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A comprehensive review of climate change's imprint on ecosystems

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ABSTRACT

In the 21st century, climate change, which is predominantly caused by human activities, has emerged as a major global concern. This paper examines in depth the profound and multifarious effects of climate change on ecosystems and the ecosystem services they provide. It further investigates the complex connections between climate change and ecosystems, focusing on terrestrial, aquatic, and marine habitats. Notably, we emphasize the unique challenges confronting ecosystems in Southeast Asia, a region of ecological significance where the ocean economy is fundamental to human livelihoods. Climate change threatens ecosystem services in numerous ways, including the provision of food and water, climate regulation, nutrient cycling, and cultural importance. We emphasize the potential transformation of ecosystems from carbon sinks to carbon sources, which has implications for climate control. Moreover, changes in disease vectors and altered landscapes raise concerns for human health and cultural traditions. We emphasize the importance of international cooperation, as exemplified by the Paris Agreement, in mitigating climate change collectively. In addition, we advocate for the inclusion of indigenous communities and traditional ecological knowledge in conservation and restoration initiatives. This paper concludes by emphasizing the profound interdependence between ecosystems and human well-being and the urgency of taking action.

Key words: anthropogenic activities, climate change, climate change impacts, ecosystems, species distribution

HIGHLIGHTS

- Climate change impacts on aquatic ecosystems, terrestrial ecosystems, ecosystem services.
- Future management.

GRAPHICAL ABSTRACT

INTRODUCTION

Climate change is becoming a prominent global concern as the 21st century progresses. Empirical evidence indicates that there is a significant impact on ecosystems, cultures, and economies due to global climatic changes, particularly the phenomenon of global warming (Adger *et al.* 2005; Feliciano *et al.* 2022). These modifications are distinguished by enduring patterns in temperature, precipitation, humidity, and many ecological elements, resulting in erratic weather phenomena, the thawing of ice sheets, and the escalation of sea levels (Lipczynska-Kochany 2018; Murshed & Dao 2020; Michel *et al.* 2021). Before the onset of the industrial revolution, the primary sources of greenhouse gas emissions were natural occurrences such as volcanic eruptions, forest fires, and seismic phenomena (Sovacool *et al.* 2021; Usman & Balsalobre-Lorente 2022). Nevertheless, it has been observed that anthropogenic activities, particularly the combustion of fossil fuels, have become the primary factors responsible for the escalated occurrence of climate change subsequent to the post-industrial revolution (Murshed *et al.* 2022). Activities such as intensive agricultural practices, widespread deforestation, and the transportation industry contribute significantly to the exacerbation of the situation, resulting in climate-related disasters, health hazards, infrastructure degradation, and reduced production. The reliance on fossil fuels is particularly apparent in emerging nations, as highlighted by Balsalobre-Lorente *et al.* (2022) and Ishikawa-Ishiwata & Furuya (2022). At the heart of this global crisis are the complex webs of ecosystems and the services they provide. Ecosystems consist of organisms that interact with one another and their physical environment. The term 'ecosystem services' refers to the numerous benefits that these systems provide to humanity, such as the provision of sustenance and clean water, climate regulation, and cultural significance (Loomes & O'Neill 2000). Due to their complexity, the subtle interdependencies between these services, climate change, and human dependence are frequently obscure. Accelerating climate change causes perturbations in ecosystems, which have direct effects on human societies (Greig *et al.* 2011). This can range from altered water patterns to the extinction of a beloved species or landscape. Managing and enhancing the resilience of ecosystems in the face of climatic changes necessitates a deeper understanding of such shifts. With the atmosphere and oceans undergoing radical transformations, the biosphere, or thin layer of life on Earth, is on the verge of experiencing profound changes. This living stratum is intimately connected to the atmosphere and hydrosphere,

forming the framework for human societies (Parmesan & Yohe 2003). Yet, human-caused emissions, which contribute to both climate change and ocean acidification, pose a growing threat to the sustainability and resilience of ecosystems. The consequences of these challenges are becoming increasingly apparent, with the planet poised for further warming absent significant interventions (Steffen *et al.* 2015). Our understanding of the Earth's climatic systems and their symbiotic relationship with the biosphere is being refined by current scientific research. According to projections, the effects of climate change on ecosystems and human societies are expected to intensify. Ecosystems are already undergoing rapid changes as a result of numerous global change drivers. Their diverse responses to such changes, resulting from complex organism interactions and external stressors, endanger global biodiversity and have far-reaching effects on global food production.

