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Analyzing the Synergistic Response of Soil Nematode Community Structure and Metabolic Footprint to the Southward Migration of Tea in the Qinba Mountain Area

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Abstract

As a strategy for adjusting the layout of the agricultural industry, the relocation of tea from the south to the north is gradually unfolding in the Qinba Mountain area. Soil nematodes, as important indicator organisms in soil ecosystems, have a sensitive community structure and metabolic footprint to changes in soil ecological environment during the process of southward tea migration. This article comprehensively elaborates on the structural characteristics and metabolic footprint of soil nematode communities in the Qinba Mountain area, and deeply analyzes their synergistic changes during the process of southward tea northward migration. The aim is to provide theoretical basis for understanding the impact of southward tea northward migration on soil ecosystems and sustainable agricultural development.

Keywords

Qinba Mountain Area; Soil Nematode Community; Metabolic Footprint; Southern Tea Moves Northward; Ecological Response; Collaborative Law.

1. Introduction

With the development of the economy and the adjustment of the agricultural industry structure, the relocation of tea from the south to the north has become an important measure to expand tea planting areas and enrich the variety of tea products. Due to its unique geographical location and ecological environment, the Qinba Mountain area has become one of the ideal areas for the northward migration of southern tea. Soil nematodes are widely present in soil ecosystems, with a wide variety of species and huge quantities, playing a key role in soil material cycling, energy flow, and maintaining ecosystem stability. During the process of southern tea migration to the north, changes occur in soil physicochemical properties, vegetation types, etc., which inevitably affect the structure and metabolic activity of soil nematode communities. In depth research on the synergistic response of soil nematode community structure and metabolic footprint to the southward migration of tea in the Qinba Mountain area is of great significance for revealing the response mechanism of soil ecosystems to tea planting changes.

2. Community Structure of Soil Nematodes in Qinba Mountain Area

(1) Classification and Diversity of Soil Nematodes

The soil nematodes in the Qinba Mountain area are rich in species, which can be divided into bacterial eating nematodes, fungal eating nematodes, plant parasitic nematodes, and omnivorous/predatory nematodes according to their diet. Nematodes with different feeding habits occupy different ecological niches in soil ecosystems, and their diversity is an important foundation for maintaining soil ecological balance. Research has shown that the diversity index of soil nematodes in the Qinba Mountain area varies significantly under different vegetation cover and soil types. For example, under natural forest vegetation, soil nematodes are abundant in species and have a high diversity index; In some artificially cultivated farmland or tea gardens, the nematode community structure is relatively simple and the diversity index is low. This difference is closely related to the physical and chemical properties of the soil, microbial communities, as well as the composition and coverage of vegetation(Zhang et al. 2021).

(2) The influencing factors of soil nematode community structure

1. Soil physical and chemical properties

The physical and chemical properties of soil, such as pH value, organic matter content, and soil texture, have a significant impact on the community structure of soil nematodes. Generally speaking, neutral to slightly acidic soils are beneficial for the survival and reproduction of soil nematodes, while high soil organic matter content provides abundant food sources for nematodes. In the Qinba Mountain area, areas with loose soil texture and good air permeability have a higher number of soil nematodes and a more complex community structure. Nematodes with different dietary habits also have different responses to soil physicochemical properties. Bacterial eating nematodes usually dominate in soils rich in organic matter and well ventilated, while plant parasitic nematodes are more abundant in areas with developed roots and high soil nutrient content(Liu et al. 2019).

2. Vegetation types

Vegetation type is one of the important factors affecting the structure of soil nematode communities. Different vegetation provides soil nematodes with different food resources and habitats through root exudates, litter, and other factors. For example, under forest vegetation, abundant litter and complex root systems provide diverse food sources and shelters for soil nematodes, resulting in a rich and diverse community structure of soil nematodes. In tea gardens, the single vegetation structure of tea trees and human management measures such as fertilization and irrigation have changed the living environment of soil nematodes, leading to changes in the nematode community structure. Research has found that with the increase of tea plantation planting years, the relative abundance of plant parasitic nematodes gradually increases, while the relative abundance of bacterial and fungal eating nematodes decreases.(Biswal 2023)

