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Carbon Sequestration in Land-Based Ecosystems: A Review of Its Role in Environmental Sustainability and Climate Regulation

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ABSTRACT: Carbon sequestration in land-based ecosystems plays a critical role in regulating atmospheric carbon dioxide and supporting global environmental sustainability. This review synthesizes current knowledge on the mechanisms, ecosystem types, benefits, challenges, and policy implications of carbon sequestration in terrestrial environments. The study highlights that carbon is absorbed through photosynthesis and stored in vegetation biomass and soil organic matter, making forests, soils, grasslands, wetlands, agricultural lands, and urban green spaces essential components of the global carbon cycle. Among these, forest ecosystems exhibit the highest carbon storage capacity due to their large biomass and long-lived vegetation, while soils represent the largest long-term terrestrial carbon reservoir through stabilized organic carbon. The review further emphasizes that sustainable land management practices such as reforestation, afforestation, agroforestry, conservation agriculture, and ecosystem restoration significantly enhance carbon sequestration potential while simultaneously improving biodiversity, soil fertility, and water quality. These ecosystems also provide important co-benefits, including climate regulation, ecosystem services, and resilience against climate change impacts. However, their effectiveness is increasingly threatened by deforestation, land degradation, unsustainable agricultural practices, and climate-induced disturbances such as droughts and wildfires, which reduce carbon storage capacity and increase greenhouse gas emissions. Strengthened monitoring systems, improved carbon accounting, and nature-based solutions are essential for enhancing the effectiveness of land-based climate actions. Overall, land-based ecosystems represent a vital natural solution for mitigating climate change and promoting long-term environmental sustainability through enhanced carbon storage and ecosystem conservation.

KEYWORDS: Carbon sequestration; land-based ecosystems; climate change mitigation; soil organic carbon; sustainable land management

1. Introduction

Climate change has become one of the most critical environmental challenges affecting ecosystems, human health, biodiversity, and global economic stability. The increasing concentration of greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere has intensified global warming and altered climate patterns worldwide. Human activities such as deforestation, industrialization, fossil fuel combustion, urbanization, and unsustainable agricultural practices have significantly contributed to the rising levels of atmospheric carbon. As a result, there is an urgent need to identify effective strategies to reduce greenhouse gas emissions and mitigate climate change impacts [1, 2].

Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide for long periods to reduce its concentration in the atmosphere. Natural carbon sequestration occurs mainly through biological, chemical, and physical processes in terrestrial and aquatic ecosystems. Among these, land-based ecosystems such as forests, grasslands, wetlands, agricultural lands, and soils play a vital role in absorbing carbon through photosynthesis and storing it in vegetation and soil organic matter. These ecosystems function as natural carbon sinks that help regulate the global carbon cycle and maintain climate balance [3, 4].

Despite the important role of carbon sequestration in climate regulation, many land-based ecosystems are increasingly threatened by human activities and environmental degradation. Deforestation, land conversion, overgrazing, soil erosion, forest fires, and intensive agricultural practices reduce the capacity of ecosystems to absorb and store carbon effectively. The degradation of natural ecosystems not only releases stored carbon back into the atmosphere but also weakens ecosystem resilience and biodiversity conservation [5, 6].

In many developing and industrialized countries, rapid urban expansion and unsustainable land management continue to accelerate carbon emissions and ecosystem degradation. Although numerous studies have investigated carbon sequestration in specific ecosystems, there remains a need for a comprehensive unde rstanding of how different land-based ecosystems contribute to environmental sustainability and climate regulation. Furthermore, there is limited integration of current knowledge regarding the mechanisms, benefits, challenges, and management strategies associated with carbon sequestration. Therefore, a review of existing literature is necessary to synthesize current findings and identify future directions for sustainable carbon management [7, 8].

Land-based ecosystems are essential components of the global carbon cycle because they absorb significant amounts of atmospheric carbon dioxide and store it in biomass and soils. Forest ecosystems are among the largest terrestrial carbon sinks due to their high vegetation density and long-term carbon storage potential. Similarly, wetlands and peatlands can store large quantities of carbon in waterlogged soils, while grasslands and agricultural soils contribute to belowground carbon accumulation through root systems and soil organic matter [9, 10].

Beyond carbon storage, these ecosystems provide additional environmental benefits, including biodiversity conservation, water regulation, soil fertility improvement, erosion control, and climate stabilization. Sustainable management of land-based ecosystems can therefore contribute not only to climate change mitigation but also to environmental sustainability and ecosystem resilience. Enhancing carbon sequestration through reforestation, afforestation, agroforestry, and sustainable land-use practices has become an important strategy in global climate policies and sustainable development goals [11, 12].

This review makes a distinct contribution to the existing literature by providing a comprehensive, cross-ecosystem synthesis that integrates mechanisms, quantitative carbon storage rates, challenges in carbon measurement and accounting, and policy implications within a single narrative framework. While prior reviews have examined individual ecosystem types or specific aspects of carbon sequestration (such as forest-focused syntheses by Ameray et al. [25] and Psistaki et al. [44], or soil-focused reviews by Almendros and González-Pérez [20]), the present review uniquely spans forests, agricultural and agroforestry systems, grasslands, wetlands, urban green spaces, and restored ecosystems, systematically comparing their quantitative carbon storage capacities using recent evidence (2019–2025). This integrative scope, combined with explicit treatment of uncertainties in carbon accounting and emerging monitoring technologies, distinguishes this review from prior syntheses and provides actionable guidance for policymakers and land managers. This review aims to examine the role of carbon sequestration in land-based ecosystems and its contribution to environmental sustainability and climate regulation. Specifically, the review discusses the mechanisms of carbon sequestration, the carbon storage potential of various terrestrial ecosystems, and the environmental benefits associated with carbon storage. In addition, the review highlights current challenges, management approaches, and future research directions related to sustainable carbon sequestration practices.

