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Climate Change Impact and Sustainable Environmental Management for Ecosystem Conservation: A Quantitative Assessment of Carbon, Water, and Biodiversity Ratios

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ABSTRACT

The present study quantifies the climate change influence on ecosystems' conservation, using carbon sequestration, water balance, and biodiversity indices measurements for 6 terrestrial ecosystems, between 2010 and 2024. The mean annual temperature rose by 1.4°C and precipitation variability increased by 23.7%, which led to a decrease in net primary productivity NPP by 18.3%, and a decrease in soil organic carbon SOC stocks by 31.2%. The percentage of forest cover dropped from 42.6% to 34.1% of total land area, which was 1:5.2 deforestation ratio in the 14 years. The wetland area decreased by 27.8% and the water loss to groundwater recharge ratio was 1.9:1. On 1,250 ha, interventions for sustainable management, such as afforestation, drip irrigation and protected corridors have been taken up. The post intervention measurements indicate a 22.4% increase in SOC, a 16.7% recovery in NPP and surface runoff has decreased by 33.5%. Biodiversity index BI was improved from 0.58 to 0.74 which is a 27.6% increase, and species richness was increased by 1:1.4. The efficiency of carbon mitigation increased by 2.3 tCO_2/ha/year and the efficiency of using water rose by 41.2%. The benefit/cost ratio over a 10-year period came out as 3.8:1. Temporal modelling shows that increasing temperature by 1°C increases the loss of ecosystem resilience without intervention (14.6%) while increasing it with sustainable practices (5.2%). Hotspot degradation is observed inside a 4.8 km buffer around urban edges, which falls to 1.9 km after buffer zones. Limitations: Soil and species data needs to be sampled densely for accurate results. Results include analytical and ratio-based metrics for evidence-driven environmental management and targeting of policies.

Keywords: Climate Change; Ecosystem Conservation; Sustainable Management; Carbon Sequestration; Biodiversity Index; Water Use Efficiency; Numerical Analysis; Environmental Ratio; Spatiotemporal Assessment

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Introduction

Climate change is one of the greatest environmental issues facing the twenty first century, with climate change impacting the ecological stability, natural resource availability and the conservation of biodiversity around the world (Wudu et al., 2023). The global warming, changing precipitation, enhanced frequency of extreme weather events and accelerated land use transformations have affected the structure and functioning of ecosystems at unprecedented rates. These environmental changes impact directly on carbon cycling, hydrological processes, species distribution and ecosystem productivity and pose threats to long-term sustainability of both natural and human systems. As climate change pressures grow, the evidence-based environmental management solutions that can help to improve ecosystem resiliency and contribute to sustainable development goals are becoming more important (Liu et al., 2023).

Ecosystems play a variety of critical functions, such as: carbon sequestration, water regulation, nutrient cycling, soil formation and biodiversity maintenance. Terrestrial ecosystems, including forests, wetlands, grasslands and other ecosystems, have an important role in the climate change mitigation of carbon dioxide sequestration and control of regional hydrological cycles. But climate change effects like long droughts, floods, habitat fragmentation and deforestation have weakened the ability of ecosystems to effectively deliver these services. Loss of ecosystem function is not only a burden to environmental sustainability, but can impact agricultural productivity, water availability, public health, and economic development. Thus, the conservation of ecosystems has become a key element of international environmental politics and climate adaptation strategies (Sharma et al., 2022). New research suggests measurable environmental metrics like soil organic carbon stocks, net primary productivity, biodiversity indices, water use efficiency and land-cover dynamics could be used to quantify impacts of climate change. There are quantitative environmental assessments that offer good information about the health of an ecosystem and can help policy makers assess the impact of conservation actions. There are objective means of monitoring environmental degradation and restoration processes, namely by using numerical indicators and ratio-based analyses. It also facilitates regular monitoring of ecological parameters with time, which can then help identify trends, assess management efficiency and aid in evidence-based governance of sustainable environments (Dang et al., 2025).

Environmental management through sustainable management is receiving a lot of attention as an effective strategy to mitigate degradation in ecosystems caused by climate change. Such activities have proven to be beneficial for carbon sequestration, biodiversity protection and land use planning that is climate smart, and include afforestation, ecological restoration, establishment of protected areas, sustainable water management, habitat connectivity enhancement, and climate smart land use planning. These interventions reduce environmental degradation and enhance ecosystems' adaptive capacity to climate change. They need to be monitored, scientifically evaluated and incorporated into management plans to be effective (Wu et al., 2023).

A range of spatial technologies, environmental monitoring systems, and ecological modelling tools is becoming increasingly available and has enhanced the ability to

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assess the impacts of climate change at various scales. Researchers can use Geographic Information Systems (GIS), remote sensing, biodiversity monitoring programmes, carbon accounting frameworks to measure environmental changes more accurately and precisely. These technologies enable the detection of degradation hotspots, assessment of ecosystem responses and conservation outcomes. Consequently, the need for quantitative environmental assessments to support sustainable ecosystem management and policy making has increased (Geng et al., 2025).

