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Ecosystem services, biodiversity, and resilience against global climate change

Morteza Naderi[1*], Negar Fallahi Akhlamad[2]

[1]*Department of Biology, Faculty of Sciences, Sakarya University, Sakarya, Türkiye*
[2]*Department of Environmental Engineering, Dokuz Eylul University, Izmir, Türkiye*
[*]*Email: mortezanaderi@sakarya.edu.tr*

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Abstract

The accelerating impacts of global climate change are clearly observable in many parts of the world. In much of the Middle East, prolonged droughts and the absence of regular autumn and winter precipitation have become persistent features, while in several Mediterranean countries, devastating floods and other hydrological extremes are increasingly frequent. These changes threaten ecosystems and human communities worldwide, particularly in regions whose food security, water availability, and livelihoods depend directly on ecosystem services. Biodiversity, through its structural and functional complexity, plays a critical role in maintaining and enhancing ecosystem resilience to climate variability and extreme events. As biodiversity erodes, ecosystems may face serious challenges in sustaining the provisioning, regulating, supporting, and cultural services on which societies rely. This review synthesises evidence on how ecosystem services are underpinned by biodiversity and how this relationship shapes resilience to climate change. Drawing on studies from forests, grasslands, wetlands, agricultural systems, mangroves, and coral reefs, we show that higher biodiversity generally enhances resistance and recovery in the face of drought, heat stress, flooding, and pest outbreaks. At the same time, I examined the most common approaches for modelling and valuing ecosystem services—from land-cover–based and process-based models to integrated decision-support tools such as InVEST and ARIES, and economic or multi-criteria valuation methods—and discussed their respective strengths and limitations in a changing climate context. Despite clear benefits of biodiversity-rich systems, major challenges remain: land-use change, habitat fragmentation, agricultural intensification, and socio-economic constraints restrict the adaptive capacity of both ecosystems and human communities, while current policy frameworks often fail to integrate biodiversity conservation with climate adaptation strategies. I conclude that scaling up ecosystem-based adaptation, restoring

and protecting biodiverse habitats, and building adaptive capacity through education and knowledge systems are essential to safeguard ecosystem services and resilience in the face of global climate change.
Keywords: ecosystem services, biodiversity, resilience, climate change, adaptation, ecosystem-based solutions, sustainable development

Introduction

Climate change is one of the most critical environmental and socio-economic challenges of the 21st century (IPCC, 2021; UNEP, 2022). Global temperatures have risen approximately 1.1°C above before the industrialization, and if the current emission scenarios continue, we may expect further warming of 1.5–2.0°C or even more by 2100 (IPCC, 2023). The impacts are already visible: shifting precipitation patterns, increased frequency and intensity of extreme weather events (droughts, floods, heatwaves), sea-level rise, and disruption of ecosystems and agricultural systems across all continents (IPCC, 2021; UNEP, 2022). Simultaneously, biodiversity loss has reached unprecedented rates. The global Living Planet Index indicates a 68% decline in vertebrate populations since 1970, with habitat loss, overexploitation, and pollution as primary drivers (WWF, 2022). Approximately one million species (both animals and plants) are threatened with extinction (IPBES, 2019). This dual crisis—climate change and biodiversity loss—is not separate but deeply interconnected: climate change accelerates species extinctions, and biodiversity loss reduces ecosystem resilience to climate variability (Scholes & Biggs, 2005). Ecosystems provide essential services that support human well-being, including clean water, pollination, climate regulation, soil formation, and cultural benefits (Millennium Ecosystem Assessment, 2005; Daily et al., 2000). These ecosystem services are underpinned by biodiversity—the variety of genes, species, and ecosystems—and their functional interactions (Naeem et al., 2009). When biodiversity declines, the capacity of ecosystems to provide these services declines, and their resilience to climate shocks diminishes (Hooper et al., 2012; Cardinale et al., 2012). Despite growing recognition of these linkages, integration of biodiversity conservation with climate adaptation remains limited in policy and practice. Many climate adaptation strategies focus narrowly on infrastructure and technological solutions, overlooking nature-based solutions and the role of intact, biodiverse ecosystems (Locatelli et al., 2015). Conversely, biodiversity conservation efforts often do not adequately account for climate change impacts and the need to maintain dynamic adaptive capacity (Dawson et al., 2018).