2. Methodology

2.1. Literature Search Strategy.

This review focused on terrestrial ecosystems, including forests, agricultural lands, grasslands, wetlands, and restored ecosystems, because of their important roles in carbon sequestration, climate change mitigation, and environmental sustainability. A systematic literature search was conducted using Scopus, Web of Science, and Google Scholar. The search employed the following keywords: *"carbon sequestration AND land-based ecosystems," "terrestrial carbon storage AND climate regulation," "soil organic carbon AND sustainable land management," "forest carbon sequestration," "agroforestry AND carbon,"* and *"wetland carbon AND peatland."* Publications from 2012–2025 were considered, with emphasis on studies published from 2019 onwards. Reference lists of relevant articles were also screened to identify additional studies.

2.2. Study Selection.

The study selection followed the PRISMA 2020 guidelines. Studies were included if they investigated terrestrial ecosystems and addressed carbon sequestration, carbon storage, or related ecosystem processes. Only peer-reviewed journal articles published in English were considered. Studies focusing exclusively on aquatic or marine ecosystems or those not directly relevant to the review objectives were excluded. A total of 847 records were identified through database searching. After removing duplicates and screening titles and abstracts, 183 full-text articles were assessed for eligibility. Following full-text evaluation, 50 peer-reviewed studies met the inclusion criteria and were included in the final review. The study selection process is summarized in Figure 1.

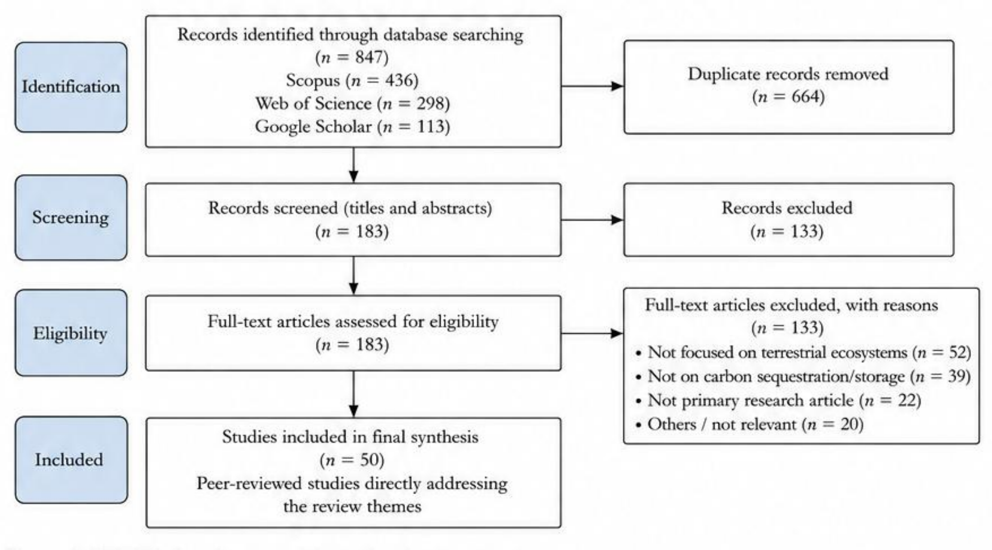

Figure 1. PRISMA 2020 flow.

2.3. Data Extraction and Synthesis.

Relevant information, including ecosystem type, study location, research methods, carbon sequestration indicators, management practices, and key findings, was extracted from each selected study. The included studies were synthesized narratively to identify major research trends, knowledge gaps, and implications for climate change mitigation and sustainable land management.

3. Mechanisms and Processes of Carbon Sequestration in Land-Based Ecosystems

3.1. Carbon Cycle and Carbon Dynamics.

Carbon sequestration in land-based ecosystems is closely linked to the global carbon cycle, which describes the movement of carbon among the atmosphere, biosphere, hydrosphere, and lithosphere. Carbon exists in different forms and continuously circulates through natural processes such as photosynthesis, respiration, decomposition, and combustion. Terrestrial ecosystems play a major role in regulating this cycle by acting as both carbon sinks and carbon sources depending on environmental conditions and land management practices [4, 13]. Atmospheric carbon dioxide is absorbed by plants during photosynthesis and converted into organic carbon compounds that support plant growth and metabolism. This carbon is temporarily stored in leaves, stems, roots, and other plant tissues. When plants die or shed organic material, carbon enters the soil through litter decomposition and root decay. Soil microorganisms decompose organic matter, releasing some carbon back into the atmosphere through respiration while retaining part of it as stable soil organic carbon. Carbon dynamics in ecosystems are influenced by the balance between carbon uptake and carbon release. Healthy ecosystems with active vegetation generally absorb more carbon than they emit, thereby functioning as carbon sinks [14, 15]. However, disturbances such as deforestation, land degradation, forest fires, and intensive agricultural activities can disrupt carbon balance and transform ecosystems into carbon sources. Understanding carbon dynamics is therefore essential for developing effective strategies to enhance long-term carbon storage and climate regulation [15, 16].

