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Research Progress and Ecological Implications of Soil Nematode Metabolic Footprint

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Abstract

Soil nematodes, as a key functional group in soil ecosystems, have a profound impact on carbon and nitrogen cycles, microbial community dynamics, and soil health. Metabolic footprint, as a core indicator for quantifying nematode ecological effects, integrates processes such as respiration, decomposition of excreta, and microbial regulation. Recent breakthroughs in molecular biology and stable isotope tracing technologies have significantly enhanced the accuracy of nematode metabolic pathway analysis. Studies have shown that interspecific differences in nematodes lead to significant variations in carbon and nitrogen transformation efficiency, for example, the organic carbon mineralization rate of fungivorous nematodes can reach 60%, while that of bacterivorous nematodes is only 30-45%. At the same time, environmental factors (such as temperature, pH) and biological interactions (such as root signaling of plants, control by predators) further affect the ecological function contributions of nematodes by regulating their metabolic activity. However, existing research still has shortcomings in the refinement of metabolic mechanisms, long-term effect assessment, and the construction of climate change response models. This article systematically reviews the research progress of nematode metabolic footprint, reveals its ecological regulatory mechanisms, and proposes that future research should focus on the integration of omics technologies and the development of cross-scale models to provide theoretical support for soil resource management and the achievement of carbon neutrality goals.

Keywords

Soil nematodes; Metabolic footprint; Carbon-nitrogen cycle; Microbial interactions; Stable isotopes.

1. Introduction

Soil nematodes, although accounting for only 0.5%-2% of the soil microbial biomass, are important energy transmitters and drivers of material cycles in soil food webs[1]. Traditional studies have focused on the direct effects of nematodes on plant growth (such as mechanical damage and chemical secretion inhibition), but have ignored their indirect regulation of ecosystem processes. With the advancement of global climate change and intensive agriculture, the community structure and function of nematode populations have changed significantly, and the potential impact of their metabolic footprint on carbon and nitrogen cycles has become increasingly prominent[2-3]. For example, in tropical rainforest ecosystems, the CO_2 emission from nematodes through the consumption of microbial products can account for 15%-20% of the total soil respiration, while in degraded farmlands, nematode metabolic activities can lead to an increase in organic matter mineralization rate by more than 30%. Therefore, a deep understanding of the spatiotemporal heterogeneity of nematode metabolic footprint and its driving mechanisms is of great significance for accurately evaluating soil ecological functions and optimizing agricultural management strategies[4]. The introduction of the concept of metabolic footprint provides a new perspective for quantifying nematode ecological effects by integrating multidimensional indicators such as respiration, decomposition of excreta, and disturbance of microbial communities, it can more comprehensively reveal the role of nematodes as the "metabolic engine" in ecosystems.

2. Metabolic Characteristics of Soil Nematodes

The metabolic characteristics of soil nematodes show significant diversity due to their feeding habits and ecological functions. Fungivorous nematodes (such as the genus Rotylenchulus) depend on rhizosphere fungi as the main carbon source, have low cellulase activity, but can decompose chitin from the cell wall of fungi efficiently by secreting chitinase, achieving a metabolic efficiency of 45%-60%. The excreta of these nematodes are rich in amino acids and organic acids, which can significantly stimulate the germination and hyphal growth of arbuscular mycorrhizal fungi (AMF)[5]. In contrast, bacterivorous nematodes (such as the genus Caenorhabditis) decompose proteins and polysaccharides within bacterial cells by an efficient protease system, with a metabolic efficiency of about 30%-45%, but the non-absorbed nitrogen-containing compounds (such as peptides, amino acids) in the residue can be released by microbial secondary mineralization. Generalist nematodes (such as the genus Pristionchus) show metabolic flexibility, being able to prioritize the use of high-quality resources in a dynamic carbon-nitrogen resource environment. For example, in nitrogen-poor soils, their feeding strategy will shift from bacteria preference to decomposition of fungal residues to maintain energy intake and growth requirements. In addition, nematode nitrogen metabolism has unique mechanisms: some species can convert urea to ammonium nitrogen by body wall nitrase, and a few nematodes (such as Paratrichodorus) even have denitrification capacity, which can reduce nitrates to nitrogen gas under anaerobic conditions. This metabolic diversity makes nematodes a key regulatory node in soil nitrogen cycling, and the ratio of ammonium nitrogen to nitrate nitrogen in their excreta can directly affect soil nitrogen availability.

3. Metabolic Footprint Measurement Techniques

The precise measurement of metabolic footprint relies on the cross-integration of multidisciplinary technologies. Microwave dielectric method, as a non-invasive technique, reflects the metabolic activity of nematode cell membranes in real-time by monitoring changes in their dielectric constants[6]. Experimental results show that this method can detect the respiration rate of living nematodes with an accuracy of ±2% and can continuously track the whole metabolic dynamic process of nematode feeding, digestion, and excretion. For example, in a simulated nematode feeding cycle experiment, the microwave signal attenuation rate significantly increased within 4 hours after feeding and then gradually stabilized, which is highly consistent with the temporal sequence of ATP synthesis and energy consumption within nematode bodies. Stable isotope tracing technology provides molecular evidence for the analysis of nematode metabolic pathways. By introducing ^{13}C-labeled glucose or cellulose into the soil, researchers have found that fungivorous nematodes have a significantly higher utilization rate of labeled carbon sources than bacterivorous nematodes, and the ^{13}C abundance distribution in their excreta is consistent with the decomposition products of fungal cell walls. Additionally, ^{15}N isotope dilution method reveals interspecific differences in nematode nitrogen transformation efficiency. For example, the nitrogen absorption efficiency of the genus Rhabditis is as high as 82%, while that of the genus Anguina is only 57%. Respirometry (RQ) measurement technology further clarifies the type of metabolic substrates of nematodes: the RQ values of bacterivorous nematodes are usually between 0.8-1.0, indicating that they use carbohydrates as the main energy source; while fungivorous nematodes can have RQ values below 0.6 under nitrogen limitation, suggesting that they may depend on the decomposition of fats or proteins. These technical breakthroughs provide multidimensional tool support for quantifying nematode metabolic footprint.

