which classifies species as Least Concern through Critically Endangered, Extinct in the Wild, and Extinct (IUCN, 2023). About 28 percent of assessed species are threatened, with higher shares for amphibians, reef-building corals, and many freshwater

groups (IUCN, 2023; Díaz et al., 2019). However, most species have not been assessed, and insects, fungi, and soil organisms are especially poorly known (IPBES, 2019). Estimates of total species numbers range from about two million described to perhaps eight million or more in total, meaning that many species may be lost before they are even described (Mora et al., 2011). This taxonomic gap is itself a conservation challenge, because unknown species cannot be protected by name, although protecting habitats can protect them indirectly.

3. Drivers of Biodiversity Loss

The IPBES Global Assessment identified five direct drivers: land- and sea-use change, direct exploitation, climate change, pollution, and invasive alien species (IPBES, 2019; Díaz et al., 2019). Figure 1 summarises their relative importance for assessed species, recognising that drivers overlap and that their ranking varies by ecosystem and region. Indirect drivers, including population growth, consumption, trade, technology, governance, and values, shape the direct drivers (IPBES, 2019).

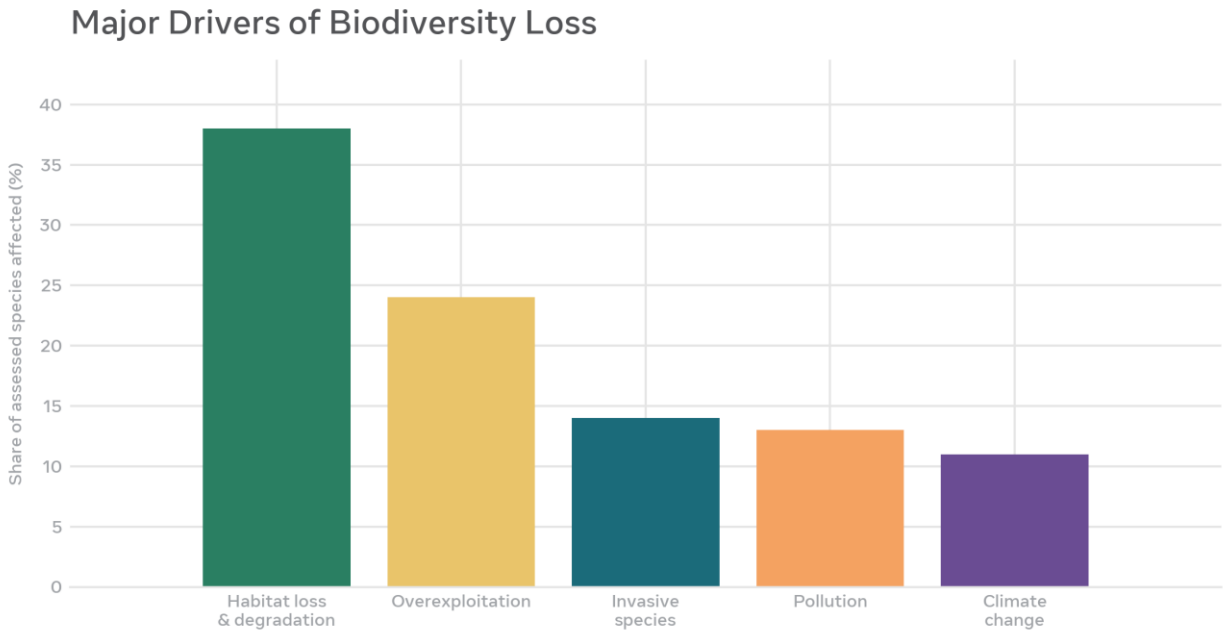

Figure 1. Major drivers of biodiversity loss, synthesised from IPBES (2019) and Díaz et al. (2019). Drivers interact and their relative importance varies by ecosystem.

