BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

REVIEW

Carbon Cycling in Natural and Managed Ecosystems: Recent Insights and Future Research Needs

Fei Wang [1*], ***Jian Wang*** [1], ***Jia Wang*** [2], ***Fangfang Li*** [1], ***Hongrui Zhang*** [3]

[1] *Zhengzhou Yongfeng Biological Fertilizer Co., LTD., Zhengzhou 450001, China*

[2] *Hainan Tianhu Application Technology Co., LTD., Haikou 571100, China*

[3] *Zhengzhou Zhituo Biotechnology Co., LTD., Zhengzhou 450001, China*

ABSTRACT

Carbon cycling is an important factor in the climate regulation of the Earth as it regulates the exchange of carbon between the atmosphere, oceans, and soils, as well as living organisms on Earth. This review discusses the processes of carbon cycling in natural and managed ecosystems and identifies the processes of photosynthesis, respiration, decomposition, and soil carbon dynamics as the major processes. It looks at the effects of activities carried out by humans, such as agriculture, forestry, and urbanization, which affect carbon fluxes to improve or interfere with carbon sequestration. Recent technological changes, such as remote sensing, eddy covariance systems, and isotopic tracers, have enormously helped to monitor carbon dynamics over a greater scale and over a greater time extent. Also, new developments in modeling methods have enhanced the forecasts of carbon cycling in different environmental conditions. Nevertheless, many issues, such as the constraint in data, complexity of ecosystem interactions, and the requirement to know more about carbon feedbacks and non-linearities as climate changes persist. These issues should be solved by interdisciplinary research, biological innovations, and more comprehensive monitoring networks. Future studies should be aimed at the effects of extreme events on carbon processes, how well the ecosystem responds to the feedback, and how to apply the scientific results to policy and management tools. This will prove very important in curbing climate change and enhancing sustainable management of ecosystems.

Keywords: Carbon Cycling; Ecosystems; Carbon Sequestration; Climate Change; Carbon Monitoring

*CORRESPONDING AUTHOR:

Fei Wang, Zhengzhou Yongfeng Biological Fertilizer Co., LTD., Zhengzhou 450001, China; Email: 16650279689@163.com

ARTICLE INFO

Received: 1 February 2026 | Revised: 29 April 2026 | Accepted: 6 May 2026 | Published Online: 17 June 2026

DOI: https://doi.org/10.30564/jees.v8i6.13306

CITATION

Wang, F., Wang, J., Wang, J., et al., 2026. Carbon Cycling in Natural and Managed Ecosystems: Recent Insights and Future Research Needs. Journal of Environmental & Earth Sciences. 8(6): 125–141. DOI: https://doi.org/10.30564/jees.v8i6.13306

1. Introduction

Carbon cycling is an important cycle in the biosphere of the earth that entails the exchange of carbon between different reservoirs, which include the atmosphere, oceans, soils, and living organisms [1]. It is critical in the process of regulating the global climate, as carbon dioxide (CO_2) is among the major greenhouse gases that cause global warming [2]. Anthropogenic activities, including fossil fuel combustion, forest clearing, and land use, have played a major role in altering the natural carbon cycle, and consequently, the increase in the levels of CO_2 in the atmosphere has contributed to climate change. The dynamics of carbon cycling are, hence, imperative in the development of strategies to curb climate change, increase the level of carbon sequestration, and sustainably manage the ecosystem [3,4].

Carbon cycling in natural ecosystems takes place in a complex cycle that involves photosynthesis, respiration, decomposition, and turnover of organic matter in soil. Plants, algae, and other photosynthetic organisms sequester CO_2 into the atmosphere through photosynthesis and transform it into organic carbon, which is the foundation of the food chain. Plants, animals, and microbes recycle carbon into the atmosphere through respiration to produce CO_2 and release carbon into the soil through decomposing dead organic matter. Carbon is also locked up in the soil organic matter as well as in biomass, and these carbon pools are also sensitive to the conditions of the environment, such as temperatures, moisture, and nutrient availability [5–7].

Human activities have altered managed ecosystems containing agricultural lands, forests, and urban landscapes to satisfy the needs of society [8]. Such changes may have a serious impact on the natural carbon cycles. As an example, agricultural activities, including tillage, monoculture, and application of artificial fertilizer may alter the carbon equilibrium of soil by increasing the decomposition and decreasing the carbon sequestration. Conversely, agroforestry and conservation tillage, as well as cover cropping, are sustainable land management practices that can enhance carbon storage in soils as well as increase the resilience of the ecosystem. Equally, climate change can be reduced through forest management methods such as afforestation, reforestation, and thinning of forests; this will raise the carbon stocks in the trees and soil [9,10].

With the rising effects of climate change, the use of the ecosystem in the absorption of carbon is getting more attention. The study of carbon cycling in natural and controlled ecosystems has progressively increased in recent decades, with better technologies and techniques for measuring and modeling carbon fluxes. The use of remote sensing instruments, eddy covariance devices, and isotopic tracers has transformed how we now characterize carbon dynamics on large spatial scales and through time [11]. Furthermore, the emergence of computational models has also promoted the knowledge of carbon cycling processes and their reaction to environmental fluctuations [12]. The developments have enabled a better prediction of the carbon fluxes amidst global change, which is essential in informing climate policy and land management policies.

Although progress has been made, there are still great gaps in the knowledge of carbon cycling within the ecosystem. The intricate interplay between carbon pools, the effects of land-use change, and the ecosystem's response to climate variability is yet to be understood [13]. In addition, bridging the gap between scientific knowledge and policy/management practices is still a problem. To have a significant improvement in efforts to reduce climate change, it would be necessary to conduct interdisciplinary studies that cut across ecology, agronomy, climatology, and socio-economic sciences. Also, further intensive data acquisitions, such as long-term monitoring of the variety of ecosystems, are required to produce a more realistic picture of the world's carbon processes.

The purpose of this review is to summarize the recent studies on carbon cycling within natural and controlled systems, with an emphasis on their main findings and future directions. It also outlines areas of critical knowledge gaps and areas of priority in future research. Through reviewing the carbon cycling processes within various ecosystems, the review will provide a better understanding of the storage, transformation, and release of carbon, which can be of great importance in enhancing carbon management measures and in guiding climate change mitigation programs. In the end, the paper will help deliver to the accumulating body of knowledge that is required to enable the promotion of maximizing sustainable land-use practices and global climate objectives [14,15].

Next, we are going to examine the processes of carbon cycling in natural ecosystems, starting by understanding the main aspects of carbon cycling, i.e., photosynthesis, respiration, and the dynamics of carbon in soil[16,17]. Then we shall look at carbon cycling within controlled ecosystems and how agricultural, forestry, and urbanization activities affect carbon sequestration[18,19]. The latest developments in carbon cycling studies, technological discoveries, and modeling solutions will be examined in more detail, and the weaknesses and gaps that we cannot fully comprehend about carbon dynamics will be evaluated[20]. We shall end by finally concluding with future research directions and the possible implications that could be given to policy and ecosystem management.

2. Mechanisms of Carbon Cycling in Natural Ecosystems

Carbon cycling in natural ecosystems is a dynamic process that is very complex and entails a continuous flow of carbon amongst the atmosphere, plants, soil, and microorganisms[17]. It is these interactions that are supported by a sequence of biological, physical, and chemical reactions that regulate the storage, transformation, and release of carbon. The processes have a crucial role in understanding how natural ecosystems help maintain carbon balances in the world, particularly in climate change. Here, we discuss the major processes in carbon cycling in natural ecosystems, such as photosynthesis, respiration, soil carbon, and decomposition.