4. Ecological Effects Research

Nematode metabolic activities profoundly shape soil ecosystem functions through direct and indirect pathways. Their direct metabolic products (such as CO_2, excreta) contribute to 60%-70% of the carbon cycle, with respiration accounting for the dominant position. For example, in the Amazon rainforest soil, nematode respiration can produce up to 3.2 Pg of CO_2 annually, equivalent to 12% of the terrestrial vegetation respiration emissions in the region. In addition, nematode feeding behavior significantly alters microbial community structure through the "bioturbation effect": an increase in the population of bacterivorous nematodes can lead to a decrease in the proportion of Gram-negative bacteria by 18%-25%, while Gram-positive bacteria such as Bacillus become relatively enriched, thereby affecting soil enzyme activity and organic matter decomposition pathways. In terms of nitrogen cycling, the ammonium nitrogen in nematode excreta can be rapidly converted to nitrate nitrogen by nitrifying bacteria, but the organic acids (such as citric acid, malic acid) secreted by nematodes can inhibit the activity of nitrate reductase, forming a dynamic regulatory network. Research has found that the soil nitrogen mineralization rate can be increased by 2-3 times in the presence of nematodes, but the risk of nitrate leaching loss also increases. More notably, the interaction effects between nematodes and plants-microbes amplify their ecological functions: the symbiosis between AMF and nematodes can enhance the phosphorus absorption efficiency of plants by 35%, and the metabolic activity of nematodes promotes the expansion of AMF hyphal networks, forming a "plant-nematode-microbe" synergistic regulatory network, significantly enhancing soil carbon sequestration capacity.

5. Analysis of Influencing Factors

The dynamic changes in nematode metabolic footprint are regulated by multiple environmental factors and biological interactions. Temperature affects the metabolic rate of nematodes according to the Q_{10} law (metabolic rate increases by 1.12 times for every 10°C increase), but the optimal temperature varies by species: tropical nematodes (such as the genus Rhabditis) reach a metabolic peak at 30°C, while temperate nematodes (such as the genus Caenorhabditis) have an optimal temperature of 25°C. pH affects the regulation of nematodes by affecting the stability of nematode cuticle proteins and enzyme activity when soil pH is below 5.5, the respiration rate of nematodes can decrease by more than 50%, and the proportion of ammonia nitrogen in excreta significantly increases. Moisture conditions are also crucial; when soil water content is below 40% of the field capacity, nematode metabolic activity completely stops, while an overly moist environment can lead to population collapse of nematodes. In the biological interaction network, the jasmonic acid and salicylic acid secreted by plant roots can induce nematodes to migrate to the rhizosphere, increasing their MF by 22%, thereby enhancing resource competition for root exudates. Predators (such as the genus Verticillium) can infect nematodes, reduce their respiration rate by 68%, and block their life cycle by inhibiting the synthesis of nematode ecdysone. In addition, the microbial community regulates nematode metabolism through "resource limitation effect" – for example, when the abundance of lignin degrading bacteria in the soil is high, the MF of fungivorous nematodes significantly increases, while their metabolic efficiency decreases significantly when bacterial resources are scarce.

6. Research Prospects

Future research needs to achieve breakthroughs in the integration of technologies and mechanism analysis. Single-cell metabolomics technology is expected to reveal the specific metabolic pathways of nematode tissues (such as intestines, epidermis), for example, to analyze the expression regulation mechanism of lignin degrading enzymes in the intestines of fungivorous nematodes. The development of nanosensors will promote the progress of real-time monitoring technology, for example, micro-sensors based on electrochemical signals can continuously record the spatiotemporal heterogeneity of nematode metabolic activities. The construction of artificial intelligence models needs to integrate environmental data, nematode physiological parameters, and metabolic flux information, for example, using machine learning to predict the spatiotemporal distribution of nematode metabolic footprint under different climate scenarios. In terms of application, it is necessary to explore the impact of nematode community control strategies on agricultural ecosystem – for example, by inoculating predator fungi or applying biological inhibitors to reduce nematode MF, thus reducing soil nitrogen loss; or by utilizing the nematode-AMF symbiotic system to enhance the carbon sequestration capacity of organic agriculture. In addition, research on climate change response needs to be deepened, for example, quantifying the nonlinear impact of warming on nematode metabolic enzyme activity, as well as the disturbance effects of extreme precipitation events on the nematode-microbe interaction network. These research directions will provide scientific evidence for soil health evaluation, the achievement of carbon neutrality goals, and sustainable agricultural practices.

7. Conclusion

The research on soil nematode metabolic footprint has moved from single-indicator analysis to multi-dimensional comprehensive evaluation, revealing its hub role in carbon and nitrogen cycles and microbial regulation. Technological innovations (such as microwave dielectric method, stable isotope tracing) have promoted the precise analysis of metabolic pathways, while ecological effect research has emphasized the irreplaceable role of nematodes in soil ecosystem service functions. In the future, further integration of omics technologies and artificial intelligence models, deepening the research on interspecific differences and environmental responses, and exploring the application potential of nematode metabolic regulation in agriculture and ecological restoration are needed. By constructing a research framework of "molecular mechanism-ecological process-management strategy," the study of soil nematode metabolic footprint will provide important theoretical support for global ecological governance and sustainable development.

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