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IMPACT OF CLIMATE CHANGE ON ECOSYSTEM HEALTH: MITIGATION AND MANAGEMENT

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Abstract- Climate change is one of the most critical environmental challenges of the twenty-first century, with far-reaching consequences for ecosystem structure, ecological functioning, and biodiversity. Changes in temperature and precipitation have altered natural processes, while the increasing frequency of climate-related disturbances has reduced ecosystems' capacity to maintain stability. As ecosystem health declines, the provision of essential services such as climate regulation, carbon storage, water purification, and habitat support is increasingly threatened. This article examines the relationship between climate change and ecosystem health by discussing the major drivers of climate change and their influence on terrestrial, freshwater, and marine ecosystems. It further explores the impacts on biodiversity, ecosystem functioning, and ecological resilience, highlighting the implications for ecosystem services and environmental sustainability. The review also summarizes commonly used approaches for ecosystem health assessment and discusses ecosystem-based adaptation and mitigation strategies that can enhance resilience under changing climatic conditions. Recent advances in remote sensing, Geographic Information Systems (GIS), artificial intelligence, and ecological modeling have significantly improved the monitoring and assessment of ecosystem change. These technologies provide valuable information for conservation planning and support sustainable ecosystem management. Strengthening ecosystem resilience through effective restoration, nature-based solutions, and science-driven management will be essential for minimizing climate-related impacts and ensuring the long-term sustainability of natural ecosystems.

Keywords: Climate change, Ecosystem health, Biodiversity, Ecosystem services, Conservation, Adaptation

I. INTRODUCTION

Climate change has become one of the most pressing environmental issues affecting natural ecosystems worldwide. Human activities, particularly fossil fuel combustion, industrialization, deforestation, and land-use change, have significantly increased atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat within the Earth's atmosphere, resulting in global warming and widespread climatic changes (Abbass et al., 2022). The consequences of climate change extend beyond increasing temperatures. Altered rainfall patterns, prolonged droughts, severe floods, hurricanes, cyclones, melting glaciers, rising sea levels, and ocean acidification are changing ecological processes at local, regional, and global scales (Afriandi et al., 2026). These environmental changes affect ecosystem productivity, species distribution, habitat quality, nutrient cycling, and biological interactions.

Ecosystem health refers to an ecosystem's ability to maintain its ecological structure, biological diversity, resilience, and essential functions while supporting both environmental and human needs. Healthy ecosystems provide numerous ecosystem services, including climate regulation, water purification, soil fertility, carbon storage, food production, and recreational opportunities (Babaniyi et al., 2026). Climate change threatens these services by reducing ecosystem stability and increasing ecological vulnerability. Understanding the interactions between climate change and ecosystem health is essential for developing effective conservation policies and sustainable management strategies. This review summarizes current knowledge of climate change impacts on ecosystems and discusses practical approaches to improve ecosystem resilience under changing climatic conditions.

II. CLIMATE CHANGE CAUSES AND DRIVERS

Climate change refers to long-term alterations in the Earth's climate system, including changes in average temperature, precipitation, humidity, wind patterns, and the frequency and intensity of extreme weather events. While Earth's climate has naturally varied over geological time due to various environmental processes, the rapid changes observed over the past century are largely attributed to human activities (Bottery et al., 2026). Since the Industrial Revolution, industrialization, urbanization, deforestation, and the extensive use of fossil fuels have significantly increased atmospheric concentrations of greenhouse gases. These gases trap heat in the Earth's atmosphere, intensifying the natural greenhouse effect and causing global warming. As a result, climate change has become one of the most significant environmental challenges, affecting ecosystems, biodiversity, human health, agriculture, and economic development worldwide (Chakrabortty et al., 2026).