3.2. Photosynthesis and Biomass Carbon Storage.

Photosynthesis is the primary biological mechanism responsible for carbon sequestration in terrestrial ecosystems. During this process, plants absorb atmospheric carbon dioxide and use sunlight energy to produce carbohydrates, which serve as the building blocks for plant biomass. Oxygen is released as a byproduct, while carbon becomes stored in plant tissues including trunks, branches, leaves, roots, and fruits. Biomass carbon storage is one of the most visible forms of carbon sequestration [4, 13]. Forest ecosystems, particularly tropical and temperate forests, have a high capacity to store carbon because of their dense vegetation and extensive biomass accumulation. Trees can retain carbon for decades or even centuries, making forests critical long-term carbon reservoirs. Grasslands and agricultural crops also contribute to biomass carbon storage, although their storage duration is generally shorter due to harvesting, grazing, or seasonal vegetation cycles. Belowground biomass, especially root systems, also plays a significant role in carbon storage. Root biomass contributes to soil carbon accumulation by depositing organic matter into the soil profile [13, 17]. In agroforestry systems, the integration of trees with crops enhances both aboveground and belowground carbon storage while simultaneously improving soil fertility and ecosystem resilience. The efficiency of biomass carbon storage depends on vegetation type, growth rate, climate conditions, and ecosystem management. Reforestation, afforestation, and sustainable vegetation management can substantially increase biomass carbon sequestration and contribute to climate change mitigation efforts [12, 18].

3.3. Soil Organic Carbon Formation and Stabilization.

Soil represents one of the largest carbon reservoirs in terrestrial ecosystems. Soil organic carbon is formed through the decomposition of plant residues, animal remains, and microbial biomass. Organic matter entering the soil undergoes biological and chemical transformation processes that determine whether carbon is rapidly released or stabilized for long-term storage. Microorganisms such as bacteria and fungi play essential roles in decomposing organic material and converting it into humus, a stable form of organic matter. Some carbon becomes physically protected within soil aggregates or chemically bound to soil minerals, reducing its decomposition rate and enhancing long-term storage stability [19, 20]. Wetlands and peatlands are particularly important for soil carbon storage because waterlogged conditions slow microbial decomposition and allow organic matter to accumulate over extended periods. The stabilization of soil organic carbon is influenced by soil texture, moisture, temperature, vegetation cover, and land management practices. Sustainable agricultural practices such as conservation tillage, crop rotation, organic amendments, and cover cropping can improve soil carbon retention and reduce carbon losses. Conversely, excessive tillage, deforestation, and soil erosion accelerate organic matter decomposition and release stored carbon back into the atmosphere. Maintaining healthy soils is therefore essential for enhancing carbon sequestration while simultaneously supporting agricultural productivity, water retention, and ecosystem sustainability [21, 22].

3.4. Factors Influencing Carbon Sequestration Capacity.

The carbon sequestration capacity of land-based ecosystems varies depending on multiple environmental, biological, and human-related factors. Climate is one of the most important determinants because temperature and precipitation directly affect plant growth, photosynthesis, and decomposition rates. Warm and moist environments generally promote rapid vegetation growth and higher carbon uptake, although excessive heat or drought can reduce sequestration efficiency [23, 24]. Vegetation type and biodiversity also influence carbon storage potential. Forests with diverse plant species and large tree biomass typically store more carbon than monoculture systems. Soil properties such as texture, nutrient availability, pH, and microbial activity further affect soil carbon stabilization and storage capacity. Human activities and land management practices are equally significant. Sustainable land management strategies such as reforestation, agroforestry, conservation agriculture, and wetland restoration can enhance carbon sequestration [25, 26]. In contrast, deforestation, urbanization, overgrazing, mining, and unsustainable farming practices reduce vegetation cover and accelerate carbon emissions. Natural disturbances including wildfires, pests, floods, and storms can also alter carbon storage dynamics by damaging vegetation and increasing decomposition rates. Therefore, long-term carbon sequestration requires integrated ecosystem management approaches that balance environmental conservation with human development needs [27, 28]. Mechanisms and processes of carbon sequestration in land-based ecosystems is summarized in Table 1.

Table 1. Mechanisms and processes of carbon sequestration in land-based ecosystems.

Thematic Area	Key Mechanism	Summary Description	References
Global Carbon Cycling Processes	Exchange of carbon among atmosphere, biosphere, hydrosphere, and lithosphere	Carbon continuously circulates through photosynthesis, respiration, decomposition, and combustion. Land ecosystems function as dynamic carbon sinks and sources depending on environmental conditions and land use. Disturbances such as deforestation, fires, and land degradation disrupt carbon balance and increase atmospheric CO_2 emissions.	[4, 13−16]
Biological Carbon Fixation and Biomass Storage	Photosynthetic carbon assimilation and vegetation biomass accumulation	Plants convert atmospheric CO_2 into organic compounds stored in leaves, stems, roots, and woody tissues. Forest ecosystems provide long-term carbon storage due to high biomass density, while grasslands and crops offer shorter-term storage. Agroforestry systems enhance both aboveground and belowground carbon sequestration and improve ecosystem resilience.	[4, 12, 13, 17, 18]
Soil Carbon Formation and Stabilization Mechanisms	Organic matter decomposition, humification, and mineral protection	Soil organic carbon originates from plant residues, microbial biomass, and animal matter. Microbial activity transforms organic matter into stable humus, with additional stabilization through soil aggregation and mineral binding. Wetlands and peatlands act as major long-term carbon reservoirs due to slow decomposition rates.	[19−22]
Regulating Factors of Carbon Sequestration Capacity	Climatic, ecological, soil, and anthropogenic controls	Carbon storage potential is influenced by climate conditions, vegetation diversity, soil properties, and land management practices. Human interventions such as reforestation and conservation agriculture enhance sequestration, while deforestation, urbanization, and environmental disturbances reduce carbon storage efficiency.	[23−28]