3. Climate factors

The climate in the Qinba Mountain area is complex and diverse, and climate factors such as temperature and precipitation also have a certain impact on the structure of soil nematode communities. Temperature affects the population size and community structure of soil nematodes by influencing their metabolic rate and growth and development. Within a suitable temperature range, the activity and reproduction of soil nematodes are more active, leading to an increase in population size. Precipitation affects soil moisture and aeration, indirectly affecting the living environment of soil nematodes. In seasons with more precipitation, soil moisture increases, which is beneficial for the survival of some aquatic or moisture loving soil nematodes. However, in dry seasons, soil nematodes may adapt to environmental changes through dormancy and other means.

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3. Metabolic Footprint of Soil Nematodes

(1) The concept and measurement method of metabolic footprint

The metabolic footprint of soil nematodes refers to the material and energy conversion traces produced by nematodes during their growth, reproduction, and metabolic processes in the soil ecosystem(Li and Xue 2022). It mainly affects the cycling of nutrients and microbial community structure in soil through physiological activities such as feeding and excretion of nematodes. At present, the methods for determining the metabolic footprint of soil nematodes mainly include isotope tracing techniques, biochemical analysis methods, and molecular biology based techniques. Isotope tracing technology can study the metabolic pathways of nematodes and their impact on material cycling by tracking the transformation of labeled nutrients within soil nematodes and their flow in soil ecosystems. Biochemical analysis methods mainly indirectly reflect the metabolic footprint of nematodes by measuring indicators such as enzyme activity and metabolite content related to nematode metabolism in soil. Based on molecular biology techniques such as high-throughput sequencing, the gene expression profile of soil nematode communities can be analyzed to understand their metabolic function changes under different environmental conditions.

(2) Metabolic footprint of soil nematodes and soil ecological functions

1. Participate in soil material cycling

Soil nematodes promote the decomposition and transformation of organic matter in soil by feeding on microorganisms (such as bacteria and fungi) and plant roots. Bacterial eating nematodes and fungal eating nematodes accelerate the decomposition of organic matter by microorganisms in the soil, converting organic nutrients into inorganic forms and releasing them into the soil for plant absorption and utilization. Although plant parasitic nematodes can cause certain damage to plant roots, they can also stimulate plant roots to secrete more organic matter into the soil, promote the growth and activity of soil microorganisms, and thus affect soil material cycling. Omnivorous/predatory nematodes regulate soil nematode community structure by preying on other nematodes and small invertebrates, indirectly affecting soil material cycling processes.

2. Impact on soil microbial community structure

The metabolic activity of soil nematodes has a significant impact on the structure of soil microbial communities. The feeding behavior of nematodes can alter the quantity and composition of microorganisms in the soil. For example, bacteria eating nematodes prefer to feed on certain types of bacteria, which can lead to changes in the structure of bacterial communities in the soil, thereby affecting ecological processes related to bacteria in the soil, such as nitrogen transformation. Meanwhile, the excrement of nematodes contains abundant nutrients, providing new growth substrates for soil microorganisms and promoting their growth and reproduction. The interaction between nematodes and microorganisms is of great significance for maintaining the functional stability of soil ecosystems(Chen et al. 2013).

3. The role of soil ecosystem stability

The metabolic footprint of soil nematodes plays an important role in maintaining the stability of soil ecosystems. By participating in soil material cycling and influencing microbial community structure, soil nematodes can regulate the interrelationships between various biotic and abiotic factors in soil ecosystems, enhancing the buffering capacity of soil ecosystems to environmental changes. When the soil environment changes (such as changes in soil physicochemical properties and vegetation types caused by the migration of tea from south to north), soil nematodes can adapt to environmental changes and maintain the basic functions of the soil ecosystem by adjusting their metabolic activities and community structure, ensuring the stability of the soil ecosystem.

