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Climate Change: Impacts on Carbob Sequestration Biodiversity and Agriculture

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A B S T R A C T

This study aims to systematically review the impacts of climate change on carbon sequestration, biodiversity, and the agricultural sector. Using a Systematic Literature Review (SLR) approach, this research analyzed scientific publications from 2020–2025 sourced from Google Schoolar, Scopus, ScienceDirect, and MDPI databases. The findings reveal that climate change reduces carbon storage capacity through temperature rise, drought, and land degradation; threatens biodiversity through habitat loss and disruption of ecosystem functions; and decreases agricultural productivity, ultimately affecting food security. Mitigation and adaptation strategies such as agroforestry systems and sustainable land management are essential to maintain ecosystem balance and ensure long-term food resilience.

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INTRODUCTION

Climate change has become a major global challenge in the 21st century, characterized by increased concentrations of greenhouse gases such as CO_2, methane, and N_2O triggered by human activities and land-use change. As a consequence, natural buminiah systems, including soils, vegetation, and agro-ecosystems, are facing increasing pressure in the form of changes in temperature, rainfall patterns, and extreme weather frequency (Muluneh, 2021). This condition directly affects the ability to store carbon (carbon sequestration) and the sustainability of ecosystems, including biodiversity and agricultural systems.

One of the important mechanisms in climate change mitigation is the ability of ecosystems to absorb and store carbon from the atmosphere in a process known as Carbon Sequestration. Soils, forests, peatlands, and other vegetation are the main "containers" for long-term carbon storage. Recent studies show that poor management or land-use change can reduce carbon stocks and make land go from "absorber" to "beggar" for carbon. (Raihan, 2023) explains that through proper agricultural practices, soil carbon stocks can be restored and contribute to agricultural sustainability.

However, the carbon storage process is inseparable from ecological conditions and land use. Some publications have found that extreme climate change such as heat waves, droughts, and extreme rainfall impair crop productivity and soil microorganisms, thereby lowering carbon storage. For example, studies in the northern hemisphere show that extreme weather events are strongly associated with a decrease in biosphere carbon sequestration (Shi, 2024). Therefore, climate change affects not only direct emissions, but also the carbon capture power of terrestrial systems.

In addition to the carbon aspect, climate change also has a major impact on biodiversity and the global agricultural system. Changes in temperature, rainfall patterns, and extreme weather events encourage species migration, phenological changes, and local extinctions of species-endemic (Muluneh, 2021). The close relationship between biodiversity and the resilience of agricultural systems suggests that when diversity declines, ecosystem services such as pollination, natural pest control, and soil fertility maintenance also decline.

In the context of agriculture, food production systems are highly vulnerable to climate change. Declining crop yields, changes in planting seasons, increasing pest and disease pressure, and declining soil quality are all real challenges (Muluneh, 2021). On the other hand, sustainable agricultural practices such as crop rotation, soil conservation, and agroforestry offer a dual potential: increasing production while strengthening carbon storage and supporting biodiversity (Jayara et al., 2023).

In Indonesia and other tropical regions, the adoption of agroforestry systems has been introduced as a climate change adaptation and mitigation strategy. Agroforestry systems are able to increase carbon stocks, improve soil quality and support biodiversity, while increasing food security for smallholders (Sari, 2025). However, obstacles such as incoherent policies, access to finance and institutional weaknesses remain challenges for large-scale implementation.

Based on the above description, it is crucial to systematically examine how climate change affects carbon storage, biodiversity, and agriculture the three interrelated pillars in the constellation of environmental and food sustainability. This study aims to integrate the latest evidence from the international and local literature to understand the dynamics of the impact of climate change on these three aspects. Thus, it is hoped that a comprehensive understanding and recommendations for relevant policies and practices can be obtained to maintain the resilience of agro-ecosystems in the era of climate change.

THEORETICAL REVIEW

Climate Change as a Global Threat to the Earth System

Climate change has become a major global challenge in the 21st century, characterized by increased concentrations of greenhouse gases such as CO_2, methane, and N_2O due to human activities and land-use change. These conditions create significant pressures on the earth's system, including changes in temperature, rainfall patterns, and extreme weather frequencies that threaten the balance of ecosystems (Muluneh, 2021). The impact is felt globally, including in Indonesia where climate change affects various sectors, especially agriculture and food security (Akmalia, 2022). Natural systems such as soils, vegetation, and agricultural ecosystems face severe challenges in maintaining their ecological functions under the increasingly intense pressures of climate change.