4. Types of Land-Based Ecosystems and Their Carbon Sequestration Potential

4.1. Forest Ecosystems.

Forest ecosystems are widely recognized as the most significant terrestrial carbon sinks due to their high biomass density and long-term carbon storage capacity. They sequester carbon in both aboveground components, such as trunks, branches, leaves, and woody debris, and belowground components, including roots and soil organic matter. Tropical forests, in particular, exhibit exceptionally high carbon uptake rates because of their rapid plant growth, dense canopy structure, and favorable climatic conditions that support year-round photosynthetic activity [4, 11, 12]. Temperate and boreal forests also contribute substantially to global carbon storage, although their sequestration patterns differ due to seasonal variations and slower decomposition rates in colder climates [4, 16]]. Boreal forests, for example, store large amounts of carbon in both vegetation and soil, where low temperatures slow microbial decomposition and promote long-term carbon accumulation. However, forest carbon storage is highly sensitive to disturbances such as deforestation, logging, forest fires, and land conversion. When forests are degraded or cleared, large amounts of stored carbon are released back into the atmosphere, contributing significantly to greenhouse gas emissions. Therefore, sustainable forest management practices, reforestation, and afforestation are essential strategies for maintaining and enhancing the carbon sequestration potential of forest ecosystems [25, 29]. Quantitatively, tropical forests store approximately 150–250 Mg C ha^{-1} in aboveground biomass alone, while temperate forests typically store 50–150 Mg C ha^{-1} [25]. Boreal forests, though slower-growing, accumulate 50–100 Mg C ha^{-1} in soil carbon due to cold temperatures that slow decomposition [29]. Mixed-species tropical forests have been shown to store up to 31% more carbon than monoculture plantations, demonstrating the importance of tree diversity for carbon sequestration [26]. Deighton et al. (2025) [29] found that long-term sustainable forest management in boreal systems maintained soil organic carbon at 80–120 Mg C ha^{-1}, while clearcut harvesting reduced these stocks by 25–40% over decades. These quantitative differences highlight the critical importance of forest type, management regime, and disturbance history in determining actual carbon storage outcomes [25, 29].

4.2. Agricultural and Agroforestry Systems.

Agricultural ecosystems traditionally have lower carbon sequestration potential compared to natural forests due to frequent soil disturbance, crop harvesting, and limited biomass accumulation. However, modern sustainable agricultural practices have demonstrated significant potential for enhancing carbon storage, particularly in soils. Conservation agriculture practices such as reduced tillage, cover cropping, crop rotation, and organic fertilization improve soil structure and increase soil organic carbon content over time [17, 30]. Agroforestry systems, which integrate trees with crops and/or livestock, represent one of the most effective land-use strategies for enhancing carbon sequestration within agricultural landscapes. Trees in agroforestry systems store carbon in woody biomass while also improving soil carbon through litter fall, root turnover, and enhanced microbial activity. Additionally, agroforestry systems improve land productivity, enhance biodiversity, and increase ecosystem resilience to climate variability [31, 32]. The combination of perennial woody vegetation and annual crops allows agroforestry systems to function as multi-layered carbon sinks. These systems are particularly important in tropical regions where agricultural expansion has led to significant deforestation and land degradation. By integrating trees into farmland, agroforestry provides a sustainable pathway for balancing food production with carbon sequestration and environmental conservation [18, 31, 32]. Quantitatively, agroforestry systems have been reported to sequester 0.5–5.0 Mg C/ha/yr depending on system design, climate zone, and tree species selection [18]. Abbas et al. [18] documented global evidence showing that smallholder agroforestry systems store 1.1–228 Mg C ha^{-1} across diverse geographic contexts. Conservation agriculture practices such as no-till and cover cropping have been estimated to increase soil organic carbon by 0.1–0.4 Mg C/ha/yr compared to conventional tillage [46]. However, these gains are not universal: Zhang et al. (2025) [23] found that carbon sequestration potential of cultivated land varied from near-zero to 0.6 Mg C/ha/yr depending on irrigation, soil type, and management intensity, highlighting the heterogeneity of agricultural carbon outcomes and the need for site-specific assessment [18, 31, 32].

4.3. Grasslands and Wetlands.

Grasslands cover large portions of the Earth's terrestrial surface and play an important role in global carbon cycling. Although they generally contain lower aboveground biomass than forests, grasslands are highly efficient at storing carbon in soils. Deep-rooted grasses contribute to soil organic carbon accumulation by continuously depositing organic matter belowground. The slow decomposition rates in some grassland soils further support long-term carbon storage [33, 34]. However, grassland carbon sequestration is highly sensitive to land-use changes such as overgrazing, conversion to croplands, and desertification. Unsustainable grazing practices can reduce vegetation cover and soil carbon stocks, leading to increased carbon emissions. Proper grassland management, including controlled grazing and restoration of degraded areas, can significantly enhance carbon sequestration potential. Wetlands and peatlands are among the most carbon-rich ecosystems on the planet. Their waterlogged conditions create anaerobic environments that slow down decomposition, allowing organic matter to accumulate over long periods. As a result, wetlands store large quantities of carbon in the form of peat. Despite occupying a relatively small proportion of global land area, they contain a disproportionate share of global soil carbon stocks. However, drainage, agricultural conversion, and urban development can rapidly turn wetlands into major carbon sources. Protecting and restoring wetlands is therefore critical for maintaining their carbon storage function and preventing large-scale carbon emissions [35, 36]. Grassland soils typically store 50–150 Mg C/ha in the top 1 m of soil, with some deep-rooted tropical savanna systems storing up to 200 Mg C ha^{-1} [9]. Liu et al. (2023) [9] noted that grassland carbon sequestration rates average 0.3–1.0 Mg C/ha/yr under optimal management, but can become net carbon sources under overgrazing, releasing 0.2–0.5 Mg C/ha/y. Peatlands store between 300 and 600 Mg C/ha, representing approximately 30% of global soil carbon stocks in just 3% of global land area [35]. However, Kustina et al. [36] identified that peatland restoration success varies markedly: fully restored sites can recover 70–85% of original carbon accumulation rates within 20 years, while poorly managed restoration results in continued net carbon loss, illustrating the importance of restoration quality over quantity alone [35, 36].

