

Review Article

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Nematodes as Biological Indicators: Managing Soil Health: A Review**S. P. Tiwari¹, Raja Husain², Nitin Vikram³, Sonika Pandey⁴ and Narendra Kumar⁵**¹Faculty of Agriculture, Mangalayantan University, Jabalpur, M.P.-482001, India²Department of Agriculture, Himalayan University, Itanagar, Arunachal Pradesh-791111, India³Zila Parishad Krishi Mahavidyalaya, Banda-210001, India⁴Division of Crop Protection, ICAR IIPR, Kanpur-208017, India⁵Faculty of Agriculture, Oriental University, Indore, M.P.-452001. India**ABSTRACT**

Indian soils are prone to nematode growth, affecting stability. Biocontrol fungi like *Trichoderma harzianum* stimulate frugivorous nematode population growth, while predators like mononchid and diplogasterid play crucial roles in soil food web dynamics. Larger, higher trophic-level creatures react more strongly to environmental changes, while microscopic soil-borne nematodes are unclear if they are similarly sensitive to size or trophic level. The Andrassy equation's maximum body width was underestimated due to the A/L ratio. Nematodes, including *Scottinema lindsayae*, *Plectus murrayi*, *Eudorylaimus antarcticus*, and *Monhystera villosa*, impact domesticated plants in Antarctic regions. They require ideal temperatures for development. Docking disorder in the English sugar beet region caused root damage to seedlings by *Trichodorus* and *Longidorus* species, affecting root shape. Soil health indicators support ecosystem functions like carbon accumulation, water movement, and microbial community activity. Improved soil physical qualities positively impact N and organic carbon contents. Soil pH, a key indicator of soil health, influences plant growth and survival rates. High concentrations of *Pratylenchus alleni* and *Hoplolaimus galeatus* colonise soybean roots. Research shows that nematode population densities, EC, and soil texture are linked. Soil biological condition is assessed using electrical conductivity for crop management. 37-59% of soil nematodes are herbivorous and sensitive to plant output. Nitrogen addition affects trophic groups, with fungivores negatively affected. Plant susceptibility to nematodes depends on attraction, repellence, and diet composition.

Keywords: *Scottinema lindsayae*, *Plectus murrayi*, *Eudorylaimus antarcticus*, and *Monhystera villosa*, impact domesticated plants in Antarctic regions

Introduction

The impacts of numerous global change drivers, such as increased atmospheric carbon dioxide levels, higher temperatures, changed rainfall patterns, and atmospheric nitrogen deposition, must be taken into account when discussing soil health in the context of climate change. The unique combination of physical, chemical, and biological traits that affect soil processes is known as soil health. Understanding the condition of the soil management techniques and climate change factors is necessary for evaluating its health. Wixon and Balsler (2009), however, raised attention to the dearth of convincing evidence for the fundamental causes of these modifications. The complex relationship between climate change and soil health has been shown by research efforts that have enhanced our understanding of the causes of climate change and their consequences on soil quality. Although the terms "soil health" and "soil quality" are sometimes used synonymously, the former emphasizes the biological processes and biodiversity of the soil, highlighting its dynamic living nature.

Because of their vital function in soil ecosystems and sensitivity to changes in soil conditions, nematodes have attracted

increased interest as biological indicators for managing soil health in recent years (Lu et al., 2020; Yeates, 2020). Nematodes, belonging to the class Soil Fauna, provide important information about the general condition and operation of soil systems. Through the examination of nematode population and variety within a specific soil sample, researchers can extract insights into elements like soil nutrient availability, organic matter breakdown, and the general ecological balance of the soil (Nisa et al., 2021; Lu et al., 2020; Hoogen et al., 2019).

Furthermore, because of their susceptibility to toxins like pesticides and heavy metals, nematodes can be used as markers of soil toxicity and pollution. Therefore, nematode community monitoring not only helps evaluate the health of the soil but also furnishes essential information for well-informed decisions on environmental remediation and soil management approaches (Pan et al., 2016; Park et al., 2016).

Nematodes have emerged as valuable biological indicators for managing soil health, offering insights into soil nutrient availability, organic matter decomposition, ecological balance, and pollution or toxicity levels. Monitoring nematode communities can facilitate informed decisions regarding soil management practices and environmental remediation efforts (Yeates, 2010; Li et al., 2005; Barker et al., 1994).

Various fields, including biology, environment, economics, society, institutions, and politics, use indicators, computed values, or statistics to assess soil health. These tools establish functional connections among properties, aiding in sustainable land management and environmental assessment. Evaluating soil health entails selecting markers, limiting data, creating

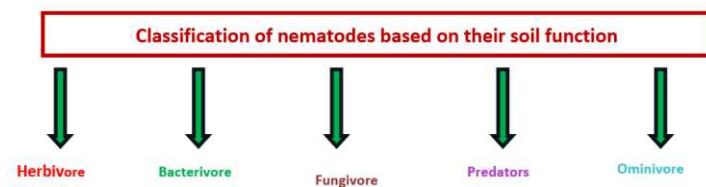
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interpretation systems, and validating findings. Despite advancements in soil health testing, the effectiveness of indicators in tracking soil functions amid climate change remains inadequately explored (Dalal et al., 2003).