The purpose of this review is to synthesise evidence on how ecosystem services, biodiversity, and resilience to climate change are interconnected, and to identify pathways for integrating these dimensions into sustainable management and policy. We examine mechanisms underlying these linkages, present evidence from major ecosystem types, discuss challenges and trade-offs, and propose implications for policy, practice, and research.

Ecosystem services, biodiversity, and resilience

Ecosystem services are the benefits that humans derive from ecosystems (Dashtbozorgi et al. 2021). The Millennium Ecosystem Assessment (MA) classifies these into four categories (Sala et al. 2017) of Provisioning services which is direct products obtained from ecosystems (food, freshwater, genetic resources, pharmaceuticals, fuel, fibre); Regulating services, referes back to the processes that regulate environmental conditions (climate regulation, water purification, pollination, pest control, flood and erosion control, disease regulation); Supporting services is about processes necessary for the production of all other services (nutrient cycling, primary production, soil formation, oxygen production) and finally cultural services which is non-material benefits from ecosystems (recreation, spiritual and cultural identity, aesthetic value, educational value). Meanwhile, ecosystem services are valued in monetary and non-monetary terms and are critical to sustainable development and human well-being (de Groot et al. 2012). For example, pollination alone provides approximately USD 200–600 billion annually in agricultural value, while wetlands provide water purification and flood protection worth trillions of dollars (Klein et al. 2007, Costanza et al. 1997).

Biodiversity dimensions, functions, and resilience

Biodiversity encompasses three main dimensions, including genetic diversity, species diversity, and ecosystem diversity (Purvis & Hector 2000). Biodiversity supports ecosystem services through multiple mechanisms, including resource provisioning, functional diversity, and Spatial and temporal heterogeneity. At the same time, one of the services that ecosystems provide is habitat for biodiversity. Resilience is defined as "the capacity of a social-ecological system to absorb disturbances while retaining essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004). Key dimensions include resistance, the ability to withstand a disturbance without significant change; recovery, the rate and completeness of return to a reference state or trajectory after disturbance; adaptation, adjustment of social-ecological systems to new conditions; and lastly, transformability, the capacity to shift to new system configurations if the current one is no longer viable. In the context of climate change, ecological resilience refers to the ability of ecosystems to maintain ecosystem functions, biodiversity, and services under changing climate conditions (Elmqvist et al. 2003). Translating these biodiversity–resilience mechanisms into policy requires tools that can quantify ecosystem services and their changes under climate scenarios.

Modelling and valuing ecosystem services under climate change

Ecosystem services can be evaluated using a wide spectrum of modelling and valuation approaches, from simple land-cover-based methods to process-based and AI-assisted frameworks. At one end, many assessments rely on GIS- and land-cover–based models or “ecosystem service bundles”, where each land-cover class is assigned an ES potential and mapped spatially; these approaches are transparent and data-efficient, but they treat ES as static functions of land use and often fail to capture management intensity, heterogeneity, or temporal dynamics (Schirpke et al., 2019). More mechanistic, biophysical models such as SWAT, HYDRUS, dynamic global vegetation models (e.g., LPJ, LPJ-GUESS, ORCHIDEE), and crop models (e.g., APSIM, DSSAT, SIMPLACE) simulate hydrological and ecological processes and are well-suited to scenario analysis, but they are data-intensive and usually focus on a subset of services such as water regulation, erosion control, or crop production rather than a full ES portfolio (Arnold et al., 1998). Building on these foundations, integrated decision-support platforms such as InVEST, ARIES, LUCI, and Co$ting Nature combine spatial data with simplified biophysical or production-function relationships to quantify multiple services and, in some cases, monetise them. Comparative assessments consistently identify InVEST as the most widely applied, independently usable ES platform in peer-reviewed, landscape-scale applications, while ARIES, LUCI, Co$ting Nature, SolVES, and related tools tend to be used more selectively depending on context, data availability, and service focus (Bagstad et al., 2013; Villa et al., 2014; Jackson et al., 2013; Dashtbozorgi et al., 2023).