Carbon Sequestration as a Climate Change Mitigation Mechanism

Carbon sequestration is an important mechanism in climate change mitigation, where ecosystems act as "absorbers" of carbon from the atmosphere. Soils, forests, peatlands, and vegetation serve as vital long-term carbon stores (Raihan, 2023). However, poor management or land use change can turn land from a carbon sink to a carbon beggar. Recent studies show that sustainable farming practices can restore soil carbon stocks and contribute to agricultural sustainability (Jayara et al., 2023). In Indonesia, the potential for carbon sequestration in ecosystems such as bamboo forests and mangroves shows the important role of natural ecosystems in climate change mitigation (Cheng et al., 2023; Lokollo et al., 2024).

Climate Change's Impact on Carbon Sequestration

Climate change directly affects the ability of ecosystems to absorb and store carbon. Extreme weather events such as heat waves, droughts, and extreme rainfall can impair the productivity of crops and soil microorganisms, thereby lowering carbon storage capacity (Shi, 2024). Research by Ke et al. (2024) revealed a significant decrease in terrestrial carbon sequestration in 2023 due to the impact of climate change. This suggests that climate change not only affects direct emissions, but also reduces the carbon capture power of terrestrial systems, which in turn exacerbates global warming.

The Impact of Climate Change on Biodiversity

Climate change is having a devastating impact on global biodiversity. Changes in temperature, rainfall patterns, and extreme weather events encourage species migration, phenological changes, and local extinctions of endemic species (Habibullah et al., 2022). The study of Price et al. (2024) projects significant biodiversity loss as global temperatures rise 1.5 to 4°C above pre-industrial levels. In Indonesia, coastal ecosystems are also under severe pressure due to climate change, which threatens the preservation of biodiversity in the region (Aisyah et al., 2025). This loss of biodiversity then weakens ecosystem services such as pollination, natural pest control, and soil fertility maintenance.

Vulnerability of Agricultural Systems to Climate Change

Global food production systems are particularly vulnerable to the impacts of climate change. Declining crop yields, changes in planting seasons, increasing pest and disease pressure, and declining soil quality are real challenges facing the agricultural sector (Malau et al., 2023). The study of Ocwa et al. (2023) confirms the significant impact of climate change on the productivity of major food crops such as corn. In Indonesia, climate change has affected productivity and food security, with a heavier impact on smallholders and rural communities (Faradiba, 2025; Sihombing et al., 2023).

Sustainable Agriculture Practices as an Integrative Solution

Sustainable farming practices offer integrative solutions to the challenges of climate change. Systems such as crop rotation, soil conservation, and agroforestry have a dual potential: increasing food production while strengthening carbon storage and supporting biodiversity (Dasgupta & Mahanty, 2024). The Sari (2025) study shows the effectiveness of agroforestry systems in increasing carbon stocks, improving soil quality, and supporting biodiversity, while increasing the food security of smallholders. The implementation of traditional agroforestry systems in Indonesian peatlands has also been shown to be effective in maintaining floristic composition and carbon storage (ISDA et al., 2025).

Policy Integration and Implementation at the Local Level

The successful implementation of climate change adaptation and mitigation strategies requires an integrated approach and coherent policies. The study by Rahmadhani et al. (2024) shows the role of contract farming in helping coffee farmers adapt to climate change in East Java. However, challenges such as uncoordinated policies, limited access to finance, and institutional weaknesses remain major obstacles to large-scale implementation. A science-based approach and consideration of socio-economic aspects are needed to optimize the implementation of climate change adaptation and mitigation strategies.

The Linkage between Carbon Sequestration, Biodiversity, and Agriculture

These three pillars are closely interrelated in the constellation of environmental and food sustainability. The interaction between climate change and biodiversity can be assessed from the perspective of the material cycle, where healthy biodiversity supports ecosystem functions in the carbon and nutrient cycle (Kim et al., 2024). A comprehensive understanding of these dynamics is important for developing effective strategies in maintaining the resilience of agro-ecosystems in the era of climate change. Integration of evidence from international and local literature is needed to produce policy and practice recommendations relevant to the specific conditions of each region.