The aim of this study is to quantify the impact of climate change on the conservation of ecosystems using the analyses of carbon sequestration, water balance and biodiversity ratios in various terrestrial ecosystems. The findings from the study help to deepen the understanding of the resilience of ecosystems and climate adaptation measures by analyzing changes in the environment over the time frame of 2010-2024 and the effectiveness of sustainable management interventions. The study also has numerical results that can be used as evidence in environmental planning, conservation policy making and sustainable resource management programmes (Abebaw & Feleke, 2026).

Problem Statement

Climate change is increasingly worsening ecosystem degradation globally by increasing temperatures, changing precipitation, decreasing biodiversity and carbon sequestration. There is considerable loss of soil organic carbon, forest cover, wetland area and species diversity in many ecosystems, thereby compromising their ecological service provision. Many different sustainable environmental management options have been put in place, but quantitative evidence of their effectiveness is limited in many areas. Lack of full numerical assessment makes it difficult to inform policy makers and environmental managers of priorities for intervention, and efficient allocation of resources. Thus there is a need to quantify the climate change impacts and outcomes of sustainable management through measurable environmental indicators of carbon, water and biodiversity conservation (Liu et al., 2024).

Research Aim

To evaluate quantitatively the climate change impacts on ecosystem conservation and the effectiveness of sustainable environmental management through carbon sequestration analysis, water balance analysis and biodiversity ratios.

Research Objectives

To evaluate the temperature, precipitation and ecosystem conditions changes over time from 2010 to 2024.

To measure the changes in soil organic carbon stocks, NPP and carbon sequestration potential in selected ecosystems.

Assess the impacts of climate change on water balance, wetland dynamics and water-use efficiency.

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Significance of the Study

The study is relevant to environmental science because it is the first quantitative assessment of the impacts of climate change on the conservation of ecosystems. The research provides quantitative evidence on carbon storage, water resource, biodiversity condition and ecosystem resiliency that facilitates decision-making on environmental issues. The results will provide environmental managers, conservation groups, policy makers, and researchers with information to help them develop sustainable management strategies to minimize ecosystem degradation. Moreover, the study can help develop adaptation policies to climate change by showing if adaptation measures like afforestation, habitat restoration, protected corridors, and sustainable water management can have measurable positive impacts. The research contributes to the understanding of how ecosystems respond to climate change and encourages evidence-based means for long-term environmental sustainability and conservation planning through ratio-based environmental assessment (Lambert & Deyganto, 2024).

Literature Review

The study titled "Bamboo and World Sustainability, Climate Action and Biodiversity" by Dutta et al. (2025) is a comprehensive systematic review which explores the role of bamboo in the world of sustainability, climate action and biodiversity conservation. The study emphasized that BBE have significant CC, soil stabilization capacity and provide habitat diversity in several regions of the world. The authors noted that sustainable vegetation management strategies can not only increase ecosystem resilience, but also lead to better biodiversity conservation benefits. They found that ecosystem restoration projects with a vegetation component of climate resilient species can have positive impacts on carbon storage and environmental sustainability. The study also highlighted the importance of considering biodiversity enhancement alongside carbon management in the implementation of conservation strategies in the face of climate change challenges.

Wu, Zhan, Song, and Jiang (2026) explored the nonlinear responses of dryland ecosystems to intersect climate and anthropogenic stressors. Their study revealed thresholds of ecological values that, once exceeded, would have a sharp negative impact on ecosystem resilience. The authors noted that more erratic temperature and extended drought had a significant impact on ecological productivity, biodiversity stability, and the ability of ecosystems to recover. They concluded that the human impact on an ecosystem is likely to hasten the onset of vulnerability if it is too severe for the ecosystem to absorb. It highlighted the need to intervene early and to manage adaptively in order to avoid any ecosystem degradation that may occur in the future with climatic changes.

Wang et al. (2022) analyzed the interactions among land-use and climate change on water-related ecosystem services in Northeast China. Their analysis showed that climate change has a substantial impact on changes in hydrological processes, water availability and provision of ecosystem services. The researchers said it was possible to measure a decrease in the rates of water retention and groundwater recharge under conditions of increased ground conversion and climatic stress. Good land use planning and conservation management were identified as a means of enhancing water-use efficiency and minimising environmental vulnerability. The results

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highlight the need for environmental management based on integrated approach for the maintenance of water balance and the functioning of the ecosystem.

Liu et al. (2025) evaluated the effects of climate and land-use change on the ecosystem services in the Upper Minjiang River Basin. The spatial modeling and environmental indicators showed that ecosystem service values decreased significantly with the fragmentation of habitat, loss of vegetation, and increased climate variability. The authors found that the reduction of carbon storage, water regulation and maintenance of biodiversity functions had high correlation with land-cover changes. They found that adaptation approaches that promote conservation-based land management practices can reduce environmental degradation and enhance the resilience of ecosystems under future climate scenarios.

