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Research Progress on the Impact of Biological Soil Crusts on Soil Nutrients and Carbon Cycling

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ABSTRACT

Biological Soil Crusts (BSCs) are complex surface structures of the ecosystem formed by cryptogams such as cyanobacteria, lichens, and bryophytes, together with soil microorganisms. They are widely distributed in arid and semi - arid regions. In recent years, the ecological functions of BSCs in soil nutrient cycling and carbon sequestration have gradually become a research hotspot. This paper reviews the regulatory mechanisms of BSCs on soil nutrients such as nitrogen, phosphorus, and organic matter, analyzes their contributions and potential impacts on the global carbon cycle, and discusses the threats of climate change and human disturbances to the functions of BSCs. Future research needs to further quantify the regional carbon sequestration capacity of BSCs and develop BSC - based ecological restoration technologies.

KEYWORDS

Biological Soil Crusts; Soil Nutrients; Carbon Cycling; Carbon Sequestration; Ecological Restoration.

1. INTRODUCTION

Biological soil crusts are complex complexes composed of cyanobacteria, green algae, lichens, bryophytes, fungi, and bacteria. They bind soil particles by secreting extracellular polysaccharides (EPS) to form a surface cover layer. Their distribution ranges from 12% to 40% of the global land area, especially playing an important role in arid ecosystem (Belnap & Lange, 2003). As "ecosystem engineers", BSCs significantly affect soil physical and chemical properties and ecological processes through functions such as nitrogen fixation, carbon sequestration, and regulation of water and nutrient cycling. In recent years, with the intensification of global climate change, the role of BSCs in carbon sequestration potential and soil degradation prevention has received much attention. This paper systematically reviews the impact mechanisms of BSCs on soil nutrients and carbon cycling, aiming to provide a theoretical basis for ecological restoration and global carbon balance research[1].

2. REGULATORY EFFECTS OF BIOLOGICAL SOIL CRUSTS ON SOIL NUTRIENTS

2.1. Nitrogen Fixation and Transformation

Cyanobacteria (such as Nostoc) and some lichens can convert atmospheric nitrogen (N_2) into ammonium nitrogen (NH_4^+) through the heterocyst nitrogenase system. Research shows that the annual nitrogen fixation amount of BSCs can reach 10 - 100 kg $N \cdot ha^{-1}$, significantly increasing the total nitrogen content in the soil. In addition, microorganisms in the crust layer (such as ammonia - oxidizing bacteria) convert ammonium nitrogen into nitrate nitrogen (NO_3^-) through nitrification, promoting nitrogen availability. However, under drought conditions, the risk of nitrogen leaching is relatively high, and it is more easily absorbed by vascular plants.

2.2. Phosphorus Activation and Organic Matter Accumulation

Organic acids secreted by cyanobacteria can dissolve soil mineral phosphorus (such as Ca - P, Fe - P) and release soluble phosphorus (PO_4^{3-}). At the same time, BSCs promote microbial activities and accelerate the mineralization of organic phosphorus by inputting organic carbon through photosynthesis. Research shows that the organic matter content in the crust layer can reach 2 - 5 times that of the underlying soil, and the humus component is mainly fulvic acid, with relatively high stability[2].

2.3. Micro - scale Nutrient Heterogeneity

BSCs form a "nutrient island" effect by changing surface roughness and water permeability. For example, the interception of precipitation by the bryophyte crust layer can reduce nutrient loss, while the cyanobacteria crust layer transports deep - layer nutrients to the surface through capillary action, intensifying the spatial differentiation of nutrients[3-4].

3. THE DUAL ROLE OF BIOLOGICAL SOIL CRUSTS IN THE CARBON CYCLE

3.1. Photosynthetic Carbon Fixation and Carbon Input

Cyanobacteria and bryophytes fix CO_2 through the C3 pathway, and the annual net primary productivity (NPP) can reach 50 - 200 g $C \cdot m^{-2}$. Among them, extracellular polysaccharides (EPS) account for 30% - 60% of the total organic carbon, which not only enhances the stability of soil aggregates but also serves as a carbon source for microorganisms. However, under drought stress, photosynthetic activity is inhibited, and the carbon input efficiency is significantly reduced.

3.2. Organic Carbon Decomposition and Carbon Release

BSCs affect the decomposition rate of organic carbon by regulating soil temperature, humidity, and microbial community structure. For example, the cyanobacteria crust reduces soil respiration, while the bryophyte crust may accelerate lignin degradation due to promoting fungal growth. Warming experiments show that climate warming may break the balance between carbon fixation and release, causing the crust layer to change from a carbon sink to a carbon source[5].

3.3. Assessment of Carbon Sequestration Potential at the Global Scale

Model estimates show that the annual carbon sequestration amount of global BSCs is approximately 3.9 Pg C, equivalent to 7% - 10% of the carbon sink of the terrestrial ecosystem. However, this data has large uncertainties and needs to be verified by combining remote sensing technology and ground observations.

4. KEY FACTORS AFFECTING THE FUNCTIONS OF BIOLOGICAL SOIL CRUSTS

4.1. Stress of Climate Change

Changes in precipitation patterns and extreme drought events lead to the fragmentation of the crust layer, and the activity of nitrogenase decreases by 50% - 80%. Warming accelerates the degradation of EPS, weakening the soil's anti - erosion ability.

4.2. Long - term Effects of Human Disturbance

Overgrazing and land reclamation damage the crust structure, resulting in a loss of 40% - 70% of soil organic carbon. It takes 10 - 50 years to restore the natural crust, and artificial inoculation of cyanobacteria can shorten the recovery period to 3 - 5 years.

5. RESEARCH PROSPECTS

Multi - scale carbon flux monitoring: Combine eddy covariance technology and isotope labeling to quantify the carbon exchange process of BSCs.Functional gene analysis: Use metagenomics to reveal the expression and regulation mechanisms of key genes for nitrogen fixation and carbon sequestration.Ecological restoration application: Develop stress - tolerant cyanobacteria - bryophyte composite inoculants to improve the restoration efficiency of degraded soils.

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