4. The Impact of Southward Tea Migration on Soil Nematode Community Structure and Metabolic Footprint in the Qinba Mountain Area

(1) Response of Soil Nematode Community Structure

1. Changes in population size

After the southward migration of tea, there was a significant change in the population of soil nematodes in the Qinba Mountain area. Research has found that the total number of soil nematodes in newly opened tea gardens may decrease in the early stages, which may be due to the damage to soil structure during tea plantation cultivation and the unstable soil ecological environment in the early stages of tea planting. As the planting years of tea gardens increase, the number of soil nematodes gradually recovers, but the population changes of nematodes with different feeding habits have different trends(Ma et al. 2022). The number of plant parasitic nematodes usually increases with the growth of tea tree roots and the implementation of tea garden management measures such as fertilization and irrigation, because tea tree roots provide suitable parasitic sites and nutrient sources for plant parasitic nematodes(Liu et al. 2016). The changes in the numbers of bacteria eating nematodes and fungi eating nematodes are more complex. On the one hand, fertilization and other measures in tea gardens may increase the number of microorganisms in the soil, providing more food for bacteria eating nematodes and fungi eating nematodes, thereby promoting their population growth; On the other hand, some pesticides and fungicides used in tea gardens may have toxic effects on soil microorganisms and nematodes, leading to a decrease in the number of bacteria eating nematodes and fungi eating nematodes(Yu et al. 2024).

2. Changes in community structure and composition

The southward migration of tea not only affects the population size of soil nematodes, but also changes their community structure composition. Under natural vegetation, the community structure of soil nematodes is relatively complex, and different feeding nematodes maintain relatively stable proportional relationships. In tea gardens, due to changes in the soil ecological environment, the nematode community structure has undergone significant changes. The relative abundance of plant parasitic nematodes in the community has increased, becoming a dominant group, which may pose a potential threat to the growth and health of tea trees. At the same time, the relative abundance of bacterial eating nematodes and fungal eating nematodes decreased, and the types and quantities of omnivorous/predatory nematodes also decreased. The changes in the composition of this community structure may affect the normal circulation of substances and energy flow in soil ecosystems, reducing the stability of soil ecosystems (Gruzdeva and Sushchuk 2010).

3. Changes in Diversity Index

The diversity index of soil nematodes is one of the important indicators for measuring the health status of soil ecosystems. After the southward migration of tea, the diversity index of soil nematodes in the Qinba Mountain area showed a downward trend. In tea gardens, due to the single vegetation and intensive soil management measures, the living environment of soil nematodes has become relatively single, resulting in the gradual disappearance of some nematode species that are sensitive to environmental changes and a decrease in community diversity. Lower soil nematode diversity may weaken the soil ecosystem's resistance to pests and diseases, as well as its adaptability to environmental changes, which is not conducive to the sustainable development of tea gardens.

(2) Changes in metabolic footprint of soil nematodes

1. Changes in metabolic pathways

The changes in soil ecological environment caused by the migration of southern tea to the north have led to alterations in the metabolic pathways of soil nematodes. In tea gardens, due to changes in the composition and content of nutrients in the soil, as well as the influence of tea tree root exudates, the feeding preferences and metabolic pathways of soil nematodes are also adjusted accordingly. For example, plant parasitic nematodes may alter their metabolic pathways related to parasitism and nutrient uptake in order to adapt to the physiological characteristics of tea tree roots. Bacterial eating nematodes and fungal eating nematodes also undergo changes in their metabolic pathways when facing changes in the microbial community structure in tea gardens, in order to better utilize new food resources. The changes in this metabolic pathway can be confirmed by analyzing the activity of related enzymes and gene expression levels in soil nematodes.

2. Impact on soil material cycling and microbial community

The changes in the metabolic footprint of soil nematodes have significant impacts on soil material cycling and microbial communities. With the changes in the community structure and metabolic pathways of soil nematodes after the southward migration of tea, their mode and intensity of action on soil material cycling have also changed. In tea gardens, an increase in the number of plant parasitic nematodes may lead to damage to tea tree roots, affecting the absorption and utilization of nutrients by plants, and thus affecting nutrient cycling in the soil. At the same time, changes in the quantity and metabolic activity of bacteria eating nematodes and fungi eating nematodes can also alter the process of microbial decomposition and transformation of organic matter in soil. In addition, changes in the metabolic footprint of soil nematodes can also affect the structure of soil microbial communities, leading to changes in the types and quantities of microorganisms related to material cycling in the soil, further affecting the functionality of soil ecosystems.