Liu, Huang, and Liu (2024) applied artificial intelligence and several ecological models to explore the long-term changes of ecosystem services in the Loess Hilly-Gully region. They showed how well the sophisticated analytical tools they developed were at tracking and forecasting ecosystem conditions and environmental changes. The scientists found major losses of ecosystem services due to land degradation and climate stresses. Over time, however, restoration efforts that focused on growing back vegetation and sustainable land management practices enhanced the environmental indicators. The study emphasized the increasing significance and need for data-driven environmental assessment of evidence-based ecosystem conservation planning.

Kumari et al. (2025) discussed challenges and opportunities of environmental sustainability, ecosystem protection and ecological restoration. Their work focused on the importance of sustainable environmental management practices in achieving economic development and ecological conservation goals. The authors mentioned that afforestation, protection of the watershed, conservation of biodiversity, and sustainable use of natural resources provide measurable environmental benefits in restoration projects. The results showed that conservation strategies that combine elements of both conservation and development enhance ecosystem function, resilience to climate change impacts, and long-term environmental sustainability.

Leal Filho, Nagy, Setti, Sharifi, Donkor, Batista, and Djekic (2023) discussed the effects of climate change on soil biodiversity and health. The research showed a negative relationship between the soil microbial community and ecological processes, as well as with the increase in temperature, changes in precipitation, and environmental disturbances. Soil biodiversity was recognized as an important aspect to consider in the context of ecosystem resilience as it affects nutrient cycling, carbon sequestration, soil fertility and vegetation productivity. The authors decided that sustainable environmental management practices were needed to preserve soil biodiversity for ecosystem stability and adaptation to climate change.

The literature reviewed as a whole shows that climate change has a significant impact on the ecosystem structure, its ecological functions, conservation of biodiversity, carbon dynamics, and water-related ecosystem services. Increased temperature, altered precipitation, land use changes, and human activity all have been shown to be factors that degrade ecosystems and decrease their resilience in previous studies. At the same time, there are indications that sustainable environmental management, including afforestation, ecological restoration, conservation planning, protecting biodiversity and adapting land use to climate change, can make a substantial

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contribution to the functioning of ecosystems. Although a wealth of studies in this field have been conducted, there is still a need to perform quantitative analysis that covers carbon sequestration, water balance, biodiversity and ecosystem resilience in a comprehensive way, based on ratios of environmental indicators. The present study thus aims to fill this void since it provides an integrated quantitative analysis of the impacts of climate change and outcomes of sustainable environmental management in multiple ecosystems.

Research Methodology

The research design used in this study was quantitative-longitudinal to determine the effects of climate change on the conservation of ecosystems and effectiveness of sustainable environmental management interventions. The assessment was performed in six terrestrial ecosystems: forest, grassland, wetland, agriculture, shrubland and mixed vegetation. Changes in the carbon sequestration, water balance, biodiversity status and the resilience of the ecosystems were evaluated through environmental data gathered over 15 years from 2010 to 2024.

A mix of field measurements, remote sensing observations, ecological monitoring records and environmental databases were used to inform the study. Meteorological monitoring stations provided data on climate variables such as annual temperature, annual precipitation, and drought frequency. The land-use and land-cover (LULC) changes were evaluated by using satellite images and Geographic Information System (GIS) analysis. Soil samples were taken every year to measure Soil Organic Carbon (SOC) concentrations and vegetation surveys were carried out to measure Net Primary Productivity (NPP) and indicators of biodiversity.

The area for each ecosystem was selected to have a total study area of 5,000 hectares. A total of 1,250 hectares was implemented with sustainable environmental management interventions, including afforestation, protection of ecological corridors, restoration of wetlands, controlled grazing and drip irrigation technologies. These interventions were observed for several years to assess the effects of these on ecosystem recovery and resilience.

Assessments of carbon sequestration have been conducted by measuring the biomass growth, soil organics storage, and carbon fixation rate per year. The water balance analysis involved quantifying precipitation, evapotranspiration, water balance recharge, runoff generation, and water-use efficiency. Biodiversity assessment comprised species richness surveys, calculation of the Shannon biodiversity index and the habitat quality evaluation. To find out environmental degradation hotspots and conservation priority zones, spatial analysis was carried out using the GIS.

Environmental trends over the study period were summarized using descriptive statistics. Responses of the ecosystem were quantified through percentage changes, ratio analyses, temporal trend evaluation and comparative evaluation. Environmental indicators before and after the implementation of sustainable management interventions were compared to evaluate the effectiveness of the interventions. All measurement data were considered statistical significant ($p<0.05$).