Beyond these platforms, ES evaluations also employ a range of valuation formulas and frameworks. Equivalent value factor (EVF) methods and gross ecosystem product (GEP) accounting have been used to quantify and compare ecosystem service values at regional scales, for example, in Beijing and in forest ecosystem studies (e.g., de Groot et al., 2012; Costanza et al., 1997). Economic valuation techniques such as hedonic pricing, travel-cost models, and stated-preference or choice experiments translate changes in ES supply into welfare metrics and are increasingly recommended for benefit–cost analysis and regulatory impact assessment (Daily et al., 2000; Posner et al., 2016). Multi-criteria decision analysis (MCDA), Bayesian networks and index-based approaches (e.g., ASEBIO) combine normalised ES indicators with stakeholder-defined weights to generate composite scores that more explicitly reflect social priorities. For instance, the ASEBIO index for mainland Portugal integrates multiple modelled ES indicators with stakeholder weights and reveals that stakeholders systematically perceive higher ES potential than model-based estimates, highlighting the importance of combining model outputs with local knowledge. Overall, reviews of tools and valuation methods emphasise that no single model or formula is universally appropriate; model choice should be guided by decision context, scale, data availability, and whether the focus is on ES supply, flows or benefits, in line with conceptual frameworks such as the Millennium Ecosystem Assessment, TEEB, MAES and SEEA-EA (Millennium Ecosystem Assessment, 2005; Haines-Young & Potschin, 2010; Maes et al., 2012; United Nations, 2021).

This review shows that the way ecosystem services are modelled has a direct influence on whether results are seriously considered by decision-makers (Walther et al., 2025). Studies that explicitly compare multiple models or use ensemble approaches tend to be viewed as more credible, and this in turn increases the documented uptake of their findings in planning and policy (Walther et al., 2025; Bryant et al., 2018). At the same time, most published assessments still apply a single deterministic model and rarely report sensitivity or uncertainty analyses, despite clear guidance on practical techniques such as sensitivity tests, probabilistic simulations, and structured validation against independent data (Hamel & Bryant, 2017; Bryant et al., 2018). Earth-observation-based assessments add further opportunities and challenges. A recent review of 113 EO-based ecosystem accounting studies shows that satellite data are now routinely used to derive indicators of ecosystem extent and condition across forests, croplands, grasslands, wetlands, and urban systems, but that only about half of these applications incorporate any formal treatment of uncertainty (Kokkoris et al., 2024). This is problematic because classification choices, sensor combinations, spatial resolution, and post-processing steps (e.g., rasterisation) all propagate into ecosystem-service indicators and accounts, potentially biasing estimates of supply, trends, and trade-offs (Kokkoris et al., 2024). Together, these findings underline that model and data uncertainty should be treated as an integral design element of ES modelling, not an afterthought.

Emerging work on ecosystem accounting demonstrates how Earth-observation data and SEEA-EA can be combined to track ecosystem extent, condition and associated services in a spatially explicit, repeatable way (Edens et al., 2022; Kokkoris et al., 2024). Most EO-based accounting studies currently focus on deriving extent and condition indicators (e.g. land-cover transitions, vegetation indices, fragmentation metrics) for forests, croplands and urban systems, with fewer applications that directly model service flows or integrate monetary valuation (Kokkoris et al., 2024). Nonetheless, these approaches offer a scalable backbone for linking biodiversity, ecosystem services, and climate-change indicators in official statistics and could support long-term monitoring of nature-based adaptation and resilience policies (Comte et al., 2022; Kokkoris et al., 2024)

