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Forest Soil Organic Carbon Review

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Abstract

As an important component of the global carbon cycle, forest soil organic carbon has a crucial impact on the stability of ecosystems and climate change. As one of the largest carbon pools in terrestrial ecosystems, the organic carbon stock in forest soils is of great significance for climate change and the health of forest ecosystems. This paper provides a comprehensive review of forest soil organic carbon, discussing its research progress, role, influencing factors, and future trends, with the aim of providing scientific evidence for forest soil carbon management to mitigate global climate change and promote the sustainable development of forest ecosystems.

Keywords

Forest, Soil Organic Carbon, Global Carbon Cycle, Soil Carbon Stock

1. Introduction

Soils play a key role in regulating the carbon and nitrogen cycles of forest ecosystems, increasing carbon and nitrogen stocks and maintaining ecological balance [1]. Forest soil is the largest store of active carbon on land and plays a key role in global carbon balance, climate change and the stability of terrestrial ecosystems [2]. Soil organic carbon (SOC) in forest soils is the sum of humus produced by microorganisms, plant and animal residues, microbial remains [3]. As a "source" (carbon source) and "sink" (carbon sink) of greenhouse gases, forest soil organic carbon is a key component of the global carbon cycle [4]. The purpose of this paper is to summarize and elaborate the sources and composition of forest soil organic carbon, as well as the research methodology of the accumulation and transformation mechanism of forest soil organic carbon, and to emphasize the importance of research on forest soil organic carbon for understanding the carbon cycle mechanism, evaluating ecosystem functions, and guiding forest management and carbon reduction strategies.

2. Sources and Spatial Distribution Characteristics of Forest Soil Organic Carbon

2.1. Sources of Organic Carbon in Forest Soils

The organic matter in forest soils is relatively complex, in which plant litter, plant roots and their secretions, soil microorganisms and animal residues are the main sources of soil organic carbon [5].

2.1.1. Plant Litter

Plant litter is one of the most important sources of soil organic carbon [6]. Plants adsorb CO_2 from the air during photosynthesis and then convert it into organic matter. With the withering of plant leaves, branches and other organs, and are degraded by microorganisms on the ground, the degraded material is gradually converted into soil organic carbon. On this basis, the effect of different types of microbial communities on different types of microbial communities was studied [1]. Therefore, vegetation plays a key role in maintaining the ecological environment and improving the soil environment.

2.1.2. Plant Roots and Their Secretions

The main components of the soil carbon pool include root secretions, exfoliated cells, and related enzymes secreted by the root system [6]. Through the study of root secretions of different types of root systems, it is found that root secretions can effectively draw nutrients from the soil and improve it [7], which improves the water-holding and aeration capacity of the soil. In addition, after the death of plant roots, their residual root debris and root secretions will be gradually converted into organic carbon. On this basis, the microorganisms in the soil will be degraded [2], making it a stable source of organic carbon.

2.1.3. Soil Microorganisms

In the soil, while maintaining their own life activities, soil microorganisms continuously produce and release various organic substances, including a variety of enzymes, metabolites and cell fragments, etc [2]. In the process, as the life history of the microorganisms ends, the degradation products remaining in the soil are transformed into the soil carbon pool. This change not only increases the storage of soil organic carbon, but also has great significance for soil structure, fertility and the stability and sustainable development of the ecosystem [8].