The need for this review paper arises from the urgent global concern surrounding climate change as the 21st century unfolds. Increasing empirical evidence has demonstrated the significant and multifaceted impact of global climatic changes on ecosystems, cultures, and economies, particularly the phenomenon of global warming. Prior to the industrial revolution, natural occurrences such as volcanic eruptions and forest fires were the primary sources of greenhouse gas emissions. Today, however, human activities, particularly the utilization of fossil fuels, are the primary causes of climate change. These activities, which include intensive agriculture, deforestation, and the transportation industry, have resulted in climate-related disasters, health risks, infrastructure degradation, and decreased production, with developing nations being disproportionately affected. Frequently, the intricate interdependencies among ecosystems, their services, climate change, and human dependence remain obscure. Accelerating climate change wreaks havoc on ecosystems, which has direct consequences for human societies. Managing and enhancing the resilience of ecosystems in the face of these changes requires a deeper comprehension of these interactions. The biosphere, or the thin layer of life on Earth, is on the verge of profound changes as the atmosphere and oceans endure radical transformations, and human-caused emissions continue to threaten ecosystem sustainability. Consequently, the significance of this review paper lies in its capacity to comprehensively assess the effects of climate change on diverse ecosystems, offer policy and management implications, provide insights into adaptation and mitigation strategies, and ultimately contribute to the informed decision-making necessary to effectively address this global challenge.

This review paper presents a comprehensive synthesis of existing research on the subject of climate change and its effects on ecosystems, drawing from a thorough exploration of several academic databases and reliable sources. A comprehensive search was undertaken on scholarly databases including PubMed, Web of Science, and Google Scholar. In addition to conducting searches, the scope of the research was expanded to encompass government publications and reports issued by renowned environmental organizations. The utilized search phrases encompassed concepts such as 'climate change', 'ecosystems', 'species distribution', 'ecosystem services', and other relevant terminologies. The search process did not involve the use of particular inclusion or exclusion criteria, so allowing for the consideration of a broad selection of relevant studies. The selection process for articles, papers, and reports was conducted with a focus on their pertinence to the subject matter of climate change and its effects on ecosystems. Emphasis was placed on contemporary research and studies that encompassed a global or regional scope. The process of data extraction encompassed the collection of information from the designated sources, encompassing several aspects such as the examination of climate change effects on terrestrial and aquatic ecosystems, alterations in species distribution, modifications in ecosystem services, and other relevant subjects. The absence of statistical or quantitative analysis is notable in this review, as its focus is mostly qualitative in nature. The synthesis of the compiled literature yielded an overview of the existing body of information regarding the effects of climate change on ecosystems. The data were systematically classified and arranged in order to comprehensively cover the several facets of the research article. The ethical aspect of adequately acknowledging and attributing the original authors and sources of the examined studies was taken into account.

The study is carried out on a spatial scale that incorporates both global and regional views. The study commences by acknowledging climate change as a significant worldwide issue and its ramifications on ecosystems, cultures, and economies at a global level. The text alludes to a range of global issues, including but not limited to global warming, the escalation of sea levels, and anthropogenic emissions. As the research advances, it explores distinct ecosystems and geographical areas, examining the influence of climate change on terrestrial, freshwater, and marine ecosystems. These topics encompass the examination of region-specific instances and the resultant impacts of climate change on these particular areas. Moreover, the research emphasizes the impacts of climate change on ecosystem services, a matter of significance at both the global and regional levels. The discourse encompasses ecosystem services, encompassing the provision of food, water, and carbon sequestration, with an emphasis on the broader consequences at both the global and regional scales.