4.4. Urban Green Spaces and Restored Ecosystems.

Urban green spaces, including parks, street trees, gardens, and green roofs, contribute to carbon sequestration in built environments. Although their individual carbon storage capacity is smaller compared to natural ecosystems, their collective impact can be significant in densely populated cities. Urban vegetation absorbs carbon dioxide through photosynthesis while also providing additional benefits such as temperature regulation, air purification, and improved human well-being [37, 38]. Restored ecosystems, including rehabilitated forests, reclaimed mining sites, and reforested degraded lands, also play an important role in carbon sequestration. These ecosystems gradually rebuild biomass and soil carbon stocks over time, depending on the effectiveness of restoration practices and environmental conditions. Restoration efforts often involve planting native species, improving soil conditions, and managing land use to support ecosystem recovery [39, 40]. Both urban green spaces and restored ecosystems highlight the importance of integrating carbon sequestration strategies into land-use planning and environmental management. While their carbon storage potential may vary, they collectively contribute to reducing atmospheric carbon dioxide levels and enhancing ecological sustainability in human-dominated landscapes [37, 39, 40]. Types of land-based ecosystems and their carbon sequestration potential is summarized in Table 2.

Table 2. Types of land-based ecosystems and their carbon sequestration potential.

Ecosystem Type	Characteristics	Summary Description	References
Forest Ecosystems	High biomass carbon storage (aboveground + belowground)	Forests are the most important terrestrial carbon sinks due to dense vegetation and long-term storage in trunks, branches, roots, and soils. Tropical forests have high carbon uptake rates due to rapid growth and year-round photosynthesis, while temperate and boreal forests store large soil carbon stocks due to slow decomposition. Forest carbon is highly vulnerable to deforestation, fires, and land-use change.	[4, 11, 12, 16, 25, 29]
Agricultural and Agroforestry Systems	Soil carbon enhancement and integrated biomass storage	Conventional agriculture has lower carbon storage due to soil disturbance and harvesting. However, conservation agriculture improves soil organic carbon through reduced tillage, crop rotation, and organic inputs. Agroforestry significantly increases carbon sequestration by combining trees with crops/livestock, enhancing both biomass and soil carbon while improving biodiversity and resilience.	[17, 18, 30−32]
Grasslands and Wetlands	Strong soil carbon storage and peat accumulation	Grasslands store most carbon in soils through deep-rooted vegetation and slow decomposition. They are sensitive to overgrazing and land conversion. Wetlands and peatlands are among the largest soil carbon reservoirs due to waterlogged conditions that slow decomposition, but drainage and conversion can release large carbon stocks.	[33−36]
Urban Green Spaces and Restored Ecosystems	Moderate carbon storage with high co-benefits	Urban green areas (parks, trees, green roofs) contribute to carbon uptake and provide additional ecosystem services such as cooling and air purification. Restored ecosystems (reforested land, reclaimed mining areas) gradually rebuild carbon stocks in biomass and soil, supporting long-term carbon sequestration in human-dominated landscapes.	[37−40]

5. Environmental Sustainability and Climate Regulation Benefits

5.1. Reduction of Atmospheric Carbon Dioxide.

One of the most significant environmental benefits of carbon sequestration in land-based ecosystems is the reduction of atmospheric carbon dioxide (CO_2), a major greenhouse gas responsible for global warming. Terrestrial ecosystems such as forests, grasslands, wetlands, and agricultural lands act as natural carbon sinks by absorbing CO_2 through photosynthesis and storing it in plant biomass and soils. This process directly reduces the concentration of greenhouse gases in the atmosphere and helps regulate Earth's energy balance [4, 13, 20]. Forests, in particular, play a crucial role in long-term carbon storage due to their high biomass density and longevity. Mature trees continuously capture carbon over decades, while soils store carbon for even longer periods. Similarly, wetlands and peatlands trap large quantities of organic carbon under anaerobic conditions, preventing its release into the atmosphere. When these ecosystems are conserved and properly managed, they function as stable carbon reservoirs that offset anthropogenic emissions [25, 26, 29]. However, when land-based ecosystems are degraded through deforestation, land-use change, or unsustainable agricultural practices, stored carbon is released back into the atmosphere, contributing to increased CO_2 levels. Therefore, enhancing carbon sequestration through reforestation, afforestation, and ecosystem restoration is essential for reducing atmospheric carbon dioxide and achieving global climate targets such as those outlined in the Paris Agreement [4, 6].

5.2. Biodiversity Conservation and Ecosystem Services.

Carbon sequestration processes are closely linked to biodiversity conservation because diverse ecosystems generally exhibit higher productivity, stability, and resilience. Ecosystems with greater species diversity tend to have more efficient carbon uptake and storage due to complementary functional roles among plant and microbial species. For example, mixed-species forests often sequester more carbon than monoculture plantations because different species contribute to varied growth patterns, root structures, and nutrient cycling processes [30, 32, 38]. In addition to carbon storage, land-based ecosystems provide a wide range of ecosystem services that support both environmental sustainability and human well-being. These services include habitat provision for wildlife, pollination, nutrient cycling, climate regulation, and cultural and recreational benefits [17, 19, 39]. Forests and wetlands, for instance, serve as critical habitats for numerous plant and animal species, many of which are dependent on intact ecosystems for survival. The conservation of carbon-rich ecosystems therefore simultaneously supports biodiversity protection and climate mitigation. Degradation of these ecosystems not only reduces their carbon storage capacity but also leads to habitat loss, species extinction, and reduced ecosystem functionality. Sustainable land management practices that promote both carbon sequestration and biodiversity conservation are essential for maintaining ecological balance and ensuring long-term environmental sustainability [21, 28, 29].