The causes of climate change can be broadly categorized into natural and anthropogenic (human-induced) drivers. Natural drivers have influenced the Earth's climate for millions of years and continue to contribute to short-term climate variability. These include changes in solar radiation, volcanic eruptions, variations in the Earth's orbit, and large-scale ocean-atmosphere interactions such as the El Niño–Southern Oscillation (ENSO). Variations in solar energy reaching the Earth's surface may slightly influence global temperatures, while major volcanic eruptions release ash and sulfate aerosols into the atmosphere, temporarily reflecting incoming solar radiation and cooling the Earth's surface (Chen et al., 2026). Similarly, long-term changes in the Earth's orbit and axial tilt, known as Milankovitch cycles, have historically controlled glacial and interglacial periods by altering the distribution of solar energy. Oceanic phenomena such as El Niño and La Niña also modify global weather patterns by influencing rainfall distribution, drought occurrence, and regional temperature fluctuations. Although these natural processes continue to shape climate variability, their contribution to the rapid warming observed during recent decades is relatively small.

The dominant drivers of current climate change are human activities that have substantially increased greenhouse gas emissions. The combustion of fossil fuels, including coal, petroleum, and natural gas, for electricity generation, transportation, industry, and domestic energy use is the largest source of carbon dioxide (CO_2) emissions (Delgado-Baquerizo et al., 2025). Carbon dioxide is the most abundant anthropogenic greenhouse gas and remains in the atmosphere for several centuries, making it the primary contributor to global warming. Deforestation and land-use change further accelerate climate change by reducing the Earth's capacity to absorb atmospheric carbon dioxide. Forests function as major carbon sinks, storing large amounts of carbon in vegetation and soils. However, converting forests to agricultural, urban, and industrial land releases stored carbon into the atmosphere while simultaneously reducing the capacity to sequester it. Wetland degradation, peatland drainage, and mangrove destruction also contribute to significant greenhouse gas emissions and reduce ecosystem resilience (Enbiale, 2026).

Agricultural activities are another major source of greenhouse gases. Livestock farming produces methane through enteric fermentation, while flooded rice cultivation releases methane under anaerobic conditions. Excessive use of nitrogen-based fertilizers results in the emission of nitrous oxide (N_2O), a greenhouse gas with a global warming potential significantly higher than that of carbon dioxide. Rapid urbanization has also intensified climate change by increasing energy consumption, transportation demand, infrastructure development, and the replacement of natural vegetation with impervious surfaces (Ferdous, 2026). These changes contribute to the urban heat island effect, where cities experience higher temperatures than surrounding rural areas due to heat absorption by buildings and roads. Industrial processes further contribute to greenhouse gas emissions through the production of cement, steel, chemicals, and refrigerants. Many industrial gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), possess extremely high global warming potentials despite being emitted in relatively small quantities. Additionally, the transportation sector, including road vehicles, aviation, and shipping, releases substantial amounts of carbon dioxide through the combustion of petroleum-based fuels, making it one of the fastest-growing sources of greenhouse gas emissions worldwide (Iqbal et al., 2025).

The increasing concentration of greenhouse gases has disturbed the Earth's natural energy balance by trapping more outgoing infrared radiation within the atmosphere. This enhanced greenhouse effect has resulted in rising global temperatures, melting glaciers and polar ice sheets, sea-level rise, altered rainfall patterns, ocean acidification, and more frequent extreme weather events such as floods, droughts, heatwaves, cyclones, and wildfires (Leemans & Eickhout, 2004). These climatic changes directly affect ecosystem structure, biodiversity, ecological processes, and the delivery of ecosystem services essential to human well-being. Understanding the various causes and drivers of climate change is essential for designing effective mitigation and adaptation strategies. Reducing greenhouse gas emissions through clean energy technologies, sustainable land management, forest conservation, climate-smart agriculture, and environmentally responsible urban planning can significantly reduce future climate risks. At the same time, strengthening ecosystem resilience through restoration and conservation measures will help natural systems better withstand the ongoing impacts of climate change (Malhi et al., 2020).