2.1. Photosynthesis and Carbon Fixation

The cycling of carbon in natural ecosystems is based on a process known as photosynthesis, whereby plants, algae, and other photosynthetic organisms absorb carbon dioxide in the atmosphere and transform it into organic carbon[21,22]. It mainly takes place in the chloroplasts of plant cells, whereby the light energy is utilized to catalyze the transformation of CO_2 and water into glucose and oxygen. Photosynthesis results in the production of glucose, which is the main source of energy in plants that grow and reproduce. The plants store carbon in their biomass as they grow, and this process is effective in storing carbon in the form of complex organic compounds. Forests, grasslands, wetlands, and oceans are carbon sinks, which store high amounts of carbon in the vegetation and biomass. These factors are temperature, precipitation, and the availability of nutrients, as they determine or control the productivity of the plants as well as the effectiveness of the carbon-fixing process. **Figure 1** provides a conceptual diagram of carbon cycling in natural ecosystems, illustrating processes such as photosynthesis, respiration, and decomposition, and how carbon moves between the atmosphere, vegetation, soil, and decomposers.

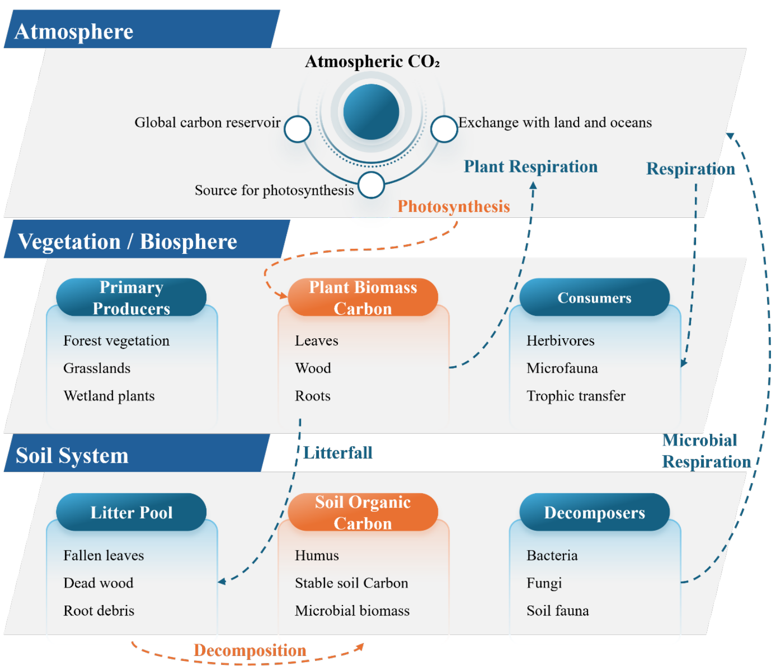

Figure 1. Conceptual diagram of carbon cycling in natural ecosystems, showing key processes such as photosynthesis, respiration, decomposition, and soil carbon dynamics.

2.2. Respiration and Carbon Release

Respiration refers to the process through which organisms such as plants, animals, and other microbes use organic carbon to release energy that is used in cellular processes [23]. Mitochondria are the site of respiration in plants, during which the glucose (generated in the process of photosynthesis) is oxidized to generate energy, water, and carbon dioxide. The carbon dioxide released in the respiration process is recycled to the atmosphere, where it may be utilized by the plants in another cycle. Likewise, the release of carbon through respiration is also done by animals and soil microorganisms, which metabolize the organic carbon of plants and other organic matter. Carbon fluxes are a controversial issue of the photosynthesis and respiration balance in natural ecosystems. Overall, in a state of high productivity of plants, the sequestration of carbon by photosynthesis exceeds the output of carbon by respiration, leading to net carbon storage. This balance, however, can be disturbed when an environmental stressor is involved, such as drought, changes in temperature, or nutrient deficiencies.

2.3. Soil Carbon Dynamics

The soil is an important part of the carbon cycle in natural ecosystems, as it is both a storage place for carbon and a producer of carbon dioxide. Soils contain organic carbon, either as litter of plants, root exudates, or biomass of microorganisms, and this may last for different durations, depending upon the type of soil and environmental conditions [24]. The carbon pools in soil may be broadly divided into two components: labile carbon that is easily degraded by microorganisms, and stable carbon that cannot be easily degraded by microorganisms and can exist in the soil over centuries and even decades. Cycling of carbon in soil depends on the factors: texture of soils, moisture content of the soil, soil temperature, and soil microbial communities [25]. When in an ecosystem where microbial rivalry is high (e.g., tropical forests), a large percentage of carbon is quickly degraded and emitted as CO_2. Contrastingly, colder or wetter soils like the ones present in boreal and wetlands have the ability to store carbon over a more significant duration, and thus are crucial carbon sinks.

2.4. Decomposition and Carbon Recycling

One of the processes in the carbon cycle is decomposition, which guarantees that organic matter is recycled [26,27]. As plants, animals, and other organisms die, their organic matter is decomposed by microbes in soil, fungi, and invertebrates. The complex organic substances, including cellulose and lignin, are decomposed into the simple ones during the process, including carbon dioxide, methane, and dissolved organic carbon. Temperature, moisture, and chemical composition of the organic matter are some of the factors that affect the rate of decomposition. As an example, in tropical ecosystems, high temperatures and moisture ensure prompt decomposition, which restores carbon to the atmosphere in CO_2 form. Conversely, decomposition in cold conditions is slower and, in such conditions, lower activities of microorganisms result in the storage of organic matter in the soil, thereby increasing the storage of carbon. Decomposition is also known to create humus, a stable state of organic carbon that may be able to remain long in soils.

The most important processes of carbon cycling in natural ecosystems, such as photosynthesis, respiration, decomposition, and soil carbon dynamics, form the basis of understanding the capture, storage, and release of carbon in natural ecosystems, as illustrated in **Table 1** [28].

Table 1. Overview of processes in carbon cycling in natural ecosystems, including photosynthesis, respiration, decomposition, and soil carbon dynamics.

Process	Description	Carbon Pools	Main Carbon Fluxes
Photosynthesis	Conversion of CO_2 into organic carbon by plants and algae	Vegetation (biomass), Atmosphere	Carbon uptake from the atmosphere
Respiration	Breakdown of organic carbon by plants, animals, and microorganisms	Vegetation (biomass), Soil, Atmosphere	CO_2 released to the atmosphere
Decomposition	Breakdown of organic matter by microbes and soil organisms	Soil organic matter, Decomposing biomass	CO_2, Methane (CH_4) released into the atmosphere
Soil Carbon Dynamics	Storage and transformation of carbon in soils	Soil (organic and inorganic carbon)	Carbon sequestration and release

2.5. Carbon Pools and Fluxes in Natural Ecosystems

The natural ecosystems are typified by different pools of carbon with their turnover rates and storage capacity. These reservoirs are the atmosphere, vegetation, soils, and oceans, all of which are interconnected and exchange carbon via a series of fluxes. Carbon pools are different in size and distribution depending on the type of ecosystem. Forests and grasslands are the most important terrestrial carbon sinks. Carbon is stored in the above-ground biomass (trees and vegetation) and in the below-ground biomass (roots and organic matter of soil). Wetlands are also significant carbon sinks, especially peatlands, which contain a lot of carbon in the soils, which are wet and thus slow to decompose. Although grasslands are not as dense a storage of carbon as forests and wetlands, they also play an important role in the global carbon cycle through soil carbon storage and root turnover. The carbon flow between these pools is very dynamic and may be affected by land use, climatic conditions, and other perturbations like fire and drought [29,30].