CLIMATE CHANGE AND ECOSYSTEM DYNAMICS

Ecosystem patterns and processes, such as primary productivity rates or the balance of chemical elements, respond to climate change in intricate ways due to multifaceted controlling factors (Schimel *et al.* 2001). For instance, a forest's role as a carbon source or sink depends on the equilibrium between primary production and ecosystem respiration. These processes react to varied drivers. Physical alterations in ecosystems, like thermal stratification changes in lakes and oceans or the intensification of the hydrologic cycle across vast basins, result in modifications in ecosystem structure and function with significant economic and human implications (Reich *et al.* 2014). Notably, shifts or extreme changes often have a more substantial impact than average changes, leading to heightened societal consequences. Climate change is ushering in considerable shifts in species range and abundance, modifying terrestrial, freshwater, and marine ecosystems (Murray *et al.* 2015). Presently, species and ecosystems are grappling with numerous environmental stresses, such as habitat loss, pollution, and invasive species (Kalantari *et al.* 2019). The cumulative effect, combined with the swift climate changes, is anticipated to disrupt ecosystem processes and services, enhancing the risk of species extinctions. Diverse species react differently to climate change, which increases the likelihood of the disruption of enduring ecological interconnections. In addition, climate change is predicted to modify the composition and function of ecosystems, resulting in changes to the species that comprise an ecosystem and the manner in which energy and materials circulate within. The character and quantity of ecosystem services will inevitably change as a result of these alterations. Nevertheless, the complexity of ecosystems makes modelling them difficult (Urban 2015). Our ability to predict the responses of species and ecosystems to climate change is limited. This limitation hinders our capacity to mitigate the negative impacts on terrestrial ecosystems. Consequently, ongoing support for biodiversity conservation and natural ecosystem protection strategies is essential (Bellard *et al.* 2012). The phenomenon of global warming is anticipated to result in alterations in the geographical ranges of various species, mostly characterized by a general migration towards higher latitudes. While it is known that species have historically responded to climate change by altering their distributions, the current rate of global warming is expected to impede the ability of many species to adapt sufficiently, potentially resulting in their extinction. According to Thomas *et al.* (2004), the presence of elevated temperatures is likely to diminish the available habitats for arctic and alpine species, resulting in heightened isolation and an augmented likelihood of extinction. Furthermore, the phenomenon of climate change will have a significant influence on the operational dynamics of various ecosystems. While the increase in temperatures has the potential to enhance plant development, it is important to acknowledge that it may also lead to an escalation in decomposition rates, contributing to the release of additional carbon dioxide into the atmosphere. The implementation of strategies aimed at augmenting carbon storage in ecosystems has the potential to mitigate the pace of carbon accumulation in the Earth's atmosphere. Emerging scientific studies suggest that there is mounting evidence to support the notion that ecosystem features and species distributions are potentially being impacted by the phenomenon of global warming. The aforementioned consequences are expected to be exacerbated in ecosystems that are already stressed by human activities. The potential consequences of climate change on ecosystems have the potential to endanger valuable ecosystem services, particularly those that are often underestimated in economic evaluations (IPCC 2014a).

IMPACT ON TERRESTRIAL ECOSYSTEMS

The impact of climate change on terrestrial ecosystems worldwide is significant. Forest ecosystems are currently encountering substantial problems. The growth, death, and reproduction of trees are being directly impacted by climate variations (LSMOH 2012). The forest ecosystems are significantly influenced by alterations in the climate, which have profound effects on several aspects such as tree growth, mortality, and reproduction. Ecosystem services encompass a range of advantages, namely sustaining, regulating, providing, and cultural services, which arise from the functioning of natural processes within ecosystems. These services are presently subject to the impacts of climate change. According to Moore & Allard (2008), climate change has the capacity to modify the physiological characteristics, defensive mechanisms, and interconnections among pests, their surroundings, and other organisms. The observed fluctuations in climate have resulted in discernible impacts on the growth of trees and saplings. As an example, elevated temperatures lead to accelerated bud bursts, leafing, and flowering, thereby heightening the susceptibility to pests (Zhu 2018). In addition, other disruptions such as fires, droughts, invasions by non-native species, and outbreaks of insects are causing significant changes to the organization, species makeup, and carbon sequestration capacity of forest ecosystems (Battles *et al.* 2008). Furthermore, it has been noticed that there are increases in forest damage, erosion, landslides, and flooding as a result of the shifting climate (Wu *et al.* 2012). The study conducted by Weiskopf

