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The Impact of Climate Change on Ecosystems and Ecological Analysis in the Context of Sustainable Development

Safura Valiyeva[1] and Elnara Isayeva[1*]

Abstract. *Climate change is one of the most significant environmental challenges of the twenty-first century, threatening the stability, resilience, and sustainability of ecosystems worldwide. Rising global temperatures, altered precipitation patterns, prolonged droughts, floods, wildfires, storms, and sea-level rise significantly affect the structure, functioning, productivity, and biodiversity of terrestrial and aquatic ecosystems. These changes alter species distributions, disrupt ecological interactions, accelerate habitat degradation, and increase extinction risks. Climate change also affects soil fertility, nutrient cycling, water availability, and plant physiological processes, reducing agricultural productivity and weakening ecosystem services essential for human well-being. This review provides a comprehensive assessment of the impacts of climate change on ecosystem dynamics based on recent scientific literature. Particular attention is given to the relationships among climate variability, biodiversity conservation, soil–plant interactions, and ecosystem resilience. The study examines the major anthropogenic drivers of climate change, including greenhouse gas emissions, deforestation, land-use change, and unsustainable exploitation of natural resources, together with their ecological and socio-economic consequences. It further evaluates adaptation and mitigation strategies, emphasizing ecosystem-based adaptation, sustainable land and water management, ecological restoration, climate-smart agriculture, biotechnology, and advanced environmental monitoring systems. By integrating terrestrial and aquatic ecosystems within the framework of the United Nations Sustainable Development Goals (SDGs), this review highlights practical approaches for strengthening ecosystem resilience and promoting sustainable development. The findings emphasize that integrated ecosystem management, long-term ecological monitoring, international cooperation, and innovative technologies are essential for reducing climate change impacts, conserving biodiversity, and ensuring environmental sustainability for future generations.*

Keywords: *climate change, ecosystem, biodiversity, sustainable development, ecological balance, adaptation, biotechnology*

Introduction

Over the past century, the sharp increase in the atmospheric concentration of greenhouse gases as a result of anthropogenic activity has fundamentally altered the Earth's climate system. Since the Industrial Revolution, the global average surface temperature has risen by approximately 1.1–1.2 °C, a process accompanied by ocean warming, glacial melting, sea-level rise, and an increasing frequency of extreme weather events (IPCC, 2023).

[1]Baku State University, PhD in Biological Sciences, Baku, Azerbaijan
[*]Corresponding author. E-mail: isayeva761@mail.ru
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Ecosystems are complex, self-regulating systems that have developed over millennia in adaptation to specific climatic conditions. However, the pace of climate change now exceeds the adaptive capacity of many species and biocenoses. This leads to shifts in species ranges, disruption of phenological processes (flowering, migration, reproductive cycles), weakening of ecosystem services, and a decline in biodiversity (Díaz et al., 2019; IPBES, 2019). The concept of sustainable development aims to harmonize economic progress with the protection of ecological balance and social justice.

The purpose of this study is to systematize the mechanisms through which climate change affects different ecosystem types, to review methods of ecological analysis, and to identify adaptation strategies within the context of sustainable development (United Nations, 2015).

In the scientific literature, the concept of "ecological resilience" refers to an ecosystem's capacity to return to its previous functional state following external disturbances (IPCC, 2023; Reid et al., 2005). As the pace and scale of climate change increase, this resilience of many ecosystems weakens, resulting in what is called a "regime shift" – the transition of an ecosystem to a qualitatively different, often less productive, state. In this regard, studying the impact of climate change on ecosystems is not only of academic interest, but also a necessary scientific basis for making practical management decisions (IPCC, 2023; United Nations, 2015).

Research Methodology

The study is analytical review in nature and is based on a systematic analysis of the scientific literature published on the topic over the last ten years. The methodological framework includes the following approaches:

Literature review method – comparative analysis of articles, reports (IPCC, IPBES) and monographs published in international scientific databases (Scopus, Web of Science, Google Scholar);
Ecosystem approach – the study of the structural-functional components of ecosystems (producers, consumers, decomposers, abiotic factors) in their interaction;
Comparative ecological analysis – assessment of the sensitivity of ecosystems in different climatic zones (tropical, temperate, arctic);
Statistical generalization – consideration of correlations between climatic indicators (temperature, precipitation, CO_2 concentration) and biological indicators (number of species, productivity, range change).

This complex methodological approach ensures the objectivity and scientific validity of the research results. During the analysis, the sensitivity of ecosystems was assessed using three main indicators: exposure, sensitivity, and adaptive capacity. The sum of these three components determines the overall vulnerability index of the ecosystem. The table below summarizes the comparative vulnerability assessment of the main ecosystem types.