Table 1: Natural and Anthropogenic Drivers of Climate Change

Driver Category	**Specific Driver**	**Mechanism**	**Major Environmental Impact**
Natural	Volcanic eruptions	Release of ash and aerosols into the atmosphere	Temporary cooling due to reflection of solar radiation
	Solar radiation variability	Changes in the intensity of incoming solar energy	Minor fluctuations in global temperature
	Ocean circulation changes	Redistribution of heat through ocean currents (e.g.,	Changes in regional rainfall and temperature

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		ENSO)	patterns
	Orbital variations	Changes in Earth's orbit, tilt, and precession	Long-term glacial and interglacial climate cycles
Anthropogenic	Burning fossil fuels	Combustion of coal, oil, and natural gas releases CO_2	Global warming and enhanced greenhouse effect
	Deforestation	Removal of forests reduces carbon sequestration	Increased atmospheric CO_2 and biodiversity loss
	Agricultural intensification	Livestock, rice cultivation, and fertilizer application emit CH_4 and N_2O	Increased greenhouse gas emissions
	Urbanization	Expansion of built-up areas increases energy demand and heat retention	Urban heat island effect and higher emissions
	Industrial emissions	Manufacturing and chemical industries emit greenhouse gases	Rising atmospheric greenhouse gas concentrations
	Transportation	Vehicle and aviation fuel combustion releases CO_2	Air pollution and climate warming

