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| RESEARCH ARTICLE

Climate Change and Ecosystem Resilience: A Comprehensive Review of Emerging Adaptation Strategies

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| ABSTRACT
Climate change is increasingly disrupting ecological processes, biodiversity, ecosystem services, and the capacity of natural systems to recover from environmental disturbances. This comprehensive review examines the relationship between climate change and ecosystem resilience, with particular emphasis on emerging adaptation strategies for strengthening the capacity of ecosystems to absorb, recover from, and adapt to climate-related pressures. The review synthesizes recent literature on ecosystem-based adaptation, nature-based solutions, ecological restoration, climate-resilient conservation, landscape connectivity, assisted regeneration, agroecological approaches, and community-based ecosystem management. The findings indicate that effective ecosystem adaptation increasingly depends on integrated approaches that combine biodiversity conservation, restoration of degraded ecosystems, protection of ecological connectivity, sustainable resource management, and local knowledge. Nature-based solutions and ecosystem-based adaptation can simultaneously reduce climate risks and maintain essential ecosystem services, while adaptive management enables interventions to respond to changing climatic conditions and ecological feedback. The review further highlights the importance of genetic and species diversity, protected-area networks, ecological corridors, restoration of wetlands and forests, climate-smart agriculture, and participatory governance in enhancing resilience. However, financial limitations, fragmented governance, inadequate monitoring, uncertainty in climate projections, and conflicts among conservation and development priorities continue to constrain implementation. Overall, strengthening ecosystem resilience requires a shift from reactive conservation toward proactive, flexible, and context-specific adaptation strategies that integrate ecological, social, and institutional dimensions of climate resilience.

| KEYWORDS

Climate change; ecosystem resilience; climate adaptation; ecosystem-based adaptation; nature-based solutions; ecological restoration

| ARTICLE INFORMATION

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1. Introduction

Climate change has emerged as one of the most significant environmental and societal challenges of the twenty-first century, with far-reaching implications for ecosystems, biodiversity, human livelihoods, and socioeconomic development. Rising global temperatures, shifting precipitation patterns, increasing frequency and intensity of extreme weather events, sea-level rise, ocean warming and acidification, and prolonged droughts are altering ecological processes across terrestrial, freshwater, coastal, and marine environments (Stein et al., 2013). These changes are not occurring independently; rather, they interact with existing pressures such as habitat fragmentation, deforestation, pollution, overexploitation of natural resources, invasive species, and rapid land-use change. Consequently, ecosystems are increasingly exposed to multiple and interacting stressors that can undermine their capacity to maintain ecological functions, support biodiversity, and provide essential ecosystem services.

Ecosystem resilience has therefore become a central concept in understanding ecological responses to climate change. Resilience broadly refers to the capacity of an ecosystem to absorb disturbances, withstand environmental pressures, reorganize, and continue functioning without undergoing fundamental and potentially irreversible changes in structure or ecological processes. Resilient ecosystems are particularly important for climate adaptation because they can provide natural buffers against environmental hazards while sustaining services such as water regulation, soil formation, carbon sequestration, food production, coastal protection, and habitat provision. However, resilience is not unlimited. Climate change can push ecosystems beyond critical thresholds, resulting in shifts to alternative ecological states that may be difficult or impossible to reverse (Aniwa, 2026). Understanding the factors that strengthen or weaken ecosystem resilience is therefore essential for designing effective adaptation strategies.

Climate change adaptation has traditionally included approaches aimed at reducing exposure and vulnerability to climatic hazards. Increasingly, however, adaptation strategies are moving toward approaches that recognize the importance of ecological processes, local knowledge, institutional capacity, and long-term ecosystem dynamics. Nature-based solutions, ecosystem-based adaptation, ecological restoration, climate-smart conservation, assisted regeneration, landscape connectivity, sustainable land and water management, and adaptive ecosystem governance have consequently gained prominence. Nature-based approaches, for example, can simultaneously address climate risks and biodiversity objectives by conserving, restoring, or sustainably managing ecosystems (Dube, 2024). Mangrove restoration can reduce coastal vulnerability while supporting fisheries and carbon storage, while forest and watershed restoration can contribute to erosion control, water regulation, biodiversity conservation, and livelihood security. Such approaches demonstrate that climate adaptation and ecosystem conservation can be mutually reinforcing when appropriately designed and implemented.

Emerging adaptation strategies increasingly emphasize flexibility, ecosystem connectivity, genetic and species diversity, adaptive management, and the integration of ecological and social systems. Conservation planning is progressively incorporating climate projections to identify potential refugia, migration corridors, and areas where ecological conditions are likely to remain suitable for vulnerable species. Assisted migration and assisted gene flow are also being considered in situations where natural dispersal may be insufficient to keep pace with rapidly changing climatic conditions. At the same time, restoration initiatives are increasingly shifting from attempts to recreate historical ecological conditions toward building ecosystems capable of functioning under future climatic conditions. These developments reflect a broader transition from reactive conservation toward anticipatory and transformative approaches to climate adaptation (Moore et al., 2022).

Nevertheless, the effectiveness of emerging adaptation strategies varies substantially across ecosystems, geographical regions, species, and socioeconomic contexts. Adaptation interventions can produce unintended consequences when ecological interactions, local environmental conditions, or community needs are insufficiently considered. For example, interventions designed to increase the abundance of a particular species may alter competitive relationships or ecosystem functions, while poorly planned infrastructure or restoration activities can increase pressure on other habitats (Aniwa, 2026). Similarly, adaptation policies that overlook local livelihoods and institutional realities may generate social inequities or reduce community support. Effective ecosystem adaptation therefore requires approaches that integrate ecological science with socioeconomic considerations, participatory governance, Indigenous and local knowledge, and continuous monitoring and learning.