METHODOLOGY

This study uses the Systematic Literature Review (SLR) approach to identify, analyze, and synthesize scientific findings on the impact of climate change on carbon sequestration, biodiversity, and the agricultural sector. This approach is carried out by following systematic methodological stages, starting from determining the focus of research, collecting literature through scientific databases such as Google schoolar, Scopus, ScienceDirect, and MDPI, to the process of filtering relevant articles based on keywords and time span 2020–2025. The results of the literature selection were used to obtain a comprehensive picture of the relationship between the variables studied.

Inclusion criteria include articles that discuss empirically or conceptually the impact of climate change on carbon sequestration ability, biodiversity sustainability, and agricultural productivity. The analysis was carried out by grouping the results of the research based on key themes such as decreasing forest carbon capacity, species loss due to increasing global temperatures, and changes in planting patterns due to climate fluctuations. Meanwhile, data that do not meet thematic and temporal relevance are excluded from the synthesis process.

Based on the formulation of the problem, this study seeks to answer three main questions: (1) **How does climate change affect carbon storage in various ecosystems?** (2) How does climate change affect biodiversity and ecosystem stability? (3) What are the implications of climate change on agricultural productivity and food security? These three questions are the basis for the synthesis of the study results, which are expected to make a theoretical and practical contribution to climate change mitigation policies and sustainable natural resource management.

RESULTS AND DISCUSSION

RQ (1): How does climate change affect carbon storage in various ecosystems?

Terrestrial ecosystems such as forests, peatlands, mangroves and agroforestry have historically played a key role as atmospheric carbon absorbers and stores of a process known as *carbon sequestration*. Forests around the world continue to absorb about 3.5 ± 0.4 billion tons of carbon per year, despite facing pressures such as fires, pests, and land warming. But climate change is beginning to disrupt this storage capacity, through mechanisms such as rising temperatures, changes in rainfall patterns, and extreme weather events.

For example, research from the Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023 showing that land carbon sink will decline drastically in 2023 to around 0.44 ± 0.21 GtC/yr the lowest since

2003 due to the combined large fires and extreme drought (Ke et al., 2024). These findings confirm that climate change not only increases emissions, but also reduces nature's ability to offset those emissions.

In Indonesia, local studies show that traditional agroforestry systems on peatlands in Rimbo Panjang, Riau are capable of storing high carbon at around 399 to 618 tons of CO_2e per ha indicating that diverse land use and native vegetation can support carbon storage (ISDA et al., 2025). However, climate change conditions such as droughts or fires have the potential to disrupt this system, so its effectiveness as carbon storage can decrease.

Climate change in various ecosystems also manifests through a decrease in the rate of absorption or even a change in function from absorbers to carbon emitters. For example, a study from Using eddy covariance observations to determine the carbon sequestration characteristics of subalpine forests in the Qinghai Tibet Plateau in the Qinghai-Tibet plateau subalpine region shows that although carbon sequestration is still present, the speed of change in environmental conditions (e.g., temperature, humidity) affects the carbon balance in the ecosystem (Zhu et al., 2024).

In the context of mangroves, which include blue carbon ecosystems, a study from Blue Carbon Potential of Mangrove Ecosystems and Its Management to Promote Climate Change Mitigation in Indonesia shows that the blue carbon potential in Indonesian mangroves reaches around 3,267.87 Megatons C, with CO_2e absorption reaching almost 11,982.21 $MtCO_2e$ – but its effectiveness is highly dependent on ecosystem management. restoration, and policy (Lokollo et al., 2024). Climate change such as rising sea levels and increased frequency of storms can damage mangroves and reduce their storage capacity.

Land management technologies and practices also play an important role in how climate change affects carbon storage. For example, a meta-analysis of The phytolith carbon sequestration in terrestrial ecosystems: the underestimated potential of bamboo forest shows that bamboo and phytoliths (plant silica residues) account for stable carbon storage in the long term (Cheng et al., 2023). However, under climate change conditions (e.g. drought or extreme temperatures) this potential can decrease if plant growth is stunted or soil degradation increases.

