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The Impact and Regulatory Mechanisms of Nitrogen Fertilizer on Soil Carbon Cycling

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Abstract: Modern agriculture must increase production to meet the growing global demand for food. However, excessive use of nitrogen fertilizer has led to a series of environmental issues. The impact of nitrogen fertilizer on soil carbon cycling is of particular concern, as agriculture is a major global carbon reservoir, and soil carbon cycling is crucial for maintaining ecosystem functionality. Previous research indicates that nitrogen fertilizer not only affects soil carbon storage but also alters the structure and function of soil microbial communities, thereby influencing carbon decomposition rates. Nevertheless, the specific mechanisms underlying the effects of nitrogen fertilizer on soil carbon cycling remain elusive. This study aims to comprehensively and systematically analyze the impact of nitrogen fertilizer on soil carbon cycling and elucidate its regulatory mechanisms. Nitrogen fertilizer exerts complex effects on soil, potentially promoting organic carbon accumulation, yet under certain conditions, it may also lead to carbon losses, closely intertwined with its impact on soil microbial communities. Regional and seasonal variations in the response to nitrogen fertilizer highlight the intricate dynamics of soil carbon storage, emphasizing the need for a thorough spatiotemporal investigation. Nitrogen fertilizer also influences soil microbial diversity, resulting in the excessive enrichment of certain microbial populations, disrupting the balance of microbial diversity in the soil. Moderate use of nitrogen fertilizer stimulates soil microbial metabolic activity, whereas excessive use may lead to a decline in metabolic activity. The regulation of soil carbon decomposition rates involves soil enzyme activity and organic matter decomposition pathways, with moderate nitrogen fertilizer application promoting soil carbon cycling, while high concentrations may impede carbon decomposition pathways. In conclusion, nitrogen fertilizer management should be guided by scientific principles to avoid excessive use. Establishing a systematic monitoring system that considers soil nutrients, microbial communities, and other factors is essential for achieving sustainable nitrogen fertilizer use. This approach aims to promote sustainable agriculture, reduce the burden on ecosystems, and enhance soil health and carbon storage.

Keywords: Nitrogenous fertilizer, Overfertilization, Agriculture, Carbon cycle.

1. Introduction

In the practice of modern agriculture, the continuous improvement of agricultural production is imperative to meet the growing global population demands. However, this increased production brings forth a series of environmental issues. Nitrogen fertilizer, as a crucial agricultural input, not only enhances crop yields but also, with its excessive use, may lead to problems such as soil quality degradation, water pollution, and greenhouse gas emissions. The impact of nitrogen fertilizer on soil carbon cycling has become a highly scrutinized topic in this context [1,2] Agriculture stands as one of the major carbon reservoirs globally, and the cycling of carbon in the soil plays a pivotal role in maintaining ecosystem functionality and preserving soil quality. Nevertheless, the widespread application of nitrogen fertilizer alters the ecological processes in the soil, potentially causing profound effects on soil carbon cycling (Figure 1)[3-5]. Understanding the influence of nitrogen fertilizer on soil carbon cycling and its regulatory mechanisms holds significant importance for formulating sustainable agricultural practices and environmental protection. Past research indicates that nitrogen fertilizer not only affects carbon storage in the soil but may also alter the structure and functionality of soil microbial communities, subsequently influencing carbon decomposition rates. However, specific mechanisms regarding the impact of nitrogen fertilizer on soil carbon cycling remain elusive. Delving into these mechanisms is crucial for a better understanding of the role of nitrogen fertilizer in agricultural production systems and for guiding policy formulations in environmental protection and climate change mitigation. This study aims to systematically analyze the impact of nitrogen fertilizer on soil carbon cycling and unveil its regulatory mechanisms. Through an in-depth understanding of this relationship, scientific foundations can be provided for the development of sustainable agricultural management policies, striking a balance between increasing agricultural yields and protecting the relationship with the ecological environment. This endeavor is not only crucial for achieving food security but also contributes to steering global agriculture towards a more sustainable future.