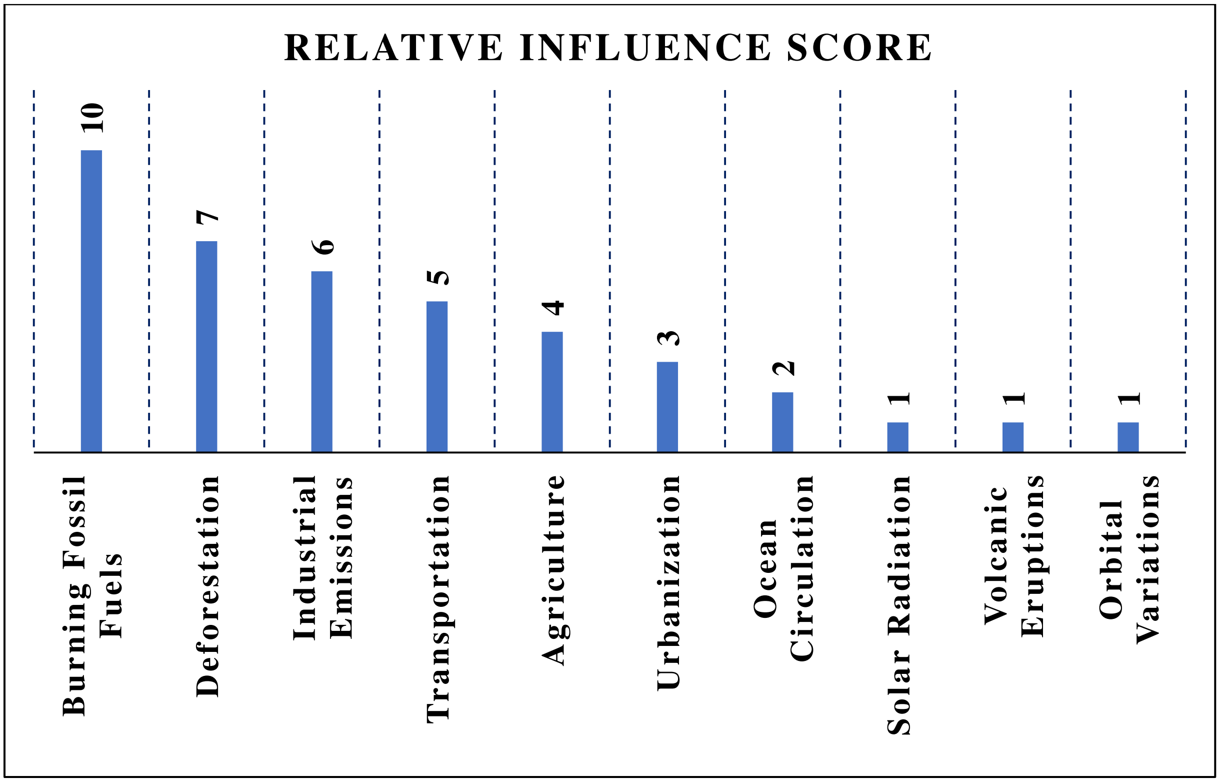

Figure 1: Relative Contribution of Major Climate Change Drivers 3

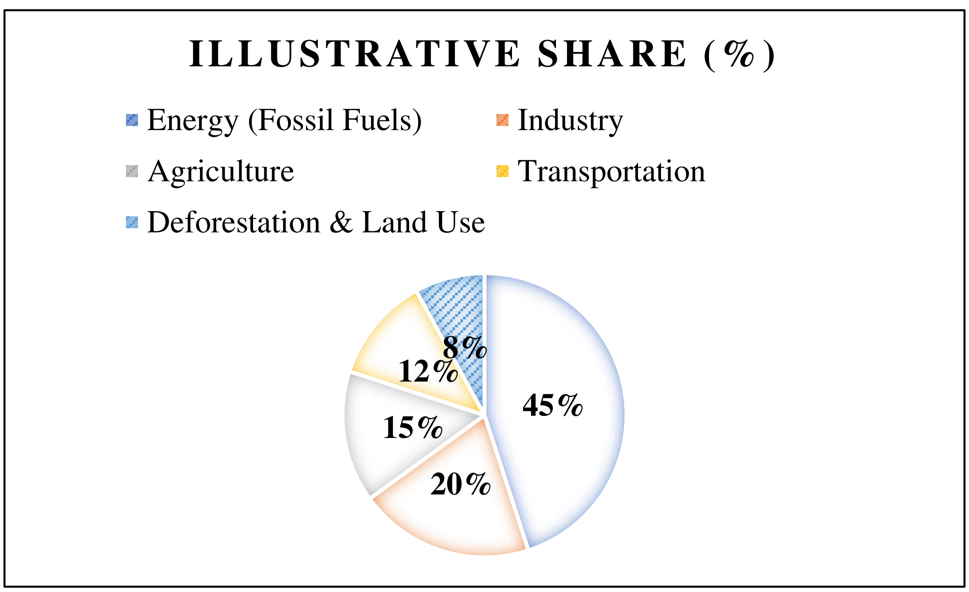

Figure 2: Greenhouse Gas Emission Sources

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III. UNDERSTANDING ECOSYSTEM HEALTH

Ecosystem health describes an ecosystem's ability to maintain its structure and function while responding to environmental change. A healthy ecosystem supports living organisms, sustains ecological processes, and continues to provide benefits to both nature and society over time. Unlike a static condition, ecosystem health is dynamic because natural systems continuously respond to changing environmental conditions. Their ability to adjust and recover determines their long-term sustainability (Mathur & Chamuah, 2026).

The concept of ecosystem health has become increasingly important because ecosystems are now experiencing greater environmental pressure than at any previous time. Climate change has altered temperature and rainfall patterns, affecting ecological processes across many regions. As these changes continue, assessing ecosystem health provides valuable insights into environmental conditions and identifies areas that require conservation or restoration. One of the most widely accepted indicators of ecosystem health is biodiversity**.** The presence of diverse plant, animal, and microbial communities reflects a stable ecological system where species perform complementary ecological roles. A decline in biodiversity often indicates ecological disturbance, as sensitive species tend to disappear before more tolerant ones. Consequently, changes in biodiversity are frequently used to evaluate the condition of terrestrial and aquatic ecosystems (McCarty, 2001).

