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Microscopic Messengers: What Soil Nematodes Reveal About a Warming Planet

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Abstract

Soil Nematodes, minute worms that are not visible with naked eyes, are being recognized as a powerful signal of environmental change in a warming world. Soil nematodes are most abundant animals present in the soil and provide a fundamental role in nutrient cycling, organic matter decomposition, and ecosystem health. Recent studies have documented how rising global temperatures have altered nematode communities, with significant shifts in abundance, diversity, and behavioural changes providing strong indications of the cascading response to the climate change. Across the globe, warming has altered soil moisture, carbon stores, and plant biomass, disrupting nematode populations from arctic tundra to alpine meadows. Some nematode species thrive in conditions with higher temperatures, while many other declines, indicating major disruptions to soil food webs and populations that are critical for agricultural systems and biodiversity.

Keyword: Soil Nematodes, Climate Change, Soil Health, Soil Ecology, Bioindicators

Introduction

On a plant-parasitizing level, nematodes can be viewed as an enormous agricultural impact around the globe. They show pronounced reaction to environmental fluxes and are thus good climate-change bioindicators. Climate change, which is characterized by a rise in temperature, alteration of precipitation regimes, and increasing frequency of weather extremes, is reworking ecosystems on Earth, including biomes of PPNs. Among the most species-rich of all animal groups, described nematodes number more than 40,000. They exploit the greatest variety of habitats, from soil to water, and are key players in nutrient cycling and ecosystem functioning. PPNs parasitize the roots of plants interfering with nutrient uptake and becoming the cause of diseases that can destroy crops. Because their existence hinges on adaptability to environmental change, they cause further concern with global warming.

Climate change interferes with the populations of nematodes in that it alters the soil temperature and soil moisture content, which directly affect the survival, reproduction, and distribution of nematodes. Warmer temperatures affect the nematodes' life cycle speed and enlarges the possibility of them

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occupying territories situated to the north that were adversely not so many years ago. In addition, extreme weather conditions may trigger survival behaviour such as cryptobiosis, a state of suspended animation under which nematodes can endure extreme conditions (Treonis & Wall, 2005). Perturbation of populations of nematodes such as *Scottnema lindsayae* in Antarctic soils by climate change has been reported with enhanced moisture to soils due to ice melting (Andriuzzi et al., 2018). This is likely to act similarly on PPNs in agricultural ecosystems around the globe. In considering the possibility of elevated atmospheric CO_2 concentrations affecting plant physiology and root exudates, the nematode would also be able to indirectly influence behaviour and establish host interactions (Virginia & Wall, 1999).

Sensitivity to Environmental Changes

Nematodes are very sensitive to environmental changes like temperature, water availability, and organic matter. Because climate change modifies these factors, nematode communities serve as useful indicators of ecological changes. For example, a nematode community's composition may change in response to warmer temperatures, with thermophilic species being favoured. These types of observations highlight the role of the nematode as an ecological driver of nutrient cycling and decomposition and other components of the ecosystem. (Bonger et al. 2001)

Diversity and Community Structure

Through nutrient cycling and decomposition of organic matter, nematodes are among the most diverse and important organisms in the processes occurring in the environment. Their community composition is determined mainly by ecological factors, like temperature, altitude and rainfall, and edaphic factors like soil pH, moisture and mineral content. They regulate nematode population dynamics and their reaction to small environmental changes is exhibited among sensitive species. Acidic soils have higher densities of nematodes which are plant-parasitic, omnivorous, and predatory; nitrogen soils support bacterivorous nematodes. Elevation gradients also affect nematode diversity and trophic structure. Lower altitudes that are generally conducive to ecosystem equilibrium and soil biota have higher generic richness. But it is higher altitudes that are connected with lower biodiversity and lower maturity indices, as well as less complex soil food webs whose energy flow is mainly by means of fungi. Climate-related parameters like mean annual rainfall and corresponding average temperature correlate very closely with nematode community composition indirectly by affecting soil properties and vegetation. (Neher et al. 2001)

Generally, nematode assemblages present the interactive manifestations of biotic and abiotic factors on soils and hence function as good predictors for ecological variation in various kinds of habitats.