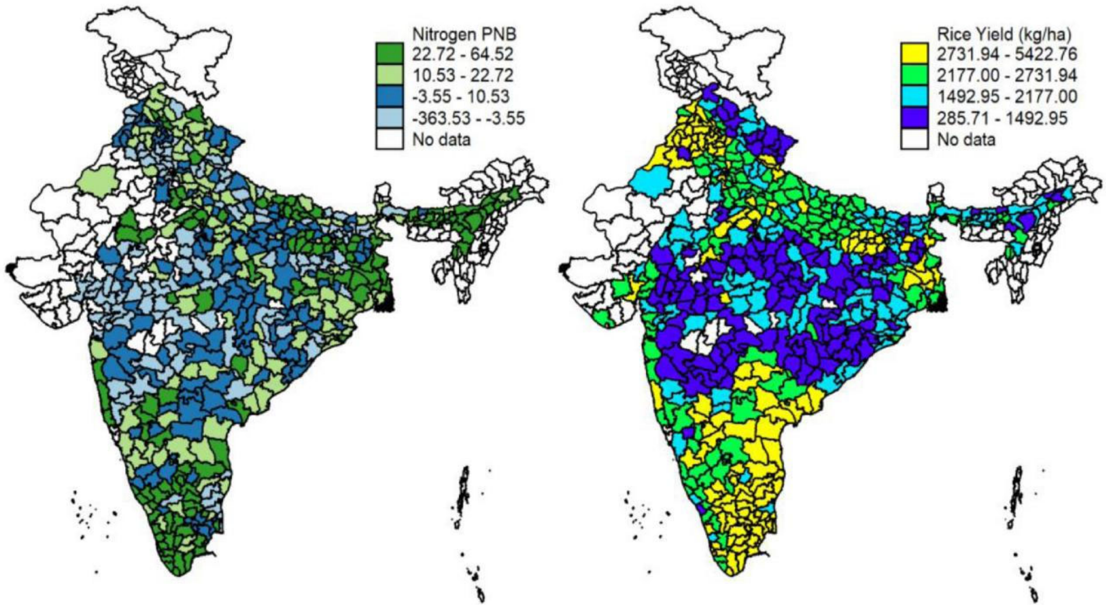

Figure 1. Partial nitrogen balance and yield (kg/ha) for rice, by selected Indian districts, 2011–12[6]

2. The Impact of Nitrogen Fertilizer on Soil Carbon Cycling

The widespread use of nitrogen fertilizer has complex and multifaceted effects on soil carbon cycling[7]. Previous studies have indicated that the application of nitrogen fertilizer may lead to changes in soil carbon storage. Some research suggests that nitrogen fertilizer can promote the accumulation of organic carbon, primarily through increased return of plant residues and enhanced soil carbon sequestration capacity. However, under certain conditions, nitrogen fertilizer may also result in soil carbon loss, especially in situations of high nitrogen input and insufficient organic matter replenishment. This variation is closely related to the impact of nitrogen fertilizer on soil microbes, as microbes play a crucial role in the decomposition of organic matter and the release of carbon.

Furthermore, the spatiotemporal dynamics of nitrogen fertilizer's impact on soil carbon storage show differential responses. Different regions and seasons may exhibit significant variations in response to nitrogen fertilizer, reflecting the complex dynamics of soil carbon storage in different ecosystems[8]. In-depth studies on spatiotemporal dynamics contribute to a better understanding of the long-term effects of nitrogen fertilizer on soil carbon storage and provide scientific support for regional agricultural management.

3. Regulation of Soil Microbial Community Structure and Function by Nitrogen Fertilizer

3.1. Changes in Microbial Diversity

Excessive use of nitrogen fertilizer may lead to changes in soil microbial diversity. Studies indicate that nitrogen fertilizer application may increase the dominance of certain microbial populations while suppressing others. Such changes in diversity not only affect the stability of the soil ecosystem but may also have profound effects on plant-microbe interactions and soil ecological functions. Researchers investigated the impact of nitrogen fertilizer on microbial diversity in rice paddy soils and found that with increasing nitrogen fertilizer application, the diversity of soil microbial communities gradually decreased. High nitrogen input may lead to the over-enrichment of certain microbial populations and the loss of other microbial communities, thereby affecting the balance of soil microbial diversity[9].