5.3. Soil and Water Quality Improvement.

Land-based carbon sequestration is strongly associated with improvements in soil and water quality. Soil organic carbon plays a fundamental role in maintaining soil fertility, structure, and productivity. High levels of soil organic matter improve soil aggregation, increase water-holding capacity, and enhance nutrient availability for plants. These improvements contribute to healthier vegetation growth, which in turn enhances carbon sequestration capacity, creating a positive feedback loop. Sustainable land management practices such as conservation tillage, agroforestry, cover cropping, and organic amendments increase soil organic carbon content while reducing erosion and nutrient depletion. These practices also enhance microbial activity, which is essential for nutrient cycling and soil ecosystem functioning [6, 28, 29]. In addition to soil benefits, carbon-rich ecosystems also contribute to improved water quality. Forests, wetlands, and riparian buffer zones act as natural filters that reduce sedimentation, absorb pollutants, and regulate water flow. Wetlands, in particular, are highly effective at removing excess nutrients such as nitrogen and phosphorus from water systems, thereby preventing eutrophication in downstream aquatic ecosystems. Healthy vegetation cover also reduces surface runoff, minimizes flooding risks, and enhances groundwater recharge. Carbon sequestration contributes to the restoration and maintenance of soil and water resources, which are essential components of environmental sustainability and ecosystem resilience [4, 41].

5.4. Contribution to Climate Change Mitigation and Adaptation.

Carbon sequestration in land-based ecosystems plays a dual role in both climate change mitigation and adaptation. As a mitigation strategy, it reduces the concentration of greenhouse gases in the atmosphere by storing carbon in biomass and soils, thereby slowing the rate of global warming. Nature-based solutions such as reforestation, afforestation, wetland restoration, and agroforestry are increasingly recognized as cost-effective approaches for achieving emission reduction targets. In terms of climate adaptation, healthy and carbon-rich ecosystems enhance the resilience of landscapes and communities to climate-related impacts [42, 43]. Forests and wetlands, for example, regulate local climates by moderating temperature extremes, maintaining humidity levels, and reducing the severity of heatwaves. Vegetation cover also protects against soil erosion, landslides, and flooding, which are becoming more frequent due to climate change. Agroforestry systems improve agricultural resilience by providing shade, reducing wind speed, and enhancing soil moisture retention, thereby helping farmers adapt to changing climatic conditions. Similarly, urban green spaces mitigate urban heat island effects and improve air quality in densely populated areas. By integrating carbon sequestration into land management strategies, societies can simultaneously address mitigation and adaptation goals. This integrated approach supports the transition toward sustainable development pathways that balance environmental protection, economic growth, and social well-being. Ultimately, enhancing carbon sequestration in land-based ecosystems is a critical component of global efforts to achieve long-term climate stability and environmental sustainability [43, 44]. Environmental Sustainability and Climate Regulation Benefits is shown in Figure 1.

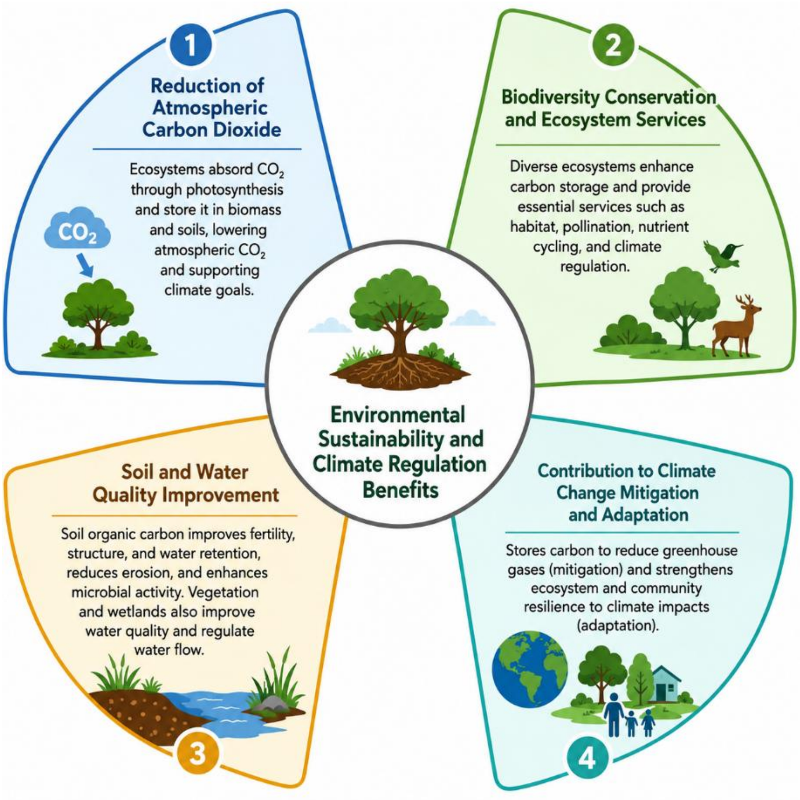

Figure 1. Benefits of environmental sustainability and climate regulation arising from carbon sequestration in land-based ecosystems..