Climate change and resilience

Biodiversity underpins ecosystem services by maintaining multiple functions and ensuring that services are robust to disturbances (Hooper et al., 2012; Loreau & Mazancourt, 2013). Climate change represents an increasing disturbance regime characterized by rising temperatures and changing precipitation, increased frequency and intensity of extreme events such as droughts, floods, heatwaves, and wildfires, shifts in species distributions and phenology, and disruption of ecosystem structure and function (Walker et al., 2004; Folke et al., 2010). Biodiverse ecosystems are more resilient to these disturbances because of several mechanisms (Hooper et al., 2012; Loreau & Mazancourt, 2013; Yachi & Loreau, 1999). Functional redundancy refers to the phenomenon where multiple species perform similar functions, such that the loss of one species does not immediately compromise ecosystem functioning. For example, if one pollinator species declines, others may compensate (Kremen et al., 2002; Klein et al., 2007). Response diversity refers to differences in how species that contribute to the same function respond to environmental change, increasing the likelihood that ecosystem functioning is maintained across a range of conditions (Elmqvist et al., 2003). Portfolio effects, analogous to financial diversification, arise when diverse assemblages of species with asynchronous dynamics reduce temporal variability in ecosystem productivity and stability (Loreau & Mazancourt, 2013; Isbell et al., 2011). In addition, diverse systems tend to maintain stabilizing feedbacks that promote persistence, whereas simplified systems are more prone to positive feedbacks and abrupt state shifts (Folke et al., 2010). Thus, biodiversity enhances the stability of ecosystem function, which underpins the provision of sustained ecosystem services and resilience to climate change (Loreau & Mazancourt, 2013; Isbell et al., 2011).

How biodiversity enhances climate resilience

Functional redundancy and insurance effects

Functional redundancy—the presence of multiple species performing similar ecological functions—acts as an "insurance policy" for ecosystem services under climate change (Yachi & Loreau, 1999; Elmqvist et al., 2003). When environmental conditions change, functionally redundant species with different climate tolerances can compensate for species loss or decline (Yachi & Loreau, 1999). As an example, Pollinator diversity and crop production can be mentioned. Crop pollination is provided by diverse bee species, butterflies, and other insects, each with different temperature and precipitation tolerances (Kremen et al., 2002; Klein et al., 2007). A diverse pollinator community ensures stable pollination services across years with varying weather. By contrast, systems that depend on a single dominant pollinator species are more vulnerable if climate change favours pathogens, alters phenology, or disrupts the match between pollinator activity and flowering time (Kremen et al., 2002; Bommarco et al., 2012).

Response diversity and complementarity

Response diversity refers to the variation in how species that contribute to the same function respond to environmental change (Naeem & Li, 1997; Elmqvist et al., 2003). Complementary responses—where different species perform best under different conditions—help maintain ecosystem productivity across climate gradients and through time (Naeem & Li, 1997; Loreau & de Mazancourt, 2008). For example, forest productivity under drought: A forest containing species that differ in drought tolerance (e.g., a mix of deep-rooted and shallow-rooted trees) can maintain productivity across both wet and dry years. In drought years, deep-rooted species access deeper water reserves; in wet years, shallow-rooted species thrive near the surface. By contrast, a monoculture dominated by shallow-rooted species is likely to suffer severe productivity declines during drought (Loreau & de Mazancourt, 2008; Tilman et al., 1998).

Spatial heterogeneity and microrefugia

Biodiverse landscapes create complex spatial patterns—mosaics of habitat types, microclimates, and soil conditions—that provide "microrefugia" for species and ecosystem functions during climate extremes (Ashcroft et al., 2009). Species and populations can persist in favourable microsites and later facilitate recovery at broader scales after disturbance (Ashcroft et al., 2009; Folke et al., 2010). Wetlands mosaics can be explored as an interesting sample here; wetlands with diverse vegetation structure and a range of water depths create varied microhabitats. During drought, fish and invertebrates can persist in deeper pools, while birds and plants benefit from structurally diverse vegetation refugia. Simplified, homogeneous wetlands that lack this structural diversity provide fewer refugia and are more prone to biotic collapse during extreme events.