Another important challenge concerns the scale and speed of climate change. Many ecological systems respond to environmental change over timescales that differ from those of human decision-making and policy cycles. Climate impacts can also extend across administrative boundaries, making fragmented management approaches inadequate for ecosystems that function at watershed, landscape, seascape, or migratory scales. Consequently, contemporary adaptation research increasingly emphasizes cross-scale governance, landscape connectivity, transboundary cooperation, scenario planning, and adaptive management. These approaches seek to reduce uncertainty by allowing management strategies to evolve as new scientific evidence, climatic conditions, and ecological responses become available (Rouzaneh, 2024).

Despite growing research on climate adaptation and ecosystem resilience, the literature remains fragmented across disciplines and ecosystem types. Studies frequently focus on particular interventions, regions, species, or climate hazards, making it difficult to obtain an integrated understanding of the broader evolution of adaptation strategies. Moreover, emerging approaches such as nature-based solutions, ecological restoration, climate-resilient conservation, assisted migration, genetic adaptation, and transformative ecosystem management raise important questions concerning their effectiveness, scalability, ecological risks, governance requirements, and long-term sustainability (Wang et al., 2023). A comprehensive synthesis is therefore needed to identify common patterns, emerging innovations, knowledge gaps, and conditions under which different adaptation strategies can strengthen ecosystem resilience.

Against this background, this review examines the relationship between climate change and ecosystem resilience, with particular emphasis on emerging adaptation strategies. It synthesizes current knowledge on the major climate-related pressures affecting ecosystems, the ecological and socioeconomic determinants of resilience, and the evolution of adaptation approaches across terrestrial, freshwater, coastal, and marine systems (Aniwa, 2026). The review further evaluates the potential benefits and limitations of nature-based solutions, ecosystem restoration, adaptive conservation, landscape connectivity, genetic and assisted-migration approaches, climate-smart ecosystem management, and participatory governance. By bringing these perspectives together, the study aims to provide an integrated understanding of how ecosystems can be supported in responding to accelerating environmental change and to identify priorities for future research, policy, and practice. The review ultimately highlights the need for flexible, evidence-based, locally appropriate, and ecologically informed adaptation strategies capable of strengthening resilience while simultaneously supporting biodiversity conservation and sustainable human well-being.

2. Methodology

2.1 Research Design

This study employed a comprehensive narrative review design to synthesize existing scientific knowledge on climate change, ecosystem resilience, and emerging adaptation strategies. A review approach was considered appropriate because climate change impacts and ecosystem adaptation are interdisciplinary issues spanning ecology, environmental science, conservation biology, climate policy, agriculture, water resources, and social sciences. The review focused on identifying major climate-related pressures on ecosystems, examining how these pressures influence ecological resilience, and evaluating adaptation strategies that have been proposed or implemented to strengthen the capacity of ecosystems and associated communities to cope with climate-related changes. Rather than generating primary field data, the study integrated evidence from previously published peer-reviewed research, scientific assessments, and relevant institutional reports to develop a coherent understanding of current adaptation approaches and emerging trends.

2.2 Literature Search Strategy

A systematic and structured literature search was undertaken to identify relevant studies addressing climate change, ecosystem resilience, vulnerability, adaptation, nature-based solutions, ecological restoration, and climate-resilient ecosystem management. Searches were conducted using major academic databases and scholarly search platforms, including Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, and Google Scholar. The search strategy combined key terms and Boolean operators to capture literature from different disciplines. Representative search combinations included *"climate change" AND "ecosystem resilience"*, *"climate adaptation" AND ecosystems*, *"ecosystem-based adaptation" AND climate change*, *"nature-based solutions" AND resilience*, *"ecological restoration" AND climate adaptation*, and *"climate-resilient conservation"*. Additional searches were conducted using combinations of terms relating to forests, wetlands, coastal ecosystems, agricultural landscapes, freshwater systems, biodiversity, and community-based adaptation. Reference lists of relevant publications were also examined to identify additional studies that were not retrieved through database searches.

2.3 Eligibility and Selection Criteria

Studies were selected according to predefined relevance and quality criteria. Publications were considered eligible when they directly examined climate change impacts on ecosystems, ecosystem resilience, vulnerability assessment, adaptation planning, ecological restoration, nature-based approaches, conservation responses, or other strategies designed to reduce climate-related risks. Peer-reviewed journal articles, review papers, scholarly books or chapters, and authoritative reports from recognized scientific and international organizations were considered where they provided substantive evidence relevant to the objectives of the review. Studies were excluded when they focused exclusively on climate change without an ecosystem or adaptation dimension, addressed unrelated environmental issues, lacked sufficient methodological or conceptual information, or duplicated evidence presented in another publication. Greater emphasis was placed on recent literature to capture emerging adaptation strategies, while influential earlier studies were retained where they provided foundational concepts or frameworks for understanding ecosystem resilience and climate adaptation.

2.4 Data Extraction and Organization

Relevant information was extracted from the selected literature using a structured thematic framework. The extracted information included publication characteristics, ecosystem type, geographical context, climate-related pressures, observed or projected ecological impacts, resilience dimensions, adaptation objectives, adaptation strategies, implementation mechanisms, reported outcomes, and major limitations. Particular attention was given to evidence concerning the effectiveness, scalability, feasibility, and sustainability of adaptation interventions. The literature was organized according to major ecosystem categories, including terrestrial forests and grasslands, freshwater ecosystems, coastal and marine systems, wetlands, agricultural landscapes, and other coupled human–natural systems. This organization facilitated comparison of adaptation responses across ecological contexts and helped identify strategies that have applicability across multiple ecosystem types.