Land- and sea-use change is the largest driver on land and in many coastal systems (IPBES, 2019; Newbold et al., 2015). Agriculture, including cropland, pasture, and plantations, now occupies about half of habitable land, and expansion into forests, savannas, and wetlands continues in many tropical regions (Foley et al., 2005; Newbold et al., 2015). Foley et al. (2005) showed that agriculture has transformed vast areas, altering nutrient cycles, hydrology, and habitat connectivity. Habitat fragmentation divides remaining habitat into smaller, more isolated patches, reducing population sizes, increasing edge effects, and limiting dispersal and gene flow (Haddad et al., 2015). Haddad et al. (2015) found, in a global fragmentation experiment, that fragmented habitats had reduced biodiversity, altered ecosystem functions, and increased vulnerability to further change. Urbanisation, mining, infrastructure, and dams add further pressure, especially in biodiversity hotspots (IPBES, 2019).

Direct exploitation includes hunting, fishing, logging, and harvesting of wild species beyond sustainable levels (IPBES, 2019; Pauly et al., 2002). In marine systems, overfishing has depleted large predatory fish, altered food webs, and reduced resilience (Pauly et al., 2002; Worm et al., 2006). Worm et al. (2006) found that loss of marine biodiversity was associated with reduced fisheries productivity, water quality, and recovery from disturbance. On land, bushmeat hunting, illegal wildlife trade, and unsustainable logging threaten many mammals, birds, and trees, especially in tropical forests (IPBES, 2019). Even legal harvesting can become unsustainable when demand grows, enforcement is weak, or populations are already stressed by habitat loss and climate change.

Climate change is an increasingly important driver that interacts with all others (Pecl et al., 2017; IPBES, 2019). Species are shifting ranges poleward and to higher elevations, altering phenology, and facing novel climates with no historical analogue (Pecl et al., 2017; Chen et al., 2011). Chen et al. (2011) found that species are moving to higher elevations and latitudes, but many cannot move fast enough, especially in fragmented landscapes. Coral bleaching, driven by marine heatwaves, threatens reef ecosystems that support a quarter of marine species and millions of livelihoods (Hughes et al., 2017). Climate change also increases fire, drought, and storms, which can transform ecosystems abruptly (Pecl et al., 2017). Species that are already threatened by habitat loss or exploitation are most vulnerable to climate change, because they have fewer refuges and less genetic diversity to adapt (IPBES, 2019).

Pollution includes nutrients, pesticides, plastics, heavy metals, light, noise, and other contaminants (Millennium Ecosystem Assessment, 2005; IPBES, 2019). Nutrient

runoff causes eutrophication, algal blooms, and oxygen depletion in lakes, rivers, and coastal waters, harming fish and invertebrates (Millennium Ecosystem Assessment, 2005). Pesticides can harm pollinators, aquatic invertebrates, and birds, even at sublethal concentrations (Hallmann et al., 2017). Hallmann et al. (2017) documented a dramatic decline in flying insect biomass in German protected areas, linked to agricultural intensification and pesticide use, although the exact causes remain debated. Plastic pollution affects wildlife through ingestion, entanglement, and habitat alteration, with freshwater and marine species both affected (Geyer et al., 2017). Light and noise pollution disrupt navigation, communication, and reproduction for many species, especially nocturnal animals and marine mammals (IPBES, 2019).

Invasive alien species are a major driver, especially on islands and in freshwater systems (IPBES, 2023; Pyšek et al., 2020). The IPBES invasive species assessment found that invasive species have contributed to about 60 percent of recorded global extinctions and cost the world economy hundreds of billions of dollars annually (IPBES, 2023). Invasive species can prey on natives, compete for resources, introduce diseases, hybridise, and alter ecosystem processes such as fire regimes and nutrient cycling (Pyšek et al., 2020). Trade, travel, and climate change increase introduction and establishment, making prevention, early detection, and rapid response more cost-effective than eradication after spread (IPBES, 2023).

Table 1. Direct drivers of biodiversity loss, synthesised from IPBES (2019), Díaz et al. (2019), and IPBES (2023).