et al. (2020) demonstrates that there have been notable impacts on biodiversity as a result of changes in plant distribution, warming trends, and precipitation patterns. Changes in species interactions, habitats, and ecosystem function are among the effects of climate change, leading to alterations in the production of natural products and services for society. By influencing plant distribution, warming, precipitation patterns, weather events, and disturbance regimes, climate change has an impact on forests. According to Nunez *et al.* (2019), continued warming trends are expected to have negative effects on biodiversity. Both direct and indirect effects affect the responses of organisms to climate change. For example, a species whose distribution shifts as a result of climate change may 'invade' the range of another species, creating new competitive relationships (Turyasingura *et al.* 2022).

The grasslands and prairie bioregions are subject to notable effects from climate change, which include elevated temperatures, alterations in precipitation patterns, and the possibility of drought. According to Kahrl *et al.* (2018), these ecosystems, characterized by their inherent aridity and pronounced seasonal climates, exhibit a heightened sensitivity to climate fluctuations and are prone to alterations in climatic circumstances. The potential consequences of regional drought in the Prairie Pothole Region are worth considering, particularly in relation to the breeding waterfowl habitat. This might have a large influence on a substantial section of the duck population across the continent (Austin *et al.* 2004). In addition, elevated temperatures and less precipitation can result in the expansion of novel species and a heightened susceptibility to wildfires (Cook *et al.* 2015). The productivity of grassland is influenced by climate variability since the warming of the environment leads to a decrease in soil moisture (Knapp & Smith 2001; Pugnaire *et al.* 2019). These oscillations in climate have a significant impact on grassland ecosystems, which are known to be particularly susceptible to such changes (Song *et al.* 2019). The Arctic region is currently undergoing significant changes as a result of climate change, which encompass the loss of habitats and disruptions to natural systems (IPCC 2014b). The decline in sea ice and glaciers is a matter of great concern, as highlighted by the Intergovernmental Panel on Climate Change in their 2019 report. The increase in temperatures is causing animals to modify their habitats, which in turn exposes them to unfamiliar predators, competitors, and infections (Tynan & DeMaster 1997; ACIA 2005). The situation is worsened by the escalating human activity in the Arctic region (AMAP 2017). The phenomenon of climate change is responsible for significant alterations in both the geographic spread and the makeup of alpine plant groups. The increase in temperatures is compelling various species to relocate to elevated elevations, causing modifications to the richness of these ecosystems (Pauli *et al.* 2012).

The retreat of glaciers, as a consequence of global warming, is having a significant impact on the hydrological cycle (Beniston *et al.* 2018). Consequently, this phenomenon is influencing streamflow, water quality, and plant growth. Moreover, the alpine fauna is currently facing challenges related to alterations in their distribution patterns, behavioural patterns, and heightened vulnerability to diseases (Gehrig-Fasel *et al.* 2007). According to a study conducted by the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL), there is evidence of significant and swift transformations in alpine flora. These changes are closely linked to the crucial influence exerted by alpine soils. The influence of climate change on the carbon-storing capacity of ecosystems has the potential to increase CO_2 emissions (WSL 2023). Deserts are among the most susceptible ecosystems to climate change due to rising temperatures, decreased precipitation, and increased atmospheric carbon dioxide (Smith *et al.* 2000; Duraiappah *et al.* 2005). These challenges are intensified by the interaction of climate change and human land use. Elevated CO_2 levels have contradictory effects on plant growth in arid regions, with shallow desert soils being particularly susceptible (Evans & Belnap 1999). It is disconcerting that desert biocrusts, which are essential for water retention and nutrient provision, are declining. The US Geological Survey discovered a significant decline in lichen populations in desert soils, which could contribute to desert expansion and negatively impact agricultural land. To protect these fragile arid ecosystems, immediate action is necessary (Wigginton 2023).