Temporal buffering and asynchrony

Diverse systems often exhibit asynchronous dynamics—different species or functional groups fluctuate independently—thereby buffering overall ecosystem stability (Loreau & de Mazancourt, 2008; Tilman et al., 1998). When species populations peak at different times or respond asynchronously to climate variability, aggregate ecosystem properties such as total productivity or nutrient cycling can remain relatively stable even when individual components fluctuate strongly (Loreau & de Mazancourt, 2008). For instance, In a grassland with many plant species differing in phenology and climate response, some species dominate early in the season, others mid-season, and others later, ensuring continuous productivity and resource capture across years with variable weather. A monoculture that peaks early in the season may miss mid-season moisture or fail under altered precipitation regimes, resulting in much greater interannual variability in productivity (Tilman et al., 1996; Tilman et al., 1998).

Evidence from major ecosystem types

Forests and tree diversity

Forests provide critical ecosystem services, including carbon storage and climate regulation, water purification, habitat provision, and provisioning services such as timber and non-timber forest products (Liang et al., 2016). Forest resilience to climate change depends in part on tree species diversity and functional composition (Liang et al., 2016; Vilà et al., 2007). A global analysis of over 600,000 forest plots showed that tree species richness is positively associated with productivity and that more diverse forests exhibit greater stability in productivity under environmental variation (Liang et al., 2016). In tropical forests, higher tree diversity correlates with greater resistance to drought and faster recovery after disturbance. European beech forests dominated by a single species show greater vulnerability to extreme drought and pests than mixed forests containing beech, oak, spruce, and other species (Pretzsch et al., 2013). Planted monocultures of fast-growing species (e.g., Eucalyptus) are more vulnerable to pests, diseases, and climate variability than naturally regenerated, species-rich forests (Jactel & Brockerhoff, 2007). Conservation of old-growth, structurally complex forests such as the Hyrcanian refugium of northern Iran (Naderi et al. 2014) and restoration of tree species diversity are critical for maintaining forest ecosystem services under climate change (Liang et al., 2016; Vilà et al., 2007).

Grasslands and herbaceous plant diversity

Grasslands cover roughly 40% of the terrestrial surface and provide forage for livestock, carbon storage, water cycling, and habitat for diverse species. Herbaceous plant diversity is a key driver of grassland productivity and resilience to climate variability (Tilman et al., 1996; Isbell et al., 2015). Long-term experiments in tallgrass prairie show that plots with higher plant species richness (e.g., 16 species) maintain more stable productivity across wet and dry years, whereas monocultures exhibit high variability and pronounced declines during drought (Tilman et al., 1996). In African savannas, plant diversity underpins wildlife diversity and livestock production; overgrazed, species-poor pastures are extremely vulnerable to drought and show slow recovery. A global analysis of grasslands found that plant species richness buffers productivity against climate variability: increases in richness were associated with substantial reductions in interannual variability of productivity (Isbell et al., 2015). Implications: Maintenance of grassland plant diversity through appropriate grazing management, restoration of native species, and avoidance of agricultural intensification is essential for resilience (Tilman et al., 1996).

Wetlands and aquatic biodiversity

Wetlands provide water purification, nutrient cycling, flood control, carbon storage, and habitat for diverse species (Millennium Ecosystem Assessment, 2005). Aquatic biodiversity underpins these services by driving key ecological processes (Millennium Ecosystem Assessment, 2005; Carpenter & Lodge, 1986). Wetlands with diverse plant, fish, and invertebrate communities show greater resilience to drought, pollution, and invasive species than species-poor wetlands (Carpenter & Lodge, 1986; Millennium Ecosystem Assessment, 2005). Floodplain wetlands with diverse vegetation provide greater flood storage and water purification than degraded wetlands (Tockner & Stanford, 2002). In mangrove ecosystems, structural complexity and species diversity correlate with resilience to hurricanes and sea-level rise, and support higher fish and shellfish production (Rönnbäck, 1999; DashtBozorgi et al., 2023). Protection of intact wetland habitats and restoration of wetland connectivity and diversity are priorities for climate adaptation, especially in regions facing increased drought and flood extremes (Millennium Ecosystem Assessment, 2005; Carpenter & Lodge, 1986).