Soil Health Indicators

Nematodes decompose organic matter and cycle nutrients, so the health of soils can be attributed to them. These changes can easily be detected by the study of the population dynamics of

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nematodes because they are good bioindicators of soil condition changes due to factors like climate change, changes in precipitation regimes, and increased temperatures (Wang and McSorley, 2005). Nematodes have different feeding habits and life strategies from opportunistic colonizers through persistent species, proving them resilient to disturbed habitats. Their capacity in the distribution of microbial propagules and development of bacteria improves nutrient mineralization and soil fertility enhancement. By the study of nematode communities according to functional guilds and indices such as enrichment index (EI) and structure index (SI), the scientists can acquire quantitative knowledge on nutrient cycling and soil health (Wang and McSorley, 2005). Thus, the observation of nematodes provides a powerful instrument for assessing ecosystem stability and improving soil management strategies.

Trophic Indicators

The presence of nematodes in the soil food web is thus of utmost importance, acting as bacteria feeders, fungi grazers, predators, and omnivorous organisms. Having considered their diverse feeding mechanisms, one may assess the health of the ecosystem with nematodes as bioindicators. Quite sensitive to climate-induced variables, temperature rises, or decrease in soil moisture affecting nutrient cycling and carbon sequestration are the two that top the nematode-trophic level which are omnivores and predators (Guixin et al., 2023). Their populations mainly increase in moist and warm soil conditions above 21°C prevailing in several soil environments, while declines are witnessed when subjected to acidic and poor soils (Shah et al., 2021). Based on ecological indicators, i.e., the maturity index (MI) and the enrichment index (EI), etc., the nematode communities serve as indicators of soil health: the forests will exhibit higher functional diversity and stability compared to disturbed system types (Kergunteuil et al., 2021). The microscopic engineers also enhance the economy of organic matter; they increase microbial biomass and therefore cause nitrogen mineralization and plant production—yet another service that is witnessing increased risk from climate change (Shah et al., 2021). Thus, nematode trophic-interaction-monitoring allows for glimpses into ecosystem resilience, acting in turn as sentinels of environmental change.

Geographic Distribution

The impact of global warming is felt by shifting climatic zones which, in turn, cause shifts in the geographical ranges of nematode species and their subsequent possible interaction with ecosystem functioning and biodiversity. The dispersal of certain nematodes, such as *Rotylenchulus reniformis* in North America and *Bursaphelenchus xylophilus* in Asia and Europe, relates to elevated temperature and changes in precipitation regimes, whereas others, such as PPNs, react according to local conditions (Hirata et al., 2017; Liu et al., 2022). One of the most common responses to warming is the latitudinal and altitudinal dispersal of nematodes-especially in alpine and temperate ecosystems-where their abundance and community structure have been altered by changes in soil

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microenvironments (Afzal et al., 2021; Dong et al., 2022). Monitoring change in ranges thus gives a good indication of ecosystem responses to climate change and enjoins climate-smart management for potential agricultural and ecological mitigation (Dutta and Phani, 2023).

Conclusion

Nematodes are interdisciplinarity bioindicators of climate change. They are highly sensitive and responsive to knock-on effects on the health and resilience of an ecosystem. They end up being very good bioindicators to demonstrate the connection of environmental change on soil quality, biodiversity, and ecological imbalance. Through the observation of nematode populations, one can be able to assess the indirect impact of climate change on terrestrial and aquatic systems, thus aiding in the formulation of sustainable conservation guidelines. Far more is required from additional research on the topic, and any further work pertaining to nematode diversity and behaviour will only contribute to the body of knowledge regarding climate change effects on ecosystems in the long term.

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