Primary productivity is another important indicator because it reflects the capacity of vegetation to convert solar energy into biomass through photosynthesis. Productive ecosystems provide the energy required to sustain food webs and maintain ecological functions. Changes in primary productivity often indicate alterations in environmental conditions and may reveal the effects of climate variability before visible ecosystem degradation occurs. Soil quality strongly influences ecosystem functioning. Healthy soil supports vegetation growth by regulating water movement and providing a suitable environment for biological activity. When soil quality deteriorates, vegetation growth declines, ecological processes slow down, and the overall stability of the ecosystem is reduced. For this reason, soil

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quality is commonly included in ecosystem health assessments (Moghaddam et al., 2025).

Similarly, water quality is essential for maintaining healthy freshwater and coastal ecosystems. The chemical and physical characteristics of water directly influence aquatic organisms and ecological processes. A decline in water quality often results in reduced biological diversity and lower ecosystem productivity, making it an important indicator of environmental condition. The integrity of natural habitats also determines ecosystem health. Habitat integrity reflects the extent to which an ecosystem retains its original characteristics without substantial alteration. When habitats become fragmented or degraded, ecological interactions are disrupted, and many species lose suitable living conditions. Protecting habitat integrity, therefore, remains a central objective of ecosystem conservation (Nguyen et al., 2026).

Another important ecological process is nutrient cycling**,** which maintains the movement of essential nutrients through the environment. Efficient nutrient cycling supports plant growth and ensures the continuous functioning of ecosystems. Disturbances that interrupt these natural cycles can reduce ecosystem productivity and alter ecological balance. The ability of ecosystems to recover after disturbance is called ecological resilience**.** Resilient ecosystems are better able to withstand environmental stress and gradually return to a stable condition following natural or human-induced disturbances. As climate change increases the frequency of extreme events, ecological resilience has become an important measure of ecosystem health (Nimma et al., 2025).

Finally, carbon sequestration has received considerable attention because of its role in regulating the global climate. Natural ecosystems absorb atmospheric carbon dioxide and store it within vegetation and soils, thereby reducing the concentration of greenhouse gases in the atmosphere. Ecosystems with high carbon storage capacity contribute to both climate change mitigation and long-term ecological stability. Since ecosystem health is influenced by multiple ecological processes, no single indicator can fully describe its condition. A comprehensive assessment, therefore, combines several indicators to

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obtain a more accurate understanding of ecosystem status. The integration of field observations with modern techniques such as remote sensing and Geographic Information Systems (GIS) has further improved ecosystem health assessment by providing reliable information across large spatial and temporal scales (Ouyang et al., 2026).

IV. MAJOR IMPACTS OF CLIMATE CHANGE ON ECOSYSTEM HEALTH

Climate change has profoundly influenced the structure, functioning, and resilience of ecosystems worldwide. Rising greenhouse gas concentrations have altered the Earth's energy balance, leading to changes in temperature, precipitation, cryospheric processes, and the frequency of extreme climatic events. These changes affect ecological interactions, species distributions, ecosystem productivity, and the provision of ecosystem services (Pecl et al., 2017). Although ecosystems possess some capacity to adapt to environmental change, the current rate of climate change often exceeds their natural adaptive capacity, resulting in ecological degradation and biodiversity loss. Among the various climatic factors, increasing temperature and changing rainfall patterns are considered the primary drivers influencing ecosystem health.

4.1 Rising Temperature

The continuous increase in global surface temperature is one of the most evident consequences of climate change. According to recent assessments, the global average temperature has increased by approximately 1.2–1.3°C above the pre-industrial level, with the past decade the warmest on record (Yan et al., 2026). Rising temperatures influence nearly every component of an ecosystem by altering physiological processes, species interactions, and ecological functions. These effects are observed across terrestrial, freshwater, marine, and polar ecosystems. Temperature regulates plant growth, microbial activity, nutrient cycling, and the metabolic rates of animals. Even small increases in temperature can disrupt ecological balance by modifying seasonal biological events such as flowering, breeding, migration, and hibernation. Species adapted to narrow temperature ranges are particularly vulnerable because they possess limited physiological flexibility to cope with rapid climatic changes (Pereira et al., 2025).