Climate change also triggers changes in land use, such as the conversion of forests to plantations or forest fires caused by drought. This conversion directly reduces carbon stocks due to biomass removal and soil disturbance. A study from Carbon sequestration costs and spatial spillover effects in China's collective forests revealed that the cost of carbon storage in China's collective forests has increased over the past 30 years, indicating the growing challenge of maintaining carbon storage in the context of land and climate change (Zhou et al., 2024).

Furthermore, climate change conditions that cause temperatures to rise and rainfall to change, can accelerate the decomposition of organic matter in the soil and trigger the release of CO_2 or methane from soils or peatlands that were previously storefronts. This is also confirmed by research that warns that the function of natural carbon storage will continue to decline if the rate of climate change is not controlled.

In agriculture and agricultural land use, research from (Dasgupta & Mahanty, 2024) shows that practices such as reducing tillage, crop rotation, and increasing soil residues and organics can improve carbon storage. However, climate change adds to the challenge because plant stress (heat, drought) can reduce biomass growth and carbon storage capacity through plant biomass.

Overall, the influence of climate change on carbon storage is highly dependent on the interaction between climatic conditions (temperature, precipitation, humidity), soil and vegetation conditions, land use and ecosystem adaptability or human practices. Resilience and adaptable ecosystems (e.g. diverse agroforestry) have a greater chance of maintaining carbon storage functions. In Indonesia, policy support, ecosystem restoration, and participatory management are key to maintaining storage capacity.

In conclusion, although many ecosystems still have significant potential as carbon stores, climate change has begun to erode these capabilities through various mechanisms. To answer RQ (1) succinctly: climate change can lower carbon storage levels in many ecosystems through mechanisms such as vegetation change, land degradation, accelerated decomposition, fires, and land conversion. Therefore, better understanding and proactive adaptation/management actions are essential to maintain the function of carbon storage in the future.

RQ (2): How does climate change affect biodiversity and ecosystem stability?

Climate change has been shown to be one of the main causes of biodiversity loss on a variety of local, regional, and global scales. Up to one million species are threatened with extinction in the coming decades largely triggered by a combination of climate change, land-use change and other human activities. Environmental changes such as rising temperatures, rising sea levels, and extreme weather force species to shift habitats or face mass deaths, which then shake the stability of ecosystems.

Global studies show that climate variables such as average temperature, rainfall, and frequency of natural disasters significantly increase the risk of species loss. An analysis in 115 countries found that increased temperatures, changes in precipitation, and drought or flooding were significantly associated with an increase in the number of threatened species (Habibullah et al., 2022). This indicates that climate change is not only an additional disruptor, but has become a key factor in biodiversity dynamics.

Specifically, although many studies take into account land change, climatic changes (such as rising temperatures, shifting rainfall patterns, extreme events) will increase pressure on already vulnerable biodiversity. For example, forest habitats burn and trees shift to higher elevations or latitudes, which creates habitat "holes" and disrupts interactions between species.

An international review article in 2024 concluded that when the global warming scenario reaches between 1.5 to 4 °C above pre-industrial, diversity is significantly reduced in both the number of species and the area of suitable habitat (refugia) for species survival (Price et al., 2024). In other words, moderate climate change alone already has a real impact on biodiversity; And the greater the heating, the worse the losses.

From the point of view of material cycles, the interaction between climate change and diversity can also be understood through the framework of carbon, nitrogen, and other elements of the cycle. (Kim et al., 2024) argue that the influence of climate change on diversity must be seen from the perspective of how the material cycle and adaptation of organisms change, not just changes in species distribution. This shows that the impact is multifaceted: not only "species lost" but also "ecosystem functions" that are changing.

In the context of Indonesia and tropical coastal regions, local research shows that coastal ecosystems including mangroves and coral reefs are highly vulnerable to climate change. A study in Indonesia on coastal ecosystems said that rising sea levels, erosion, and extreme weather accelerate habitat degradation, leading to a decline in the diversity of marine and coastal species (Aisyah et al., 2025). While local community adaptation is occurring, the response is still reactive with limited resources.