2.6. Impact of Climate Change on Carbon Cycling

Climate change can also cause a tremendous shift in carbon cycling in natural ecosystems. The changes in temperature, changes in precipitation, and frequency of extreme weather events can be used to influence both mechanisms of carbon uptake and release. To illustrate, an increase in temperatures can result in an increase in the rate of plant respiration and microbial activity in soils, thus increasing the amount of CO_2 produced. On the same note, precipitation alteration can affect plant productivity and water supply, which can decrease carbon sequestration in certain ecosystems. Climate change can also change the balance between carbon storage and carbon release in the soils, especially in high-latitude regions, including tundra and boreal forests, where thawing permafrost might cause large stores of carbon in the soils to release into the atmosphere. Moreover, ocean warming and acidification are likely to have an effect on marine carbon cycling by influencing phytoplankton photosynthesis capacity or the oceans' CO_2 absorption capacity. These transformations highlight the importance of having an in-depth account of carbon cycling in natural environments, and more so in the face of environmental change in the world [31,32].

3. Carbon Cycling in Managed Ecosystems

Human activity has altered managed ecosystems to a large extent, especially in agricultural farms, forests, and urban landscapes, to suit the demands of society [8]. Such alterations may significantly influence the process of carbon cycling in terms of carbon sequestration and emission. Whereas natural processes and disturbances determine the composition of natural ecosystems, land-use activities, including farming, forestry, and urban development, change the carbon storage-release balance in the managed ecosystem. In this section, the authors will discuss the processes of carbon cycling in the controlled ecosystem, how various land management systems can influence carbon processes, and what the prospects are for enhancing carbon sequestration and carbon emission reduction.

3.1. Agricultural Practices and Carbon Cycling

One of the most notable human-made changes to the carbon cycle is agriculture. Farming, in terms of tillage, monoculture farming, and synthetic fertilizer use, can significantly affect both the sequestration and release of carbon [33,34]. An example is tillage, which disrupts the soil makeup and causes the decomposition of organic matter to occur too swiftly, releasing the stored carbon as CO_2. The extensive farming practices also limit the capacity of the soil to store carbon by reducing the organic matter content and interfering with the microbial ecosystem of the soil. Also, monoculture cultivation (i.e., planting one species of crops over large plots of land) may cause a lack of nutrients in the soil and a loss of biodiversity, thus limiting the ability of the soil to store carbon. Conversely, agroforestry, crop rotation, and conservation tillage practices have been observed to increase the level of carbon sequestration by promoting soil health, plant, and microbial diversity. Cover crops and less tillage can be used to preserve carbon stocks in the soil because it decreases the erosion and enhance the input of organic matter.

Additionally, farmers use synthetic fertilizers on their farms, which, in addition to increasing crop productivity, also lead to the release of nitrous oxide (N_2O), which is a strong greenhouse gas[35]. Application of fertilizers can also change the microbial communities in the soil, whereby some processes like the denitrification process will be encouraged, resulting in the release of N_2O. These emissions can be curtailed by the management of the use of fertilizers, as well as the use of organic farming methods, which will increase the sequestration of carbon in the agricultural systems. They include integrated solutions (like agroecology and regenerative agriculture) to provide a balance between agricultural output and carbon sequestration and environmental sustainability.

3.2. Forest Management and Carbon Dynamics

Forests are also considered one of the most significant terrestrial ecosystems in terms of carbon sequestration, as they accumulate high levels of carbon in the aboveground biomass (trees and vegetation) and in the belowground biomass (roots and soil organic matter)[36,37]. The afforestation, reforestation, and sustainable harvesting as forest management practices can have major effects on carbon flux in forest ecosystems. Planting of trees in regions where trees have not been planted will help in augmenting the soil carbon storage by creating new carbon sinks through a process known as afforestation. On the same note, reforestation, which is a process of replenishing forests that have been destroyed or damaged, will also be useful in replenishing the lost stocks of carbon and increasing biodiversity.

Sustainable forest management practices are used to ensure that carbon storage is maintained or enhanced, and society demands timber, fuelwood, and other forest products[38,39]. Carbon losses linked with the timber harvesting process and the process of forest degradation can be minimized through practices like selective logging, reduced-impact logging, and preservation of forest structure and biodiversity. Nonetheless, unsustainable logging activities (e.g., clear-cutting) may cause massive release of biomass and soil-bound carbon to the environment, raising the atmospheric CO_2 levels. Climate change is also a major cause of forest fires in certain areas, which in turn pose a considerable threat to carbon reserves as the biomass burns and the carbon is released into the atmosphere at a rapid rate.

Besides the direct effects of forest management activities, land-use changes, including urbanization and agriculture, also affect the forest ecosystems and may contribute to the disappearance and fragmentation of forest landscapes. Deforestation is one of the greatest causes of carbon emissions, as it causes a decrease in the capacity of the land to absorb carbon, and the carbon that is stored in trees and soils is released. In order to overcome these effects, it is necessary to have policies that encourage forest conservation, reforestation, afforestation, and sustainable management of forests to increase carbon sequestration in forest ecosystems[40,41].

3.3. Urbanization and Land Development

Urbanization and land development, such as the development of infrastructure, industrialization, and the establishment of residential areas, can greatly change carbon cycling in local and global systems. The cities have dense populations, transport systems, and energy demands that lead to high carbon emissions. The burning of fossil fuels is the main source of carbon emissions. In addition to this, urbanization also affects the natural carbon cycle through changes in land cover and natural ecosystems. Urban sprawl usually results in the transformation of agricultural land, forests, and wetlands into impervious surfaces, which include roads, buildings, and parking lots, significantly lowering the capacity of the land to capture carbon[42].

Despite these difficulties, there is also an opportunity for carbon management in urban ecosystems. Green areas in cities can contribute to the reduction of the carbon footprint through elevated local carbon sequestration and improved air quality in cities (parks, gardens, and green roofs). Planting of trees in cities is also a significant measure toward enhanced carbon storage in cities. Moreover, the carbon footprint of urban centers can be minimized by the introduction of sustainable urban planning practices, e.g., energy-saving buildings, transportation systems, and encouraging renewable energy sources. Cities can limit their net emissions and become part of the global climate by incorporating carbon management approaches into the development of their cities[43,44].

3.4. Carbon Sequestration Technologies in Managed Ecosystems

Besides the natural process, managed ecosystems can be lucky to have emerging technologies that focus on increasing carbon capture. Bioenergy with carbon capture and storage (BECCS) is one of the most eminent technologies because it involves both the generation of bioenergy (biomass) and the separation of the CO_2 and storage. With the right carbon sequestration ability of the biomass-energy source and the ability to capture carbon effectively, this method can generate carbon-neutral (or even carbon-negative) energy. BECCS can be incorporated into the agricultural and forestry systems, whereby crops, wood, and other organic substances are utilized to make energy [45].

Other carbon sequestration methods, like soil carbon capture, entail the process of enhancing the natural processes that stimulate carbon sequestration in soils [46]. Some practices, like biochar application that incorporates the pyrolysis of organic substances to form a stabilized form of carbon that can be incorporated into soil, have been investigated as possible ways of augmenting carbon stocks in soils. Moreover, the application of afforestation and reforestation initiatives to reclaim degraded lands and create carbon sinks is also picking up as a cost-effective method of reducing climate change. When used with sustainable management of the land, these technologies may serve to maximize carbon sequestration in the managed ecosystems. **Table 2** compares the carbon sequestration potential of different ecosystem types, highlighting the role of forests, wetlands, grasslands, and agricultural lands in carbon storage and fluxes.

Table 2. Carbon sequestration potential in different ecosystem types, comparing the carbon storage and sequestration mechanisms across forests, wetlands, grasslands, and agricultural systems.