Nematodes flourish in soil, with a 100-cc sample of soil capable of holding thousands of nematodes. While much is known about plant-parasitic nematodes due to their significance in agriculture, the majority of soil nematode species aid in the breakdown of organic matter rather than parasitizing plants, often referred to as free-living nematodes. Nematodes can reside in the thin layer of wetness surrounding soil particles, with the rhizosphere soil around small plant roots and root hairs providing an especially rich environment. Within the Phylum Nematoda, there are between 16 and 20 separate orders, with four—Rhabditida, Tylenchida, Aphelenchida, and Dorylaimida—being particularly prevalent in soil. While most plant-parasitic nematodes are well-known, research on most free-living nematodes remains limited. Consequently, there is a likelihood of undiscovered species of free-living nematodes in most soil ecosystems. Identifying these groups is challenging, with only a few nematode taxonomists worldwide capable of formally describing new species of free-living worms to science. As such, most nematode ecologists face difficulties in this regard.



Herbivore

Herbivorous nematodes, comprising about 50% of all nematodes, feed on plants and contribute positively to crop health by controlling pests. However, plant-parasitic nematodes pose a threat to crop biodiversity by diverting nutrients from plants, often leading to plant death. Ingham and Detling (1994). Farmers mitigate these risks through crop rotation. Beneficial nematodes also play a crucial role in agriculture by preying on soil-dwelling insects, contributing to pest control without harming beneficial organisms. McSorley and Frederick (2000). These nematodes, safe for gardens and harmless to humans and pets, can be purchased and applied as per instructions. Additionally, nematodes play a vital role in decomposition and nutrient cycling in soil ecosystems. Predatory nematodes regulate populations by consuming plant-parasitic and other nematodes, as well as protozoans and some insects. Remarkably, nematodes exhibit resilience to extreme conditions, as evidenced by the survival of species like *C. elegans* during space shuttle re-entry and Antarctic nematodes enduring intracellular freezing, dependent on food availability. Yeates *et al.*, (1993)

Bacterivore

Bacterivore nematodes play crucial roles in soil ecosystems and can exhibit diverse responses to environmental stressors. Studies have shown that different bacterivorous nematode species, such as *Caenorhabditis elegans* and *Acrobeloides tricornis*, have distinct life traits and ecological strategies for exploiting habitats over varying time periods Je-Hyun et al., (2022). These nematodes can influence soil functional stability following stress, with some species displaying higher resistance and resilience to stressors like copper and heat Xiaoyun

et al., (2020). Additionally, the interactions between bacterivorous nematodes and fungi like *Pleurotus* species highlight species-specific dynamics, where some nematodes are susceptible to nematophagous fungi while others can consume the fungi, emphasizing the importance of understanding host ranges for biological control purposes (Annette et al., 2020; Maria, et al., 2019; Tongbin et al., 2018).

Fungivore

Fungivore nematodes are nematodes that primarily feed on fungi. Research indicates that the presence of biocontrol fungi, such as *Trichoderma harzianum*, can stimulate the population growth of frugivorous nematodes, ultimately reducing the biocontrol ability of the fungi to parasitize other fungi like *Sclerotinia sclerotiorum* (Tae et al., 2021; Zhaoyang 2022). Additionally, studies have shown that fungivory by nematodes can decrease fungal and bacterial diversity in soil, while stimulating carbon and nitrogen cycling, potentially through impacts on bacterial communities Ting-Hao et al., (2020). Furthermore, nematode-trapping fungi have been identified as natural antagonists of nematodes, with the ability to switch to a predatory stage in the presence of nematodes, producing various metabolites that exhibit species-specific bioactivities against nematode prey (Akhona et al., 2018; Gabriela et al., 2017).

Predators

Predatory nematodes play a crucial role in biological control, exhibiting diverse feeding habits and prey ranges. They include Mononchid predators in colder environments (Harjot et al., 2020), diplogasterid predators like *Fictor composticola* that consume various nematode categories (Ting-Hao et al., 2020), and predacious mites such as *Parasitus fimetorum* and *Macrocheles muscaedomesticae*, which are effective against root-knot nematodes (Guillermo et al., 2018). Additionally, nematode-trapping fungi like *Arthrobotrys* spp. switch to a predatory stage to capture and consume nematodes, producing various metabolites with bioactivities against nematode prey (Nithinya and Ramani, 2019). These predators exhibit distinct mechanisms for prey capture, including attraction, recognition, trap formation, adhesion, penetration, and digestion (Ching-Ting et al., 2020).

Omnivore

Omnivorous nematodes, including species such as *Eudorylaimus*, *Aporcelaimellus*, and *Mesodorylaimus*, thrive in diverse environments ranging from Florida, the USA, to various regions in Europe. These nematodes demonstrate resilience across extreme conditions and different soil types (Hossain et al., 2016). They are particularly sensitive to moisture levels and the presence of pollutants, with studies showing adverse effects from inorganic fertilizers and agrichemicals (Robert, 2012). Research has also revealed the presence of plant-parasitic nematode DNA within the gastrointestinal tracts of both predatory and omnivorous nematodes, highlighting their integral role in soil food web dynamics (Cabos et al., 2013; Caspe et al., 2017). Furthermore, nematode communities, including omnivores, are recognized as effective bioindicators for evaluating the health of soil biota, reflecting their ubiquitous presence across all trophic levels of the food web (Stefan et al., 2015; Franciszek et al., 2008).

