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Research Progress on Carbon Sequestration Potential of Farmland Soil

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Abstract

The farmland ecosystem is a crucial component of the terrestrial ecosystem and plays a significant role in the global carbon cycle. Understanding the main factors influencing the sequestration of soil organic carbon in farmland and the stabilization mechanisms of soil organic carbon is not only conducive to enhancing the carbon sequestration potential of farmland soil but also helpful for accurately evaluating the impact of agricultural production on global climate change. Therefore, this paper reviews the factors affecting soil organic carbon sequestration and outlines the physical, chemical, and biological stabilization mechanisms of soil organic carbon. Based on previous studies, the shortcomings of existing research are summarized, and the future research directions of soil carbon sequestration are prospected. It is believed that soil microorganisms play an important role in the soil carbon cycle, but the current research in this area is still not systematic enough. Thus, it is of great significance to conduct in - depth research on the mechanism of microorganisms in the soil organic carbon cycle from the perspective of soil microbiology.

Keywords

Farmland soil; Carbon sequestration; Influencing factors; Stabilization mechanism.

1. Introduction

The soil carbon pool is the largest carbon pool in the surface terrestrial ecosystem and a vital part of the global carbon cycle. Statistics show that the total carbon content in the global soil surface layer (calculated at a depth of 1 m) is 2100 Pg, and the storage of the soil organic carbon (SOC) pool is approximately 1550 Pg, which is three times that of the atmospheric carbon pool and 2 - 4 times that of the terrestrial vegetation carbon pool (Lal et al., 1999). The farmland ecosystem, as an important part of the terrestrial ecosystem, stores 8% - 10% of the carbon in the terrestrial soil carbon storage. Therefore, the soil organic carbon pool in farmland plays a particularly important role in the global carbon cycle and climate change. It is not only a key component of the global carbon pool but also the most active part. Under the combined action of natural factors and human agricultural activities, the quantity and quality of the farmland carbon pool change frequently. Such frequent changes not only alter the soil fertility level but also affect the atmospheric CO_2 concentration, having a direct impact on climate change (Lal et

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al., 1999). Research shows that long - term and large - scale reclamation on a global scale has not only disrupted the carbon cycle balance between the soil carbon pool and the atmospheric carbon pool but also caused a large amount of soil organic carbon to be oxidized and released into the atmosphere in the form of CO_2 and other gases, increasing greenhouse gas emissions. At the same time, inappropriate agricultural management measures and land - use patterns can easily transform farmland soil from a carbon sink to a carbon source. With the increasing global attention to greenhouse gas reduction and food security, the dynamic changes of soil organic carbon in farmland have increasingly become a hot topic in global organic carbon research. Increasing the carbon sequestration potential of farmland soil has become one of the important means to evaluate soil fertility and mitigate CO_2 emissions (Six et al., 2010).

Therefore, in the context of global climate change, deeply understanding the main influencing factors of farmland soil carbon sequestration and its stabilization mechanisms is of great theoretical significance for formulating reasonable agricultural management measures to enhance the carbon sequestration potential of farmland soil and accurately evaluating the impact of agricultural production on global climate change. This paper systematically discusses the main factors affecting carbon fixation in farmland soil and the stabilization mechanisms of soil organic carbon, with a focus on elaborating the role of biological stabilization mechanisms in the process of carbon interception in farmland soil.

2. Factors Affecting Organic Carbon Sequestration

2.1. Influence of Climate on Organic Carbon Sequestration

Climate factors play a crucial role in the dynamic change process of soil organic carbon. On the one hand, climate conditions restrict the vegetation type and affect its productivity, thereby influencing the amount of carbon input into the soil. On the other hand, in terms of the output of soil organic carbon, soil microorganisms are the main driving force for its decomposition and transformation. Microorganisms rely on decomposing soil organic carbon to maintain their life activities, and changes in precipitation, temperature, and other conditions will affect the decomposition and transformation of soil organic carbon, thus having a significant impact on the sequestration and mineralization decomposition of soil organic carbon (Davidson et al., 2019).