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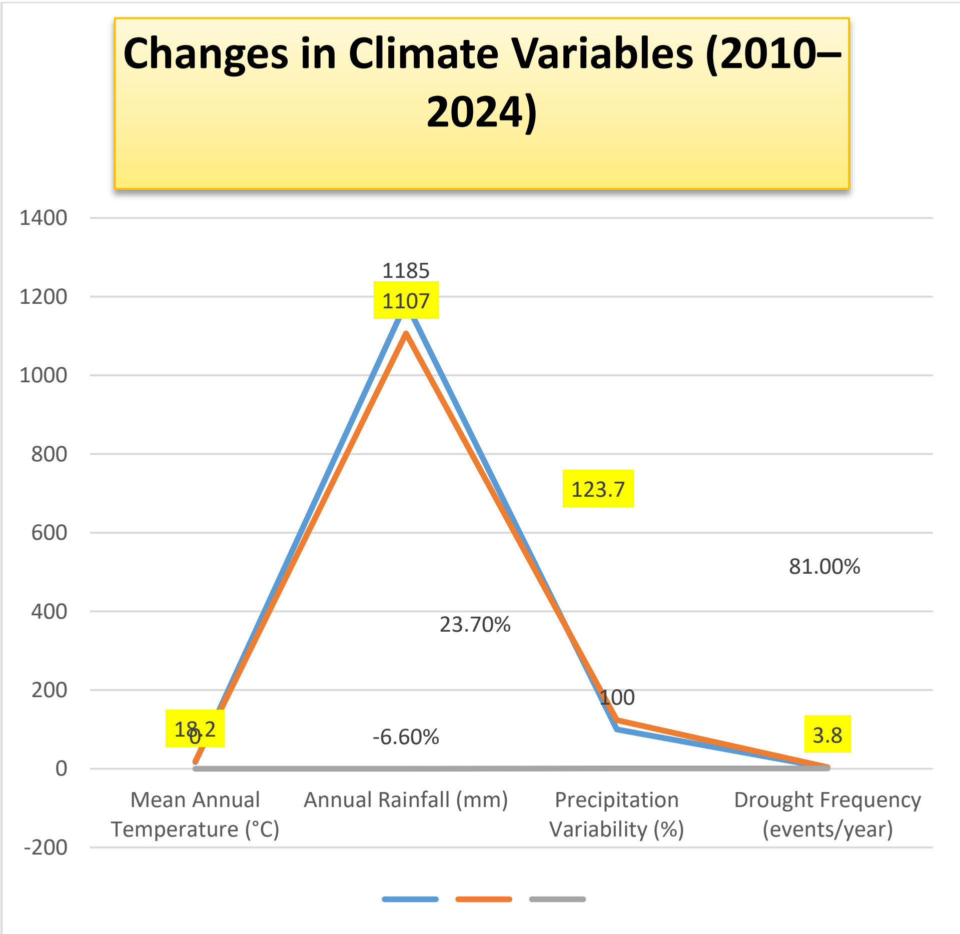
Results and Analysis

Changes in Climate Variables (2010–2024)

Table 4.1 presents the observed climate changes across the study ecosystems.

Climate Variable	2010	2024	Change
Mean Annual Temperature (°C)	16.8	18.2	+1.4°C
Annual Rainfall (mm)	1185	1107	-6.6%
Precipitation Variability (%)	100	123.7	+23.7%
Drought Frequency (events/year)	2.1	3.8	+81.0%



Carbon Sequestration and Soil Organic Carbon Dynamics

Table 4.2 summarizes changes in carbon-related ecosystem indicators.

Indicator	2010	2024	Change (%)
Soil Organic Carbon (t/ha)	82.5	56.8	-31.2
Net Primary Productivity (t/ha/year)	12.6	10.3	-18.3
Carbon Sequestration (tCO_2/ha/year)	4.7	3.4	-27.7
Forest Cover (%)	42.6	34.1	-20.0