3. Relationship with the stability of soil ecosystem functions

The changes in the metabolic footprint of soil nematodes are closely related to the stability of soil ecosystem functions. If soil nematodes can adapt to new environmental changes by adjusting their metabolic activities and maintain relative stability in soil material cycling and microbial community structure during the process of southward tea migration, then the functional stability of the soil ecosystem can be guaranteed. However, if the changes in the metabolic footprint of soil nematodes exceed the self-regulation capacity of the soil ecosystem, leading to disrupted soil material cycling and imbalanced microbial community structure, it will reduce the functional stability of the soil ecosystem and increase the risk of tea garden ecosystems being invaded by pests and environmental stress. Therefore, in-depth research on the changes in the metabolic footprint of soil nematodes during the migration of tea from south to north is of great significance for maintaining the health and stability of tea garden soil ecosystems(Wiesel et al. 2015).

5. The Synergistic Relationship Between Soil Nematode Community Structure and Metabolic Footprint, and the Response Mechanism to the Northward Migration of Southern Tea

(1) Performance of collaborative relationships

1. The impact of community structure on metabolic footprint

The composition and diversity of soil nematode community structure determine the characteristics of its metabolic footprint. Nematodes with different diets have different metabolic pathways and functions, and they interact with each other in soil ecosystems, jointly affecting soil material cycling and energy flow. For example, bacteria eating nematodes and fungi eating nematodes promote the decomposition of organic matter by microorganisms in the soil, and their metabolites play an important role in the transformation and release of soil nutrients. The parasitic behavior of plant parasitic nematodes on plant roots not only affects

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plant growth and health, but also alters the composition and quantity of plant root exudates, thereby affecting soil microbial communities and the metabolic activities of other soil organisms. Omnivorous/predatory nematodes indirectly affect the metabolic footprint of soil nematode communities by regulating the population size of other nematodes. Therefore, any changes in the community structure of soil nematodes, such as those caused by the migration of tea from south to north, may trigger corresponding changes in their metabolic footprint.

2. Metabolic footprint feedback affects community structure

The metabolic footprint of soil nematodes also affects their community structure in reverse. The metabolic activity of nematodes changes the distribution of nutrients and microbial community structure in the soil, creating new living environments for themselves and other soil organisms. For example, the excrement of nematodes contains abundant nutrients such as nitrogen and phosphorus, which can promote the growth and reproduction of soil microorganisms, thereby providing more food resources for bacterial and fungal eating nematodes, which is beneficial for their population growth. Meanwhile, changes in soil microbial community structure can also affect the survival and reproduction of plant parasitic nematodes, as different types of microorganisms have varying impacts on the health and disease resistance of plant roots. In addition, some signaling substances produced during the metabolism of soil nematodes may affect the interactions between nematodes and the stability of community structure. Therefore, changes in the metabolic footprint of soil nematodes can affect the composition and dynamic changes of their community structure through feedback mechanisms.

(2) Response mechanism for collaborative response to the northward migration of southern tea

1. Ecological niche differentiation and adaptation

During the process of southward migration of tea, soil nematodes adapt to new environmental changes through niche differentiation. Nematodes with different feeding habits occupy different ecological niches in soil ecosystems. With changes in the soil ecological environment of tea gardens, nematodes will adjust their feeding strategies and metabolic patterns to better utilize limited resources. For example, in tea gardens, plant parasitic nematodes may gradually adapt to the special physiological environment of tea tree roots, obtaining more nutrients by changing their parasitic sites and feeding methods. Bacterial eating nematodes and fungal eating nematodes adjust their feeding preferences for different types of microorganisms based on changes in the microbial community structure in the soil. This ecological niche differentiation enables soil nematodes to survive and reproduce in the new environment after the southward migration of tea, maintaining their community structure and relative stability of metabolic activity.