IMPACT ON AQUATIC ECOSYSTEMS

Freshwater ecosystems

The effects of climate change on freshwater ecosystems, such as lakes, reservoirs, and wetlands, are profound. The warming of lake surface waters is among the most alarming consequences. Between 1985 and 2009, lake summer surface temperatures increased by a global average of 0.34 °C per decade (O'Reilly *et al.* 2015), with variable rates across regions. O'Reilly *et al.* (2015) attributed these rapid changes to a combination of climate and local factors, resulting in the rapidest warming lakes being dispersed across various geographic locations. Lakes are crucial barometers for climate change, functioning as indicators of the lake's and its catchment area's impacts. Although factors such as eutrophication, acidification, and land

use can occasionally obscure the clarity of these climate signals, the sensitivity and rapid response of lakes to environmental changes make them essential for comprehending the effects of climate change (Adrian *et al.* 2009). As climate change advances, regional climate changes have been observed. Some regions experience more intense monsoons, whereas others face droughts, rising sea levels, and crop failures. Reduced snowpack and diminishing glaciers consequently result in less snowmelt entering water bodies. This influences not only wildlife and fish but also the availability of water for drinking and irrigation. The limited capacity of aquatic ecosystems to adapt to these changes emphasizes the need for mitigation efforts and enhanced adaptation strategies. The predicted increase of 1.5–5.8°C in average global surface temperatures by 2100 could disrupt species distribution and ecological processes in aquatic ecosystems (Efe & Bemigho 2021). Many species will be forced to migrate to more favourable habitats as global temperatures rise. Some cold-water fish may become extinct in certain regions, whereas warm-water fish may expand their ranges. In addition, climate change will likely continue the current trend of shorter ice cover durations. Recent data indicates that ice cover has decreased by 31 days over the past 165 years, with recent ice loss rates being six times greater (Sharma *et al.* 2021). Many freshwater species will experience altered thermal habitats as a result of rising temperatures, and some may struggle to adapt (Kraemer *et al.* 2021). Such temperature variations will have an impact on lake limnology, highlighting the need to comprehend how diminished ice and snow cover affects photosynthesis in lakes (Smol & Douglas 2007).

Reservoirs, which are essential for the production of potable water, are also affected by climate change, which impacts water quality and production reliability. In contrast to lakes, reservoirs actively manage their storage and outflows, so their response to climate change is distinct. The active management of withdrawal rates, schedules, and depths in reservoirs has a direct impact on heat and material storage, thermal stability, and mixing resistance. Due to their capacity to regulate greenhouse gases, wetlands play an important role in climate change mitigation. Nevertheless, their location between aquatic and terrestrial ecosystems makes them vulnerable to the effects of climate change, particularly hydrological shifts (IPCC 2007). These changes, combined with disturbances such as urbanization, can exacerbate the effects on wetland ecosystems. Moreover, the direct and indirect effects of climate change may transform wetland carbon sinks into carbon sources, thereby amplifying greenhouse gas emissions (Flanagan & Syed 2011). The need for modelling, field surveys, and mesocosm experiments is emphasized for the monitoring of these changes (Stewart *et al.* 2013).

Marine ecosystems

Due to climate change, the oceans are undergoing significant alterations, including warming, acidification, and deoxygenation. These changes have caused marine species' geographic ranges to shift (IPCC 2021). Due to the fact that a sizable portion of the population lives along the coast and heavily relies on marine resources, Southeast Asia is particularly affected (Neumann *et al.* 2015). In some of these countries, the ocean economy accounts for up to 20% of the GDP (Ebarvia 2016). There are significant ecologically significant areas in Asia and the South, such as the Coral Triangle, which sustains the majority of coral species worldwide (Veron *et al.* 2011). Consequently, the effects of climate change on marine life in this region are of great concern. The earliest and most severe effects of climate change on the productivity of marine fisheries are predicted to occur in tropical regions (Lam *et al.* 2020). In addition, climate change poses a threat to aquaculture, which is vital to food security in Southeast Asia (Monnier *et al.* 2020). Climate change poses a significant hazard to coral reefs, particularly in regions such as the Coral Triangle (Burke *et al.* 2012). Temperature increases can cause coral bleaching events on a large scale (Hughes *et al.* 2018), and increasing ocean acidification inhibits coral growth (Kay 2021). High sea surface temperatures are a significant contributor to coral bleaching, according to research (Goreau & Hayes 1994). Multiple biological interactions connect primary producers to apex predators, including humans, in marine ecosystems. These interactions are crucial for the overall function of marine ecosystems, providing essential societal benefits such as fisheries production and shoreline protection (National Research Council 2011). Nonetheless, these ecosystems are subject to enormous pressure from human activities, such as climate change. Increasing CO_2 levels result in increased ocean temperatures (Bindoff *et al.* 2007) and acidity (Doney *et al.* 2009), leading to secondary effects such as decreased sea ice and oxygen levels (Keeling *et al.* 2010). These rapid changes test the adaptability of numerous marine species. In addition, habitat degradation, exploitation, and invasive species exacerbate the pressure on marine ecosystems (Diaz & Rosenberg 2008). Notably, coastal ecosystems are experiencing severe degeneration, with habitats such as coral reefs and mangroves experiencing significant losses (Jackson 2010). Therefore, it is essential to evaluate the cumulative effects of all these stressors holistically (Doney 2010).