Temperature and precipitation are the main climate factors affecting the sequestration and decomposition of soil organic carbon (Triberti et al., 2018). Existing data show that the content of the terrestrial carbon pool increases with the increase in precipitation. When the rainfall is the same, there is a negative correlation between temperature and carbon content. Rainfall and temperature jointly determine the zonality of soil carbon density (Li Tiantian et al., 2009). The research results of Zhang et al. (2010) on dryland in northern China indicate that the fixation rate of soil organic carbon decreases with the increase in effective accumulated temperature and annual average precipitation. The change in soil moisture content affects the soil aeration, thus influencing the utilization and sequestration of soil organic carbon by microorganisms. Bolinder et al. (2013) found that the carbon sequestration efficiency of soil in arid and semi - arid regions is significantly higher than that in humid regions. Some research results also show that in areas where the temperature is ≤ 10°C, there is a highly significant negative correlation between soil organic carbon storage and temperature. In areas with a temperature range of 10°C - 20°C, there is no obvious correlation between soil organic carbon storage and temperature and precipitation. Davidson et al. (2019) showed that whenever the temperature rises by 10°C, the cumulative degradation rate will double, indicating that low temperature is conducive to the accumulation of organic carbon. Epstein et al. (2016) believed that the impact of temperature on the degradation of soil organic carbon is greater than that of precipitation through the study of the degradation pattern of soil organic carbon in the Great Plains of the

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western United States. Cui Siyuan et al. (2019) used the CENTURY model to simulate the changes of organic carbon in the cultivated black soil in Northeast China under natural conditions over 48 years and found that when the temperature rises by 2°C, regardless of whether the precipitation remains unchanged, decreases, or increases by 20%, the soil organic carbon content will decrease by 4.17%.

2.2. Influence of Soil Properties on Organic Carbon Sequestration

Numerous studies have shown that there is a relationship between soil clay content and soil organic carbon content. Tai Jicheng et al. (2012) took Guichi District, Anhui Province as the research area to study the distribution and changes of soil organic carbon in farmland in this area. The results showed that there was no obvious linear relationship between soil clay content and soil organic carbon content in dryland, but there was a positive correlation with that in paddy fields. This is because the soil clay content has a significant impact on the soil organic carbon content in paddy soil. However, this positive correlation does not mean that the soil organic carbon content will continue to increase with the increase in soil clay content. Qin Zhangcai et al. (2010) found that when the soil clay content is less than or equal to 30%, as the clay content increases, the soil organic carbon content also increases, but the increase rate gradually decreases. When the soil clay content is greater than 30%, the increase rate gradually approaches zero. Li Dawei et al. (2013) took the alkalized meadow soil in the Songnen Plain as the research object to study the particle - size distribution characteristics of soil organic carbon. They found that after long - term application of organic fertilizer in the research area, the organic carbon content of alkalized meadow soil of all particle sizes showed an upward trend over time, and the average organic carbon content was the highest in the soil particles with a particle size of 2 - 5 mm.

Soil pH is also an important factor affecting soil organic carbon storage, and its value determines the soil's acid - base environment. Acidic soil will inhibit the activities of microorganisms that play a key role in the mineralization of soil organic carbon, while alkaline soil will promote the decomposition of organic matter by microorganisms in the soil, accelerating the mineralization process of soil organic carbon. Li Jinquan et al. (2016) believed that when the soil pH is less than 7, there is no significant relationship between soil pH and soil organic carbon content. When the soil pH is greater than 7, the two are significantly negatively correlated, verifying this view. However, Tai Jicheng et al. (2012) found that the influence of pH varies in different soil types. The organic carbon density of paddy soil is positively correlated with pH, while that of dryland soil is weakly negatively correlated with soil pH.

3. Stabilization Mechanisms of Soil Carbon

The stability of soil organic carbon in the soil depends on the interaction between the soil itself and environmental factors. Understanding the protection mechanisms of organic carbon in the soil helps to develop reasonable measures to enhance the carbon sequestration potential of the soil. At present, the action mechanisms of soil carbon stability are not yet fully understood, and there is no complete consensus in the academic community. The commonly recognized stabilization mechanisms mainly include chemical, physical, and biological stabilization mechanisms.