Microbial Biomass in Soil

The primary regulators of essential ecosystem activities, including organic matter decomposition, nutrient cycling, and gaseous fluxes, are the variety and biomass of soil microbial communities. plant communities, to completely understand the relationships between biomass and diversity in soil microbial communities. Determining the regulation of microbial-driven processes on a changing globe requires knowledge of such phenomena. Although many organisms are geographically separated in soil, several studies have concluded that competitive exclusion is more significant for aboveground communities than for belowground populations. Soil carbon (C) fluxes drive microbial biomass and belowground production. The long-running conversation in ecology about the relationship between biomass and biodiversity began with studies of plant communities, which proposed that resource availability is a major factor regulating plant productivity and/or biomass and that there is an unimodal ("humped-back") relationship between productivity and plant diversity. Less than 5% of the total soil organic matter is usually made up of microbial biomass, but this biomass is extremely important for many important soil processes, including as nutrient release, maintaining a healthy soil structure, and suppressing plant diseases. Measurements of the soil's microbial biomass may offer the data required for ecosystem-level monitoring of the initial disturbance and recovery. Given that major N, P, and S transfers take place in terrestrial ecosystems, the significance of microbial biomass in global nutrient cycles is well recognized. When it comes to their contribution to the worldwide soil microbial biomass (7 Gt C), bacteria are the most prevalent organisms in the soil, second only to fungi. The living part of soil organic matter, microbial biomass is thought to be the most variable carbon pool in soils and a sensitive indicator of changes in soil processes. It has connections to the dynamics of soil nutrients and energy, and it also plays a role in mediating the transfer of carbon between soil organic carbon fractions. (Saha and Mandal 2009). The shift in microbial biomass at 13°C, when paired with the 13°C isotope tagging technique, may offer a more sensitive estimate of changes in soil carbon processes in response to changes in land use and climate than the total microbial biomass carbon (Paterson et al. 2009). Since fungus and bacteria produce more ammonium than nematodes require, the excess is discharged in a form that is accessible to plants.

Microbes and tiny metazoans dominate soil biodiversity and are responsible for many ecological activities, including soil carbon cycling and plant performance. Nematodes thereby catalyze the cycling of nutrients and both favorably and unfavorably impact plant growth. Soil water and organic carbon are the main climatic and edaphic factors that influence nematode abundances and change the character of nematode communities, whereas higher soil pH and temperature decrease nematode diversity and density. Nematode diversity and abundances, especially those of fungivores, herbivores, and omnivores, have been shown to decline with elevation due to changes in these and other climatic and edaphic features. Most of the information available on the fluctuation of nematode communities along environmental and spatial gradients has come from compositional data obtained using non-quantitative genetic methods or abundance-based data of certain taxa or functional categories. Particularly vulnerable to fluctuations in the environment and global change is body size. Studies on collembola in soils have shown that size-based or biomass-based techniques can offer a thorough understanding of both

functional changes in the community and the distribution of body sizes. It has been demonstrated that variations in body size among various kinds of organisms in the soil, such as nematodes, influence ecological processes including community assembly. Changes in soil and benthic food webs have been used as markers of habitat quality, and alterations in nematode body size have been used to measure these changes (Shunran, 2023). Larger and higher trophic-level creatures found above ground frequently react to environmental changes more strongly than smaller and lower trophic-level organisms. Still unclear is whether the most common creatures, microscopic soil-borne nematodes, are similarly sensitive to size or trophic level. Nematode biomass $G(\text{fLg}) = (U72 \times L) \times (16 \times 1\{-5)$ was the An-drassy equation. The maximum body width, which is typically employed in the Andrassy equation, was understated because of body width W (J. Lm) was computed as the A/L ratio.

How do nematodes function in soil?

In the soil food web, nematodes are not the highest organisms. As previously mentioned, the soil contains predatory nematodes that eat other nematodes. Being biocontrol agents—that is, able to eradicate other organisms and nematodes that cause disease—is one of the main roles of soil nematodes. Because tropical groupings respond to changed environmental conditions differently than other groups, species-level analysis is more insightful and favored for research. The majority of nematodes, which are incredibly diverse groups, are involved in a variety of tasks at various stages of the soil food web. Both species-level taxonomy and trophic-level guilds serve as the foundation for nematode diversity in both natural and agroecosystems. Nematodes can prime the beneficial services of other species in the food web by either boosting exudate leakage or acting as prey for parasites and predators when they feed on plants at low population densities without clearly harming their hosts (phase 1). This nematode's larger size makes it nearly stationary in individual soil pore spaces. It can only reach large populations in high porosity soils, such as sands and well-structured clay loam soils. Because the pores in fine sandy loam soils are smaller, population growth is constrained. The formula used to compute nematode biomass was $W = L \times D2/(1.6 \times 106)$, where W represents the fresh weight of each worm. Tiny roundworms called nematodes are found in the soil of our landscapes, crop fields, and gardens. Several nematodes are beneficial to plants, though others are harmful to plants. By feeding on plant roots, these harmful nematodes cause damage to plants and negatively affect their growth. Counting the number of nematodes in different trophic groups or families has been proposed by many scientists as a means of assessing the quality of soil, because nematode populations are relatively stable in response to changes in temperature and moisture content. Because they are tiny, inhabit a water film, and create long-lasting soil microenvironments, they are valuable indicators. Protozoa and other soil nematodes serve as food for predatory nematodes. Depending on the habitat and the availability of food, omnivores can consume a variety of foods. For instance, omnivorous nematodes can be predators but can also eat bacteria or fungi in the absence of their main food supply. Nematodes improve soil quality, eat disease-causing organisms, mineralize minerals into forms that plants can use, and supply food for other soil creatures. It is thought of nematodes as grazers.