2.2. Spatial Distribution Characteristics of Forest Soil Organic Carbon

Influenced by natural factors such as climate and soil, forest soil carbon pools also show different degrees of lateral drive and verticality. From a worldwide perspective, the region's plant carbon storage is largest in tropical forests at low latitudes, followed by the northern part of high latitudes, and the lowest at mid-latitudes [9], these conclusions are mainly related to temperature. However, the soil organic carbon in forested land at different scales in China showed significant spatial and temporal differentiation characteristics, which manifested as high in the east and low in the north [10]. Geographically, the research by Wang Chunyan *et al.* shows that SOC increased exponentially with increasing altitude in temperate regions, and the SOC in temperate regions is significantly higher than that in tropical rainforests [11], its cause may be related to temperature and humidity. The study of Huang Congde *et al.* found that the SOC of forest land gradually decreased with increasing latitude [11] [12]. Existing research has shown that soil organic carbon in high altitude regions has obvious spatial distribution characteristics, which is related to the relatively high temperature, suitable atmospheric environment, and vigorous microbial activities [13]. At the same time, different altitudes will also have a certain effect on the carbon pool of the forest floor. And the study by Wang Zhen *et al.* shows that soil organic carbon in the central Tianshan Mountains decreased with increasing altitude and its causes may be related to temperature and humidity [14]. Studies have shown that the key factor affecting the distribution pattern of soil carbon pools is the soil hydrothermal condition, because the soil hydrothermal condition can affect the distribution of vegetation, soil physicochemical properties, and microbial community structure [15] [16].

3. Accumulation and Transformation Mechanisms of Forest Soil Organic Carbon

3.1. Accumulation of Organic Carbon in Forest Soil

Vegetation input: through the photosynthesis of plants, vegetation draws CO_2 from the air and then converts it into organic matter. There is a large pool of organic carbon in our farmland ecosystem, most of which is secreted from plant residues such as leaves and branches and root secretions. In forest ecosystems, plant species and production are important factors in determining their ecological functions [17].

Physical protection: Forest soils can effectively prevent the loss of organic carbon through physical protection of agglomerates [18]. Small pores between soils can reduce direct contact between bacteria and enzymes, which in turn reduces their degradation rate [19]. Meanwhile, fine particles such as clay and powder have a strong adsorption capacity for organic matter, which can effectively inhibit its loss [20].

Chemical stabilization: heavy metal oxides (*e.g.*, iron, aluminum, etc.) combine with the soil to form a stable composite and improve the chemical stability [21]. Such composite can remain in the soil for a long period of time without being degraded.

Biological processes: microorganisms are the main factors affecting the accumulation and transport of soil organic carbon [22]. Their main function is to decompose various organic matter (*e.g.* plant and animal stubble, root secretions) and provide nutrients to plants. And the metabolic activity of microorganisms plays an important role in its accumulation and stability [23].

3.2. Transformation Mechanisms of Forest Soil Organic Carbon

3.2.1. Decomposition

Microorganisms in the soil will secrete various enzymes, which can effectively decompose organic substances, such as plant residues and animal excreta. During this decomposition process, microorganisms convert organic matter into nutrients such as carbon dioxide, water, and various minerals, which are subsequently absorbed and utilized by plants, thereby supporting plant growth and development [24]. The intensity and rate of decomposition is influenced by a variety of factors, including soil temperature, moisture, pH, and microbial community structure. The level of soil temperature directly affects the metabolic activities of microorganisms. When the temperature is appropriate, the activity of microorganisms is enhanced and decomposition is accelerated, while too low or too high, the activities of microorganisms will be inhibited and the decomposition will slow down, resulting in a reduced decomposition rate. Humidity is also an important factor affecting decomposition. Suitable soil humidity can provide a good living environment for microorganisms and promote their metabolic activities, while too wet or too dry soil conditions will limit microbial activities and affect decomposition efficiency. In addition, the pH value of the soil also affects the activity of microorganisms and enzyme [23]. Different microorganisms have different adaptive ranges of pH value, and the appropriate pH value can promote the growth of microorganisms and enzyme activity, thus accelerating the decomposition rate. Finally, the diversity of microbial community structure also affects decomposition, different kinds of microorganisms have different decomposition ability, and a diversified microbial community structure can decompose various organic substances more effectively and improve decomposition efficiency [24].