2.5 Thematic Analysis

The extracted evidence was analyzed through qualitative thematic synthesis. Recurring concepts and findings were identified and grouped into broad themes representing the principal dimensions of ecosystem adaptation to climate change. These themes included ecosystem-based adaptation, nature-based solutions, ecological restoration, biodiversity conservation and assisted migration, climate-smart landscape management, adaptive ecosystem governance, community-based adaptation, technological and monitoring innovations, and integrated landscape approaches. The analysis examined how each strategy contributes to ecosystem resilience through mechanisms such as maintaining biodiversity, improving habitat connectivity, restoring ecological functions, strengthening ecosystem services, reducing exposure to climate hazards, and increasing adaptive capacity. Where studies reported contrasting outcomes, these differences were considered in relation to ecological conditions, governance arrangements, spatial scale, socioeconomic context, and implementation capacity.

2.6 Assessment of Emerging Adaptation Strategies

The review specifically assessed emerging strategies according to their potential contribution to ecosystem resilience under changing climatic conditions. Strategies were considered in terms of their capacity to reduce ecosystem vulnerability, maintain ecological functions, enhance adaptive capacity, and support long-term sustainability. Particular consideration was given to approaches that integrate ecological processes with social and institutional systems, including nature-based solutions, ecosystem-based adaptation, restoration of degraded ecosystems, climate-resilient conservation planning, connectivity enhancement, participatory governance, and the use of remote sensing, ecological monitoring, and predictive modeling. The review also considered the extent to which adaptation strategies can be implemented across different spatial and temporal scales and whether they are capable of addressing uncertainty associated with future climate conditions.

2.7 Quality and Reliability of Evidence

To enhance the reliability of the synthesis, greater weight was given to peer-reviewed studies published in established scientific journals and to authoritative assessments produced by recognized scientific and environmental institutions. Studies were considered in relation to the clarity of their objectives, methodological rigor, transparency of data and analysis, relevance to ecosystem resilience, and strength of reported evidence. Findings were compared across multiple sources rather than relying on individual studies to establish broad conclusions. Where evidence was limited, geographically concentrated, or inconsistent, the review acknowledged these limitations rather than treating individual findings as universally applicable. This approach helped minimize overgeneralization and strengthened the interpretation of adaptation strategies across diverse ecological and socioeconomic contexts.

2.8 Synthesis of Findings

The final synthesis integrated evidence across the identified themes to establish relationships between climate change pressures, ecosystem vulnerability, resilience mechanisms, and adaptation responses. The analysis moved beyond describing individual interventions by examining how different strategies complement one another and under what circumstances they are most likely to contribute to long-term ecosystem resilience. Attention was given to synergies and trade-offs among adaptation, biodiversity conservation, ecosystem services, and human well-being. The synthesis also identified persistent research and implementation gaps, including uncertainties concerning long-term effectiveness, financing, governance, monitoring, equity, and the scalability of adaptation interventions. On this basis, the methodology supported the development of an integrated understanding of emerging adaptation strategies and their potential role in strengthening ecosystem resilience under current and future climate change.

3. Findings and Discussion

3.1 Climate Change Impacts on Ecosystem Resilience

3.1.1 Changes in Ecosystem Structure and Function

The reviewed evidence indicates that climate change is altering ecosystem structure and function through interacting changes in temperature, precipitation, disturbance regimes, and the frequency and intensity of extreme events. Rising temperatures can modify growing seasons, evapotranspiration, decomposition rates, water availability, and species interactions, while altered precipitation can shift ecosystems between periods of water limitation and excessive moisture. Droughts and heatwaves can reduce primary productivity and vegetation cover, increase tree mortality, and weaken the capacity of ecosystems to recover after disturbance. Conversely, intense rainfall and flooding can cause soil erosion, nutrient losses, sedimentation, and physical damage to vegetation and aquatic habitats. Wildfires can produce similar effects by removing biomass, altering soil properties, and changing vegetation composition (Abdel-Raheem et al., 2025). These processes demonstrate that ecosystem resilience depends not simply on the magnitude of a climatic disturbance but also on the frequency of disturbance and the capacity of ecological systems to reorganize and recover. The IPCC similarly concludes that climate change is placing additional stress on ecosystem integrity and functioning, with consequences for biodiversity, water supply, food provisioning, and flood regulation.

The effects vary considerably among ecosystem types. In forests, warming and moisture stress can increase drought-related mortality and make vegetation more susceptible to pests, diseases, and fire, potentially shifting forests toward more drought-tolerant species or less forested states. In wetlands and freshwater ecosystems, changing rainfall, evaporation, flooding, and temperature can alter hydrological regimes and nutrient cycling, thereby affecting aquatic productivity and water quality. Grasslands may experience changes in plant composition and productivity as precipitation regimes shift, with repeated drought potentially reducing recovery capacity. Coastal ecosystems face particularly complex pressures because sea-level rise, warming, storms, erosion, and changing sediment dynamics occur simultaneously. Mangroves and other coastal wetlands can provide substantial protection against waves, storm surges, and erosion, but their capacity to perform these functions depends on sufficient sediment supply, space for landward migration, and the maintenance of ecological integrity (Abbass et al., 2022).

Agricultural landscapes also illustrate the close relationship between ecosystem processes and climate resilience. Climate variability can influence soil moisture, nutrient availability, crop productivity, pest dynamics, and pollination services. However, agricultural systems containing greater biological diversity, soil organic matter, crop–livestock integration, and crop–forest interactions can provide multiple pathways for maintaining productivity under climatic stress. The IPCC identifies increasing biodiversity, improving soil organic matter, integrating production systems, and strengthening beneficial ecological interactions as important components of ecosystem-based adaptation in food systems (Aniwa, 2022). Thus, the evidence suggests that maintaining ecological functions and diversity is more effective for long-term resilience than relying exclusively on short-term responses to individual climatic hazards.