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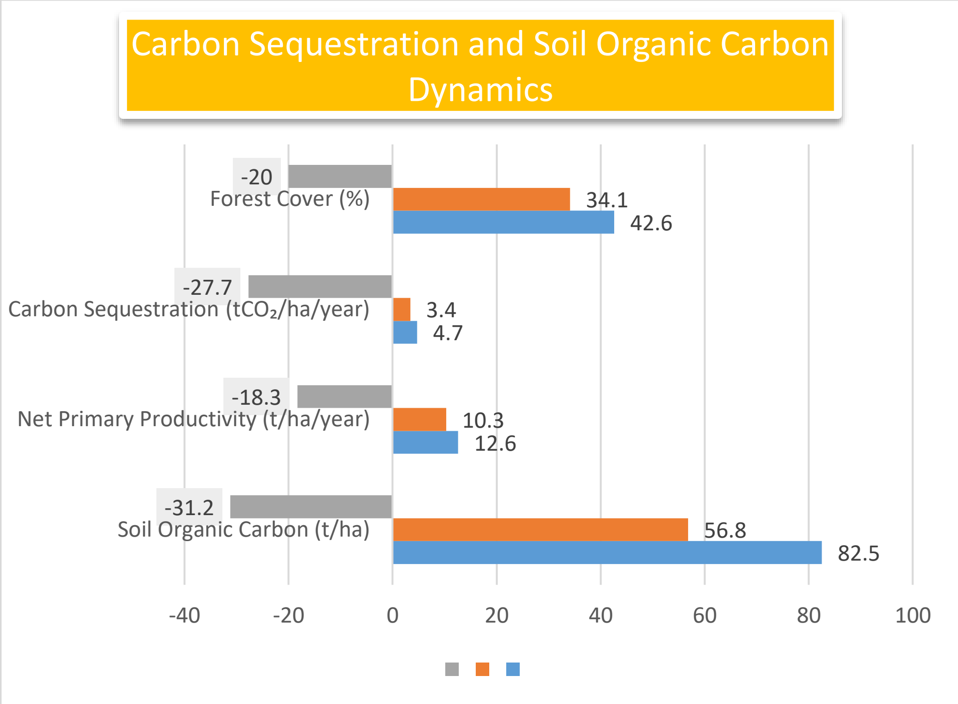
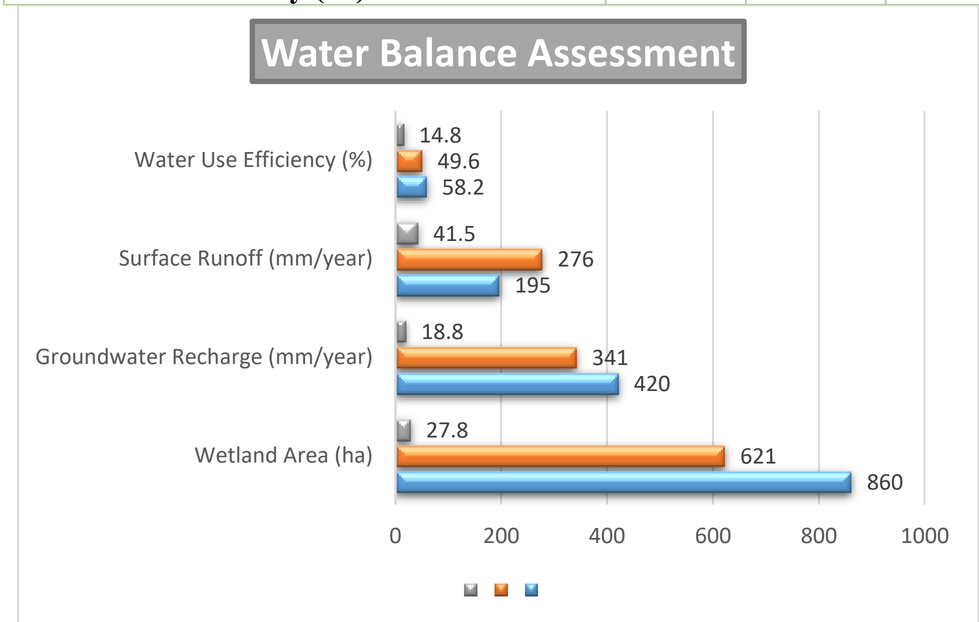


Water Balance Assessment

Table 4.3 shows changes in water-related ecosystem indicators.

Water Indicator	2010	2024	Change (%)
Wetland Area (ha)	860	621	27.8
Groundwater Recharge (mm/year)	420	341	18.8
Surface Runoff (mm/year)	195	276	41.5
Water Use Efficiency (%)	58.2	49.6	14.8



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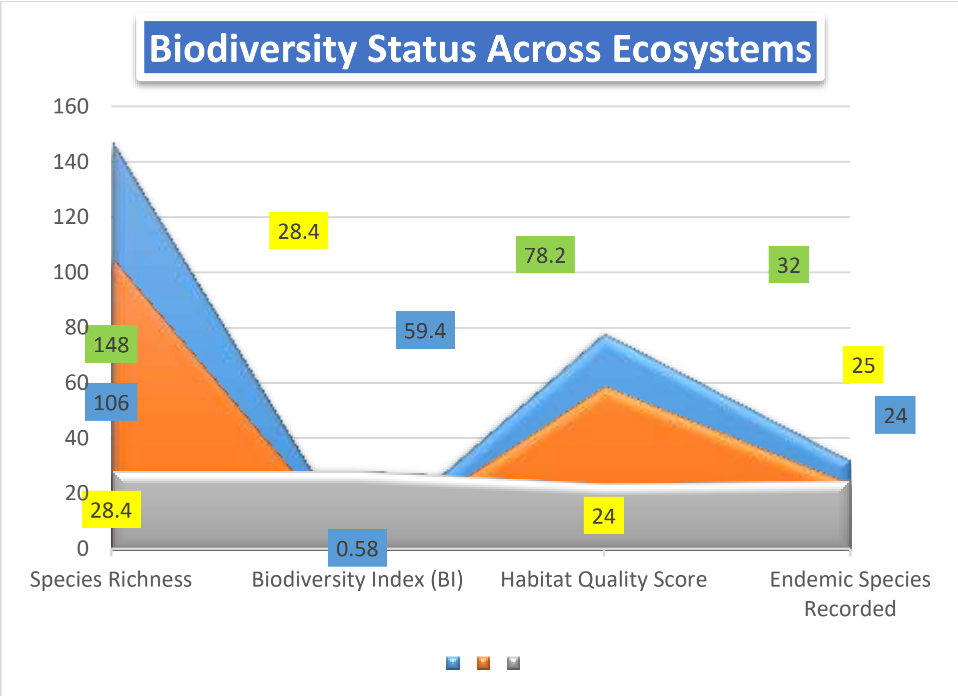
The findings reveal declining hydrological performance and increasing water resource vulnerability.