One of the earliest ecological responses to warming is the shift in species distribution. Many plant and animal species have gradually expanded their geographical ranges toward higher latitudes or higher elevations where climatic conditions remain suitable (Yadav et al., 2023). Although this migration represents a natural adaptation mechanism, not all species can move at the same pace. Species with restricted habitats or limited dispersal ability often experience population decline or local extinction. Rising temperatures also increase evapotranspiration, resulting in greater water loss from soil and vegetation. Higher atmospheric demand for moisture accelerates evaporation from land surfaces and increases transpiration through plants, reducing available water for ecosystem functioning. Consequently, vegetation experiences water stress even in regions where annual rainfall has not changed substantially. Another major consequence of rising temperatures is reduced soil moisture. Prolonged warming enhances soil drying, decreases microbial activity, and limits nutrient availability for vegetation. Reduced soil moisture lowers plant productivity and increases ecosystem vulnerability to drought and wildfire (Quesada-Román, 2026).

Marine ecosystems are particularly sensitive to thermal stress. Elevated sea surface temperatures cause coral bleaching, a phenomenon in which corals expel their symbiotic algae due to prolonged exposure to heat (Vitousek, 1994). Since these algae provide most of the coral's energy requirements, bleaching weakens coral reefs and frequently results in large-scale coral mortality. The degradation of coral reefs subsequently affects fisheries, coastal protection, and marine biodiversity. High temperatures also produce heat stress in both plants and animals (Rawat et al., 2024). Plants may experience reduced photosynthetic efficiency, impaired reproductive development, and lower biomass production. Animals respond by altering behavior, increasing metabolic demand, and reducing reproductive success. Heat stress has become increasingly common during prolonged heatwaves, affecting wildlife populations and agricultural systems.

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The warming climate has accelerated glacier retreat in mountain regions and polar environments. Melting glaciers alter river discharge, reduce freshwater availability during dry seasons, and contribute to global sea-level rise. Glacier-fed ecosystems are therefore undergoing substantial ecological transformation, affecting both biodiversity and downstream human communities. Collectively, these processes reduce ecosystem stability by influencing species composition, ecological productivity, and nutrient dynamics. Continued warming is expected to intensify these impacts unless greenhouse gas emissions are substantially reduced (Saxena, 2025).

Table 2: Ecological Impacts of Rising Temperature on Ecosystem Health

Impact	**Ecological Response**	**Implications for Ecosystem Health**
Habitat shifts	Species migrate toward cooler regions	Altered species composition and community structure
Increased evapotranspiration	Greater water loss from vegetation and soil	Increased drought stress and reduced productivity
Reduced soil moisture	Decline in soil water availability	Lower vegetation growth and soil biological activity
Coral bleaching	Loss of symbiotic algae in corals	Declining coral reef biodiversity and fisheries
Heat stress	Physiological stress in plants and animals	Reduced survival, reproduction, and ecosystem stability
Glacier retreat	Loss of glacier mass and altered river flow	Reduced freshwater availability and habitat alteration