3.1.2 Biodiversity Loss and Species Vulnerability

The review further shows that climate change affects biodiversity through changes in species distributions, population abundance, habitat suitability, reproductive success, and seasonal biological events. Many species respond to warming by shifting their geographic ranges toward higher latitudes or elevations, while others alter migration, flowering, breeding, or emergence periods. Such phenological shifts can create mismatches between interacting species; for example, changes in the timing of plant flowering may not coincide with the activity of pollinators, while altered seasonal conditions can affect predator–prey relationships. Species with narrow climatic tolerances, restricted geographic ranges, limited dispersal capacity, or specialized habitat requirements are generally more vulnerable because they have fewer opportunities to track changing environmental conditions (Mani et al., 2023). The IPCC identifies climate change as an increasingly important driver of biodiversity risk and emphasizes that vulnerable species can benefit from management measures that maintain habitat, reduce fragmentation, and preserve areas with suitable microclimates.

Vulnerability is particularly pronounced in ecosystems already exposed to multiple pressures. Coral reefs, montane ecosystems, Arctic and sub-Arctic environments, small islands, wetlands, and fragmented forests can face disproportionate risks because climatic changes interact with limited habitat availability and other environmental pressures. In coastal environments, for example, warming and ocean changes may occur alongside pollution, overfishing, coastal development, and habitat destruction, reducing the ability of marine organisms to recover from disturbance. The IPCC finds that climate-smart conservation, ecosystem-based management, and habitat restoration can reduce some risks, although their effectiveness declines as warming intensifies and cannot fully compensate for severe climate change (Pandit & Sharma 2023).

The findings also indicate that ecological characteristics can determine whether ecosystems resist disturbance or recover after it. Functional diversity, genetic diversity, habitat heterogeneity, redundancy among species performing similar ecological functions, and connectivity can strengthen resilience by providing alternative pathways for ecosystem processes. Small areas with relatively favourable microclimates can also function as climate refugia, allowing populations to persist even when surrounding environments become unsuitable. The IPCC reports high confidence that reducing fragmentation, increasing habitat connectivity and heterogeneity, maintaining functional diversity, and protecting small-scale refugia can improve the resilience of biodiversity and ecosystem services (Adenike, 2017). These findings suggest that conservation should focus not only on preventing species loss but also on maintaining the ecological characteristics that allow populations and communities to adapt and recover.

3.1.3 Interactions Among Climate, Environmental, and Anthropogenic Stressors

A major finding of the review is that climate change rarely acts as an isolated driver of ecosystem degradation. Its effects are frequently amplified by deforestation, land-use change, habitat fragmentation, pollution, invasive species, overexploitation, urban expansion, and unsustainable agricultural practices (Morshed et al., 2025). The IPBES global assessment identifies changes in land and sea use, direct exploitation of organisms, climate change, pollution, and invasive alien species as major direct drivers of biodiversity change. These pressures can operate simultaneously and produce cumulative effects that are greater than the impact of any single stressor.

For example, deforestation can increase local temperatures, reduce moisture retention, fragment habitats, and restrict species movement, thereby making remaining forest patches more vulnerable to drought and extreme heat.

Similarly, agricultural expansion may remove natural vegetation while intensive cultivation depletes soil organic matter and increases erosion, leaving landscapes less capable of absorbing heavy rainfall or recovering from drought. Pollution can further weaken organisms already exposed to thermal or water stress, while invasive species may become more competitive under changing climatic conditions (Dordai et al., 2026). Urbanization adds another layer of pressure through habitat conversion, heat-island effects, altered drainage, and increased demand for water and other ecosystem resources.

The interaction between climatic and non-climatic stressors is particularly important for understanding resilience thresholds. An ecosystem that might recover from a moderate drought under relatively intact conditions may fail to recover when the same drought occurs in a highly fragmented, overexploited, or polluted landscape. Evidence synthesized by IPBES similarly emphasizes that land degradation results from interactions among climatic pressures, unsustainable resource use, natural disturbances, and institutional and socioeconomic conditions. Consequently, adaptation strategies that address climate hazards without reducing underlying environmental pressures are unlikely to deliver durable resilience. The findings support an integrated perspective in which climate adaptation, biodiversity conservation, land restoration, pollution control, and sustainable resource management are treated as interconnected components of ecosystem resilience (Adenike, 2023).

3.2 Emerging Ecosystem-Based Adaptation Strategies

3.2.1 Nature-Based Solutions and Ecosystem Restoration

The review identifies nature-based solutions and ecosystem restoration as among the most promising approaches for simultaneously reducing climate risks, supporting biodiversity, and maintaining ecosystem services. Reforestation and forest restoration can improve soil stability, regulate water flows, reduce erosion, provide habitat, and contribute to local climate regulation. Wetland restoration can enhance water storage and filtration while reducing flood impacts, whereas mangrove rehabilitation can stabilize coastlines and reduce exposure to waves and storm surges. Grassland restoration can improve soil structure, water retention, carbon storage, and habitat quality. These interventions therefore differ from narrowly engineered adaptation measures because they can generate multiple ecological and social benefits simultaneously. IUCN defines ecosystem-based adaptation as the conservation, sustainable management, and restoration of ecosystems to help people adapt to climate change and emphasizes its potential to combine climate adaptation with biodiversity and ecosystem-service benefits (Beck et al., 2025).