Driver	Main mechanisms	Most affected systems	Examples
Land- and sea-use change	Habitat loss, fragmentation, degradation	Forests, grasslands, wetlands, coastal	Deforestation, agricultural expansion, urbanisation
Overexploitation	Unsustainable hunting, fishing, logging	Marine, tropical forests	Overfishing, bushmeat, illegal wildlife trade
Climate change	Range shifts, phenology, bleaching, extremes	Coral reefs, polar, mountains, freshwater	Coral bleaching, range shifts, drought
Pollution	Eutrophication, pesticides, plastics, toxins	Freshwater, coastal, agricultural landscapes	Nutrient runoff, pesticide impacts on pollinators
Invasive species	Predation, competition, disease, hybridisation	Islands, freshwater, lakes	Invasive predators on islands, aquatic invaders

4. Consequences for Ecosystems and People

Biodiversity loss affects ecosystem functioning through multiple pathways. Cardinale et al. (2012) reviewed experimental evidence and concluded that biodiversity loss reduces the efficiency of resource capture, biomass production, decomposition, and nutrient recycling, and that these effects can be as large as those of other global change drivers. Hooper et al. (2005) found that species richness and functional composition influence ecosystem processes, with greater effects when species have complementary traits. Loss of key species, such as top predators, pollinators, or ecosystem engineers, can have disproportionate effects, triggering trophic cascades (Estes et al., 2011). Estes et al. (2011) showed that loss of apex predators can reshape ecosystems, from kelp forests to savannas, by releasing herbivores and altering vegetation. Functional redundancy can buffer some losses, but redundancy is often lower than assumed, and multiple species may be needed across varying conditions (Cardinale et al., 2012).

Ecosystem services are being eroded. Pollination, provided largely by insects, supports about three-quarters of leading food crops, and declines in pollinators threaten yields and nutrition (Potts et al., 2016; IPBES, 2019). Potts et al. (2016) warned that pollinator declines, driven by habitat loss, pesticides, disease, and climate change, pose risks to food security, especially for smallholders who depend on diverse crops. Freshwater ecosystems provide water purification, flood regulation, and fisheries, but they are among the most threatened, with freshwater vertebrate populations declining faster than terrestrial or marine groups (WWF, 2022; Tickner et al., 2020). Tickner et al. (2020) called for an Emergency Recovery Plan for freshwater biodiversity, combining habitat protection, water quality improvement, flow restoration, and invasive species control. Marine ecosystems provide fisheries, coastal protection, and carbon storage in mangroves, seagrasses, and salt marshes, all of which are declining in many regions (Worm et al., 2006; IPBES, 2019).

Forests, which host most terrestrial biodiversity, also store carbon and regulate water. Deforestation and degradation release carbon, reduce rainfall recycling, and increase vulnerability to fire and drought (Foley et al., 2005; IPBES, 2019). Soil biodiversity, including bacteria, fungi, and invertebrates, underpins nutrient cycling, soil structure, and crop productivity, yet it is poorly monitored and threatened by intensive agriculture, erosion, and pollution (FAO, 2020). The Food and Agriculture Organization (2020) warned that soil biodiversity loss threatens food security, because healthy soils depend on diverse communities. Biodiversity loss also affects human health: loss of genetic diversity in crops and livestock reduces resilience to pests and climate change, while habitat change can increase zoonotic disease risk by altering host-pathogen dynamics (IPBES, 2019; Pecl et al., 2017).

Cultural and economic consequences are also large. Indigenous Peoples and local communities, who steward a disproportionate share of remaining biodiversity, depend on wild species for food, medicine, income, and identity (Garnett et al., 2018; Jonas et al., 2014). Garnett et al. (2018) found that Indigenous lands cover about a quarter of the global land surface and intersect with a large share

of protected areas and remaining wilderness, yet Indigenous rights are often insecure. Loss of species can erode cultural practices, languages, and knowledge, which are themselves repositories of ecological understanding (Díaz et al., 2019). Economically, the World Economic Forum has repeatedly ranked biodiversity loss and ecosystem collapse among the top global risks, reflecting dependence of agriculture, fisheries, forestry, tourism, and pharmaceuticals on nature (World Economic Forum, 2023).

5. Conservation and Restoration Strategies

Protected areas are the cornerstone of conservation, covering about 17 percent of land and inland waters and about 8 percent of oceans, with targets to reach 30 percent by 2030 under the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022; IPBES, 2019). Protected areas can reduce habitat loss, protect threatened species, and maintain ecosystem services, but their effectiveness depends on location, management, funding, and community support (Geldmann et al., 2013; Watson et al., 2014). Geldmann et al. (2013) found that many protected areas reduce deforestation, but that effectiveness varies, and that paper parks with no management provide little benefit. Watson et al. (2014) warned that protected areas are increasingly isolated and under pressure from surrounding land use, reducing their long-term value unless connectivity is improved.