In addition to consuming smaller creatures, they spread bacteria or fungi on them and in their digestive systems as they travel through the soil profile. Predatory nematodes consume other soil nematodes and protozoa. Omnivores can eat a wide range of foods, depending on their environment and the availability of food. If their primary food source is absent, omnivorous worms, for example, can both consume bacteria and fungi and function as predators. Nematodes will accelerate the growth rate of prey populations if their number is low. Nematodes may be detrimental to the health of the soil if their number is large. The population of other nematodes is balanced by predatory nematodes. Nematodes expel more ammonium (NH_4^+) as they eat bacteria or fungi. Soil microarthropods and Nematodes provide a food source for bacteria, fungus, and insects. *Helicotylenchus* and *Paratylenchus* feed slowly on the root cortex or epidermis appears to have less of an impact on plants compared to root knot, *Meloidogyne* and cyst nematode, *Heterodera*. Both parasites are vascular feeders. Nematodes play a crucial role in mineralizing nutrients and releasing them in a form that plants can use. When nematodes eat bacteria or fungi, ammonium (NH_4^+) is released since nematodes don't need as much nitrogen as bacteria and fungus do. At low worm density, feeding by nematodes increases the pace at which populations of prey increase. Plant feeders encourage plant development; bacterial feeders encourage bacterial growth, and so on. At larger densities, nematodes will decrease the population of their prey. This can have a detrimental effect on mycorrhizal fungus, lower plant yield, and slow down the rates at which bacteria and fungi decompose and immobilize. To stop bacterial and fungal-feeding nematodes from overgrazing, predatory nematodes may control their populations. The species composition of the microbial community and the equilibrium between bacteria and fungus may be regulated by nematode grazing. Nematodes carry both active and dormant microbes on their surfaces and in their digestive tracts, which aids in the distribution of bacteria and fungi through the soil and along roots. Higher-order predators, predatory nematodes, soil microarthropods, and soil insects all eat nematodes. They are also parasitized by bacteria and fungi. Some nematodes cause disease. Others consume disease-causing organisms, such as root-feeding nematodes, or prevent their access to roots.

Microbiological indicators as integrative

Soil microbial properties need to be considered with soil health indicators. *Scottinema lindsayae*, *Plectus murrayi*, *Eudorylaimus antarcticus* and *Monhystera villosa* were suitable for their habituated under influenced soil moisture, carbon, and salinity in Antarctic regions.

Functional and genetic diversity in soils

Due to potential evolutionary changes that permit the spread of virulence factors and genes that support environmental survival, changing climatic conditions are also a cause for concern (French et al. 2009). The variety of soil nematode species is frequently high, both at the ecosystem and individual soil-core levels. The long-term stability of soil functioning depends on the diversity of soil nematodes. Numerous nematologists have also noted the connections between environmental factors, such as greenhouse gas fluxes, and the functional genes of soil microbial communities.

Choosing the most important indicators of soil health:

Many soil health indicators predict climate change scenarios.

The indicators of soil health are connected to worldwide shifts. conceptualization of the relationships between soil health indices, land management, and climate change (Balser 2006). The primary markers of soil health and their functions and relevance climate change, and the frequency with which they are incorporated into a minimal data set for evaluating soil health. Idowu et al.(2009) suggested the following essential indicators as:

1. Sensitive to changes resulting from management and climate variations
2. Integrated soil properties
3. Relatable to important soil functions
4. Applicable to field conditions
5. Accessible to many users should be included in a minimum data set for the assessment of soil health

Activity of enzyme

Since soil enzyme activities

1. Closely linked to the cycling of nutrients and soil biology
2. Easily measured
3. Integrated information on both the microbial status and the physicochemical soil conditions
4. Showing rapid response to changes in soil management, they may serve as an indicator of change within the plant-soil system (García-Ruiz et al. 2009). Elevated CO_2 may promote microbial enzyme activity by changing the amount and quality of carbon uptake by plants below ground, as demonstrated by Dorodnikov et al. (2009). Furthermore, the deposition of atmospheric N may impact extracellular enzymes. Homogenates and extracts of *Ditylenchus iriformis*, *D. dipsaci* and *Pratylenchus zae* were assayed for hydrolytic, respiratory and terminal oxidative enzymes by viscosity, titration, colorimetric and spectrophotometric techniques identified that lactic dehydrogenase activity was present in extracts from *D. trifornnis* but doubtful in *D. dipsaci*. Fumarase and cytochrome oxidase were detected in extracts from *D. iriformis*. Variable protease and no polygalacturonase activity were found in homogenates of the above nematode species.

Drivers of climate change

Temperature

The reniform nematode is well known for its capacity to endure in the absence of a host. It is widely found throughout the world's tropical, subtropical, and temperate climates. A wide variety of domesticated plants are impacted by nematodes. The nematode exhibits obligatory, stationary, semi-endoparasitic behavior as a root-dwelling parasite. *Rotylenchulus reniformis* has a very brief life cycle at room temperature. One-celled eggs laid by mature females reniform nematode into a gelatinous matrix are developed into first-stage juveniles (J_1). While the nematode is still inside the egg, the first cuticle molt takes place. The juvenile second stage (J_2) emerges from the egg, and subsequent juvenile stages (J_3 and J_4) remain in the soil until when one reaches to maturity. Without the assistance of a host plant, eggs can hatch in water, and juveniles can develop into pre-adult females and males on their own without food. *R. reniformis* directly responds to high relative humidity (RH) conditions that mimic natural dehydration regimes by inducing an-hydrobiosis larval or pre-adult could withstand short-term, direct exposure to 97% RH. Nevertheless, coiling and a successful transition into an-hydrobiosis were produced by dehydrating larvae on model substrates that replicate the usual rate of soil moisture loss.