Ecosystem Type	Carbon Storage (g C/m^2/year)	Carbon Sequestration Mechanism	Vulnerabilities
Tropical Forests	400–700	Photosynthesis, soil carbon storage	Deforestation, land-use change, climate impacts
Temperate Forests	200–300	Photosynthesis, long-term soil storage	Logging, forest degradation
Grasslands	150–250	Root turnover, soil carbon accumulation	Overgrazing, soil erosion
Wetlands (Peatlands)	500–1,500	Anaerobic decomposition, soil organic carbon	Draining, land conversion to agriculture

3.5. Challenges and Opportunities in Managed Ecosystems

Although there are considerable opportunities for carbon sequestration in managed ecosystems, there are some challenges that should be overcome in order to maximize its benefits. The initial issue is the competition for land use. Carbon sequestration is often in conflict with agricultural growth, urbanization, and infrastructure development. Moreover, management of land should be sustainable in terms of productivity and sustainability, so as not to cause soil carbon depletion or ecosystem destruction through agricultural and forestry activities. Climate change itself creates a problem as well, since the effectiveness of the carbon sequestration strategies can be impacted by the rising temperature, the way precipitation patterns change, and the rising frequency of extreme weather events [47].

Nevertheless, there are also substantial opportunities to mitigate climate change using managed ecosystems. Carbon sequestration can be increased by sustainable land management practices that promote soil health, biodiversity, and ecosystem services, increase food security, and mitigate climate change. The great importance of managed ecosystems in lowering atmospheric CO_2 concentrations and of climate change impact can be achieved by incorporating carbon management strategies in agricultural, forestry, and urban planning [48,49].

4. Recent Advances in Carbon Cycling Research

Minor strides in carbon cycling research over the past few years have greatly boosted the knowledge on the process of cycling of carbon in natural and contrived ecosystems. The increased demand to address the issue of climate change has been followed by a global campaign to refine measurement methods, create new models, and understand the contribution of ecosystems to carbon sequestration and greenhouse gas emissions. The developments are critical in developing more precise forecasts of future carbon processes and also in influencing policies and management plans to curb climate change. Here, we will discuss the most recent developments in the study of carbon cycling, including technological and modeling aspects, and the effects of climate variability on carbon [50].

4.1. Technological Innovations in Carbon Monitoring

The carbon fluxes in the ecosystems have been altered by technological advancements in terms of measuring and monitoring. Conventional techniques used to measure carbon, including soil sampling and direct observation, have been complemented by more advanced instruments that can be used to measure carbon dynamics on a large scale in a high-resolution manner. Satellites and unmanned aerial vehicles (UAVs), which are remote sensing technologies, have taken over in the monitoring of vegetation cover, biomass, and land-use changes. These devices are capable of giving real-time information about carbon stocks on expansive landscapes and hence can estimate the rate of carbon sequestration across various ecosystems and determine the effects of land management practices [51,52].

The application of eddy covariance systems, which determine the exchange of CO_2 and other gases between the atmosphere and the earth's surface, is one of the most important developments in carbon monitoring [53]. These systems are used to continuously and with high frequency record carbon fluxes at different ecosystems such as forests, grasslands, and even agricultural areas. This technology has enhanced our comprehension of the exchange of carbon in the ecosystems, and it has enabled researchers to examine the impact of environmental factors, including temperature and moisture, on carbon cycling. Also, isotopic tracers that track the movement of carbon in ecosystems through stable carbon isotopes have given information on the dynamics of carbon in soil, decomposition, and carbon sources in various ecosystems. A combination of these technological advances has facilitated increased monitoring of carbon fluxes on a large scale and more accurately, which is important in informing climate change mitigation.

4.2. Advances in Carbon Cycling Models

Efforts in modeling have also advanced remarkably in recent years, contributing to the improved predictability of carbon dynamics under altering environmental conditions [54]. Models play a vital role in the comprehension of complicated interactions between pools and flows of carbon in the natural and managed ecosystems. They enable the researcher to model the outcomes of various land management regimes, climate conditions and interference events on carbon cycling over time. Models of the new generation, including machine learning and artificial intelligence ones, have helped enhance the simulation of carbon fluxes more accurately [55]. These models are capable of combining a vast type of data from various sources such as remote sensing, field observations and experimental studies in order to produce predictions on the sequestration of carbon, as well as its emissions, in diverse ecosystems. In addition, these models have the ability to take into consideration non-linear processes like the carbon cycling feedback loop with climate change, which were not easy to model before.

Among the most remarkable contributions to the modeling of carbon cycling is the creation of ecosystem models that incorporate the impact of land-use change, loss of biodiversity, and socio-economic factors on carbon fluxes. The models enable a more holistic evaluation of the role of human activities such as agriculture, deforestation, and urbanization on natural processes in order to alter the carbon cycles around the globe. Process-based models that are simulated models of biological, physical, and chemical processes that drive carbon fluxes have also become more common. These models have helped to gain some important insights into the role of plants, soil organisms, as well as microbes in the carbon cycling process; they are still undergoing further development as more information becomes available [56]. **Figure 2** illustrates the different technological approaches used to monitor carbon fluxes in ecosystems, highlighting their applications and respective advantages and limitations.

4.3. Impact of Climate Variability on Carbon Cycling

Recent studies have placed more emphasis on the role of climate variability in carbon cycling in natural and managed ecosystems. Climate change is likely to induce some changes in the carbon cycle in ecosystems by manipulating some of the most important processes, such as photosynthesis, respiration and decomposition. An increase in temperature, a change in the magnitude of precipitation, and the occurrence of extreme weather conditions are likely to influence the effectiveness of plants in taking in carbon and soils in releasing carbon [57,58].

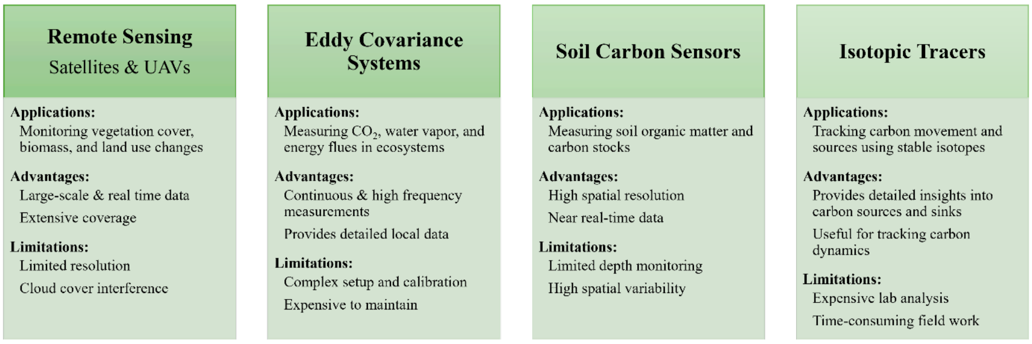

Figure 2. Technological approaches to monitoring carbon fluxes in ecosystems, illustrating the application of remote sensing, eddy covariance systems, and soil carbon sensors in carbon cycle research.

The possibility of positive feedback between climate change and carbon cycling is one of the areas of special concern [59]. As an example, when temperatures get higher, there is a possibility of increased soil microbial activity, which results in faster rates of decomposition and the release of CO_2 that is stored in soils. On the same note, higher temperatures and the change of the precipitation pattern could lead to a decrease in plant productivity, which narrows down the possibilities of carbon sequestration. There are specific ecosystems that are susceptible to these changes, e.g., boreal forests and wetlands, which are commonly vulnerable because their soils are rich in carbon and are prone to warming and drying. The melting of permafrost in the Arctic, such as that, can potentially cause significant amounts of methane and CO_2, which will further increase global warming.

Another area of research has been on the impact of extreme events on perturbing the carbon cycle, including droughts, floods, and forest fires [58]. Extremes in weather conditions may cause a substantial change in terms of carbon storage and fluxes. As an example, the long-term droughts may decrease the productivity of plants and raise their vulnerability to forest fires that can emit many carbon stores in biomass and soils. On the same note, floods may also cause changes in soil carbon by changing the microbial communities and accelerating the rate of organic matter breakdown.