6. Challenges, Management Strategies, and Future Perspectives

6.1. Threats to Carbon Sequestration in Land-Based Ecosystems.

Despite the critical role of land-based ecosystems in carbon sequestration, their capacity is increasingly threatened by a combination of anthropogenic pressures and environmental changes. One of the most significant threats is deforestation, driven by agricultural expansion, urban development, logging, and infrastructure projects. The removal of forest cover not only reduces carbon uptake capacity but also releases large quantities of stored carbon from biomass and soils into the atmosphere. Land degradation, including soil erosion, desertification, and nutrient depletion, further weakens ecosystem productivity and reduces soil organic carbon storage [5, 27, 28]. Unsustainable agricultural practices such as intensive tillage, excessive use of chemical fertilizers, and monocropping contribute to soil carbon loss over time. In grassland ecosystems, overgrazing leads to vegetation decline and soil compaction, reducing both aboveground and belowground carbon storage potential [45, 46]. Climate change itself also poses a major threat. Rising temperatures can accelerate soil organic matter decomposition, releasing carbon dioxide and methane. Increased frequency and intensity of wildfires, droughts, floods, and pest outbreaks further destabilize ecosystems and reduce their ability to function as reliable carbon sinks. Wetlands are particularly vulnerable, as drainage and warming conditions can rapidly convert them from carbon sinks into carbon sources. Together, these pressures highlight the fragility of terrestrial carbon storage systems [1, 6, 13].

6.2. Sustainable Land Management and Restoration Approaches.

To enhance carbon sequestration, sustainable land management practices are essential. Reforestation and afforestation are among the most widely implemented strategies, involving the planting of trees in deforested or previously non-forested areas to increase biomass carbon storage. Similarly, agroforestry systems integrate trees with crops and livestock, improving both productivity and carbon capture while maintaining land usability. Conservation agriculture practices such as reduced tillage, crop rotation, cover cropping, and organic soil amendments help maintain and increase soil organic carbon levels. These practices improve soil structure, enhance microbial activity, and reduce erosion, leading to long-term carbon stabilization in soils [38, 39, 42]. Ecosystem restoration also plays a critical role in recovering degraded landscapes. Restoring wetlands, rehabilitating mined areas, and reintroducing native vegetation can significantly rebuild carbon stocks over time. Assisted natural regeneration, where natural recovery processes are supported rather than replaced, has also proven to be a cost-effective and ecologically sound approach [36, 40]. Effective land management must also consider landscape-level planning to ensure connectivity between ecosystems, enhance biodiversity, and maximize carbon storage potential. Integrating climate-smart agriculture and ecosystem-based adaptation approaches can further strengthen resilience while enhancing sequestration outcomes [47, 48].

6.3. Policy, Monitoring, and Carbon Accounting.

Strong policy frameworks are essential to support carbon sequestration initiatives at local, national, and global levels. International agreements such as the Paris Agreement emphasize the importance of land-based mitigation strategies, including REDD+ (Reducing Emissions from Deforestation and Forest Degradation). These frameworks encourage countries to conserve forests and enhance carbon sinks through sustainable land use. Monitoring and verification systems are crucial for ensuring transparency and effectiveness in carbon sequestration projects. Advances in remote sensing, geographic information systems (GIS), and satellite-based monitoring have improved the ability to track land-use changes and estimate carbon stocks accurately. These technologies enable better assessment of ecosystem performance over time. Carbon accounting systems are also necessary to quantify emissions and removals from land-based ecosystems. Standardized methodologies allow governments and organizations to measure progress toward climate goals and support carbon credit markets. However, challenges remain in ensuring data consistency, reducing uncertainties, and integrating local-level measurements with global reporting systems [4, 49, 50]. A key unresolved challenge is the substantial uncertainty in carbon stock estimates: global forest biomass estimates carry uncertainties of ±10–30% depending on the measurement method used, with satellite-based estimates often diverging from ground-truthed inventory data by 15–25% in tropical regions [25, 28]. Soil carbon accounting faces even greater uncertainty because soil carbon stocks vary dramatically at sub-field scales (coefficients of variation of 30–60%) and because standard measurement protocols differ between countries, making cross-national comparisons unreliable [20, 22]. Carbon permanence is another critical challenge: carbon stored in vegetation can be rapidly released by wildfire, pest outbreaks, or land-use change, undermining the permanence assumption required for carbon credit markets [6, 50]. The additionality problem, demonstrating that carbon gains would not have occurred without deliberate intervention, remains methodologically complex, particularly for avoided deforestation projects under REDD+ [50]. These measurement and verification challenges are compounded by the heterogeneity of ecosystem responses to climate change itself: rising temperatures may simultaneously increase vegetation growth (enhanced CO_2 fertilization) and accelerate decomposition, creating conflicting signals in net ecosystem carbon budgets that are difficult to disentangle with current observational methods [1, 4, 13, 49, 50].

6.4. Future Research Directions and Recommendations.

Future research should focus on improving the accuracy of carbon sequestration measurements across different ecosystems and spatial scales. Long-term studies are needed to evaluate how climate variability, land-use change, and management practices influence carbon dynamics over time. Greater attention should also be given to soil carbon stabilization mechanisms, particularly in tropical and subtropical regions where significant knowledge gaps remain. Integrating ecological, social, and economic perspectives will support the development of holistic land management strategies. Emerging approaches, including biochar application, climate-resilient agroforestry, and nature-based solutions, should be further explored to maximize carbon sequestration while simultaneously enhancing biodiversity conservation and local livelihoods. Strengthening policy integration, stakeholder participation, and interdisciplinary collaboration will also be essential for scaling up land-based carbon sequestration initiatives. The major challenges, management strategies, and future priorities identified in this review are summarized in Table 3. Recent technological advances are expected to further improve carbon monitoring and management. Satellite-based remote sensing platforms, such as ESA's BIOMASS satellite and NASA's GEDI LiDAR system, now provide high-resolution estimates of above-ground biomass, substantially reducing uncertainties associated with conventional forest inventories [28,38]. Likewise, machine learning and artificial intelligence algorithms integrating optical, radar, and LiDAR data enable continuous mapping of ecosystem carbon stocks at regional and national scales [38]. AI-assisted forest disturbance detection can identify deforestation events within days, facilitating rapid policy enforcement [28]. At the soil level, proximal sensing technologies, including near-infrared spectroscopy (NIRS) and X-ray fluorescence (XRF), provide rapid and cost-effective measurements of soil organic carbon, supporting more accurate greenhouse gas inventories [20]. Furthermore, digital twin models that integrate satellite observations, field measurements, and process-based carbon cycle models offer promising opportunities for real-time ecosystem carbon assessment, reducing uncertainties between bottom-up inventories and top-down atmospheric approaches [4,13,50].