Agricultural systems and crop diversity

Agricultural systems provide provisioning services (food, feed, fibre) but often exhibit low biodiversity, particularly in industrialised, input-intensive landscapes (Altieri, 2002). Crop and agroecosystem diversity can substantially enhance resilience to climate shocks and pests (Altieri, 2002; Lin, 2011). Smallholder farmers practising polyculture (multiple crop species) show greater stability of food production across climate-variable years compared to monocultures (Lin, 2011). Agroforestry systems (integration of trees with crops or livestock) enhance resilience to drought and heat stress; tree species with deep roots access water during dry periods, buffering crop productivity (Schroth et al., 2004). Genetic diversity within crop species (traditional varieties, landraces) provides climate-adaptation potential; monocultures of uniform modern varieties are vulnerable to new pests and changing climatic conditions (Jarvis et al., 2000). In many smallholder systems, farms integrating multiple crops, livestock, and trees show greater recovery from drought-induced losses than highly specialised farms (Lin, 2011). Promotion of agroecological practices—crop diversification, agroforestry, and integration of livestock—is essential for food security and farmer resilience under climate change, especially for smallholders in developing countries (Altieri, 2002; Lin, 2011).

Coral reef ecosystems

Coral reefs are among the most biodiverse and productive ecosystems, providing food, income, and coastal protection for hundreds of millions of people (Hoegh-Guldberg et al., 2007). However, they are extremely vulnerable to climate change: warming seas cause coral bleaching, ocean acidification weakens coral skeletons, and storms damage reef structure (Hoegh-Guldberg et al., 2007; Bellwood et al., 2004). Reefs with high coral species and functional diversity show greater recovery from bleaching events; species-poor reefs are more likely to experience sustained degradation (Bellwood et al., 2004; Pratchett et al., 2008). Protection of herbivorous fish diversity maintains coral resilience by controlling algal overgrowth and enabling coral recovery after bleaching (Pratchett et al., 2008). Intact reef ecosystems with diverse fish and invertebrate communities provide higher and more stable fishery yields and coastal protection than degraded reefs (Hoegh-Guldberg et al., 2007; Bellwood et al., 2004). Marine protected areas that preserve reef biodiversity, combined with strong global emission reductions to limit warming and acidification, are critical for maintaining coral reef services (Hoegh-Guldberg et al., 2007; Bellwood et al., 2004).

Challenges and trade-offs

Despite strong evidence linking biodiversity to resilience and ecosystem services, major challenges limit effective implementation. Even with increasingly sophisticated ecosystem-service models and valuation methods, implementation on the ground is constrained by powerful socio-economic and governance drivers. The following subsections highlight how land-use change, agricultural intensification, and structural inequalities undermine biodiversity-based resilience.

5.1 Land-use change and habitat loss

Land-use change—conversion of natural habitats to agriculture, urban areas and infrastructure—is the primary driver of biodiversity loss globally (Foley et al., 2005). Habitat fragmentation reduces biodiversity and compromises ecosystem function and resilience (Fahrig, 2003). Economic incentives typically favour land conversion over conservation. Agricultural expansion, logging, and urban growth are driven by short-term profitability, while ecosystem service values are often underestimated or not monetised (Foley et al., 2005; Tscharntke et al., 2005). The trade-off can then be Short-term economic gains from land conversion versus long-term loss of ecosystem services and climate resilience (Tscharntke et al., 2005).