3.1. Chemical Stabilization Mechanism

The chemical stabilization mechanism is a stabilization mechanism formed by the interaction of chemical/physical bonds between soil minerals (i.e., silt and clay) and organic substances, including ligand exchange, polyvalent cation bridges, hydrogen bonds, and van der Waals forces. Hassink (1996) believed that the carbon sequestration ability of the soil depends on the binding ability between organic carbon and silt and clay. The carbon combined in the form of organic -

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inorganic complexes in the soil is the carbon protected by the chemical mechanism, and its quantity increases with the increase in the content of silt and clay in the soil. Some studies have found that the organic matter in silt and clay is older than that in other larger - sized particles and has a longer turnover time (Anderson et al., 2009), which provides direct experimental evidence for this stabilization mechanism. The research results of some researchers using microbial characteristic products (such as amino sugars) also support this view. For example, Puget et al. (2008) showed that in both no - tillage and conventional tillage soils, compared with the sand - sized fraction, the carbohydrates of microbial origin are significantly enriched in the silt and clay - sized fractions, but the accumulation amounts of different microbial metabolites in the silt and clay - sized fractions vary. Guggenberger et al. (2006) found that under no - tillage conditions, the content of glucosamine of fungal origin in the silt and clay fractions is higher than that of muramic acid of bacterial origin. Stotzky (2012) believed that small molecules adsorbed on mineral surfaces can only be utilized by microorganisms after desorption. However, due to the desorption being caused by the secretion of microorganisms, it is difficult to directly prove the difficult - to - utilize characteristics of these adsorbed molecular compounds through experiments. Generally, the adsorption of macromolecular substances by mineral particles is irreversible. During the adsorption process, the conformation of macromolecules changes, making them difficult to be degraded by relevant enzymes (Khanna et al., 2018). Mineral clay can also reduce the possibility of substrate degradation by adsorbing relevant enzymes. Regarding the chemical protection mechanism, it is still necessary to further clarify the action mechanisms affecting the adsorption of organic matter and degradation rates (Six et al., 2010).

3.2. Physical Stabilization Mechanism

The soil matrix is composed of aggregates of different sizes and organic - inorganic mixtures. Aggregates of different particle sizes have different protective effects on soil organic carbon. The physical stabilization mechanism of the soil mainly protects carbon from being decomposed by microorganisms and enzymes through the compartmentalization of soil aggregates, improving the stability of soil carbon. In addition, it also includes the hydrophobic protection of organic matter, coating effects, and the protection of organic carbon entering the interlayer of layered silicates. The protective effect of aggregates on organic carbon has always been regarded as an important mechanism for soil carbon sequestration. Its physical protection mainly occurs through three ways: First, the compartmentalization blocks the contact between the substrate and microorganisms; second, it reduces the diffusion ability of oxygen into macro - aggregates and micro - aggregates; third, it limits the contact between substrate carbon and soil microorganisms and soil enzymes (Elliott et al., 2016). The research of Hattori et al. (2015) showed that the microbial richness is the highest outside the aggregates, while a large amount of organic carbon is rich inside the aggregates, supporting the compartmentalization between the substrate and microorganisms formed by the aggregates. Jastrow et al. (2016) used the 13C tracer method to confirm that the formation time of organic carbon in micro - aggregates is earlier than that in macro - aggregates, and macro - aggregates contain more organic carbon than micro - aggregates. Six et al. (2010) found that compared with no - tillage soil, fine - particle organic carbon in tilled soil mainly exists in the micro - aggregates contained in macro - aggregates, and there is no obvious difference in coarse - particle organic carbon between the two tillage methods, indicating that micro - aggregates are of great significance for the physical protection and long - term fixation of organic carbon. The impacts of soil management measures such as land - use patterns, tillage systems, and fertilization are first reflected at the macro - aggregate level, while the organic carbon in micro - aggregates remains relatively stable. Although macro - aggregates cannot directly protect soil organic carbon in the long - term, they can fix more organic carbon and promote the formation of micro - aggregates through interactions with organic matter and the soil environment, creating conditions for the long -

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term protection of organic carbon by micro - aggregates (Six et al., 2010). The transformation dynamics of organic matter in the components of aggregates are closely related to the turnover cycle of the aggregates themselves. Analyzing the structure and turnover rate of organic matter in aggregates at different levels is helpful for a deeper understanding of the important role of aggregates in the stabilization of soil organic carbon (Besnard et al., 2017).