In ten to twelve days, the maximum degree of coiling occurred, and only coiled larvae were able to become pre-adults by surviving dehydration. Larvae could withstand severe dehydration at 80 and 40% relative humidity when coiling was induced, but not direct exposure to 0% RH.

As poikilothermic creatures, root-knot nematodes typically depend on temperature for their development. The lower threshold temperature value, the thermal environment to which these nematodes are acclimated, and the thermal constant, which indicates the relative rate of development, may all be estimated thanks to the linear relationship between temperature and rate of development. Tropical species are typically linked to lower threshold temperature values that are higher, and temperate species to lower levels. For *M. hapla* and a few other species acclimated to cold climates, the ideal temperature range is 15–25°C; for *M. javanica* and other species adapted to warm climates, it is 25–30°C. No development or very little activity happens in any *Meloidogyne* species above 40°C and below 5°C. In commercially significant crops, virulent species such as *Meloidogyne enterolobii* and *M. floridensis* can overcome resistance to nematodes known to cause knotting in roots. Our goals were to calculate the variations in duration and thermal-time requirements for these two species second-stage juveniles (J_2) to finish their developmental cycle, as well as the impact of temperature on their infectivity. The generation time and reproduction of *Meloidogyne incognita* were investigated using five different soil temperatures. Tomatoes completed their life cycle at average soil temperatures of 16.2°C to 30.0°C, but not at 35.4°C. In growth chambers maintained at consistent temperatures (10–35°C), the life cycle of a Portuguese *Meloidogyne hispanica* isolate on susceptible cv. Easy peel and resistant (Mi-1.2 gene) cv. Rossol tomato plants were examined. The hatching and internal development of the egg were compared to an isolate of *M. arenaria* from Portugal. It did not develop any eggs at 10°C or 35°C. A temperature rise was associated with a greater number of *M. hispanica* second-stage juveniles (J_2 s) invading tomato roots.

The optimal hatching temperature of the two forms of cyst nematodes has been determined to differ. It appeared that the ideal range of temperatures for *H. schachtii* hatching was between 15 and 30°C, and for *H. betae*, it was between 20 and 30°C. At 5°C, young specimens of both species of beet cyst nematodes arose, albeit in minimal proportions. Notable differences were seen between the usual temperature range and the higher temperature range of 4°C for both types of beet cyst nematodes when comparing the final cumulative hatch percentages.

Rainfall

Although the exact process is yet unknown, there is evidence that soil biodiversity does provide stability to stress and disturbance. It seems to rely on the type of stress and disturbance as well as the interaction between the effects of the two. On the other hand, the structure of the community might matter. Based on the research that is currently available, mycorrhizal variety may have a positive impact on water and nutrient usage efficiency. Although diversification effects may be indirect due to effects on soil structure, soil fauna effects on nutrient and water usage efficiency are also evident. After a lot of rain, docking disorder developed throughout the English sugar beet region. Root damage to seedlings is primarily caused by *Trichodorus* and *Longidorus* species. In locations where symptoms persisted, root shape was the worst. Both the temperature and atmospheric CO₂ have elevated by 0.3–0.6°C.

Climate change may have a beneficial effect on plant diseases, a detrimental influence, or no effect at all. To evaluate the effect of desiccation treatment on gene expression, a 35 mm Petri plate containing a 200 µl slurry of about 1000 nematodes was exposed to different relative humidity conditions. Pre-treat + desiccation (3 days of exposure to 75% RH following pretreatment), desiccation, and pre-treat + rehydration (rehydrate with 4°C water after pre-treat + desiccation) were the treatments that were applied to the nematodes.

Soil Structure

Because each soil aggregate fraction has different physical and/or resource limits, nematode and microbial communities differ as well, which influences management effects on entire soil food webs. The LM fraction had higher levels of microbial biomass, gram-positive bacteria, and eukaryotes than the IS fraction, according to phospholipid fatty acid (PLFA) studies, whereas the SM fraction had intermediate levels of PLFA linked to these categories. Under RC and ORG, the total PLFA was higher than under CC or CON. While nematode abundance showed no such association, total PLFA showed a favorable correlation with the percentage C in soil fractions.

Soil is home to a wide variety of biota: sand, sediment, clay, pores, and organic matter. It is used as a soil health indicator because it supports the maintenance of important ecosystem functions within soil, such as the accumulation of organic carbon, the infiltration capacity, water movement, and storage, and the activity of root and microbial communities. Soil resistance to erosion can be measured, and its relationship to the storage of SOI organic carbon and water can be used as a guide to climate adaptation strategies. This is especially important in areas with high and frequent rainfall, as this increases the risk of erosion events. Pore characteristics are closely associated with soil physical quality. Bulk density, as well as macro porosity, are related to pore volume. Porosity and water discharge characteristics are directly related to several soil physical parameters, such as soil aeration capability, plant availability of water, relative field capacity, and so on (Reynolds et al. 2009).