3.2.2. Respiration

Soil respiration is one of the main ways in which soil releases carbon dioxide [25]. This process encompasses both autotrophic and heterotrophic respiration. Autotrophic respiration mainly refers to the respiration generated by root respiration and the decomposition of organic substances by microorganisms, while heterotrophic respiration involves the respiratory activities of soil animals and microorganisms themselves. The intensity and rate of soil respiration largely determine the dynamics of forest soil carbon pools [10]. Specifically, the intensity and rate of soil respiration are affected by multiple factors, such as soil temperature, humidity, organic matter content, and the activity of microorganisms and soil animals. These factors jointly determine the overall level of soil respiration, which in turn affects the accumulation and release of forest soil carbon pools. Therefore, understanding and monitoring soil respiration is important for assessing the carbon cycle in forest ecosystems.

3.2.3. Leaching and Erosion

Rainwater leaching and soil erosion may result in the loss of organic carbon from the soil [26]. Especially in those areas with higher slopes or more concentrated rainfall, this loss will become more significant and serious. Therefore, it is extremely important to take some effective measures to reduce the occurrence of soil erosion and to protect the organic carbon pool in the soil. This is because soil organic carbon is one of the important carbon sinks, which not only helps to maintain soil fertility and structure but also mitigates climate change [23]. By implementing measures such as vegetation restoration, soil and water conservation projects and rational farming, soil erosion can be effectively reduced, thereby protecting the soil organic carbon pool and ensuring sustainable agricultural development.

4. Factors Affecting Forest Soil Organic Carbon

4.1. Climate Factors

Temperature and rainfall have significant regulatory effects on forest soil organic carbon accumulation and conversion [24]. Rising temperatures will accelerate microbial metabolic activity in the soil as well as the degradation rate of organic matter [27]; While changes in rainfall will have an impact on plant growth and litter input [28].

In the context of global change, climate change has an important impact on the budget of soil organic carbon, and in areas with favorable hydrothermal environments, there is a large amount of plants, deadfall, and higher carbon pools. Meteorological factors are key factors influencing forest soil carbon pools. Vegetation in areas under suitable hydrothermal environments grows better and is more productive. Deadfall, as an important source of organic carbon, plays an important role in regulating the soil carbon pool. In certain temperate and humid regions, their forests are covered with dense deadfall and have relatively high organic carbon. In addition, climate has an effect on microbial activity in the soil. A suitable temperature and humidity environment has a positive effect on the activity of microorganisms in the soil, which promotes the degradation and transformation of organic matter. On this basis, through the action of microorganisms in the soil, organic matter is transformed to organic carbon in the soil, which in turn increases its contribution to soil organic carbon. However, global warming can likewise adversely affect the forest carbon pool [28]. For example, with the increase in temperature, changes in rainfall patterns will have an effect on plant growth, which in turn decreases the amount of deadfall and thus reduces the contribution to soil organic carbon. In the context of global warming, significant changes in the structure and function of soil microbial populations are occurring [25], with important implications for their degradation processes.

4.2. Physicochemical Properties of Soil

Physicochemical properties such as soil texture, structure, pH, and nutrient content have significant effects on the accumulation and transformation of organic carbon [29]. For example, soils with higher clay particle content usually have higher organic carbon content [30]. Clay minerals are one of the most active soil minerals, and the clay mineral organic carbon complex formed with organic carbon is an important form for the stable existence of soil organic carbon and a key component of the "soil mineral carbon pump", while soil acidification may affect microbial community structure and organic carbon stability [28]. There is a significant positive correlation between the amount of clay minerals in a soil and its total carbon pool [31]. Research shows that different soil types have significant differences in the soil carbon pools of different types of forestlands. The higher the clay mineral content, the larger its surface area, the stronger the absorption of organic matter, and the greater the effect on soil carbon pool [29]. Research results indicate that different soil structures have a significant contribution to the distribution of soil organic carbon. Due to the differences in soil texture, there are large differences in pore structure and aeration properties, which in turn have a certain impact on the degradation and conversion of organic matter. For example, soils with fine and dense layers have strong water-holding and aeration capacities, which are conducive to the activity of microorganisms in the soil, can promote the degradation of organic matter, and facilitate the transformation of soil organic carbon. Meanwhile, the pH value and nutrient content of the soil play an important role in the stability and distribution of the soil carbon pool [29]. For example, under acidic conditions, the degradation of organic matter is slow, while the organic carbon in the soil is relatively high. At the same time, nutrients such as N, P and K also play an important role in crop growth and soil microbial activity, which in turn play an important role in the accumulation and degradation of soil organic carbon.