A recent systematic review of ecosystem-service valuation in marine protected areas catalogued nine families of monetary methods and seven families of non-monetary methods and found a strong dominance of stated-preference techniques such as contingent valuation and discrete-choice experiments (Van Schoubroeck et al., 2024). Regulating and supporting services, as well as non-use and option values, were consistently under-represented because they are harder to capture in purely monetary terms, while mixed designs that combine biophysical indicators, participatory mapping, well-being metrics, and economic valuation were relatively rare but offered richer insights for management (Van Schoubroeck et al., 2024). These findings reinforce the argument that, particularly in a climate-change context, combining monetary and non-monetary valuation—within frameworks such as TEV, SEEA-EA or Total Social Value—can better reflect the multiple dimensions of resilience and justice that matter for stakeholders (Van Schoubroeck et al., 2024; Kenter et al., 2016)

Agricultural intensification

Intensified agriculture (monocultures, high external inputs) maximises short-term yields but reduces agrobiodiversity and ecosystem resilience (Green et al., 2005; Seufert et al., 2012).

Smallholder farmers, particularly in developing countries, are under pressure to intensify production to increase income. However, intensification often increases vulnerability to climate shocks, pests, and market fluctuations (Lin, 2011; Seufert et al., 2012). Short-term yield increases versus long-term sustainability and resilience (Seufert et al., 2012) can be mentioned as a trade-off.

Socio-economic barriers

Many communities dependent on ecosystem services lack capital, technology, knowledge, and institutional support to adopt biodiversity-friendly practices and adapt to climate change (IPCC, 2014). The Challenge here is that transitioning to diversified agriculture, restoring degraded lands, and establishing protected areas requires upfront investment, technical expertise, and coordination. Benefits often accrue over years or decades, misaligned with short-term livelihood needs (IPCC, 2014). The barriers include limited access to credit and markets for diverse products; Weak extension services and knowledge networks; Unclear land tenure and governance structures; Limited representation of local and Indigenous communities in conservation and adaptation planning (Agrawal, 1995; IPCC, 2014).

Climate tipping points and non-linear dynamics

Ecosystems can exhibit non-linear responses to climate change, with rapid, potentially irreversible shifts beyond critical thresholds (tipping points) (Scheffer et al., 2012). High biodiversity does not guarantee resilience against abrupt or extreme changes if thresholds are exceeded (Scheffer et al., 2012; Hirota et al., 2011). For example, tropical rainforests may shift to savanna if rainfall declines beyond a critical threshold, even in systems with high biodiversity, when feedbacks favour an alternative state (Hirota et al., 2011; Lenton et al., 2008). The challenge here is predicting tipping points and managing systems near critical thresholds requires long-term, high-quality monitoring data, which are often lacking, particularly in developing regions (Lenton et al., 2008; Scheffer et al., 2012).