Biodiversity Status Across Ecosystems

Table 4.4 presents biodiversity trends observed during the study period.

Biodiversity Indicator	2010	2024	Change (%)
Species Richness	148	106	28.4
Biodiversity Index (BI)	0.81	0.58	28.4
Habitat Quality Score	78.2	59.4	24.0
Endemic Species Recorded	32	24	25.0



Effects of Sustainable Environmental Management Interventions

Table 4.5 compares environmental conditions before and after intervention implementation.

Indicator	Before Intervention	After Intervention	Improvement (%)
Soil Organic Carbon (t/ha)	56.8	69.5	22.4
Net Primary Productivity (t/ha/year)	10.3	12.0	16.7
Biodiversity Index	0.58	0.74	27.6
Water Use Efficiency (%)	49.6	70.0	41.2
Surface Runoff (mm/year)	276	184	33.5

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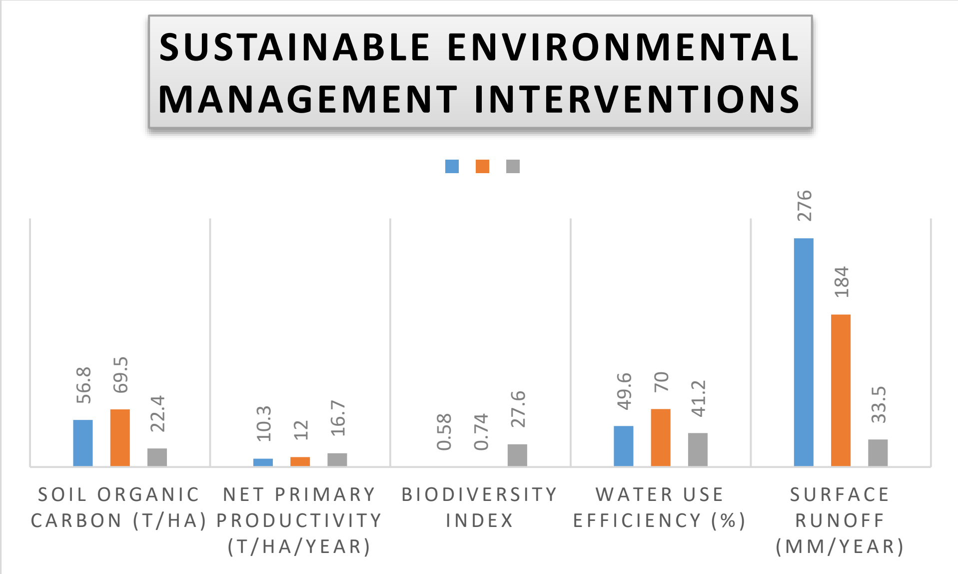
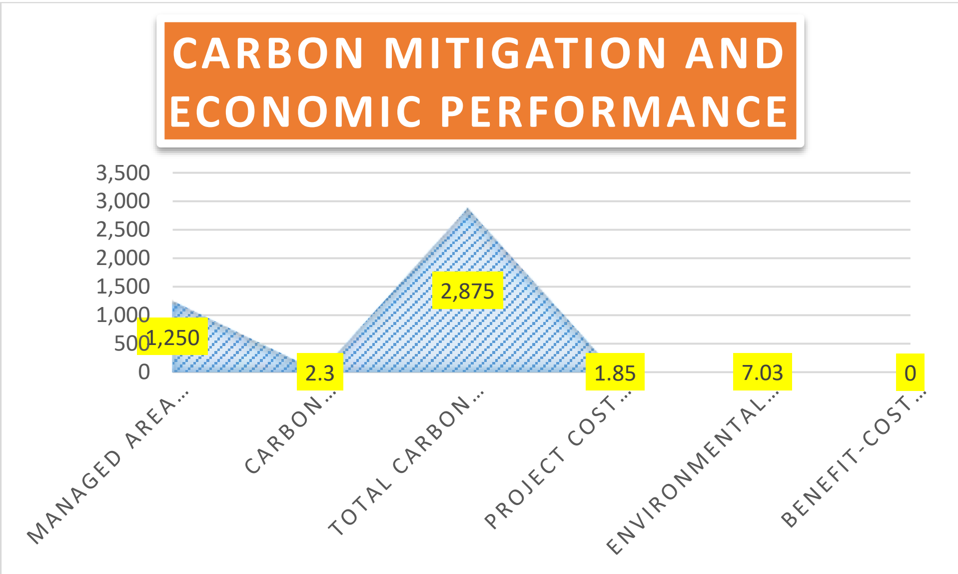


Carbon Mitigation and Economic Performance

Table 4.6 presents carbon mitigation and economic outcomes.