4.4. Biological Innovations in Carbon Capture

Along with technical and modeling progress, insights into the ways through which biological innovations help to increase carbon capture and storage have been made. Genetic modification of plants to enhance their capacity to sequester carbon is one of the fields of research that has considerable potential [60]. Researchers are trying to develop plants with a higher photosynthetic rate, which would enable them to absorb more CO_2 in the atmosphere and store it in their biomass or roots. Also, there are attempts to create crops with a deeper root system, which would lead to higher carbon storage in the soil, as it would add to the quantity of organic matter in the soil.

Microbial novelties are also being investigated to increase the process of carbon cycling [61]. The microorganisms present in soil are very important in the breakdown of carbon and the stabilization of organic carbon in soils. Studies are examining ways to control microbial communities to enhance carbon sequestration by enhancing the stability of soil organic matter. Indicatively, there are known examples of bacteria and fungi found on soil that enhance the growth of stable carbon compounds, which can last in the soil long enough. The knowledge and utilization of these microbial mechanisms may result in more effective ways of capturing carbon in soils and positively change the soil condition of farming systems.

4.5. Carbon Feedbacks and Global Carbon Budgets

Carbon feedback as a concept has received more and more interest in recent years, especially as it applies to climate change. Carbon feedbacks denote how climate changes or the carbon cycle changes are affected by carbon changes or sequestration [59]. As an example, higher temperatures might cause more decomposition, which would produce more CO_2 in the atmosphere and contribute to global warming. Equally, alteration in the distribution of precipitation may also change the productivity of ecosystems, which means that they will not be able to store carbon.

Studies of these feedback processes have indicated how multifaceted the carbon cycle is and how difficult it is to predict future carbon interactions. This feedback is important in understanding the future curve of global carbon budgets and in the process of coming up with effective mitigation measures for climate change. Through consideration of feedback in carbon models, researchers are in a position to produce more valid forecasts of the manner in which ecosystems will react to future climatic conditions and also how human actions will relate to the natural carbon cycles [62].

5. Challenges and Gaps in Understanding

Although this field has come a long way toward research in carbon cycling, there are a number of shortcomings and gaps in our knowledge of carbon flow within natural and managed ecosystems. Such gaps prevent the formulation of more tangible models and efficient approaches to combating climate change by means of better carbon management. These challenges can be attributed to the complexity of the carbon cycle, the inconsistency in the responses of ecosystems to climatic changes, and the inability to combine scientific knowledge with policy. Here, we discuss some of the major barriers to research in the field of carbon cycling, such as limitations in the data, ecosystem complexity, and the synthesis of interdisciplinary knowledge [63–65].

5.1. Complexity of Carbon Cycling in Ecosystems

The carbon cycle is a complex process by its nature, as it encompasses a wide variety of biological, chemical, and physical processes, and the number of interacting factors that affect carbon fluxes within ecosystems is huge [66]. These interactions are imperative to comprehend, but difficult. An example is that carbon processes differ in all ecosystems (forests, wetlands, grasslands, and agricultural lands); each has its own processes, pools of carbon, and fluxes. Furthermore, it is complicated by the interaction between carbon, nitrogen, phosphorus, and other nutrients, which makes the study of ecosystem functioning and carbon cycling a bit harder.

The heterogeneity of ecosystems is one of the major problems [67]. Carbon cycling is not equally distributed on a landscape scale; it is affected by the local conditions, which include the type of soil, composition of plant species, moisture conditions, temperatures, and microbial activities. This inconsistency complicates the application of generalized carbon-cycling models to other ecosystems or forecasting the influence of alterations in one aspect of an ecosystem on carbon transfers in other aspects. As an example, carbon cycling response to droughts could vary between tropical forests and temperate grasslands because of the differences in the physiology of the plants and water retention in the soils. One of the main causes of uncertainty in future carbon dynamics predictions is the challenge of integrating spatial and temporal variability in carbon models.

5.2. Data Limitations and Monitoring Gaps

The lack of data, along with its quality, is an important obstacle to further research on carbon cycling [20]. Although new ways of measuring carbon fluxes, such as remote sensing and eddy covariance systems, have been made available with the use of technology, there remain some gaps in data, especially in remote areas or underrepresented ecosystems. Carbon cycling depends on long-term data collection to comprehend the response of carbon cycling to interannual climate variability, in addition to long-term alterations like climate change, land-use changes, and ecosystem degradation. But the long-term monitoring stations in distant or unstable political areas are usually logistically challenging and costly to install.

In addition, no unified procedures exist for the measurement of carbon in soils and vegetation in various ecosystems, which may create gaps in data collection and reporting [68]. Such a non-standardization complicates the possibility of comparing results across the studies and may lead to impediments to creating a comprehensive global carbon budget. Specifically, carbon dynamics in the soils are frequently poorly comprehended because of the issues related to the accurate measurement of soil organic matter, particularly that in deep or inaccessible layers of soil. This lack of knowledge constrains our capacity to evaluate the real capacity of soils to serve as carbon sinks, especially in the tropical, boreal and wetland ecosystems.

5.3. Understanding Ecosystem Feedbacks and Non-Linearities

Another important gap in the current research is the feedback mechanism between carbon cycling and climate change. Feedbacks are processes where a change in a section of the carbon cycle causes other changes that may enhance or reduce the initial change. Such feedback may either be positive or negative. An example of this is that higher temperatures could cause an increase in the decomposition of soils and more CO_2 in the atmosphere, which in turn causes acceleration of climate change—a positive feedback loop. Conversely, an improved growth of plants as a result of elevated CO_2 levels may raise vegetative carbon uptake in plants, which will serve as a negative response [69].

This feedback is important for the proper prediction of future carbon dynamics. Non-linear interactions between carbon cycling and climate drivers are, however, not always easy to model. The example is that even minor variations in temperature or precipitation can have a disproportionately high impact on carbon fluxes, especially in sensitive ecosystems like wetlands or permafrost areas. On the same note, the interaction of various stressors, such as droughts, fires, and temperature increases, on carbon cycling is not well known, and it is difficult to forecast. Further studies are required to help us better understand these complicated feedbacks and their contribution to the global carbon cycle regulation [59].

5.4. Integration of Interdisciplinary Knowledge

The other challenge that is of great importance in carbon cycling research is the ability to incorporate knowledge from various fields. The processes of carbon cycling are affected by numerous biological, chemical, physical, and social factors, and this implies that the complex processes of carbon in ecosystems can only be comprehensively addressed on interdisciplinary grounds. There should be collaboration among ecologists, climatologists, agronomists, soil scientists, and others to come up with combined models and ideas that would address all by looking at the entire carbon cycling process, starting with the physiology of plants and ending with land-use policies [70].

Nevertheless, the fusion of the knowledge of such different fields does not always take place. Such differences in the disciplines in terms of approaches, terminologies, and methodologies may be barriers to communication and collaboration. Additionally, most studies are also concerned with a particular aspect of the carbon cycle, e.g., carbon fluxes in soil or vegetation, but pay no attention to how these areas respond to each other. To come up with effective strategies to manage carbon, a more holistic approach to the interactions of carbon pools, ecosystem services, and human interactions of humans is necessary [71].

Furthermore, integrating scientific research with policymaking remains a persistent challenge [72]. While scientific advances provide essential information on carbon cycling, translating this knowledge into actionable policies and land management practices requires close collaboration between researchers, governments, and stakeholders. In many cases, there is a disconnect between scientific recommendations and the political or economic realities that shape land-use decisions. Bridging this gap and ensuring that scientific research informs policy will be crucial for addressing climate change and promoting sustainable land management practices. **Table 3** summarizes the primary challenges and knowledge gaps in carbon cycling research, including data limitations, ecosystem complexity, and the need for a better understanding of feedback mechanisms. **Figure 3** illustrates the feedback loops in the carbon cycle, showing how changes in carbon fluxes can create positive or negative feedback, influencing global warming and climate change.