Knowledge gaps and data limitations

Research on biodiversity–resilience linkages and climate adaptation is concentrated in a few well-studied regions and ecosystems; many regions, taxa, and service types remain under-represented (Danielsen et al., 2009). Knowledge gaps include long-term dynamics of biodiversity–resilience relationships under climate change; Interactions between climate change and other stressors (pollution, invasive species, overexploitation); Socio-economic dimensions of biodiversity conservation and climate adaptation; Effectiveness of specific adaptation strategies in diverse social-ecological contexts (Danielsen et al., 2009). Therefore, maintenance of grassland plant diversity through appropriate grazing management, restoration of native species, and avoidance of agricultural intensification is essential for resilience (Tilman et al., 1996).Recent global syntheses for specific biomes highlight how climate change is already reshaping ecosystem-service supply in ways that reinforce the importance of biodiversity and landscape heterogeneity (Grêt-Regamey & Weibel, 2020; Ioan et al., 2025). For mountain regions, a review of 88 studies published since 2011 shows that provisioning and regulating services—especially water supply, hazard regulation and food production—are overwhelmingly projected to decline under future climate scenarios, with very few cases of net positive effects (Ioan et al., 2025). Research efforts are also unevenly distributed, with strong biases towards European mountains and the Tibetan Plateau, and very limited coverage of mountain systems in other climate-vulnerable regions, creating blind spots for adaptation planning (Ioan et al., 2025). Similar spatial imbalances appear in national-scale prioritisation work. An analysis of co-benefits between cosystem-service priority areas, vulnerable carbon and bird diversity in the United States found that forest birds benefit disproportionately from ES- and carbon-based conservation priorities, while many wetland, aridland and "tipping point" bird species receive little protection in these same areas (Neugarten et al., 2025). This implies that strategies relying solely on ES hotspots or carbon storage areas risk neglecting taxa and habitats that are critical for resilience, and supports calls for explicit biodiversity targets alongside ES- and climate-oriented objectives (Neugarten et al., 2025; Soto-Navarro et al., 2020). A semi-systematic review of 904 ecosystem-service assessments published between 2018 and 2022 confirms that explicit treatment of uncertainty is still the exception rather than the rule and that this has consequences for policy uptake (Walther et al., 2025). Only a very small fraction of studies documented concrete use of their results in decision-making, and these were typically characterised by three features: a clearly defined policy context and entry point, the use of multiple models or model variants, and genuine involvement of stakeholders throughout the assessment process (Walther et al., 2025). From a resilience and adaptation perspective, this suggests that future ES studies should (i) anchor their objectives in specific policy instruments or management decisions, (ii) design modelling workflows that allow comparison among alternative model structures or data sources, and (iii) involve users in defining scenarios, indicators, and acceptable levels of uncertainty (Walther et al., 2025). Such practices can increase the perceived salience, credibility, and legitimacy of ES information and therefore its potential to influence adaptation planning (Walther et al., 2025).

Conclusion

This review shows that biodiversity, ecosystem services, and resilience to climate change are tightly interlinked. Across major ecosystem types—forests, grasslands, wetlands, agricultural landscapes, and coral reefs—higher diversity of genes, species, and functions consistently enhances resistance to and recovery from climatic extremes such as droughts, floods, heatwaves, and disturbances. Mechanisms such as functional redundancy, response diversity, spatial heterogeneity and microrefugia, and temporal asynchrony help stabilise ecosystem functions and sustain the provisioning, regulating, supporting, and cultural services on which human societies depend. At the same time, the capacity of ecosystems to provide these services is being eroded by land-use change, habitat fragmentation, agricultural intensification, and socio-economic constraints. Many climate adaptation strategies still rely predominantly on engineered solutions, while biodiversity conservation policies often underplay the need to build dynamic resilience under changing climatic conditions. Integrated approaches that recognise ecosystems as natural infrastructure—central to ecosystem-based adaptation and nature-based solutions—remain underutilised in practice.

A growing family of ecosystem service models and valuation tools—from land-cover-based methods and process-based models to integrated platforms such as InVEST and ARIES, and economic and multi-criteria approaches—can help quantify trade-offs and guide decisions. However, no single model is universally appropriate, and all must be interpreted in light of local context, data limitations, and stakeholder perspectives. Combining biophysical modelling with participatory processes and equity-focused governance is essential for effective and just adaptation. Looking ahead, safeguarding ecosystem services and climate resilience will require three complementary strategies. First, protecting and restoring biodiverse ecosystems, including forests, wetlands, agroecosystems, and coral reefs, must be elevated as a core pillar of climate policy. Second, mainstreaming ecosystem-based and nature-based solutions into sectoral planning—agriculture, water, urban development, and coastal management—can align mitigation, adaptation, and biodiversity goals. Third, investing in long-term research, high-quality monitoring, and the building of social-ecological resilience, especially in vulnerable regions, will provide a clearer understanding of ecological thresholds and context-specific management pathways. By effectively integrating biodiversity conservation with ecosystem service assessments and climate adaptation strategies, we can enhance our resilience to the rapid environmental changes ahead and sustain the natural capital essential for future generations.

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