In addition, there is a close relationship between biodiversity and ecosystem services such as pollination, pest control, water purification, and others. Loss of diversity means the loss of these services, which in turn weakens the resilience and stability of ecosystems. For example, low diversity makes ecosystems more susceptible to disturbances such as pests or diseases. This is also noted in the WHO review of the link between climate change, biodiversity, and human health.

Climate change also drives changes in species distribution, either migration to higher elevations or higher latitudes, as well as phenological changes (e.g., shifting flowering or egg-laying times). (Mehta, 2024) suggests that these changes alter the composition of species communities and interspecies interactions, ultimately altering the structure and function of ecosystems. Thus, diversity is not only reduced in terms of numbers, but also in terms of ecological functions.

Furthermore, some studies show that the diversity of endemic species or narrow habitat species is particularly vulnerable to climate change. The combination of global warming and land-use change puts endemic species at high risk of extinction or loss of suitable habitat. This is confirmed by previous global studies showing that terrestrial and insular endemic species will face two to ten times greater impacts than non-endemic species. (although not the primary source on this list) If translated to the context of Indonesia as a mega-biodiversity country, the implications are huge.

From the perspective of ecosystem stability, a loss of diversity or a major change in species composition causes ecosystems to lose functional redundancy, which is the ability of different species to perform similar ecological functions. When this is lost, the ecosystem becomes more vulnerable to disturbance and more difficult to return to its original state (resilience). Maintaining diversity is key to mitigating climate change while maintaining ecosystem stability.

For mitigation and adaptation, it is important to create biodiversity-based strategies (nature-based solutions) that strengthen ecosystem stability. (Schipper et al., 2024) note that in order to integrate the climate change scenario with IUCN threats to diversity, conservation planning must consider the heat tolerance of species, adaptability, and long time frames (2081–2100). Thus, climate change demands a paradigm shift in biodiversity conservation: from just preserving species to also maintaining function, adaptation, and long-term time frames.

In summary, it can be concluded that climate change affects biodiversity and ecosystem stability through several main pathways: habitat change and species distribution, disruption of ecosystem function, increased local extirpation or extinction, and decreased ecosystem services. All of this increases the vulnerability of ecosystems to disturbances and lowers their capacity to adapt. Therefore, answering RQ (2) shows that efforts to protect biodiversity are an integral part of the strategy to deal with climate change: not just as a result, but as part of the solution.

RQ (3): What are the implications of climate change on agricultural productivity and food security?

Climate change has a very real impact on the agricultural sector, which in turn affects the productivity of food crops and food security. (Yuan et al., 2024) show that changes in temperature, precipitation, and frequency of extreme weather events have a direct impact on crop growth cycles, productivity and crop quality.

In the Indonesian context, research (Malau et al., 2023) found that phenomena such as the El Niño Southern Oscillation (ENSO) cause large variability in rainfall and have been shown to affect food production such as rice, corn, and soybeans in various Indonesian provinces. This kind of condition shows that climate change has touched the operational aspects of national agriculture, not just long-term projections.

Furthermore, a systematic analysis in Indonesia (Akmalia, 2022) concluded that average food crop production decreased due to changes in climatological-related environmental elements, such as rising temperatures and decreasing effective rainfall. The study also highlights that adaptation strategies are still limited and uneven among smallholders, so the potential for productivity decline is greater.

From international studies, for example (Ocwa et al., 2023) it was found that for maize, a temperature increase of 1–4 °C leads to a decrease in yield of between 5–14 % in warm regions, and even decreased rainfall leads to a decrease in yield of up to 25–32 %. This shows that climate change does not only impact one type of crop, but can affect many varieties and food production systems.

Factors that reinforce the negative impact of climate change on productivity include: heat stress on plants, water deficit, increased pests and diseases, and shortening of plant growth periods. Climate change has shortened the vegetative period of plants, decreased photosynthesis, and disrupted plant nutrients.

On the other hand, some limited mitigation/positive influence factors were also found, for example, an increase in atmospheric CO_2 levels can increase the efficiency of photosynthesis and the growth of certain plants (the effect of CO_2 fertilization). Despite these effects, the negative impact of temperature and poor rainfall remains predominant, so the end result remains declining.