Other effective area-based conservation measures, including Indigenous territories, community conserved areas, and sustainably managed fisheries, can complement protected areas (Jonas et al., 2014; Convention on Biological Diversity, 2022). These areas may not have conservation as their primary objective, but they can deliver biodiversity outcomes while supporting livelihoods (Jonas et al., 2014). Connectivity is essential: corridors, stepping stones, and landscape permeability allow species to move, genes to flow, and ecosystems to adapt to climate change (Haddad et al., 2015; Pecl et al., 2017). Without connectivity, protected areas become islands, vulnerable to inbreeding, stochastic events, and climate shifts.

Ecological restoration aims to assist recovery of degraded ecosystems, from forests and wetlands to coral reefs and grasslands (Gann et al., 2019; IPBES, 2019). The United Nations Decade on Ecosystem Restoration (2021-2030) calls for preventing, halting, and reversing degradation (United Nations, 2019). Gann et al. (2019) set standards for restoration that emphasise native species, ecological integrity, and social engagement, rather than simply planting trees. Tree planting can restore forests and store carbon, but monoculture plantations can harm biodiversity, water, and livelihoods if they replace native ecosystems or displace communities (Holl and Brancalion, 2020). Holl and Brancalion (2020) argued that natural regeneration, assisted regeneration, and diverse native plantings often deliver greater biodiversity and resilience than large-scale monocultures, at lower cost. Restoration must be measured by ecological outcomes, not only by area planted or trees counted.

Species-focused interventions include captive breeding, reintroduction, translocation, and control of invasive species and poaching (IPBES, 2019). These interventions can save species on the brink, such as the California condor or black-footed ferret, but they are costly and work best when habitat and threats are also addressed (Frankham et al., 2010). Ex situ conservation in zoos, botanical gardens, and seed banks provides insurance, but it cannot replace wild populations and their ecological roles (Convention on Biological Diversity, 1992). Community-based conservation, where local people manage wildlife, forests, or fisheries and benefit from them, has shown success in Namibia, Nepal, and elsewhere, but it requires secure tenure, fair benefit-sharing, and strong local institutions (Jonas et al., 2014; Garnett et al., 2018).

Table 2. Conservation and restoration strategies, synthesised from IPBES (2019), Gann et al. (2019), and Jonas et al. (2014).

Strategy	What it does	Strengths	Limits and risks
Protected areas	Protect habitat and species in designated areas	Reduces habitat loss, protects threatened species	Isolation, underfunding, displacement if poorly designed
Other area-based measures	Conservation in Indigenous and community areas	Supports livelihoods, large coverage	Recognition and tenure often insecure
Ecological restoration	Assist recovery of degraded ecosystems	Restores function, carbon, services	Can fail if species, soils, or threats ignored
Species interventions	Captive breeding, reintroduction, anti-poaching	Saves species on brink	Costly, needs habitat and threat reduction
Sustainable use	Manage fisheries, forestry, hunting sustainably	Maintains livelihoods and incentives	Requires monitoring, enforcement, and quotas
Invasive control	Prevent, detect, eradicate invasives	Cost-effective if early	Difficult after spread, non-target risks

6. Governance, Finance, and the Kunming-Montreal Framework

The Kunming-Montreal Global Biodiversity Framework, adopted in 2022, sets four goals and 23 targets for 2030, including protecting 30 percent of land and seas, restoring 30 percent of degraded ecosystems, reducing extinction risk, and ensuring sustainable use and equitable benefit-sharing (Convention on Biological Diversity, 2022). It also calls for reforming harmful subsidies, mobilising finance, and respecting Indigenous rights (Convention on Biological Diversity, 2022). Implementation will require national strategies, monitoring, and accountability, which

have been weak under previous targets (IPBES, 2019). The Aichi Targets for 2020 were largely missed, partly because they were not integrated into economic and sectoral policy (IPBES, 2019; Díaz et al., 2019). The new framework seeks to address this by linking biodiversity to climate, agriculture, fisheries, and finance, but its success depends on political will and resources.