3.2. 3.2 Impact on Soil Microbial Metabolic Activity

In addition to influencing microbial diversity, nitrogen fertilizer may also regulate the metabolic activity of soil microbes. This regulation directly affects the carbon decomposition and transformation processes of microbes, thereby influencing the overall soil carbon cycle. Moderate use of nitrogen fertilizer can stimulate the metabolic activity of soil microbes. By promoting the growth of maize plants, nitrogen fertilizer increases the input of organic matter into the soil, thereby making microbial communities more active[10]. However, some studies suggest that excessive use of nitrogen fertilizer may lead to a decrease in the metabolic activity of soil microbes. High nitrogen input alters the carbon-nitrogen ratio in the soil, thereby affecting microbial metabolic processes. This indicates that the excessive application of nitrogen fertilizer may have adverse effects on the ecological functions of soil microbial communities[11].

4. Regulation Mechanisms of Nitrogen Fertilizer on Soil Carbon Decomposition Rate

4.1. Relationship between Nitrogen Fertilizer and Soil Enzyme Activity

The application of nitrogen fertilizer has complex and diverse effects on soil enzyme activity, involving the types, quantity, and functions of enzymes, as well as changes in soil environmental conditions[12]. Soil pH and temperature are crucial environmental factors influencing enzyme activity. Nitrogen fertilizer application may alter soil pH, directly affecting enzyme activity. Simultaneously, nitrogen fertilizer can indirectly regulate enzyme activity by changing soil temperature and humidity conditions.

4.2. Impact of Nitrogen Fertilizer on Soil Carbon Decomposition Pathways

The application of nitrogen fertilizer has a direct impact on urease activity in the soil. Some studies suggest that moderate nitrogen fertilizer can stimulate an increase in urease activity, promoting the decomposition of organic nitrogen[13]. However, high concentrations of nitrogen fertilizer may inhibit urease, affecting the degradation rate of urea-like organic compounds. Peroxidase is one of the key enzymes involved in the decomposition of organic matter in the soil. Adequate nitrogen fertilizer may increase peroxidase activity, facilitating the degradation of organic compounds. However, high concentrations of nitrogen fertilizer may have negative effects on peroxidase activity, inhibiting its function.

The application of nitrogen fertilizer can influence the decomposition rate of organic matter in the soil. Moderate nitrogen fertilizer can accelerate the rapid decomposition of some organic matter, releasing nutrients. However, excessive nitrogen fertilizer may lead to the rapid decomposition of organic matter, affecting the accumulation of soil carbon. Carbon released during the decomposition of some organic matter may be quickly utilized by microorganisms, resulting in short-term carbon cycling. Nonetheless, moderate nitrogen fertilizer application may improve the stability of soil carbon, reducing the loss rate of carbon. High concentrations of nitrogen fertilizer may have a negative impact on the stability of soil carbon, increasing the risk of carbon emissions.

5. Conclusion

Moderate application of nitrogen fertilizer can promote soil carbon cycling, increase enzyme activity, and facilitate the decomposition of organic matter. This has positive effects on nutrient release, plant growth promotion, and maintaining the health of the soil ecosystem. High concentrations of nitrogen fertilizer may lead to enzyme inhibition, reduced microbial diversity, and excessive decomposition of organic matter, thereby slowing down soil carbon decomposition pathways. This may have negative impacts on the soil ecosystem, including declining soil quality and increased carbon emissions. The influence of nitrogen fertilizer on soil carbon cycling is the result of the comprehensive interaction of various factors, such as nitrogen concentration and form, soil pH and temperature, microbial community structure, and more. Therefore, when formulating nitrogen fertilizer management strategies, it is essential to consider factors such as soil characteristics, vegetation types, and climate to gain a more comprehensive understanding of their impact.

Nitrogen fertilizer management should be based on scientific principles, avoiding excessive use, especially in modern agricultural practices. Scientifically sound nitrogen fertilizer management strategies should take into account agricultural production needs, soil characteristics, vegetation types, and other factors to achieve optimal soil carbon cycling and ecosystem services. To achieve sustainable nitrogen fertilizer use, it is necessary to establish a systematic monitoring system, closely monitoring soil nutrient status, microbial community structure, enzyme activity, and other indicators. Based on actual monitoring results, adjust nitrogen fertilizer management strategies in a timely manner to ensure the health of the soil ecosystem. In agricultural practices, there is encouragement and promotion of sustainable agriculture, including the adoption of organic farming, intercropping, crop rotation, etc., to reduce dependence on nitrogen fertilizer, lower the burden on ecosystems, and simultaneously promote soil health and carbon storage.

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