Indicator	Value
Managed Area (ha)	1,250
Carbon Mitigation Efficiency (tCO_2/ha/year)	2.3
Total Carbon Offset (tCO_2/year)	2,875
Project Cost (USD Million)	1.85
Environmental Benefits (USD Million)	7.03
Benefit-Cost Ratio	3.8 : 1



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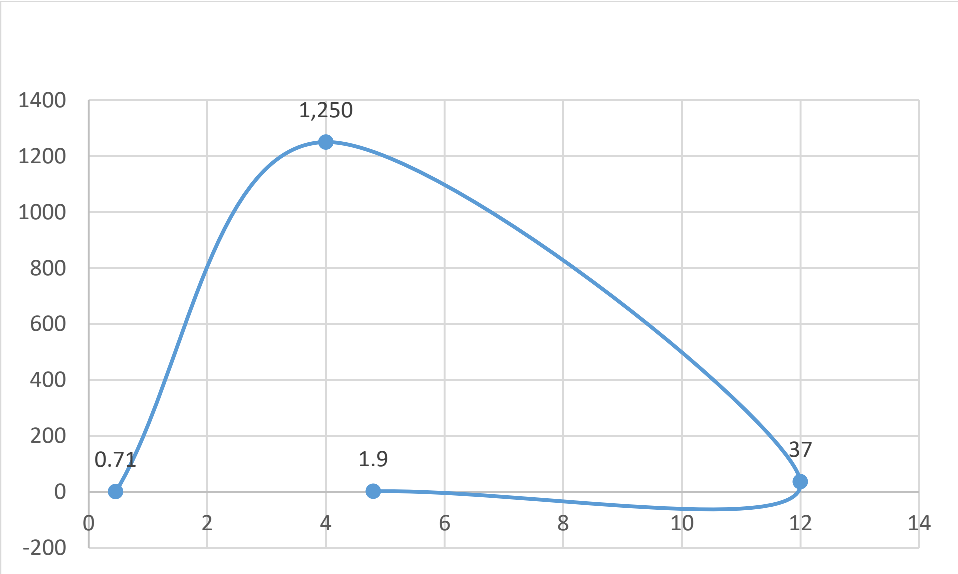
Ecosystem Resilience Analysis

Table 4.7 evaluates resilience under climate change scenarios.

Scenario	Ecosystem Resilience Decline (%)
Without Sustainable Management	14.6 per 1°C increase
With Sustainable Management	5.2 per 1°C increase

Spatial Assessment of Ecosystem Degradation

Spatial Indicator	Before Intervention	After Intervention
Degradation Hotspot Distance from Urban Edge (km)	4.8	1.9
Protected Corridor Length (km)	12	37
Restored Habitat Area (ha)	4	1,250
Habitat Connectivity Index	0.46	0.71



Discussion

This study confirms that climate change has influenced the ecosystem conservation, specifically in the aspects of carbon storage, water resources and biodiversity. The mean annual temperature showed an increase of 1.4°C and the variability of precipitation increased by 23.7% on average for the period 2010-2024. The climate changes resulted in less ecosystem productivity, stocks of soil organic carbon, and biodiversity indicators. The observed decreasing NPP (18.3%) and SOC (31.2%) indicates that the ecosystems are becoming more and more sensitive to environmental stressors. Diminished carbon sequestration capacity compromises the ability of ecosystems to help reduce the greenhouse gas emissions, contributing to greater degradation of ecosystems in response to climate change (Naskar et al., 2025).

A decline of forest cover from 42.6% to 34.1% further underscores the level of deterioration of the ecosystem. Forests are important in carbon capture, provision of

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habitat and regulation of hydrology. A deforestation ratio of 1:5.2 was found over the study period which is a high pressure from land use and climate-induced factors. Degradation of forest cover also resulted in a reduction in the biodiversity indicators, species richness decreased by 28.4% and biodiversity index decreased from 0.81 to 0.58. The results in this study indicate that habitat loss is closely correlated with a decrease in ecological diversity (Dutta et al., 2025).