Aggregate stability, which refers to the ability of soil aggregates to withstand external energy sources such as intense rainfall and cultivation, is influenced by many chemical and biological qualities, management techniques, and soil structure. The N and organic carbon contents were positively impacted by improvements in the physical qualities of the soil. One element of the biological control of the phytopathogenic nematode *Helicotylenchus multicinctus* might be *P. phaseoloides* (Banful and Hauser, 2011). The microbial and soil nematode communities in soil aggregates change after fertilization, and nematodes and microbe interactions can either promote or inhibit microbial activity. Protorhabditis and *Pratylenchus* abundances as well as the overall number of nematodes are influenced by aggregate fractions.

Microbial biomass and diversity were also impacted by aggregate components. While both fertilization and aggregate fractions considerably changed the composition of the microbial community, only fertilization had a major impact on the compositions of the nematode groups. Total C had the biggest impact on microbial biomass, according to aggregated boosted trees (ABT) research, although pH had an impact on the total number of nematodes. Microbial activity may be reduced by microbivores grazing on microorganisms.

Bulk Density

Bulk density is thought to be a helpful indicator for evaluating the health of the soil concerning its functions (aeration and infiltration). Because bulk density and soil organic matter (SOM) or soil organic content are generally negatively correlated (Weil and Magdoff 2004), loss of organic C from increased decomposition due to elevated temperatures (Davidson and Janssens 2006) may cause bulk density to increase, making soil more susceptible to compaction (land management practices and climate change stresses), variable and high-intensity rainfall, and drought events (Birka's et al. 2009). Compaction not affect the overall population of nematodes; however, it did cause a shift in the distribution of these animals among the different feeding types, with a greater number of herbivores and a lower number of bacterivores and omnivores/predators. The nematode assemblage's altered structure is linked to unfavorable crop growth circumstances. The effects on the nematode assemblage and soil food web of continuous cropping (CC), intermittent fallow (F), standard tillage (ST), and no tillage (NT).

Rooting Depth

Rooting depth is seen as a soil health parameter as changes in this parameter are likely to have an effect on the plant's available water capacity (Birka's et al., 2009), subsoil salt content (Rangaswami, 2010), SOC content (Bhatnagar et al., 2010), and other physicochemical constraints of the soil profile. In the event of prolonged drought, subsoil constraints (e.g. salinity, high chloride concentration) are likely to have a greater effect on plant availability of water and hence on plant productivity. The Nematode density decreased with depth and the root mass decreased as well. Lesion nematodes were found to be higher at the 30'–60' cm depth as compared to the shallower layer. However, it was decided to repeat the bimonthly sampling at a depth of approximately 30's to account for areas of sandy clay loam soils that are shallower in depth. The *Meloidogyne* spp. and the *Tylenchulus semiipenetrans* were higher at the depth of 30–60 cm. However, this did, this did not apply to all nematodes, especially *Criconebella xenoplax*.

Soil Surface Cover

A layer of crop residues or biological soil crust plays a crucial role in various ecological functions. These include protecting the soil surface from raindrop impact energy, stabilizing the soil, reducing erodible surface area, retaining water and nutrients, fixing carbon and nitrogen, supporting native seed germination, and impacting ecosystem functions and plant productivity. Assessing their contribution to mitigating the adverse effects of climate change is essential for climate change adaptation. Nematodes play a direct role in soil processes and can indicate the structure and function of other organisms within the soil food web. Nematode indices help in understanding the impact of environmental stress, dominant decomposition pathways, and soil suppressiveness on plant parasites and pathogens. Cover crops offer an appealing alternative by reducing erosion, alleviating soil compaction, increasing soil organic matter, and influencing soil organisms. Nematodes serve as valuable indicators of soil food web dynamics.

pH

Soil pH is one of the primary chemical indicators of soil health, depending on parent material, weathering period, vegetation, and climate.

At pH6.0, the highest concentrations of *Pratylenchus alleni* and *Hoplolaimus galeatus* colonized soybean roots; at pH6.0, *Tylenchinae*-*Psilenchinae* had the best survival rate, and the highest concentrations of *Dorylaimoidea* were found between pH6.0 and 8.0. More of the non-stylet nematodes were found in the pH 8.0 soil. To evaluate the effects of land use change and agricultural practices, soil pH has thus been included in integrated soil health testing (Gil et al. 2009). Brinkman and Sombroek (1999) suggested that most soils would not be subjected to rapid pH changes resulting from drivers of climate change such as elevated temperatures, CO₂ fertilization, variable precipitation, and atmospheric N deposition are the drivers of climate changes and these affect organic matter status, C and nutrient cycling, plant available water resulting plant productivity. According to Brinkman and Sombroek (1999), the majority of soils would not experience abrupt pH changes as a result of climate change drivers like high temperatures, CO₂ fertilization, erratic precipitation, and atmospheric N deposition. These factors also have an impact on the availability of water for plants, the cycling of carbon and other nutrients, the status of organic matter, and plant productivity.

Electrical Conductivity

Along with pH, soil electrical conductivity can serve as a proxy for soil structural deterioration, particularly in sodic soils. It also provides information on trends in salinity, crop performance, nutrient cycling, and biological activity. Sandy soils pose a bigger threat from nematodes. Numerous researchers have already established studies on the spatial association between nematode population densities, EC, and soil texture. The biological condition of soil has been assessed using electrical conductivity as a chemical indicator concerning crop management techniques (Gil et al. 2009). According to Smith et al. (2002), in a semi-arid environment, pH rose and EC fell.