IMPACTS ON ECOSYSTEM SERVICES

Ecosystem services comprise the wide range of benefits that human beings obtain without charge from the natural environment and properly functioning ecosystems. The spectrum of services provided encompasses the provisioning of resources such as food and water, the regulation of services related to climate and disease control, the support of services such as nutrient cycling and soil formation, and the provision of cultural services that offer recreational and spiritual advantages. The services' stability and sustainability are jeopardized by climate change, mostly influenced by anthropogenic activity. One example of a vital provisioning function that faces difficulties is food production, which is impacted by climate change and its effects on agricultural yields, fisheries, and animal output. The aforementioned issues stem from changes in temperature and precipitation patterns, the rising frequency of severe weather events, and the shifting dynamics of pests and diseases, as emphasized by Rosenzweig *et al.* (2014). The provision of water supplies, which is another crucial ecosystem service, is also facing significant challenges. Barnett *et al.* (2005) illustrate how variations in precipitation, along with the melting of glaciers and alterations in snowpack dynamics, have significant effects on the distribution and characteristics of water resources in numerous areas.

In addition, it should be noted that the well-being and efficiency of forest ecosystems, which serve as valuable sources of timber and fibre, are adversely affected by fluctuations in temperature and precipitation regimes, as well as an escalation in the prevalence of pests and diseases (Boisvenue & Running 2006). In the context of regulating services, ecosystems such as forests and wetlands have conventionally functioned as carbon sinks, exhibiting a capacity to sequester more carbon dioxide than they release into the atmosphere. However, it is important to acknowledge that climate change possesses the capacity to alter these sinks, potentially leading to their transformation into carbon sources (Pan *et al.* 2011). Furthermore, the geographical range of disease vectors, such as mosquitoes, may undergo expansion as a result of climate modifications, hence exerting an impact on the transmission dynamics of illnesses such as malaria and dengue. This problem has been highlighted by Ryan *et al.* (2019). Wetlands, which function as natural barriers against flooding, are currently confronted with challenges arising from the rise in sea levels and changing precipitation patterns. These factors pose a risk to the wetlands' ability to effectively regulate floods (Junk *et al.* 2013).

According to Davidson & Janssens (2006), supporting services are impacted by elevated temperatures, as they can alter the rates of decomposition and nutrient availability in ecosystems, thereby influencing nutrient cycle. The impact of climate change extends to soil formation and fertility, as it affects crucial soil attributes such as erosion rates, organic matter content, and others (Lal 2004). In relation to cultural services, it has been observed that the landscapes which individuals appreciate for recreational and aesthetic purposes are undergoing modifications due to the shifting climate conditions. This phenomenon has significant implications for tourism and various outdoor activities (Scott *et al.* 2012). For example, changing weather patterns, temperature shifts, and other climate-related factors can alter the appearance and accessibility of natural areas such as forests, lakes, and mountains that people visit for leisure and enjoyment. These changes can impact tourism and outdoor activities, as the attractiveness and suitability of these places for such activities may be compromised. For instance, if a once-popular ski resort can no longer maintain consistent snowfall due to warmer temperatures, it could negatively affect the tourism industry in that area. Furthermore, Adger *et al.* (2013) argue that climate change poses a significant threat to certain natural locations that hold spiritual importance for communities. The potential alteration or annihilation of these sites could have profound implications for cultural and religious practices. Many indigenous, religious, or cultural groups have sacred sites within nature, like mountains, rivers, or forests, that are deeply intertwined with their beliefs and traditions. Climate-induced alterations to these sites can be devastating. If, for example, a sacred river dries up due to changing precipitation patterns, it could disrupt important rituals and practices of the community that relies on it for spiritual significance.