Table 3. Challenges and knowledge gaps in carbon cycling research: Summarizing the main obstacles to improving our understanding of carbon dynamics and carbon management strategies.

Challenge	Description	Research Gap	Implications for Carbon Management
Data Limitations	Insufficient long-term data and inconsistent methodologies for measuring carbon fluxes	Need for more standardized, global data	Hinders global carbon budget estimation
Ecosystem Complexity	Variability of carbon cycling across different ecosystems and environmental conditions	Lack of models that integrate ecosystem heterogeneity	Impedes accurate prediction of carbon dynamics

Table 3. *Cont.*

Challenge	Description	Research Gap	Implications for Carbon Management
Feedback Mechanisms	Understanding the interactions between climate change and carbon cycling processes	Limited understanding of non-linear feedbacks	Affects future climate predictions and mitigation strategies
Integration of Knowledge	Collaboration across disciplines to enhance ecosystem and policy integration	Need for better interdisciplinary cooperation	Limits the effectiveness of carbon management strategies

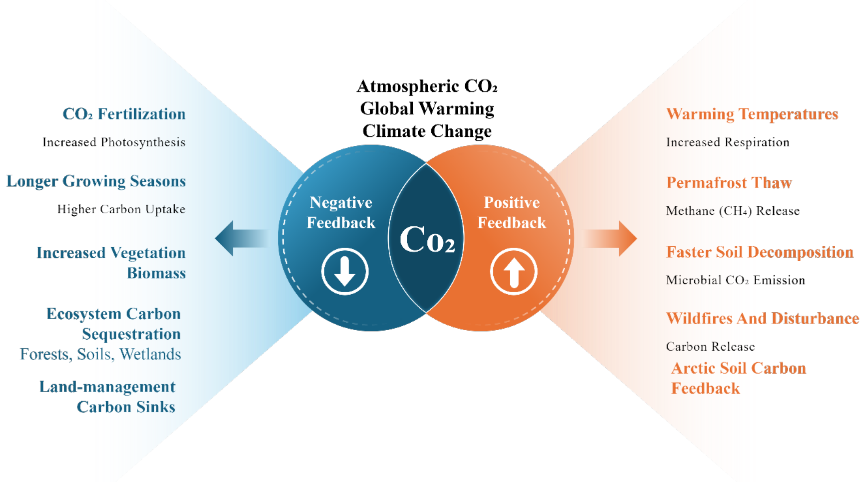

Figure 3. Global carbon feedbacks and climate change, depicting the positive and negative feedbacks in the carbon cycle and their implications for future climate scenarios.

5.5. Socio-Economic Factors and Carbon Management

Socio-economic factors profoundly influence the implementation of effective carbon management strategies in managed ecosystems, often determining whether scientifically sound practices are adopted on the ground. Economic constraints, land tenure systems, and local political dynamics directly affect the feasibility and uptake of carbon sequestration practices. For instance, farmers and landowners may resist adopting conservation tillage or agroforestry when upfront costs are high, benefits accrue over long time horizons (often 5–10+ years), and land tenure is insecure, renters or short-term leaseholders have little incentive to invest in soil carbon improvements they will not personally benefit from[73].

Carbon credit markets represent one prominent mechanism to incentivize carbon sequestration; yet their practical application reveals significant socio-economic barriers. Voluntary carbon markets (e.g., Verra's Verified Carbon Standard, Gold Standard) allow agricultural and forestry projects to generate tradeable credits. However, smallholder farmers in developing regions face prohibitive transaction costs, including baseline establishment, third-party verification (often $5,000–$20,000 per project), and monitoring requirements, that effectively exclude them from participation. A case study from sub-Saharan Africa found that fewer than 5% of smallholder farmers could access carbon markets despite adopting improved agricultural practices, primarily due to high upfront validation costs and a lack of technical assistance.

Payment for Ecosystem Services (PES) programs offer another approach, where governments or private buyers compensate landowners for carbon sequestration. Costa Rica's national PES program (PSA) has successfully incentivized reforestation and forest conservation since 1997, sequestering an estimated 8–10 million tons of CO_2 annually. However, implementation challenges persist: monitoring and enforcement costs remain high, and wealthier landowners disproportionately enroll lands with lower opportunity costs, while poorer households face barriers related to formal land titling requirements. China's Sloping Land Conversion Program, the world's largest PES initiative, similarly achieved significant carbon gains but also generated equity concerns, as compensation rates often failed to match lost agricultural income for the poorest participants [74].

Additional socio-economic barriers include: (1) misaligned subsidy regimes, as many agricultural subsidies in developed economies still support conventional tillage and synthetic fertilizer use rather than carbon-enhancing practices; (2) risk aversion among smallholders, who cannot afford potential yield declines during transitions to carbon-friendly practices; (3) a lack of technical extension services for practices like biochar application or rotational grazing; and (4) land use competition, where carbon sequestration conflicts with food production or urban development pressures, particularly in rapidly urbanizing regions of Southeast Asia and sub-Saharan Africa.

Addressing these barriers requires policy designs that explicitly account for local socio-economic contexts. Promising approaches include bundled carbon credits that aggregate smallholder projects to reduce per-participant transaction costs, results-based PES with upfront financing to alleviate liquidity constraints, and community-led monitoring systems that lower verification expenses. Future research should prioritize quantifying the socio-economic trade-offs of carbon management strategies and evaluating which incentive mechanisms achieve both carbon outcomes and equitable participation across diverse landowner types.

6. Conclusion and Future Research Directions

The carbon cycle is a very significant process that determines the climate and the regulation of ecosystems on Earth. Knowledge of carbon cycling in natural and managed ecosystems is crucial to the formulation of effective carbon-reduction strategies to promote carbon sequestration and sustainable land management processes. In the last several decades, the scientific knowledge about carbon cycling has evolved greatly, both in the technological discovery of the monitoring and modeling of carbon cycling, as well as the understanding of the effect of climate change on the carbon dynamics within the ecosystem. Nevertheless, even with such improvements, there are still considerable limitations and areas of ignorance, with ecosystem feedbacks, data constraints, and interdisciplinary research synthesis being the key ones.

Carbon cycling in natural ecosystems involves intricate interrelationships among plants, soils, microbes, and atmospheric processes. These processes are very environmentally sensitive in terms of temperature, moisture, and nutrient availability. Human activities like agriculture, forestry, and urbanization in managed ecosystems have brought drastic changes to the natural carbon cycle. Although the managed ecosystems provide a way of carbon sequestration, the dilemma lies in the fact that there is a need to balance between land productivity and carbon storage, particularly in light of the ever-increasing human population and climate change.

Recent developments in technologies to support the monitoring, including remote sensing, eddy covariance systems, and isotopic tracers, have enhanced our ability to provide carbon fluxes over scales and time. Moreover, the development of computational models and the incorporation of ecosystem feedbacks have made it possible to predict more accurately the characteristics of ecosystem feedbacks to climate change and human actions. Despite these advances, there are gaps in knowledge, especially in relation to the intricacies of carbon cycling within diverse ecosystems, the variability of carbon fluxes both across space and time, and how extreme events and feedback processes influence the dynamics of carbon.

In the future, such gaps are going to need to be filled through further interdisciplinary research incorporating ecology, climatology, agronomy, soil science, and economics. Innovations in data gathering, such as long-term observations of carbon stocks and carbon fluxes in various ecosystems, will be instrumental in enhancing carbon models and coming up with better initiatives to limit climate change. In addition, further studies are needed to better understand the hybrid interaction between carbon, nitrogen, and other nutrients in ecosystems and the role of microbial communities in carbon sequestration. Incorporation of biology innovations, including genetically engineered plants and soil microorganisms, has the potential to increase carbon storage in soils and plants.