Carbon dioxide (CO₂)

Because plant responses have ecological ramifications that extend across the ecosystem, net ecosystem reactions to increasing CO₂ cannot be anticipated merely from plant physiological responses. Root production, exudation, root to shoot ratios, and fine root turnover are all increased by increased C fixation. The most prevalent and varied class of soil organisms are nematodes. The extraction of nematodes from roots revealed variations in the population densities of several species in the soil. The effects of CO₂ treatment were greater on nematode respiration when measured as a function of average individual size and population density than on community structure. For instance, increased CO₂ reduced predaceous nematode respiration by 180% and herbivorous nematode respiration and biomass by 150%. These carbon subsidies have the potential to promote short-term, mineral-producing microbiological activity in the rhizosphere. But unless there is a corresponding increase in the breakdown of decomposing organic matter, labile stocks of phosphorus (P) and nitrogen (N) will be rapidly depleted, and soil processes may ultimately restrict how ecosystems respond to CO₂ enrichment. In instance, nematodes are an excellent option for researching soil food webs. According to Yeates et al. (1993), they play at least five different trophic functions, including those of herbivores or plant-parasites, fungivores, bacterivores, omnivores, and predators. More information is known about their taxonomy, life cycles, metabolism, and eating habits than about any other group of soil invertebrates.

These animals are tiny (0.3 to 2.5 mm in length), have short life cycles (7 to 9 generations annually), and adapt rapidly to environmental and resource changes. They are common, usually found in the upper 15 cm, and range from 105 to 107 m² in the upper 15 cm of forest soils (Sohlenius 1980).

Since 37–59% of all soil nematodes are herbivorous and sensitive to variations in plant output, they are probably going to react to increased CO₂ (McClure 1997). At last, effective methods for removing nematodes from soils have been created (Neher 2001). On defense-dominated genotypes, elevated CO₂ increased the amount of nematode-induced galls, but not on the roots of wild-type or defense-recessive genotypes (Sun et al., 2010). The quantity and variety of soil nematodes were significantly impacted by increased CO₂ and N fertilizer. increased CO₂ and N fertilization at the wheat ripening stage; increased omnivore-predator abundance; and enhanced maturity index (MI) and structural index (SI) of nematode assemblage at the jointing stage of wheat (Li et al. 2007).

At the wheat jointing stage, the abundance of fungivores was significantly influenced by two levels of N fertilization. On the other hand, the nematode channel ratio (NCR) exhibited responses to different N fertilization levels and the combined effects of elevated CO₂ and N fertilization at the wheat ripening stage (Li et al. 2007). It is important to note that soil porosity and pore size distribution, which are closely linked to root development and soil enzyme activities, may be impacted by future climate change scenarios such as elevated CO₂ and temperature, as well as variable and extreme rainfall events. Consequently, soil functions may be affected in unexpected ways, highlighting the need for further research on the relationship between soil health and climate change. Interestingly, the presence of elevated CO₂ and nematode infection did not qualitatively alter the volatile organic compounds (VOC) emitted by plants. However, elevated CO₂ did increase the VOC emission rate specifically in defense-dominated genotypes that were not infected with nematodes.

N deposition

Nematodes have been suggested as valuable indicators for changes in soil ecosystem functioning due to nitrogen enrichment. In general, the addition of nitrogen led to a decrease in total nematode abundance and diversity, although the responses varied across different trophic groups. The decrease in populations of herbivores, fungivores, omnivores, and predators, along with an increase in some opportunistic bacterivores, in forests, grasslands, and croplands in response to nitrogen addition has been well-documented. Additionally, the responses of soil nematodes to nitrogen addition often differ depending on the time elapsed after application. Soil acidification resulting from nitrogen addition has been identified as a key factor inhibiting soil nematode abundance post nitrogen addition, with NO₃⁻-N and NH₄⁺-N concentrations showing a negative correlation with root herbivores and fungivores, indicating direct impacts of nitrogen addition on soil nematodes. It is important to note that changes in physicochemical soil conditions and shifts in plant community composition can also indirectly influence soil nematodes. The trophic groups of nematodes exhibited varied responses to nitrogen addition, with fungivores being negatively affected by the increase in nitrogen; their numbers decreased linearly with nitrogen addition. On average, the abundance of fungivores was higher in August compared to September. Root herbivores were significantly impacted by nitrogen addition in August and September.

While ammonium has been recognized as toxic to a wide range of organisms, it could not fully explain the responses of microbial-feeding and omnivorous-predatory nematodes.

Plant Available Nutrients

The cycle of nutrients, particularly N, is closely related to the cycling of soil organic C and to factors that contribute to climate change, including temperature increases, fluctuating precipitation, and atmospheric N deposition. The background is provided by the chemistry of the soil system, and the soil biota can adapt to shifting environmental conditions (Kibblewhite et al. 2008). Because biological indicators entail intricate adaptation processes, they are essential to the evaluation of soil health in the context of climate change. According to data provided by Ritz et al. (2009), there has been a nearly exponential rise in possible biological indicators since 1970.