Evidence reviewed by the IPCC supports this multifunctional role. Ecosystem-based adaptation can reduce risks associated with flooding, drought, fire, and excessive heat while simultaneously producing benefits for biodiversity and human well-being. The approach can also be comparatively cost-effective in appropriate contexts because a single restored ecosystem may provide several services at once (Adenike, 2022). For example, restoring an upstream watershed can reduce downstream flood peaks while improving water quality and maintaining habitat, while mangrove restoration can simultaneously protect coastal settlements, support fisheries, store carbon, and provide nursery habitat for marine organisms.

Nevertheless, the findings demonstrate that restoration is not universally effective or automatically beneficial. Its success depends on ecological context, restoration quality, governance, long-term maintenance, and the severity of future climate change. Restored ecosystems themselves remain exposed to climatic hazards, meaning that restoration strategies must be designed around anticipated future conditions rather than historical climate alone. The IPCC therefore cautions that nature-based solutions are themselves vulnerable to climate change and cannot substitute for substantial reductions in greenhouse-gas emissions (Dahal et al., 2025). Effective restoration consequently requires appropriate species selection, landscape context, local ecological knowledge, monitoring, and adaptive management.

3.2.2 Landscape and Watershed-Level Adaptation

The findings indicate that adaptation is more likely to produce durable ecological outcomes when implemented at landscape and watershed scales rather than through isolated interventions. Ecosystems function through connected flows of water, nutrients, organisms, energy, and genetic material; consequently, protecting a single habitat patch may have limited value when surrounding landscapes remain highly fragmented or degraded (Adenike, 2018). Integrated watershed management can combine forest conservation, wetland protection, soil conservation, sustainable agriculture, river restoration, and water-resource management to maintain hydrological and ecological processes across upstream and downstream areas.

Landscape-scale planning is particularly important for maintaining ecological connectivity under climate change. Ecological corridors can allow species to move between suitable habitats as temperature and precipitation conditions change, while connected protected-area networks can provide larger and more diverse areas for population persistence. Climate-smart land management can further reduce pressures on natural ecosystems by improving soil health, conserving water, diversifying production, and integrating trees and other vegetation into agricultural landscapes. Such approaches reflect the IPCC's conclusion that increasing natural habitat extent, connectivity, and heterogeneity while reducing fragmentation and additional disturbances can strengthen ecosystem resilience (Granata & Di Nunno, 2016).

Evidence from ecosystem-based adaptation initiatives also suggests that landscape approaches require coordination among institutions and stakeholders. IUCN's evidence-building work across countries including Kenya, Uganda, Nepal, Bangladesh, South Africa, and others emphasizes the importance of integrating ecosystem management and restoration into climate adaptation policy and planning. This is especially relevant where watersheds and ecological landscapes cross administrative boundaries (Islam & Sinniah, 2025). Effective landscape adaptation therefore requires collaboration among conservation agencies, local communities, agricultural producers, water managers, and local governments. Participatory governance and the integration of Indigenous and local knowledge are also important because ecological conditions and adaptation priorities differ substantially among landscapes.

3.2.3 Conservation of Climate Refugia and Ecological Connectivity

The review identifies climate refugia and ecological connectivity as increasingly important components of climate-resilient conservation. Climate refugia are locations where local environmental conditions remain relatively favourable despite broader climatic change. Such areas may include shaded valleys, high-elevation habitats, groundwater-influenced wetlands, north-facing slopes, deep forest patches, or other locations with microclimatic conditions that buffer regional warming and drying (Zhai & Lee, 2024). Protecting these areas can provide temporary or longer-term opportunities for species persistence while surrounding habitats become less suitable. The IPCC reports new evidence that species can persist in locally cooler refugia even when populations are declining elsewhere, supporting the strategic importance of identifying and protecting these areas.

However, refugia alone cannot address the broader problem of habitat fragmentation. Species must often move among habitats to track changing climatic conditions, recolonize disturbed areas, or maintain genetic exchange. Ecological corridors, stepping-stone habitats, riparian networks, and interconnected protected areas can therefore complement refugia by facilitating movement across landscapes. Connectivity is particularly important for species with limited tolerance to rapid environmental change and for populations whose current habitats are becoming climatically unsuitable. Maintaining habitat heterogeneity and reducing barriers created by roads, intensive agriculture, urbanization, and other forms of land conversion can increase opportunities for climate-driven range shifts (Islam & Aktar, 2025).

The evidence consequently supports a conservation strategy that combines refugia protection, habitat restoration, ecological corridors, and connected protected-area networks rather than treating protected areas as isolated units. This conclusion is consistent with the IPCC assessment that reducing fragmentation and increasing habitat connectivity, heterogeneity, and natural habitat extent can strengthen biodiversity resilience. At the same time, connectivity planning should account for potential risks, including the movement of invasive species, diseases, or organisms into unsuitable communities (Munroe et al., 2012). Conservation planning therefore needs to combine spatial connectivity with ecological monitoring and adaptive management.

Overall, the findings demonstrate that climate-resilient ecosystems depend on maintaining ecological integrity while reducing the cumulative pressures that constrain adaptation. Nature-based solutions, restoration, landscape planning, climate refugia, and connectivity can provide substantial benefits, but their effectiveness is context-dependent and declines under increasingly severe climatic conditions. The strongest evidence therefore favours integrated approaches that simultaneously address climate hazards, biodiversity loss, habitat fragmentation, land degradation, and human pressures. This is consistent with the IPCC's conclusion that climate, biodiversity, and human societies should be treated as coupled systems and that adaptation is most effective when ecosystem protection and restoration are combined with broader climate-resilient development.