The physical protection mechanism of organic carbon also includes hydrophobicity. The hydrophobicity of organic carbon limits the decomposition ability of microorganisms by reducing the wettability of the substrate surface. The chemical composition of soil organic carbon, especially the presence of certain non - polar lipid substances, is the main cause of soil hydrophobicity (Dejonge et al., 2009). Hydrophobicity not only directly affects the contact between organic carbon and microorganisms but also enhances the stability of soil organic carbon by improving the stability of aggregates (JAND et al., 2007). In addition, some researchers believe that active organic carbon can be coated in the network structure of refractory polymers or (quasi) humic macromolecules to avoid degradation, that is, the coating effect of organic macromolecules on organic carbon (Knicker et al., 2014). Spaccini et al. (2012) indirectly proved the existence of this mechanism through experiments. The experiments showed that active dimethylethanolamine is not easily degraded after entering the humic acid, and as the hydrophobic properties of humic acid increase, its protection strength also increases. However, the mechanism of active organic carbon being coated by organic macromolecules to avoid degradation still lacks sufficient experimental evidence and needs further research (JAND et al., 2004).

4. Research Prospects

Farmland soil, as an important soil carbon pool in the terrestrial ecosystem, its reservoir size and stability have a significant impact on global climate change and soil sustainable productivity. The carbon sequestration process and stability characteristics of farmland soil are jointly affected by environmental factors such as climate and soil texture and farmland management measures. Accurately understanding and recognizing the main influencing factors in the process of soil organic carbon fixation is the key scientific issue for accurately evaluating the change direction and rate of soil organic carbon. Existing research mostly focuses on the impact of single - factor on the quantitative change of organic carbon, lacking comprehensive research on the saturation, spatiotemporal variability, and other aspects of farmland soil organic carbon storage, making it difficult to comprehensively explore the characteristics of carbon storage and its changes. At the same time, previous soil carbon sequestration research has focused more on the relationship between the total change of soil carbon pools and agricultural management measures, but there is a lack of understanding of the components and structures of organic carbon, its chemical characteristics of anti - decomposition, turnover time, and the synergistic action mechanism between the accumulation and transformation of soil organic carbon and soil fertility. It is necessary to strengthen research in these aspects in the future, which is also the key to studying the turnover and stability characteristics of soil organic matter.

Deeply understanding the soil carbon stability mechanism is helpful for exploring and enhancing the carbon sequestration potential of the farmland soil carbon pool and improving soil and environmental quality. Currently, the understanding of soil carbon stability mechanisms is still incomplete, especially the biological stability mechanism. In the research of soil biological carbon sequestration mechanisms, it is urgent to clarify the role mechanism of microorganisms in the carbon input and fixation process of the soil - crop system. Previous research has made great progress in understanding the above - ground part, but the research on the underground ecosystem involving soil microorganisms is relatively weak, and the

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contribution of soil microorganisms to soil organic matter has also been somewhat neglected. Therefore, it is of great theoretical significance to explore the soil carbon stability mechanism by connecting the above - ground and underground ecosystems from the perspective of soil microbiology. Due to the complexity of soil microorganism activities and community structures, the variability of their quantities, and the differences in the biochemical characteristics and turnover characteristics of microbial components in the soil environment, it is difficult to study the role mechanism of soil microorganisms in the process of soil organic carbon interception and stabilization. However, microorganisms produce relatively stable metabolites during the metabolic process, such as cell secretions and cell wall residues, which gradually accumulate in the soil and form part of the soil stable organic carbon pool. Therefore, it is possible to select microbial - derived substances with certain stability and specificity, namely biological markers (such as phospholipid fatty acids and amino sugars), and combine them with isotope tracer technology to study the role mechanism of soil microorganisms in the synthesis and transformation of organic carbon and their contribution to the soil organic carbon pool. This provides new research ideas for further exploring the soil carbon sequestration stability mechanism and will also be the key research direction in the future.

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