Table 1
Comparative assessment of the sensitivity of major ecosystem types to climate change

Ecosystem type	Exposure	Sensitivity	Adaptive capacity	Overall vulnerability
Coral reefs	High	Very high	Low	Very high
Mountain ecosystems	High	High	Low	High

Ecosystem type	Exposure	Sensitivity	Adaptive capacity	Overall vulnerability
Arctic tundra	Very high	High	Medium	High
Tropical forests	Medium	Medium	Medium	Medium
Temperate forests	Medium	Medium	High	Medium-low
Grasslands and savannas	Medium	Low-medium	High	Medium-low

Source. Compiled by the authors based on IPCC (2023) and IPBES (2019).

As can be seen from the table, coral reef and mountain ecosystems have the highest vulnerability, as these systems have both high sensitivity and limited adaptive capacity. This indicates the necessity to prioritize the protection of ecosystems with limited adaptive potential (IPCC, 2023; IPBES, 2019).

The Impact of Climate Change on Dry Ecosystems

Forest ecosystems play an important role in the global carbon cycle, but they are themselves severely affected by climate change. Rising temperatures and prolonged drought periods are increasing the frequency and scale of forest fires, leading to the extinction of trees due to water shortage (IPCC, 2023; Pörtner et al., 2021). The expansion of the habitat of insect pests (e.g. bark beetles) creates additional pressure (Pörtner et al., 2021). As a result, forests are shifting from net carbon sinks to net carbon sources.

The instability of the precipitation regime affects the composition of vegetation in steppe and savanna zones, reduces pasture productivity, and accelerates soil erosion (FAO, 2021; IPCC, 2023). This process creates serious problems for both wildlife and the local population engaged in livestock farming.

Mountain ecosystems are particularly sensitive to temperature changes (Chen et al., 2011; IPCC, 2023). The melting of snow and ice cover, and the migration of plant and animal species to higher altitudes are observed. This process can lead to a phenomenon called the "mountaintop trap" – the depletion of space for species to migrate.

Changes in soil temperature and moisture regimes affect the composition of the soil microbiome, the pace of mineralization of organic matter, and the supply of nutrients to plants (FAO, 2021). In particular, disruption of mycorrhizal symbioses makes it difficult for plants to absorb water and phosphorus, which can indirectly affect the health status of original plants used in plant tissue culture and micropropagation processes.
Ocean and marine ecosystems absorb most of the additional heat from the atmosphere, which leads to ocean warming, ocean acidification, and the expansion of oxygen-deficient zones (Hoegh-Guldberg et al., 2007; Pörtner et al., 2021). Coral reefs bleaching occurs as a result of the loss of symbiotic algae, leading to the destruction of these ecosystems over large areas.

In freshwater ecosystems, changes in river flow regimes, including temporary increases in discharge caused by glacier melting followed by long-term water scarcity, negatively affect the life cycles of fish populations (IPCC, 2023; FAO, 2021). Rising temperatures in lakes accelerate eutrophication processes and increase the frequency of cyanobacterial blooms.

Enclosed water basins such as the Caspian Sea basin are particularly sensitive to climate change, as the water balance in these ecosystems depends not only on the ratio of precipitation and evaporation but also on the regime of the rivers flowing into the basin (Volga, Ural, Kura) (Kosarev & Kostianoy, 2005; Chen et al., 2011). The changes in water levels observed in recent decades are causing a shrinking of coastal wetland ecosystems, including the habitat of rare fish species (e.g. sturgeon). Changes in the Caspian Sea level and salinity can also significantly affect aquaticvegetation, benthic communities, and the distribution of aquatic organisms (Mukhtarova & Khanbutayeva, 2021). This increases the importance of transboundary water management and environmental monitoring at the regional level.

Estuarine and delta ecosystems are subject to salinization as a result of sea level rise, which narrows the habitat of freshwater plant and animal species and causes salinization of areas suitable for agriculture.

Impact on Biodiversity

Climate change is one of the leading factors in the decline of biological diversity. According to the International Union for Conservation of Nature (IUCN), a significant portion of assessed species are at high risk of extinction due to climate change (IPBES, 2019).

The main mechanisms are:
Phenological mismatch – the disruption of synchrony between seasonal biological events, such as the arrival of migratory birds and the peak availability of their food resources (Parmesan & Yohe, 2003; Chen et al., 2011);
Range shift – the migration of species to cooler regions, altitudes, or latitudes;
Spread of invasive species – changing climate conditions favoring invasive species over native species (Pörtner et al., 2021).

In terms of plant genetic resources conservation, biotechnological tools such as *in vitro* micropropagation and gene banks are increasingly important in preserving climate-resistant varieties and rare species (FAO, 2021). Such approaches both provide ex situ conservation and expand the genetic material base for breeding programs.

The decline in biological diversity is not limited to a decline in the number of species, but also includes the loss of genetic and functional diversity (Díaz et al., 2019). A decrease in functional diversity weakens the ability of the ecosystem to perform various functions (pollination, decomposition of organic matter, formation of soil structure). The decline in the number of pollinating insects (bees, butterflies) directly affects the productivity of agricultural crops, which is a serious concern in terms of food security.