4.3. Anthropogenic Activities

Anthropogenic factors (*e.g.*, excessive deforestation, overgrazing, land management, etc.) play an important role in regulating soil carbon pools [32], causing changes in the plant species and physicochemical properties of the ground cover, and have a significant impact on the rate of soil organic carbon degradation. Anthropogenic activities have a significant impact on the forest soil carbon pool, and excessive deforestation, as a major anthropogenic disturbance factor, has played a key role in the reduction of soil carbon pools. With the degradation of forests, the decrease in vegetation coverage and the reduction in the input of litter, combined with the effects of environmental factors such as sunlight and wind, the decomposition and loss of soil organic matter have been significantly aggravated. In addition, forest destruction has led to changes in soil structure, which in turn affects the water retention and air permeability of the soil, and negatively affecting soil carbon accumulation and decomposition [30]. Overgrazing also adversely affects forest carbon pools, leading to vegetation destruction and soil compaction, which reduces soil organic matter content. At the same time, livestock farming activities also cause changes in soil physical and chemical properties, and have a significant impact on the activity of soil microorganisms [6].

Anthropogenic factors can cause changes in the forest floor, which can have a significant impact on the SOC and carbon pool composition of the forest floor [33]. Previous work showed that selective harvesting can increase the organic carbon content of forest ecosystems under natural conditions [34]. Some studies have reached diametrically opposite conclusions [22]. The previous work of Li Haitao *et al.* showed that logging of willow plantation forests would lead to a decrease in the carbon pool of forest ecosystems [35]. Lei *et al.* showed that due to different stands and different felling patterns, there is great uncertainty in the changes of soil organic carbon among different tree species [36]. After investigating early Cunninghamia lanceolata forestlands under different thinning densities, Ye Jianfeng *et al.* found that high-density thinning can increase the carbon pool of forestlands [37]. Chang Yapeng *et al.* found that the total SOC decreased by 171.7 t/hm^2 when spruce forests were converted to cropland in the snowy ridge area on the northern slope of Tianshan Mountain [38]. Forest fires play an important role in the carbon pool of forest ecosystems, but the contribution to SOC varies due to differences in burning intensity and burning time. The previous work of Qian Guoping *et al.* showed that t after the forest ecosystems in North Asia were disturbed by fire, the organic carbon content of the vegetation increased significantly during the recovery process [39].The previous work of Guo Jianfen *et al.* showed that the contribution of forest fires to SOC varied to different degrees under different forest fire levels, and SOC decreased significantly under complete fire disturbance [40]. In addition, due to the influence of anthropogenic factors, the large release of pollutants such as SO_2 and NO_2 may increase the probability of acid rain formation, thus affecting the soil pH value and further influencing the composition of soil organic carbon [41]. Studies have shown that anthropogenic factors alter the forest type, above-ground and below-ground biomass distribution, and microbial community structure, which in turn have a significant impact on forest soil organic carbon [38].

It was also found that different farmland management modes have a certain regulatory effect on farmland soil carbon pools. Through scientific farmland management methods (*e.g.*, afforestation, crop rotation, organic fertilizer application, etc.), the input of farmland organic carbon can be increased, and the ground strength, water holding, and organic matter accumulation can be enhanced [38]. While inappropriate farmland management methods (*e.g.*, excessive fertilizer application, excessive pesticide application, etc.) can lead to changes in farmland soil structure, which in turn affects the stability of farmland ecosystems [6]. Different land use methods contribute differently to soil organic carbon as well. For example, the process of converting from forest land to cropland or urban construction will cause changes in the types and characteristics of plants covering the ground surface, thus accelerating the degradation of soil organic carbon and reducing the amount of carbon pools [11]. Returning farmland to forest can promote the accumulation of soil carbon pools and improve the ecological function of soil.