Soil Organic Matter

As the quantity of coarse sand increased, the extent of nematode colonization also increased significantly ($r^2 = 0.91$). Conversely, with the increase in silt ($r^2 = 0.97$), clay ($r^2 = 0.80$), and fine sand ($r^2 = 0.83$), the population of soil nematodes decreased. Free-living nematodes play a vital role in decomposing organic matter and enriching soil nutrients. Instead of directly consuming organic materials in the soil, nematode bacterivores, and fungivores feed on the bacteria and fungi responsible for breaking down organic matter. A plant's susceptibility to a specific nematode species depends on various factors, such as the plant's attraction to the nematode, the plant's ability to either attract or repel the nematode, and the composition of the nematode's diet. Soil organic matter (SOM) is a complex and diverse component of soils, encompassing both living and non-living elements. Key indicators for assessing SOM status include soil organic carbon (SOC), which constitutes approximately half of soil organic matter; organic nitrogen (N), which is closely linked to organic carbon and is a crucial nutrient for plant growth; and easily mineralizable carbon and nitrogen (Haynes, 2008). SOM is fundamental in driving most soil functions. A reduction in soil organic matter can result in a decline in fertility and biodiversity, along with the deterioration of soil structure. This can lead to a decrease in water retention capacity, an increased risk of erosion, higher bulk density, and ultimately soil compaction. Due to their small size, nematodes can easily infiltrate the majority of soil aggregates and pores. Belonging to the phylum Nemata, these organisms are notorious for transmitting diseases to humans and other animals, yet they play a vital role in the ecosystem of crops and soil. Practices related to land use and management that promote the accumulation of soil organic matter can aid in the absorption of CO₂ from the atmosphere, thereby helping to combat global warming. Nematodes, commonly referred to as roundworms, are unsegmented creatures with a head, tail, and tapered ends, typically possessing central nervous systems. They are considered one of the most primitive animals due to their complete digestive and reproductive systems.

Soil Carbon

There are several reasons why soil carbon can be utilized as a change indicator, including its familiarity, directness, relationship to ecosystem performance, and "memory," or ability to change over time. Janzen (2005) said. Although there are many different forms and residence times of carbon in the soil, the SOC form has received a lot of attention from researchers because it has been significantly altered by human

activity and is expected to decrease with rising mean global temperatures. These two factors could have negative impacts on crucial soil processes and functions as well as soil quality and health (Lal et al. 2007). Soil organic carbon (SOC) is largely obtained as organic matter from plant residues, microbial residues, and root exudates; these materials are all considered secondary resources.

Potentially Mineralizable C and N

Because it serves as a bridge between autotrophic and heterotrophic organisms during the nutrient cycling process, the amount of mineralizable organic matter in soil is a good measure of the quality of organic matter. Since mineralizable organic matter influences the dynamics of nutrients during individual growing seasons and can be used to evaluate management strategies and C sequestration over long periods, it could be a valuable indicator for evaluating soil health in the context of climate change (Gregorich et al. 1994).

Soil Respiration

Soil respiration is commonly used as a biological indicator for soil health due to its positive correlation with soil organic matter content. It can be measured either as CO₂ production or O₂ consumption (Haynes 2008). The temperature response of soil respiration, especially, is widely recognized as a crucial link between climate change and the global carbon cycle (Wixon and Balsler 2009). However, the exact nature of this relationship is currently a subject of scientific debate (Kuzyakov and Gavrichkova 2010). The four phases involved in respiration are glycolysis, the Krebs cycle, the link reaction, and oxidative phosphorylation. During glycolysis, six-carbon glucose molecules are enzymatically converted into two three-carbon pyruvates. Both anaerobic and aerobic respiration are involved in this process. Pulverization of the soil increases the availability of soil organic matter to microorganisms, stimulating soil respiration and the microbial consumption of nematodes (bacterivores and fungivores). Diffusion plays a crucial role in nematode respiration, allowing gas molecules to move from regions of higher concentration to lower concentration. This process facilitates various stages in the respiration and circulation of nematodes, including gas exchange through their skin. However, in nematodes, waste excretion and gas exchange occur through diffusion across the gut wall, rather than through a true coelom (a body cavity lined with tissue).

Summary and Future Prospects

Indicators that link the physical, chemical, and biological properties of soil can be used to comprehend the effects of climate change on soil health. Significant markers of soil health are influenced by climate change. The ability of indicators to integrate and link to other soil functions, their sensitivity to management and climatic change, their ease of use, repeatability, and measurement cost all play a role in the selection of indicators within a minimal data set. For P. murrayi, the ability to withstand extended periods of low moisture availability and cold temperatures is extremely important for adaptation.

There is a necessity to utilize phytopathogen-feeding nematodes as bio-fertilizers for the cultivation of robust plants or crops. According to previous research, the practical application of nematodes appears to be highly suitable as they effectively boost nitrogen and carbon levels in the soil. The use of nematodes as bio-fertilizers has proven advantageous in agriculture, leading to increased productivity.

Approximately thirty percent of the total inorganic nitrogen is mineralized in the form of soil organic matter, which is then utilized by soil microorganisms. Microphagous nematodes form a significant group that influences microorganism activity and serves as crucial regulators of decomposition and nutrient release processes. Interactions between nematodes and microbes have been examined in temperate soil conditions. Nematodes, found in various habitats, play a pivotal role in advancing ecosystems, enhancing soil properties, increasing soil microbe diversity, promoting plant growth, and boosting crop production. The beneficial nematode fauna in agriculture improves soil health by facilitating the fixation of rhizobacteria, nitrogen-fixing cyanobacteria, beneficial plant bacteria, and the decomposition of microbes.

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