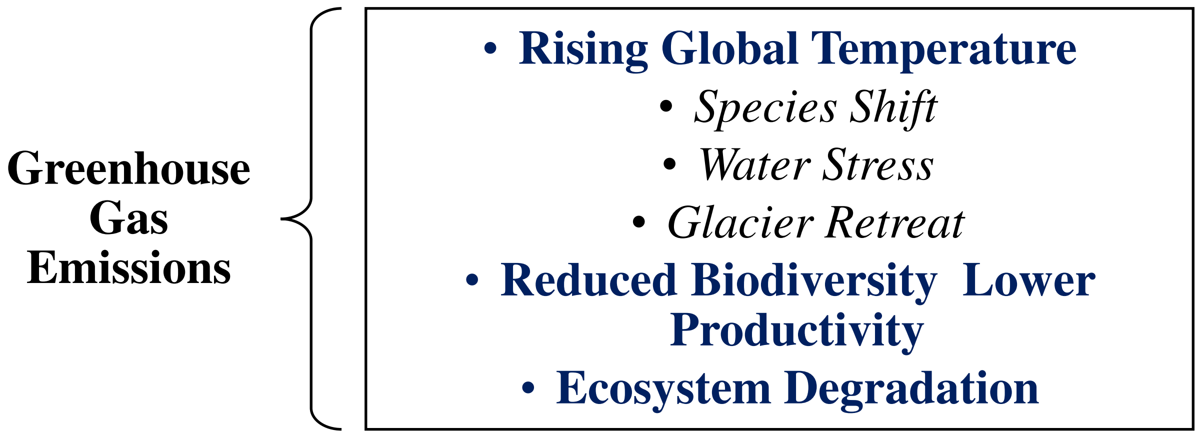

Figure 3. Conceptual framework illustrating the ecological consequences of increasing global temperature on ecosystem health.

4.2 Changes in Rainfall Patterns

Climate change has substantially altered the global hydrological cycle, resulting in significant changes in the amount, intensity, timing, and spatial distribution of precipitation. Some regions have experienced prolonged droughts, whereas others have recorded increasingly frequent and intense rainfall events (Verma, 2021). These changes directly influence water availability, ecosystem productivity, and ecological resilience. Rainfall regulates numerous ecological processes, including soil moisture, groundwater recharge, vegetation growth, and nutrient transport. Changes in precipitation, therefore, affect both terrestrial and aquatic ecosystems by altering year-round water availability (Scholes, 2016). One of the most significant consequences of changing rainfall patterns is the increased occurrence of agricultural drought. Reduced precipitation combined with higher evapotranspiration decreases soil moisture and limits water availability for crops and natural vegetation. Prolonged drought weakens plant growth, reduces agricultural productivity, and increases the ecosystem's susceptibility to degradation.

Conversely, many regions now experience more frequent episodes of intense rainfall and flooding. Excessive precipitation saturates soils, damages vegetation, displaces wildlife, and transports large quantities of sediments and pollutants into rivers and lakes (Valsala et al., 2026). Recurrent flooding also modifies river morphology and affects aquatic habitat quality. Changes in rainfall also influence groundwater recharge. Reduced infiltration during prolonged dry periods lowers groundwater storage, decreasing the availability of freshwater for ecosystems and human use. In semi-arid regions, declining groundwater levels have become a major environmental concern because many wetlands and rivers depend on groundwater discharge (Sharma et al., 2026). Wetlands are particularly sensitive to altered precipitation regimes. Reduced water availability contributes to wetland degradation, resulting in habitat loss, declining biodiversity, and reduced carbon storage capacity. Seasonal wetlands may experience shorter hydroperiods, affecting breeding habitats for aquatic organisms and migratory birds.

Changes in rainfall intensity also increase soil erosion. Heavy rainfall generates stronger surface runoff, which removes fertile topsoil and transports sediments into rivers and reservoirs. Soil erosion reduces land productivity while increasing water turbidity and sedimentation in downstream ecosystems (Upadhyay, 2020). Overall, altered rainfall patterns disrupt ecosystem processes by changing water availability, ecological productivity, and habitat conditions. The increasing variability of precipitation is expected to remain a major challenge for ecosystem management under future climate scenarios.