Politically, more needs to be done to ensure a balance between scientific research and climate action. Strategies aimed at carbon management should be based on sound scientific evidence and specific to the conditions of various areas and ecosystems. The socio-economic impact of the policies towards carbon management should also be taken into account by the policymakers so that the solutions would not only be effective in terms of the environment but also socially in terms of equity. The participation of various sectors, such as agriculture, forestry, urban planning, and local communities, in the development and application of carbon sequestration practices at the landscape level will be essential.

Conclusively, although the challenges are very high, the possibilities of the ecosystems to help mitigate climate change due to better carbon sequestration are enormous. Further investigation of the carbon cycling mechanisms, along with new management approaches and policy frameworks, provides a way to combat climate change. With further understanding of the dynamics of carbon and applying scientific knowledge to practical solutions, we will be able to exploit the full potential of both natural and managed ecosystems to lower atmospheric CO_2 and solve global warming. The research on carbon cycling in the future is to fill existing gaps, optimize carbon management practices, and evolve global collaboration that will result in the attainment of long-term sustainability as well as climate resilience.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All the data is presented in the article.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Ussiri, D.A.N., Lal, R., 2017. Introduction to global carbon cycling: An overview of the global carbon cycle. In Carbon Sequestration for Climate Change Mitigation and Adaptation. Springer International Publishing: Cham, Switzerland. pp. 61–76.

[2] Yoro, K.O., Daramola, M.O., 2020. CO_2 emission sources, greenhouse gases, and the global warming effect. In: Rahimpour, M.R., Farsi, M., Makarem, M.A. (Eds.). Advances in Carbon Capture: Methods, Technologies and Applications. Elsevier: Cambridge, UK. pp. 3–28.

[3] Prajapati, S.K., Choudhary, S., Kumar, V., et al., 2023. Carbon sequestration: A key strategy for climate change mitigation towards a sustainable future. Climate Change. 2, 1–14.

[4] Imran, 2025. Carbon cultivation for sustainable agriculture, ecosystem resilience, and climate change mitigation. Communications in Soil Science and Plant Analysis. 56(9), 1430–1456.

[5] Mistry, A.N., Ganta, U., Chakrabarty, J., et al., 2019. A review on biological systems for CO_2 sequestration: Organisms and their pathways. Environmental Progress & Sustainable Energy. 38(1), 127–136.

[6] Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. Biogeochemistry. 48(1), 7–20.

[7] Jackson, R.B., Lajtha, K., Crow, S.E., et al., 2017. The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. Annual Review of Ecology, Evolution, and Systematics. 48, 419–445.

[8] DeFries, R.S., Foley, J.A., Asner, G.P., 2004. Land-use choices: Balancing human needs and ecosystem function. Frontiers in Ecology and the Environment. 2(5), 249–257.

[9] Hussain, S., Hussain, S., Guo, R., et al., 2021. Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. Plants. 10(10), 2001.

[10] Psistaki, K., Tsantopoulos, G., Paschalidou, A.K., 2024. An overview of the role of forests in climate change mitigation. Sustainability. 16(14), 6089.

[11] Baldocchi, D., 2014. Measuring fluxes of trace gases and energy between ecosystems and the atmosphere—The state and future of the eddy covariance method. Global change biology. 20(12), 3600–3609.

[12] Keenan, T.F., Davidson, E., Moffat, A.M., et al., 2012. Using model-data fusion to interpret past trends, and quantify uncertainties in future projections, of terrestrial ecosystem carbon cycling. Global Change Biology. 18(8), 2555–2569.

[13] He, X., Liang, J., Zeng, G., et al., 2019. The effects of interaction between climate change and land-use/cover change on biodiversity-related ecosystem services. Global Challenges. 3(9), 1800095.

[14] Basile-Doelsch, I., Balesdent, J., Pellerin, S., 2020. Reviews and syntheses: The mechanisms underlying carbon storage in soil. Biogeosciences. 17(21), 5223–5242.

[15] Liu, E., Lu, X., Wang, D., 2023. A systematic review of carbon capture, utilization and storage: Status, progress and challenges. Energies. 16(6), 2865.

[16] Johnston, C.A., Groffman, P., Breshears, D.D., et al., 2004. Carbon cycling in soil. Frontiers in Ecology and the Environment. 2(10), 522–528.

[17] Stuart Chapin III, F.S., McFarland, J., McGuire, A.D., et al., 2009. The changing global carbon cycle: Linking plant–soil carbon dynamics to global consequences. Journal of Ecology. 97(5), 840–850.

[18] Lorenz, K., Lal, R., 2018. Carbon Sequestration in Agricultural Ecosystems. Springer: Cham, Switzerland.

[19] Hutyra, L.R., Duren, R., Gurney, K.R., et al., 2014. Urbanization and the carbon cycle: Current capabilities and research outlook from the natural sciences perspective. Earth's Future. 2(10), 473–495.

[20] Ciais, P., Dolman, A.J., Bombelli, A., et al., 2014. Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system. Biogeosciences. 11(13), 3547–3602.

[21] Ivlev, A.A., 2017. Global photosynthesis and its regulatory role in natural carbon cycle. Journal of Ecosystem & Ecography. 7(2), 233.

[22] Ivlev, A.A., 2015. Global redox cycle of biospheric carbon: Interaction of photosynthesis and earth crust processes. BioSystems. 137, 1–11.

[23] Carlson, C.A., Del Giorgio, P.A., Herndl, G.J., 2007. Microbes and the dissipation of energy and respiration: From cells to ecosystems. Oceanography. 20(2), 89–100.

[24] Janzen, H., 2004. Carbon cycling in earth systems—A soil science perspective. Agriculture, ecosystems & environment. 104(3), 399–417.

[25] Schimel, J.P., Schaeffer, S.M., 2012. Microbial control over carbon cycling in soil. Frontiers in microbiology. 3, 348.

[26] Horwath, W., 2007. Carbon cycling and formation of soil organic matter. In: Paul, E. (Ed.). Soil Microbiology, Ecology and Biochemistry. Elsevier: Oxford, UK. pp. 339–382.

[27] Galvez, M.E., Fischer, W.W., Jaccard, S.L., et al., 2020. Materials and pathways of the organic carbon cycle through time. Nature Geoscience. 13(8), 535–546.

[28] Ontl, T.A., Schulte, L.A., 2012. Soil carbon storage. Nature Education Knowledge. 3(10), 35.

[29] Dixon, R.K., Solomon, A.M., Brown, S., et al., 1994. Carbon pools and flux of global forest ecosystems. Science. 263(5144), 185–190.

[30] Pouyat, R., Groffman, P., Yesilonis, I.,et al., 2002. Soil carbon pools and fluxes in urban ecosystems. Environmental pollution. 116, S107–S118.

[31] Luo, Y., Weng, E., 2011. Dynamic disequilibrium of the terrestrial carbon cycle under global change. Trends in ecology & evolution. 26(2), 96–104.

[32] Kondratyev, K.Y., Krapivin, V.F., Varotsos, C., 2003. Global Carbon Cycle and Climate Change. Springer: Berlin/Heidelberg, Germany.

[33] Lal, R., 2004. Agricultural activities and the global carbon cycle. Nutrient cycling in agroecosystems. 70(2), 103–116.

[34] Lorenz, K., Lal, R., 2018. Agricultural land use and the global carbon cycle. In Carbon Sequestration in Agricultural Ecosystems. Springer: Cham, Switzerland. pp. 1–37.