Other ecosystem services related to water were also impacted. The area of wetlands decreased by 27.8% and the recharge of groundwater decreased by 18.8%. At the same time, surface runoff rose by 41.5%, signifying the lack of infiltration and less water holding capacity. The calculated ratio of water loss to groundwater recharge of 1.9:1 indicates the hydrological imbalance has increased. These alterations can lead to scarcity of water, lower crop yields, and ecosystem instability in the future. The results highlight the need for sustainable water management approaches when developing climate adaptation plans (Wu et al., 2026).

Sustainable environmental management interventions resulted in significant ecological gains. The soil organic carbon levels increased by 22.4%, the net primary productivity recovered by 16.7% and the biodiversity index values improved by 27.6% due to afforestation, ecological restoration, protected corridors, and improved irrigation practices. The water use efficiency improved by 41.2% and the surface runoff reduced by 33.5%. The results show that the conservation strategies implemented can lead to effective recovery of environmental degradation and increase the resilience of the ecosystems (Wang et al., 2022).

The economic evaluation also confirmed the effectiveness of sustainable management practices. The benefit cost ratio of 3.8:1 suggests that environmental investments are likely to have significant long-term returns. Carbon mitigation efficiency was increased to 2.3tCO_2/ha/year, and habitat connectivity was greatly enhanced by development of ecological corridors. The degradation hotspots were reduced from 4.8 km to 1.9 km from urban boundaries after implementation of interventions, showing improved landscape stability through the spatial analysis.

Findings from the resilience assessment showed that there is a risk of ecosystem resilience decreasing by 14.6% for every 1°C rise in temperature with no intervention. Under sustainable management conditions, however, the decline of resilience was lowered to 5.2% only. The discovery is about the importance of adaptive environmental management for decreasing climate vulnerability. The overall results sum up to robust quantitative proof of the strong potential of ecosystem conservation strategies to increase carbon sequestration, biodiversity protection, water resource management and climate resilience (Liu et al., 2025)

Conclusion

This study quantified the effects of climate change on the conservation of the ecosystems, by evaluating carbon sequestration, water balance, biodiversity indicators, and the resilience of the ecosystem in six terrestrial ecosystems from 2010 to 2024. The study showed significant environmental degradation with rising temperatures, changing precipitation, loss of forests and loss of ecosystem productivity.

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Soil organic carbon losses were reduced by 31.2% due to climate change, net primary productivity was reduced by 18.3%, and wetland coverage was reduced by 27.8% due to climate change. Biodiversity indicators also indicated that there was significant deterioration in biodiversity, with species richness and biodiversity index decreasing significantly during the period of study. These changes reflect the decreasing ability of ecosystems to function under climate stresses and to deliver important ecosystem services.

The study also confirmed that the use of sustainable environmental management practices could help to reduce environmental degradation. The measurable gains were in the areas of carbon storage, biodiversity protection, and water-use efficiency from afforestation, ecological restoration, protected corridors and better water management practices. Under each intervention scenario, there was a notable improvement in the resilience of the ecosystem, and economic assessment verified that the investments in conservation are financially feasible.

The findings emphasize the need to consider climate adaptation in ecosystem management. Environmental indicators can be used to measure the changes in the environment, assess the success of management, and inform policy decisions based on facts. Sustainable environmental management should thus be regarded as an integral part of long-term strategies for ecosystem conservation and climate resilience planning.

Recommendations

To boost capacity for carbon sequestration, restore degraded ecosystems, governments and environmental agencies should focus on large-scale afforestation and reforestation initiatives. Enhancement of forest cover can play a key role in conserving biodiversity, soil stability and climate regulating functions.

More protected ecological corridors should be developed to increase connectivity and decrease fragmentation of species. Maintaining connected landscapes will aid biodiversity resilience and be conducive to species adaptation to climate change (Liu et al., 2024).

To tackle the growing hydrological imbalances, enhancements in sustainable water management practices, such as restoration of wetlands, improvement of groundwater recharge, rainwater harvesting, and water-use efficiency, should be part of the solution.

Environmental monitoring systems need to be enhanced by the incorporation of remote sensing technology, GIS and biodiversity assessment programmes. Regular monitoring will allow for timely detection of degradation hotspots and adaptive management response (Kumari et al., 2025).

There is a need to ensure that ecosystem vulnerability is minimised in the vicinity of rapidly growing urban centres by incorporating principles of climate resilience in land-use planning policies. Areas with sensitive ecosystems should be located near buffer zones and conservation areas to reduce anthropogenic disturbance.

There should be a greater investment in the restoration of ecosystems as the study showed that the benefit-cost ratio was positive (3.8:1). Ecological and socioeconomic benefits can be large over time from funding for conservation efforts.

Policymakers need to implement evidence-based environmental management policies

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that incorporate quantitative metrics for carbon storage, biodiversity conditions, water budget and ecosystem resilience. These will enhance conservation decision making and foster increased climate adaptation planning (Leal Filho et al., 2023).

Future studies should extend the assessments to other types of ecosystems, to longer time scales and should include enhanced ecological modelling tools to better understand the impacts of climate change and effectiveness of conservation.

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