FUTURE PERSPECTIVES AND MANAGEMENT STRATEGIES

As a result of the unalterable effects of climate change on ecosystems, the scientific community, policymakers, and conservationists are shifting their attention to potential mitigation and adaptation strategies. Not only are these strategies crucial for preserving biodiversity but also for ensuring human survival and well-being. Building ecosystem resilience entails enhancing ecosystems' inherent capacity to recover from disturbances and adapt to new conditions. This involves fostering biodiversity in the context of climate change, as diverse ecosystems are generally more resilient to stressors (Holling 1973). Adaptive management, which prioritizes a flexible decision-making process that can be modified in response to feedback from an

ecosystem, is gaining popularity. Incorporating climate-smart agricultural practices and establishing green infrastructure in urban areas are additional ways to boost resilience (Challinor *et al.* 2017). Conservation and restoration have progressed beyond the simple establishment of protected areas. Modern endeavours recognize the significance of ecological corridors that connect fragmented habitats, allowing species migration and genetic exchange, which are essential for adapting to changing conditions. Restoration ecology also plays a significant role, with initiatives such as reforestation and wetland rejuvenation playing a central role in mitigating the effects of climate disruptions (Hobbs & Harris 2001).

To address the global challenge of climate change, robust international cooperation is required. International agreements, such as the Paris Agreement, establish a framework for countries to collectively limit the rise in global temperature and mitigate its effects. To be truly effective, however, these top-down policies must be complemented by bottom-up initiatives at the national and local levels, ensuring that policies are tailored to the requirements and vulnerabilities of specific regions (Ostrom 2010). Engaging indigenous communities and recognizing their traditional ecological knowledge can contribute to the development of sustainable management practices (Berkes 2009). While substantial research has been conducted on climate change and its effects, it is necessary to prioritize areas with the largest knowledge deficits. This includes understanding the synergistic effects of multiple stressors on ecosystems, refining climate models to provide more accurate local predictions, and researching carbon sequestration and ecosystem restoration technologies (Conway *et al.* 2019). Long-term ecological studies can also provide crucial insights into post-disturbance ecosystem responses and recovery.

CONCLUSION

In conclusion, this comprehensive review paper emphasizes the profound and multifaceted impact of climate change on ecosystems, cultures, and economies on both global and regional scales. The paper highlights the importance of addressing this urgent global issue and provides a comprehensive analysis of how climate change impacts terrestrial, freshwater, and marine ecosystems. In addition, the effects on ecosystem services, such as food production, water supply, carbon sequestration, and cultural significance, are investigated. The study underscores that climate change is causing significant alterations in the range and abundance of species, thereby disrupting ecological interconnections and ecosystem function. It is anticipated that this transition will result in modifications to the composition and function of ecosystems, thereby altering the quantity and nature of ecosystem services. Importantly, the paper addresses the need for effective mitigation and adaptation strategies to enhance the resilience of ecosystems and mitigate the effects of climate change. These strategies include promoting biodiversity, implementing climate-smart agricultural practises, creating ecological corridors, and engaging in ecological restoration. The assessment also highlights the importance of international cooperation, as exemplified by the Paris Agreement, to combat climate change on a global scale. In addition, the paper identifies research gaps, such as the interaction of multiple stressors on ecosystems, the improvement of climate models for more precise local predictions, and the exploration of technologies for carbon sequestration and ecosystem restoration. Emphasis is also placed on long-term ecological studies as a means to obtain a deeper understanding of how ecosystems respond to disturbances and recover. It is a valuable resource for policymakers, scientists, and conservationists who are developing strategies to protect ecosystems and maintain human well-being in the face of climate change.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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