Table **3.** Ecological Consequences of Changes in Rainfall Patterns

Rainfall Change	**Environmental Effect**	**Impact on Ecosystem Health**
Agricultural drought	Reduced soil water availability	Declining vegetation growth and productivity
Flooding	Waterlogging and sediment transport	Habitat disturbance and biodiversity loss
Reduced groundwater recharge	Declining groundwater storage	Water scarcity and ecosystem stress
Wetland degradation	Reduced hydroperiod and habitat quality	Loss of aquatic biodiversity and ecosystem services
Increased soil erosion	Removal of fertile topsoil	Reduced soil fertility and increased

	sedimentation

V. CURRENT TREND (2024–2025)

Recent climate observations indicate that 2024 was the warmest year on record, with global average temperatures exceeding 1.5°C above the pre-industrial baseline for extended periods, although long-term Paris Agreement thresholds are based on multi-decade averages. In parallel, many regions experienced unprecedented rainfall extremes, including severe floods in parts of Asia, Europe, and South America, while prolonged drought affected portions of Africa, the Mediterranean, and South America (Singh & Singh, 2016). These concurrent warming and hydrological extremes demonstrate that rising temperatures and altered precipitation are interacting to increase ecosystem vulnerability, underscoring the urgent need for climate-resilient ecosystem management and restoration strategies.

VI. CURRENT TRENDS IN ECOSYSTEM ADAPTATION AND MITIGATION (2024–2026)

Recent global initiatives increasingly emphasize Nature-based Solutions (NbS) as an effective strategy for addressing climate change while conserving biodiversity. Large-scale restoration programs, including the UN Decade on Ecosystem Restoration (2021–2030), continue to promote the recovery of degraded forests, wetlands, grasslands, and coastal ecosystems. Carbon sequestration through blue carbon ecosystems, regenerative agriculture, and landscape restoration has become a major research focus because these approaches provide simultaneous climate, ecological, and socioeconomic benefits (Srivastava & Vickram, 2026). Advances in satellite remote sensing, artificial intelligence, and cloud-based geospatial platforms are also enabling real-time monitoring of ecosystem restoration and carbon dynamics, supporting evidence-based environmental management and climate policy. These developments indicate a growing shift from conventional engineering-based interventions toward ecosystem-based adaptation and mitigation strategies that enhance both environmental sustainability and human well-being.

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Table 4: Ecosystem Adaptation and Mitigation Strategies

Strategy	**Approach**	**Primary Objective**	**Major Ecological Benefits**
Ecosystem restoration	Adaptation	Restore degraded ecosystems	Improved biodiversity and ecological resilience
Protected areas	Adaptation	Conserve critical habitats	Species conservation and habitat connectivity
Sustainable land management	Adaptation	Reduce ecosystem vulnerability	Improved soil and water conservation
Watershed management	Adaptation	Maintain hydrological balance	Enhanced water security and ecosystem stability
Biodiversity conservation	Adaptation	Maintain ecological functions	Increased ecosystem resilience
Forest conservation	Mitigation	Increase carbon storage	Carbon sequestration and habitat protection
Afforestation and reforestation	Mitigation	Remove atmospheric CO_2	Climate regulation and biodiversity enhancement
Wetland conservation	Mitigation	Protect carbon-rich ecosystems	Flood control and long-term carbon storage
Blue carbon ecosystem conservation	Mitigation	Preserve coastal carbon sinks	Coastal protection and carbon sequestration
Nature-based Solutions (NbS)	Adaptation & Mitigation	Address climate change through ecosystem management	Climate resilience, biodiversity conservation, and sustainable development

VII. CONCLUSION

Climate change poses significant challenges to ecosystem health by altering ecological processes, reducing biodiversity, and weakening ecosystem resilience. Rising temperatures, changing precipitation

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patterns, sea-level rise, extreme weather events, and ocean acidification are affecting terrestrial, freshwater, and marine ecosystems worldwide. These impacts threaten essential ecosystem services that support human health, food security, water availability, and climate regulation. Advances in remote sensing, GIS, artificial intelligence, and ecological modeling have greatly enhanced the ability to monitor ecosystem changes and support evidence-based management. Strengthening ecosystem resilience through conservation, ecological restoration, sustainable land-use practices, and climate-smart policies is critical for reducing future environmental risks. Integrating scientific research, technological innovation, and effective governance will be essential to protect ecosystem health and achieve sustainable development under a changing climate.

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