Food security as a consequence of agricultural productivity is also threatened. For example, research (Sihombing et al., 2023) shows that the symptoms of drought and flooding due to climate change cause a change in the planting season, an increase in the number of weeds, pests and diseases, and a rise in temperature that reduces crop yields—all of which have a direct impact on national food availability.

The impact of climate change is also uneven: small-scale farmers, especially those in the tropics and who do not have adequate access to technology or adaptation, are the most vulnerable groups. Food production systems in the region already have a smaller margin of tolerance for climate change. An international systematic review (Faradiba, 2025) states that the decline in production in developing countries can reach 5-30%.

In Indonesia, in addition to the technical factors of plants, there are also institutional, economic and social factors that strengthen vulnerability to climate change. An example of a study on coffee in East Java, (Rahmadhani et al., 2024) found that although farmers are aware of climate change (e.g. rain changes, temperatures rise, length of rainy season shifts), adaptation strategies have not been optimal so that results are still affected.

In the long term, if climate change continues without significant adaptation, then the global food production scenario shows that world food production could decline significantly even if technology and adaptation are improved. Adaptation and mitigation strategies are key to minimizing the impact of climate change on productivity and food security. Several studies in Indonesia propose the development of climate-resistant varieties, crop diversification, better water management, and agroecology-based agricultural systems (Akmalia, 2022). But the challenge is huge: technology, funding, training, and policies must be coordinated to truly result in increased productivity and food security.

In conclusion, answering RQ (3) shows that climate change significantly threatens agricultural productivity and food security through various mechanisms of temperature increase, changes in rainfall patterns, extreme phenomena, changes in planting patterns including the vulnerability of smallholders and limited adaptation. To maintain national and global food security, rapid and integrated adaptation and mitigation measures are essential. Without it, agricultural productivity can decrease and food security can be significantly disrupted.

CONCLUSION

Climate change has been shown to have a multidimensional impact on global ecosystems, especially on three key aspects: carbon storage, biodiversity, and agricultural productivity. Rising temperatures, shifting rainfall patterns, and increasing frequency of natural disasters significantly reduce the ability of terrestrial and marine ecosystems to absorb and store carbon. In addition, environmental degradation due to climate change accelerates the rate of carbon loss and decreases the effectiveness of natural systems as emission offsetters. These impacts continue to habitat loss, species migration, and disruption to ecosystem functions that ultimately threaten overall ecological stability.

From the agricultural side, climate change causes a decrease in food crop yields, disruptions to the planting season, and an increase in the risk of pests and diseases that have a direct impact on global and national food security. Smallholder farmers are the most vulnerable group due to the limitations of technology and adaptive resources. Therefore, maintaining a balance between mitigation and adaptation is a key step in facing the challenges of climate change. Collaborative efforts between the government, academics, and the community are urgently needed to maintain ecosystem sustainability and food security in the future.

RECOMMENDATION

An integrated and science-based adaptation policy is needed to deal with the impacts of climate change. The government needs to strengthen support for the implementation of sustainable agricultural practices such as agroforestry, soil conservation, and integrated water management. In addition, increasing the capacity of farmers through education, carbon incentives, and adaptive technologies should be a priority. On the ecological side, critical land restoration, biodiversity protection, and the development of carbon monitoring systems based on scientific data can strengthen the resilience of ecosystems to climate change.

FURTHER STUDY

Climate change generates multidimensional impacts on global ecosystems, particularly on carbon storage, biodiversity, and agricultural productivity. Rising temperatures, altered rainfall patterns, and more frequent natural disasters reduce the capacity of terrestrial and marine systems to absorb and store carbon, while environmental degradation accelerates carbon loss and weakens natural emission-offset functions. These disruptions lead to habitat loss, species migration, and impaired ecosystem functioning, threatening overall ecological stability. In agriculture, climate change lowers crop yields, disrupts planting seasons, and increases pest and disease risks, directly affecting food security—especially for smallholder farmers with limited adaptive capacity. Addressing these challenges requires a balanced approach between mitigation and adaptation, supported by strong collaboration among governments, researchers, and communities to ensure long-term ecosystem resilience and food security.

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