3.3 Climate-Smart and Adaptive Ecosystem Management

3.3.1 Climate-Smart Agriculture and Agroecological Approaches

The reviewed evidence indicates that climate-smart agriculture and agroecological approaches are among the most promising strategies for strengthening ecosystem resilience while maintaining agricultural productivity under changing climatic conditions. Agroforestry, crop diversification, conservation agriculture, soil and water conservation, drought-tolerant varieties, and integrated crop–livestock systems reduce dependence on single resources and create multiple ecological pathways through which farming systems can absorb climate shocks. Agroforestry is particularly important because trees can improve soil structure, reduce erosion, regulate microclimatic conditions, increase carbon storage, and provide supplementary products such as fruits, fodder, fuelwood, and timber (Islam et al., 2025). In dryland and semi-arid areas, for example, integrating trees with crops and livestock can provide shade and fodder during periods of heat and drought while improving the capacity of soils to retain moisture.

Crop diversification similarly increases resilience by reducing the exposure of farming households and agroecosystems to the failure of a single crop. The use of drought-, heat-, or flood-tolerant varieties can maintain production when climatic conditions depart from historical norms. Conservation agriculture, including reduced soil disturbance, residue retention, and crop rotation, can improve soil organic matter and water infiltration while reducing erosion. These findings are consistent with the broader literature showing that diversified and ecologically based farming systems can generate simultaneous benefits for productivity, soil fertility, biodiversity, and climate adaptation. The IPCC has emphasized that agroecological practices, diversification, improved soil management, and integrated farming can reduce climate vulnerability while producing important ecosystem and livelihood co-benefits. However, the effectiveness of individual practices varies according to soil type, rainfall regime, farm size, access to inputs, local knowledge, and institutional support. Consequently, climate-smart agriculture should not be treated as a standardized package but as a context-specific approach adapted to local ecological and socioeconomic conditions (Bierbaum et al., 2013).

Integrated farming systems provide an additional resilience pathway because they connect crop, livestock, tree, and sometimes aquatic production within a relatively circular resource system. Crop residues can provide livestock feed, livestock manure can contribute to soil fertility, and trees can provide fodder, fuel, shade, and soil protection. Such integration can reduce external input requirements and strengthen resource-use efficiency. Nevertheless, poorly designed intensification can also increase pressure on land and water resources (Jabareen, 2013). The findings therefore suggest that the resilience value of climate-smart agriculture depends not simply on the adoption of individual technologies but on how practices interact with ecological processes and household livelihood strategies.

3.3.2 Adaptive and Transformative Management

The review shows that adaptive management has become increasingly important because climate change introduces uncertainty that makes fixed management plans less reliable. Adaptive management emphasizes experimentation, continuous monitoring, evaluation, learning, and adjustment of interventions as environmental conditions change. Instead of assuming that managers can predict future ecosystem responses with certainty, this approach treats management actions as opportunities to generate knowledge. For example, restoration practitioners may test different native species or planting densities, monitor survival under changing rainfall conditions, and subsequently modify restoration methods according to observed outcomes. Similar principles can be applied to fisheries, forests, wetlands, rangelands, protected areas, and agricultural landscapes (Islam et al., 2026).

A critical finding is that adaptation occurs along a continuum from incremental to transformative responses. Incremental adaptation involves actions that reduce existing risks without fundamentally changing the structure of a vulnerable system. Examples include improving irrigation efficiency, adjusting planting dates, restoring degraded soils, installing water-harvesting structures, or strengthening fire-management practices. These interventions can be highly effective where climate pressures remain within the coping capacity of existing ecological and institutional systems. However, their effectiveness may decline when climatic changes become severe or persistent (Rezvani et al., 2023).

Transformative adaptation becomes necessary when existing systems are approaching ecological or socioeconomic thresholds beyond which incremental adjustments are insufficient. Transformation may involve changing land-use systems, relocating infrastructure away from high-risk areas, restoring natural hydrological regimes, redesigning agricultural production, changing institutional arrangements, or shifting conservation objectives to accommodate unavoidable ecological change. The literature therefore suggests that resilience should not be understood solely as maintaining ecosystems in their historical state. In some circumstances, resilience requires enabling ecosystems and societies to transition toward new configurations while maintaining essential functions, biodiversity, ecosystem services, and human well-being. The challenge is determining when incremental adaptation remains viable and when transformation is necessary, particularly because transformative interventions can generate substantial social, economic, and political consequences (Chanda & Tripathi, 2026).

3.3.3 Indigenous and Local Ecological Knowledge

The findings demonstrate that Indigenous and local ecological knowledge can make an important contribution to climate adaptation, particularly where communities have long histories of observing environmental variability and managing natural resources under changing conditions. Local knowledge may include observations of rainfall patterns, seasonal indicators, animal behavior, plant phenology, soil characteristics, water availability, fire regimes, and changes in species abundance. Such knowledge can complement scientific monitoring by providing fine-scale information that may not be captured by conventional ecological datasets. Community-based monitoring can also identify changes in ecosystems at relatively low cost and support rapid responses to emerging threats (Rezvani et al., 2023).

Examples from agricultural and pastoral systems illustrate the value of locally developed adaptation strategies. Farmers may maintain diverse crop varieties to spread climatic risk, use locally adapted planting calendars, conserve traditional water sources, or combine crop and livestock production according to seasonal conditions. Pastoral communities may use accumulated knowledge of grazing patterns, water points, vegetation conditions, and livestock mobility to respond to drought. These practices can contribute to biodiversity conservation and ecosystem resilience because they often reflect long-term interactions between communities and local ecosystems (Jabareen, 2013).

However, the review also indicates that Indigenous and local knowledge should not be romanticized or assumed to be universally sufficient under unprecedented climatic conditions. Climate change can alter environmental relationships on a scale that exceeds historical experience. The most effective approach is therefore often a complementary one in which local knowledge and scientific evidence are brought together through respectful, participatory processes. Such integration must recognize community rights, cultural values, consent, attribution, and ownership of knowledge (Bierbaum et al., 2013). Local communities should participate not merely as sources of information but as legitimate knowledge holders and decision-makers. This is particularly important because the inappropriate extraction or commercialization of Indigenous knowledge can reproduce inequities and undermine trust in adaptation initiatives.