Table 3. Challenges, management strategies, and future perspectives for enhancing carbon sequestration in land-based ecosystems.

Area	Key focus	Description	Ref
Threats to terrestrial carbon sequestration	Anthropogenic and climate pressures	Deforestation, land degradation, and unsustainable agriculture reduce carbon storage. Climate change increases decomposition, extreme events, and ecosystem instability. Wetlands may shift from sinks to sources.	[1, 5, 6, 13, 27, 28, 45, 46]
Sustainable land management and restoration	Practices enhancing carbon storage	Reforestation, agroforestry, and conservation agriculture increase biomass and soil carbon. Restoration and natural regeneration rebuild degraded ecosystems and improve resilience.	[36, 38−40, 42, 47, 48]
Policy, monitoring, and carbon accounting	Governance and measurement systems	Paris Agreement and REDD+ support mitigation. Remote sensing and GIS improve monitoring. Carbon accounting ensures standardized reporting, though uncertainty and data gaps remain.	[4, 49, 50]

The wide variation in carbon storage capacity, sequestration rates, ecosystem benefits, and management requirements across major terrestrial ecosystems demonstrates that no single ecosystem can provide a universal solution for climate mitigation. A comparative synthesis of these characteristics is presented in Table 4, highlighting ecosystem-specific strengths, limitations, and recommended management approaches to support informed conservation and restoration planning.

Table 4. Comparative summary of carbon storage potential, strengths, limitations, and management recommendations for major terrestrial ecosystem types.

Ecosystem Type	C Storage (Mg C/ha)	Sequestration Rate (Mg C/ha/yr)	Main Advantages	Main Limitations	References
Tropical forests	100–250	2.0–8.0	Highest biomass C; high biodiversity	Deforestation; fire; land conversion	[4,17,25,26]
Temperate forests	80–150	0.5–3.0	Stable long-term C storage	Fire, pests, drought	[16,25,29]
Boreal forests	80–200	0.3–1.5	Large soil C stocks	Permafrost thaw; wildfire	[25,29]
Agroforestry	10–228	0.5–5.0	Biomass and soil C; food production	Site-dependent performance	[18,31,32]
Grasslands	50–200	0.3–1.0	Large soil C; drought resilience	Overgrazing; land conversion	[9,33,34]
Wetlands/Peatlands	300–600	0.2–1.0	Highest soil C density	Drainage; CH_4 emissions	[22,35,36]
Conservation agriculture	30–100	0.1–0.4	Improves soil health and C	Slow C accumulation; N_2O trade-offs	[10,42,46]
Urban green spaces/Restoration	5–50	0.1–1.0	Urban climate and biodiversity benefits	Limited C storage	[37–40]

Mg C = Megagram of carbon; ha = hectare; yr = year; C = carbon; N_2O = nitrous oxide; CH_4 = methane; NTFP = non-timber forest products. Storage and rate values are indicative ranges synthesized from reviewed literature; actual values vary with climate zone, species composition, soil type, and management history.

7. Conclusions

Land-based ecosystems play a vital role in global carbon sequestration through carbon storage in vegetation and soils, thereby contributing significantly to climate change mitigation. Forests represent the largest biomass carbon sinks, while soils, wetlands, and peatlands constitute the largest terrestrial carbon reservoirs. Sustainable agricultural practices, agroforestry, grasslands, urban green spaces, and ecosystem restoration further enhance carbon sequestration while providing co-benefits such as biodiversity conservation, improved soil and water quality, and enhanced ecosystem resilience. Despite their importance, terrestrial carbon sinks are increasingly threatened by deforestation, land degradation, climate change, and unsustainable land-use practices. Although practices such as conservation agriculture, agroforestry, and peatland restoration show considerable potential, their effectiveness varies across ecosystems, management conditions, and time scales, highlighting the need for long-term monitoring and standardized carbon accounting. Protecting existing high-carbon ecosystems should remain the highest priority, complemented by reforestation, ecosystem restoration, and sustainable land management. Strengthening policy integration, technology-based monitoring, and nature-based solutions will improve the effectiveness and transparency of carbon sequestration initiatives. Overall, maximizing the climate mitigation potential of land-based ecosystems requires coordinated scientific, policy, and management efforts to ensure their long-term contribution to global sustainability goals.

Competing Interest

The authors declare that there are no competing interests regarding the publication of this manuscript. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

All authors contributed equally to the conception, writing, and revision of this manuscript. Each author participated in literature review, content synthesis, drafting, and critical revision of the manuscript. All authors approved the final version for publication.

Data Availability Statement

All data used in this review article are derived from previously published studies, which are properly cited and listed in the references section. No new primary datasets were generated or analyzed during the preparation of this manuscript. Further information can be obtained from the corresponding author upon reasonable request.

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