Finance is a major gap. The IPBES assessment estimated that harmful subsidies, including for agriculture, fisheries, and fossil fuels, far exceed biodiversity finance, creating perverse incentives (IPBES, 2019). Reforming subsidies that drive deforestation, overfishing, and pollution is therefore as important as increasing conservation funding (Convention on Biological Diversity, 2022). Innovative finance includes biodiversity credits, payments for ecosystem services, debt-for-nature swaps, and green bonds, but these instruments must be designed to avoid greenwashing, ensure additionality, and respect community rights (IPBES, 2019). Payments for ecosystem services, where landholders are paid to maintain forests or watersheds, can work when payments are sufficient, monitoring is credible, and tenure is secure, but they can fail if they displace communities or create dependence (Jonas et al., 2014).

Governance must be inclusive. Indigenous Peoples and local communities are often the most effective stewards, yet they face insecure tenure, limited funding, and exclusion from decisions (Garnett et al., 2018; Jonas et al., 2014). Free, prior, and informed consent, secure land rights, and support for community monitoring and management are essential for both equity and effectiveness (Convention on Biological Diversity, 2022). Gender, youth, and social inclusion also matter: women, who often manage seeds, forests, and water, are underrepresented in conservation governance, while youth bring innovation and long-term stakes (Díaz et al., 2019). Cross-sectoral governance, linking biodiversity with climate, agriculture, health, and urban planning, can reduce trade-offs and create co-benefits, for example through nature-based solutions that protect biodiversity while reducing flood risk and storing carbon (IPBES, 2019; Pecl et al., 2017).

7. Research Gaps and Future Directions

Several gaps deserve priority. First, monitoring needs expansion, especially for insects, fungi, soil, freshwater, and deep-sea systems, and for genetic diversity (IPBES, 2019; FAO, 2020). Environmental DNA, remote sensing, and citizen science can help, but they need validation, standards, and long-term funding (WWF, 2024). Second, research on interactions among drivers is needed, because drivers rarely act alone and their combined effects can be synergistic (Pecl et al., 2017; IPBES, 2019). Third, research on ecosystem function, resilience, and tipping points is needed to identify when ecosystems shift irreversibly, such as coral reefs, tropical forests, and drylands (Hooper et al., 2005; Hughes et al., 2017). Fourth, research on restoration outcomes, including long-term biodiversity, carbon, and livelihood effects, is needed to guide investment (Gann et al., 2019; Holl and Brancalion, 2020). Fifth, social science research on governance, equity, behaviour, and finance is needed, because technical solutions alone will not address the underlying causes of loss (Díaz et al., 2019; Jonas et al., 2014). Finally, research must be co-produced with Indigenous Peoples and local communities, respecting their knowledge and rights, not merely extracting data (Garnett et al., 2018).

Future directions should also address the biodiversity-climate nexus. Nature-based solutions, such as forest protection, wetland restoration, and mangrove conservation, can deliver both biodiversity and climate benefits, but they must be designed for biodiversity, not only carbon (IPBES, 2019; Pecl et al., 2017). Planting trees in grasslands or peatlands, for example, can harm biodiversity and release carbon, even if it is counted as climate action (Holl and Brancalion, 2020). Integrated approaches that protect primary ecosystems, restore degraded ones, and transform food, energy, and urban systems are needed, rather than offsetting destruction in one place with planting in another (Díaz et al., 2019).

8. Conclusion

Biodiversity loss is a defining challenge of this century, driven by habitat change, overexploitation, invasive species, pollution, and climate change, and amplified by consumption, trade, and governance failures (IPBES, 2019; Díaz et al., 2019). Its consequences extend far beyond wildlife, eroding pollination, water, fisheries, carbon storage, soil health, and cultural values (Millennium Ecosystem Assessment, 2005; Cardinale et al., 2012). Conservation has tools that work, including protected areas, restoration, sustainable use, and community-led management, but they must be scaled, funded, and integrated into all sectors (Gann et al., 2019; Jonas et al., 2014). The Kunming-Montreal Framework provides a shared vision, but its targets will only be met if governments, businesses, and communities act together, respect rights, and address the drivers of loss (Convention on Biological Diversity, 2022). Protecting biodiversity is not a luxury; it is essential for a livable, resilient, and just future.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

This review is based on published literature cited in the reference list. No new experimental data were generated. Figures present synthesised indicative values from the cited sources.

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