4.4. Vegetation Types and Diversity

Different vegetation types show significant differences in their contribution to soil organic carbon [33]. Specifically, mixed forests are more effective in contributing to the accumulation and stabilization of soil organic carbon compared to nonspecific forests. Mixed forests form a more complex ecosystem structure through the interaction of multiple tree species, thus providing more favorable conditions for soil organic carbon accumulation. In addition, an increase in vegetation diversity can significantly improve the productivity level of forest ecosystems [37] and enhance their resistance stability [34]. This diversified vegetation structure can better adapt to environmental changes, reduce the occurrence of pests and diseases [19], and create a more favorable environment for the accumulation of soil organic carbon. Therefore, by increasing vegetation diversity, the accumulation of soil organic carbon can be effectively promoted and the overall health and stability of forest ecosystems can be improved.

5. Forest Soil Organic Carbon Estimation Methods

5.1. Soil Type Method

The soil type method refers to conducting precise measurements on soil within a certain range and correlating them with corresponding classification units to obtain corresponding quantitative results. This research can integrate national or regional soil survey data, realize the quantification of the uncertainty of SOC remote sensing inversion in specific regions, and then achieve the quantitative assessment of the uncertainty of SOC remote sensing inversion in the study area [5]. However, the technique has problems such as a cumbersome process and not easy to realize, which causes great difficulties to the practice of researchers.

5.2. Vegetation Type, Life Zone Method and Ecosystem Type Method

The vegetation type method, life zone method, and ecosystem type method are based on soil organic carbon concentration of vegetation type, life zone type, and its distribution in different areas. Its advantage is that it is relatively easy to understand the total SOC storage under different vegetation, different life zones and different ecosystems. This project proposes to determine the carbon pools of different types of SOC by measuring the SOC concentrations in different vegetation types, different life zones and different types of SOC and comparing them with their distribution areas in different geographic regions. One prominent example is that some scholars, based on the Holdridge life zone model [42], conducted the first spatial distribution analysis of soil carbon concentrations worldwide. The implementation of this method will help to gain insight into the relative contribution of alpine meadow grassland SOC in the Tibetan Plateau on a global scale, and provide a scientific basis for scientific questions on regional climate and carbon cycle [43].

5.3. Correlation Statistics

Correlation statistics is an important tool in current study of soil carbon pools

[36], and its core technology is to study the correlations among various environmental factors, climate factors, and soil properties in the soil sample. Based on this, researchers can construct some mathematical and statistical models to accurately estimate and predict the soil organic carbon stock with limited information. The key is to use statistical methods to reveal the interrelationships between various elements from multiple angles, thus laying the foundation for in-depth knowledge and understanding of the changing law of soil carbon pool. On this basis, the project proposes to use a combination of field survey and indoor simulation to monitor soil organic carbon content, environmental temperature, rainfall, soil texture and pH. On this basis, this project intends to adopt a combination of field investigations and indoor simulations to explore the interaction of the factors and their effect on enterprise performance. In this way, a mathematical model can be established that can be used to portray the quantitative changes of soil carbon pools with different environmental factors and different properties. Through the implementation of this project, an accurate estimation of soil organic carbon stock in a certain region can be realized, laying the foundation for research on soil carbon management, climate change research and sustainable development [44].

5.4. Model Simulation

In the research on forest soil organic carbon models, model simulation mainly involves the process-oriented multi-component box model, the food network model centered on biological processes, and the decomposition sequence model based on time series [45]. Each of these models has unique characteristics and scope of application, among which the core model has gradually received widespread attention [42]. The process-oriented multi-component box-based model subdivided the soil organic carbon pool into multiple small units, aiming to describe the dynamic conversion process of soil carbon among the units more accurately. Based on the ecosystem theory, the model simulation constructs a model with the ecosystem as the core of the study and proposes an innovative method for analyzing high-resolution remote sensing images, *i.e.*, high-precision inversion technique based on remote sensing data. The core model has gained increasingly wide application worldwide because of its excellent adaptability and accuracy [44].