2. Functional redundancy and complementarity

There is a certain degree of functional redundancy in soil nematode communities, where different types of nematodes may have similar ecological functions. In the process of environmental changes caused by the migration of southern tea to the north, functional redundancy enables soil nematode communities to maintain the basic functions of soil ecosystems through functional complementarity between different types of nematodes. For example, when the number of certain species of bacteria eating nematodes that are sensitive to environmental changes decreases, other species of bacteria eating nematodes with similar metabolic functions may increase to ensure that the process of bacterial decomposition of organic matter in the soil is not greatly affected. This mechanism of functional redundancy and complementarity helps maintain the relative stability of soil nematode community structure and metabolic footprint in the face of environmental changes, enhancing the adaptability of soil ecosystems to the southward migration of tea.

3. Signal transmission and regulation

There are complex signaling and regulatory mechanisms between soil nematodes, as well as between nematodes and soil microorganisms and plants. These signaling mechanisms play an important role in the synergistic response of soil nematode community structure and metabolic footprint during the southward migration of tea. For example, when plant roots are invaded by parasitic nematodes, they secrete some signaling substances that can be sensed by other organisms in the soil, thereby affecting the structure and metabolic activity of soil nematode communities. Meanwhile, soil nematodes also produce some signaling molecules during their metabolic processes, which can regulate their own growth, reproduction, and behavior, as well as their interactions with other organisms. Through this signal transmission and regulation mechanism, soil nematodes can better coordinate to cope with environmental changes caused by the northward migration of tea from south to north, and maintain the balance and stability of soil ecosystems.

6. Research Prospects

(1) Multiscale research

At present, research on the synergistic response of soil nematode community structure and metabolic footprint to the southward migration of tea in the Qinba Mountain area mainly focuses on local regions and shorter time scales. Future research needs to expand to larger spatial and temporal scales, taking into account the effects of climate, soil types, topography, and tea plantation management measures in different regions on soil nematodes. Through long-term positioning monitoring and large-scale investigation and research, the dynamic changes in soil nematode community structure and metabolic footprint during the southward migration of tea can be more comprehensively revealed, providing a more solid theoretical basis for formulating scientific and reasonable ecological management strategies for tea gardens.

(2) Interdisciplinary intersection

The study of soil nematode community structure and metabolic footprint involves multiple disciplines such as soil science, ecology, microbiology, and biochemistry. In the future, it is necessary to strengthen interdisciplinary integration and comprehensively use various research methods such as molecular biology, isotope tracing technology, high-throughput sequencing technology, and ecological model simulation to deeply explore the ecological response mechanism of soil nematodes in the process of southward tea migration. For example, combining molecular biology techniques and biochemical analysis methods to study the response of soil nematodes to environmental changes at the gene expression level and metabolite level; Using ecological models to simulate and predict the changes in soil nematode community structure and metabolic footprint under different scenarios of southward tea migration, providing more accurate guidance for agricultural production practices.

(3) Assessment of ecosystem functional services

Soil nematodes play important functional service roles in soil ecosystems, such as promoting soil material cycling, maintaining soil structure stability, and regulating soil microbial communities. In the context of the southward migration of tea, it is necessary to further investigate the impact of changes in soil nematode community structure and metabolic footprint on soil ecosystem functional services, and establish a scientifically reasonable evaluation index system. By evaluating the contribution of soil nematodes to the functional services of tea garden soil ecosystems, we clarify their important role in the health and sustainable development of tea garden ecosystems, and provide scientific basis for optimizing tea garden management measures and improving tea yield and quality.

(4) Biodiversity Conservation and Sustainable Agricultural Development

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The changes in soil nematode community structure and metabolic footprint during the migration of southern tea to the north may have a certain impact on soil biodiversity. Future research should focus on how to protect soil biodiversity and achieve sustainable agricultural development while developing the tea industry. By implementing reasonable tea garden planning and scientific planting management measures (such as rational fertilization, reducing pesticide use, and protecting natural vegetation), creating an ecological environment conducive to the survival and reproduction of soil nematodes, and maintaining

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