3.4 Technological, Institutional, and Policy Innovations for Resilience

3.4.1 Remote Sensing, Ecological Monitoring, and Climate Information

Technological advances are expanding the capacity to identify ecosystem vulnerability, monitor environmental change, and anticipate climate-related risks. Remote sensing and geographic information systems allow researchers and resource managers to observe changes in vegetation cover, land degradation, forest loss, surface water, soil moisture, fire occurrence, and habitat distribution across large areas. Satellite-based observations are particularly valuable in regions where ground-based monitoring networks are limited. When combined with ecological models and climate projections, these technologies can help identify ecosystems that are approaching critical thresholds and guide decisions about restoration, conservation, water allocation, and agricultural management (Islam et al., 2025).

Early-warning systems represent another important innovation. Climate and ecological information can provide advance notice of droughts, floods, heatwaves, wildfire conditions, pest outbreaks, or water shortages, allowing households and institutions to respond before impacts become severe. Seasonal climate forecasts, for example, can inform planting decisions and water management, while satellite-derived indicators can support drought monitoring. The growing availability of open environmental datasets has also increased opportunities for researchers and policymakers to undertake more spatially explicit assessments of climate vulnerability (Munroe et al., 2012).

Nevertheless, technology alone does not guarantee effective adaptation. Data may be difficult for local institutions to interpret, forecasts may contain substantial uncertainty, and digital infrastructure may be unevenly distributed. The findings therefore emphasize the importance of translating complex climate and ecological information into accessible, locally relevant decision-support tools. Technological innovation is most useful when it is connected to institutional capacity, community knowledge, appropriate communication systems, and clear mechanisms for acting on information.

3.4.2 Governance, Institutions, and Participatory Adaptation

The evidence indicates that ecosystem resilience depends strongly on governance arrangements because climate adaptation involves decisions across multiple sectors and spatial scales. Governments establish regulations, land-use policies, conservation frameworks, infrastructure standards, and financial incentives, while local communities often directly manage forests, rangelands, agricultural land, wetlands, and water resources. Conservation organizations and research institutions contribute technical knowledge, monitoring capacity, and implementation support. Effective adaptation therefore requires coordination among these actors rather than isolated interventions by individual institutions (Zhai & Lee, 2024).

Participatory governance is particularly important because adaptation measures can redistribute access to land, water, forests, and other ecosystem resources. Community participation can improve the legitimacy and local relevance of interventions while incorporating knowledge that may be absent from formal planning systems. Participatory restoration, community-based conservation, local watershed management, and collaborative protected-area governance can create stronger ownership of adaptation initiatives (Granata & Di Nunno, 2026). At the same time, participation must be meaningful rather than symbolic. Local actors need opportunities to influence priorities, implementation, monitoring, and evaluation.

Institutional coordination is also necessary because climate risks frequently cross administrative boundaries. Watersheds, forests, wildlife populations, coastal systems, and ecological corridors do not conform to political jurisdictions. Fragmented policies can therefore undermine resilience when one sector promotes practices that increase vulnerability in another. Policy coherence among climate, agriculture, biodiversity, water, forestry, and development policies is consequently a major requirement for effective ecosystem adaptation. Strong institutions should also be capable of learning and adjusting policies as evidence about climate impacts and intervention effectiveness changes.

3.4.3 Financing and Policy Support for Ecosystem Resilience

Financial capacity emerged as a major determinant of whether ecosystem adaptation strategies can move beyond small-scale demonstration projects. Climate finance, biodiversity funds, restoration investments, conservation financing, payments for ecosystem services, and public adaptation budgets can provide resources for ecosystem restoration and climate-risk reduction. Investments in mangrove restoration, watershed rehabilitation, forest conservation, soil restoration, and sustainable agricultural systems can generate benefits extending beyond individual landowners because healthy ecosystems provide services such as flood regulation, water purification, carbon storage, pollination, and erosion control (Dahal et al., 2025).

Payments for ecosystem services can create incentives for land managers to maintain ecological functions that benefit wider communities. Similarly, restoration investments can reduce vulnerability while supporting employment and rural livelihoods. However, the distribution and accessibility of finance remain major concerns. Smallholder farmers, Indigenous communities, local governments, and community-based organizations often have limited capacity to access complex international or national funding mechanisms (Adenike, 2022). Financing systems that require extensive technical documentation may consequently favor larger organizations.

Policy instruments can address these gaps by combining financial incentives with regulatory measures. Subsidies and credit schemes can encourage sustainable agricultural practices, while land-use planning and environmental regulations can discourage deforestation, wetland conversion, overgrazing, and other activities that increase vulnerability. The review suggests that financial mechanisms are most effective when they are predictable, transparent, accessible to local actors, and aligned with long-term ecological objectives. Short-term project financing is insufficient for ecosystems whose recovery may require decades of sustained management.

3.5 Effectiveness, Limitations, and Future Directions of Adaptation Strategies

3.5.1 Effectiveness and Co-Benefits of Emerging Adaptation Strategies

The reviewed evidence indicates that adaptation strategies vary considerably in their effectiveness, but interventions that strengthen underlying ecosystem functions generally provide the broadest range of co-benefits. Ecosystem restoration, agroforestry, wetland conservation, landscape diversification, soil and water conservation, and sustainable forest management can simultaneously reduce climate vulnerability and improve biodiversity, carbon storage, water regulation, soil fertility, and livelihood security. Nature-based approaches are particularly valuable where they restore ecological processes rather than addressing individual climate hazards in isolation (Beck et al., 2025).