In the field of conservation biology, the concept of "climate corridors" – the creation of connected natural areas so that species can freely migrate to new areas in response to climate change – is widely used.

Ecological Analysis Methods and Monitoring

A number of analytical tools are used in modern ecology to assess the impact of climate on ecosystems:
Remote sensing and Geographic Information Systems (GIS) – large-scale monitoring of vegetation dynamics, forest areas, and soil moisture;
Bioindication – assessing ecosystem health using the sensitivity of certain species (e.g. lichens, amphibians) to environmental changes;
Modeling – the application of Species Distribution Models and climate scenarios (RCP, SSP) to predict species ranges;
Molecular genetic methods – assessment of genetic diversity and adaptive capacity of populations based on DNA markers.

The integration of these methods allows for the assessment of the current state of ecosystems, as well as the prediction of future changes and the scientific justification of management decisions (IPBES, 2019; IPCC, 2023; Pörtner et al., 2021).

Adaptation and Mitigation in the Context of Sustainable Development

Within the framework of sustainable development, the management of the environmental consequences of climate change is carried out through two main strategies: mitigation (reducing greenhouse gas emissions) and adaptation (adapting to changing conditions).

The Ecosystem-based Adaptation (EbA) approach involves harnessing the protective function of natural ecosystems themselves – for example, restoring coastal forests acts as a natural buffer against storm surges, while expanding urban green spaces reduces the heat island effect.

The creation of climate-resistant species, water-saving irrigation technologies, and agrotechnical methods that preserve soil fertility play an important role in the agricultural sector (FAO, 2021). Plant tissue culture technologies are of particular importance in this regard: the rapid reproduction of disease-free, genetically homogeneous, and more stress-resistant planting material contributes to maintaining stable yields under climate change (Long et al., 2022; FAO, 2021). Obtaining pathogen-free plant material through meristem culture, as well as studying resistance to temperature and water stress *in vitro*, are important components of climate adaptation strategies. Within the framework of international cooperation, the Paris Agreement, the Convention on Biological Diversity (CBD), and the Framework Convention on Climate Change (UNFCCC) ensure information exchange, financial support, and the application of uniform monitoring standards among state (UNFCCC, 2015). The coordinated implementation of sustainable development goals requires balancing environmental, economic and social dimensions.

Economic and Social Consequences of Climate Change

Ecosystem degradation has direct economic consequences because human society depends on ecosystem services (clean water, pollination, soil fertility, climate regulation, recreational opportunities) (Reid et al., 2005). According to World Bank (2021) estimates, the loss of biodiversity and ecosystem services could cost the global economy trillions of dollars each year.

Declining productivity in the agricultural sector poses a direct threat to food security, especially in arid and semi-arid regions that are susceptible to climate change. The fishing industry is suffering from declining fish stocks due to ocean warming and acidification. The tourism sector is affected by the decline in the attractiveness of coral reefs, snow-capped mountains, and other climate-sensitive natural monuments. From a social perspective, climate change is intensifying the phenomenon of "environmental migration" – people are forced to leave their homes as a result of land degradation, water scarcity, and extreme weather events (United Nations, 2015; World Bank, 2021). This process deepens socio-economic inequality, especially in developing countries, as the most vulnerable communities often have the fewest resources for adaptation.In this regard, the principle of climate justice has become one of the central elements of the sustainable development agenda (United Nations, 2015).

Discussion

The analysis shows that the impact of climate change on ecosystems is unstable and cumulative – different stressors (temperature, drought, invasive species, anthropogenic pressure) can reinforce each other and exceed the resilience levl of the ecosystem (IPBES, 2019; IPCC, 2023). This indicates that traditional conservation measures alone are not sufficient and that complex, multi-level management approaches are necessary. At the same time, there are some inconsistencies between the results of scientific studies – for example, different regional models can provide different precipitation forecasts for the same area. This highlights the importance of expanding monitoring networks and continuing long-term data collection. The integration of biotechnological solutions (micropropagation, gene banks, molecular selection) with traditional ecological conservation measures is considered a promising direction for future research (FAO, 2021).

Conclusion

Climate change is having a serious and increasing impact on the structure, function, and biodiversity of terrestrial and aquatic ecosystems. Changes observed in forest, steppe, mountain and aquatic ecosystems are leading to a weakening of ecosystem services, which in turn has a negative impact on human well-being and economic activity. Within the framework of sustainable development principles, the protection of ecosystems should be considered not only as an integral part of environmental policy, but also as an integral part of economic and social policy. Ecosystem-based adaptation, strengthening scientific monitoring, application of biotechnological innovations, and deepening international cooperation play a crucial role in reducing the negative impacts of climate change and restoring ecological balance. For future research, it is recommended to expand long-term ecological monitoring programs at the regional level, create climate-resistant plant material through biotechnological methods, and improve methodologies for the economic valuation of ecosystem services.

Declaration of Competing Interests

The authors declare that they have no conflict of interest.

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