6. Future Trends in Forest Soil Organic Carbon

6.1. Climate Warming and Deep Soil Organic Carbon Decomposition

Against the background of global warming, the changes in the forest surface—soil carbon pool have drawn people's attention [46]. In a previous study by Tian Peng *et al.*, it was found that the way atmospheric exogenous C addition and N addition change the deep SOC degradation process under the background of warming is still of great uncertainty [47]. At moderate temperatures, the application of carbon sources can effectively prevent the degradation of SOC at different levels, which is manifested as a negative inducing force, and this negative inducing force will be affected by warming as the soil layer deepens [48]. At an appropriate temperature, the addition of nitrogen can cause the negative induction effect to change from negative to positive and weaken the negative induction effect during warming. The excitation effect of N application was stronger in topsoil than in the surface layer and decreased with increasing temperature, and microbial activities and acid phosphatase in soil played a significant role in regulating the change of excitation effect [49].

Nie Ming *et al.* through laboratory simulation experiments on 90 representative soil samples with a depth of 1 m in China, confirmed that the loss of carbon pools in the lower soil layer is greater under global warming, and therefore, its spatial partitioning properties must be introduced into the carbon cycle model to improve the response to greenhouse gas emissions [50].

6.2. Latitudinal Pattern of Forest Soil Organic Carbon Sources in Eastern China

Tan Xiangping *et al.* found that the concentrations of lignin phenolics and microbial residue organic carbon in forest soils in eastern China showed an increasing trend year by year as the elevation increased [51]. With the rise of organic carbon, the contribution of microbial residues to SOC gradually increased, while the contribution of lignin to SOC was not significant [52]. On this basis, used multivariate statistical methods to study the effects of microbial community structure and microbial community structure on the accumulation of lignin phenolics under different climatic conditions, whereas the average annual temperature, microbial diversity and biomass ratio are the main controlling factors determining the accumulation of microbial residual carbon. This suggests that the accumulation effect of carbon from microbial sources is more significant in eastern China compared with that from plant sources.

6.3. Global Patterns of Forest Soil Organic Carbon

China's leadership in exploring the global pattern of forest soil organic carbon has shown a worldwide pattern of forest soil carbon pool distribution. Soil, climate and forest type are the main factors influencing the production and stabilization of soil organic carbon, and the impact of climate change on global forest carbon stocks is of great significance [53]. Soil factors contribute more to mineral soil SOC relative to net primary productivity. Mineral soil organic carbon, particulate organic carbon and decay-resistant organic carbon content decreased with increasing temperature. Temperature plays an important role in the concentration of mineral and organic carbon in the soil, which in turn are closely related to microbial activities in the soil [29]. In addition, due to the addition of clay particles and iron oxides, physical protection of organic carbon in the soil can be provided. Soil organic carbon in our temperate and Mediterranean soils is higher than the carbon pool in northern and subtropical soils. The organic carbon content of mixed forest soils is higher than that of broadleaf evergreen and coniferous forests, which is mainly due to the fact that mixed forests have higher productivity and the effect of deadfall from different species on soil organic carbon [54] [55].

7. Conclusion

In conclusion, the study of forest soil organic carbon is of great significance for the stability of ecosystems and the response to climate change. In the future, we should further study the accumulation mechanism, role, influencing factors and future development trend of forest soil organic carbon, so as to provide a scientific basis for ecosystem management and the response to global climate change. At the same time, we should strengthen the protection and management of forest soil organic carbon, take reasonable forest management measures to reduce the negative impact of human activities on forest soil organic carbon, and improve the stability and carbon sink potential of forest soil organic carbon.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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