[35] Menegat, S., Ledo, A., Tirado, R., 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Scientific Reports. 12(1), 14490.

[36] Lal, R., Smith, P., Jungkunst, H.F., et al., 2018. The carbon sequestration potential of terrestrial ecosystems. Journal of soil and water conservation. 73(6), 145A–152A.

[37] Singh, S.K., Thawale, P.R., Sharma, J.K., et al., 2015. Carbon sequestration in terrestrial ecosystems. In: Lichtfouse, E., Schwarzbauer, J., Robert, D. (Eds.). Hydrogen Production and Remediation of Carbon and Pollutants. Springer: Cham, Switzerland. pp. 99–131.

[38] Sheppard, J.P., Chamberlain, J., Agúndez, D., et al., 2020. Sustainable forest management beyond the timber-oriented status quo: Transitioning to co-production of timber and non-wood forest products—A global perspective. Current Forestry Reports. 6(1), 26–40.

[39] Ameray, A., Bergeron, Y., Valeria, O., et al., 2021. Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. Current Forestry Reports. 7(4), 245–266.

[40] Bogaert, J., Barima, Y.S.S., Mongo, L.I.W., et al., 2011. Forest fragmentation: Causes, ecological impacts and implications for landscape management. In: Li, C., Lafortezza, R., Chen, J. (Eds.). Landscape Ecology in Forest Management and Conservation. Springer: Berlin/Heidelberg, Germany. pp. 273–296.

[41] Tilahun, D., Gashu, K., Shiferaw, G.T., 2022. Effects of agricultural land and urban expansion on peri-urban forest degradation and implications on sustainable environmental management in southern Ethiopia. Sustainability. 14(24), 16527.

[42] Churkina, G., 2016. The role of urbanization in the global carbon cycle. Frontiers in Ecology and Evolution. 3, 144.

[43] Shadman, S., Ahanaf Khalid, P., Hanafiah, M. M., et al., 2022. The carbon sequestration potential of urban public parks of densely populated cities to improve environmental sustainability. Sustainable energy tech-

nologies and assessments. 52, 102064.

[44] Strohbach, M.W., Arnold, E., Haase, D., 2012. The carbon footprint of urban green space—A life cycle approach. Landscape and Urban Planning. 104(2), 220–229.

[45] Hayat, M.A., Alhadhrami, K., Elshurafa, A.M., 2024. Which bioenergy with carbon capture and storage (BECCS) pathways can provide net-negative emissions? International Journal of Greenhouse Gas Control. 135, 104164.

[46] Lal, R., Negassa, W., Lorenz, K., 2015. Carbon sequestration in soil. Current Opinion in Environmental Sustainability. 15, 79–86.

[47] Ussiri, D.A., Lal, R., 2017. Carbon Sequestration for Climate Change Mitigation and Adaptation. Springer: Cham, Switzerland.

[48] Marland, G., Pielke, R.A., Apps, M., et al., 2003. The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. Climate policy. 3(2), 149–157.

[49] Pandey, D.N., 2002. Global climate change and carbon management in multifunctional forests. Current science. 83(5), 593–602.

[50] Smith, P., Soussana, J.F., Angers, D., et al., 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology. 26(1), 219–241.

[51] Goetz, S., Dubayah, R., 2011. Advances in remote sensing technology and implications for measuring and monitoring forest carbon stocks and change. Carbon Management. 2(3), 231–244.

[52] Harle, S., Bhagat, A., Dash, A.K., 2024. Remote sensing revolution: Mapping land productivity and vegetation trends with unmanned aerial vehicles (UAVs). Current Applied Materials. 3(1), e070224226752.

[53] Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. Global change biology. 9(4), 479–492.

[54] Friend, A.D., Arneth, A., Kiang, N.Y., et al., 2007. FLUXNET and modelling the global carbon cycle. Global Change Biology. 13(3), 610–633.

[55] Grunwald, S., 2022. Artificial intelligence and soil carbon modeling demystified: Power, potentials, and perils. Carbon Footprints. 1(1), 5.

[56] Upadhyay, T., Solberg, B., Sankhayan, P.L., 2006. Use of models to analyse land-use changes, forest/soil degradation and carbon sequestration with special reference to Himalayan region: A review and analysis. Forest Policy and Economics. 9(4), 349–371.

[57] Schlesinger, W.H., 2005. The Global Carbon Cycle and Climate Change. In: Sinnott-Armstrong, W., Howarth, R.B. (Eds.). Perspectives on Climate Change: Science, Economics, Politics, Ethics. Emerald Group Publishing Limited: Leeds, UK.

[58] Frank, D., Reichstein, M., Bahn, M., et al., 2015. Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. Global change biology. 21(8), 2861–2880.

[59] Friedlingstein, P., 2015. Carbon cycle feedbacks and future climate change. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 373(2054), 20140421.

[60] Jansson, C., Wullschleger, S.D., Kalluri, U.C., et al., 2010. Phytosequestration: Carbon biosequestration by plants and the prospects of genetic engineering. Bioscience. 60(9), 685–696.

[61] Bardgett, R.D., Freeman, C., Ostle, N.J., 2008. Microbial contributions to climate change through carbon cycle feedbacks. The ISME Journal. 2(8), 805–814.

[62] Canadell, J.G., Ciais, P., Dhakal. S., et al., 2010. Interactions of the carbon cycle, human activity, and the climate system: A research portfolio. Current Opinion in Environmental Sustainability. 2(4), 301–311.

[63] Keenan, T.F., Davidson, E.A., Munger, J.W., et al., 2013. Rate my data: Quantifying the value of ecological data for the development of models of the terrestrial carbon cycle. Ecological Applications. 23(1), 273–286.

[64] Neutel, A.M., Thorne, M.A., 2014. Interaction strengths in balanced carbon cycles and the absence of a relation between ecosystem complexity and stability. Ecology letters. 17(6), 651–661.

[65] You, H.S., Marshall, J.A., Delgado, C., 2021. Toward interdisciplinary learning: Development and validation of an assessment for interdisciplinary understand of global carbon cycling. Research in Science Education. 51(5), 1197–1221.

[66] Ciais, P., Sabine, C., Bala, G., et al., 2014. Carbon and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK; New York, NY, USA. pp. 465–570.

[67] Premke, K., Attermeyer, K., Augustin, J., et al., 2016. The importance of landscape diversity for carbon fluxes at the landscape level: Small-scale heterogeneity matters. Wiley Interdisciplinary Reviews: Water. 3(4), 601–617.

[68] Hu, Y., Zhang, Q., Hu, S., et al., 2022. Research progress and prospects of ecosystem carbon sequestration under climate change (1992–2022). Ecological Indicators. 145, 109656.

[69] Matthews, H.D., Weaver, A.J., Meissner, K.J., 2005. Terrestrial carbon cycle dynamics under recent and future climate change. Journal of Climate. 18(10), 1609–1628.

[70] Gaziulusoy, A.I., Ryan, C., McGrail, S., et al., 2016.

Identifying and addressing challenges faced by transdisciplinary research teams in climate change research. Journal of cleaner production. 123, 55–64.
[71] Angst, G., Mueller, K.E., Castellano, M.J., et al., 2023. Unlocking complex soil systems as carbon sinks: Multi-pool management as the key. Nature communications. 14(1), 2967.
[72] Dilling, L., 2007. Towards science in support of decision making: Characterizing the supply of carbon cycle science. Environmental Science & Policy. 10(1), 48–61.
[73] Sykes, A.J., Macleod, M., Eory, V., et al., 2020. Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. Global Change Biology. 26(3), 1085–1108.
[74] Kikuchi, R., 2011. Environmental and socio-economic factors in carbon offsets: An approach to sustainable management and planning in climate change strategy. Journal of Environmental Planning and Management. 54(3), 355–367.