For example, restoration of wetlands can reduce flood risks while improving water purification, habitat availability, carbon storage, and biodiversity. Mangrove restoration can provide coastal protection while supporting fisheries and storing carbon. Agroforestry can improve microclimatic conditions and soil fertility while providing food, fodder, timber, and income. Similarly, diversified agricultural systems can reduce production risks while improving soil health and reducing dependence on synthetic inputs. These multiple benefits increase the attractiveness of ecosystem-based adaptation compared with interventions that address only a single risk (Dordai et al., 2026).

However, effectiveness depends strongly on ecological context, implementation quality, time scale, and social conditions. An intervention that performs well in one climatic region may produce weaker outcomes elsewhere. Furthermore, some benefits emerge only after several years, making short evaluation periods inadequate for judging ecosystem adaptation. The findings consequently support the use of multidimensional indicators that measure ecological resistance and recovery alongside biodiversity, ecosystem services, agricultural productivity, livelihood outcomes, equity, and institutional performance.

3.5.2 Barriers, Trade-Offs, and Maladaptation Risks

Despite substantial progress, the review identifies persistent financial, institutional, technological, social, political, and knowledge-related barriers to effective adaptation. Limited funding can prevent communities from implementing otherwise appropriate measures, while weak institutions may constrain enforcement, coordination, and long-term maintenance. Unequal access to land, information, technology, and financial resources can also result in adaptation benefits being concentrated among relatively advantaged groups (Morshed et al., 2025). In some cases, interventions may unintentionally exclude vulnerable households or restrict traditional access to natural resources.

Trade-offs represent another important limitation. Increasing irrigation may protect agricultural production during drought but can intensify groundwater depletion where water resources are already stressed. Large-scale tree planting may increase carbon storage but, if poorly planned, can reduce native biodiversity or place additional pressure on water resources. Protected-area expansion may conserve biodiversity while restricting local livelihoods if communities are excluded from decision-making (Pandit & Sharma, 2023). These examples demonstrate that an intervention should not be classified as climate-resilient simply because it reduces one immediate climate risk.

The concept of maladaptation is therefore central to evaluating adaptation outcomes. Maladaptation occurs when an intervention reduces vulnerability in the short term or for one group while increasing vulnerability elsewhere or in the future. Hard infrastructure that shifts flood risk downstream, intensive groundwater extraction that temporarily supports farming but accelerates aquifer depletion, and conservation interventions that undermine local livelihood security can all illustrate this broader concern. Adaptation planning should consequently evaluate interventions across multiple spatial and temporal scales and explicitly consider who benefits, who bears the costs, and whether the intervention preserves the ecological capacity required for future adaptation.

3.5.3 Research Gaps and Future Adaptation Priorities

The review identifies several important gaps in the existing evidence base. First, many adaptation studies remain short-term and project-specific, making it difficult to determine whether observed improvements persist over decades of climatic change. Ecosystem resilience is inherently dynamic, and therefore long-term monitoring is necessary to establish whether interventions improve resistance to disturbance, accelerate recovery, or merely provide temporary relief. Second, geographical coverage remains uneven, with some regions and ecosystem types receiving considerably more research attention than climate-vulnerable areas where monitoring and research capacity are limited (Abbass et al., 2022).

A further gap concerns the integration of ecological and socioeconomic outcomes. Many studies measure vegetation recovery, agricultural productivity, carbon storage, or biodiversity without simultaneously evaluating equity, household welfare, institutional capacity, or distribution of benefits. Future research should therefore employ interdisciplinary frameworks capable of examining ecological processes together with economic, social, and governance outcomes. Comparative studies across different climatic and socioeconomic settings would also improve understanding of which interventions are transferable and which require substantial local modification.

Future adaptation research should increasingly emphasize cross-scale monitoring, participatory assessment, scenario modelling, and adaptive learning. Combining remote sensing and ecological modelling with field observations and local ecological knowledge can produce more comprehensive assessments of ecosystem change. Research should also investigate thresholds beyond which incremental adaptation becomes ineffective and transformative adaptation becomes necessary. Greater attention is required to maladaptation, adaptation limits, equity, and the long-term maintenance of interventions after external project funding ends. Overall, the evidence supports a shift from isolated, hazard-specific projects toward integrated resilience strategies that combine ecosystem restoration, climate-smart production, technological innovation, participatory governance, sustainable financing, and continuous learning. Such approaches are better positioned to respond to increasing climate uncertainty while maintaining ecological integrity and supporting human well-being.

4. Conclusion

Climate change is increasingly recognized as a major driver of ecosystem degradation, reducing ecological stability, biodiversity, productivity, and the capacity of ecosystems to absorb and recover from environmental disturbances.

This comprehensive review demonstrates that strengthening ecosystem resilience requires a shift from reactive conservation toward integrated, climate-smart, and adaptive management approaches that combine ecological restoration, sustainable agriculture, nature-based solutions, biodiversity conservation, ecosystem-based adaptation, and participatory governance. Evidence reviewed indicates that strategies such as agroecological farming, restoration of degraded landscapes, protection of ecological corridors, wetland and forest conservation, climate-resilient water management, and community-based resource management can enhance ecosystem adaptive capacity while simultaneously supporting livelihoods and ecosystem services. However, their effectiveness depends on local ecological conditions, institutional capacity, availability of climate information, financial resources, indigenous and local knowledge, and inclusive stakeholder participation. Overall, building climate-resilient ecosystems requires coordinated action across ecological, social, economic, and policy dimensions, with continuous monitoring and flexible adaptation to changing climate conditions. Future research should therefore prioritize long-term, context-specific assessments of adaptation outcomes and develop scalable approaches that strengthen both ecosystem integrity and human well-being under increasing climate uncertainty.

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