

Functional Diversity of Plant-Parasitic Nematodes in Agro-ecosystems: From Crop Damage Paradigm to Ecosystem Functioning and Soil Health Frameworks

Malti and Lavi Sharma

¹Department of Zoology, Janta Vedic College, Baraut (Baghpat) U. P. – 250611

*Corresponding E- mail: maltitomar@gmail.com

Abstract

Plant-parasitic nematodes (PPNs) have been traditionally classified as some of the most important agricultural pests because of their economic impact on agriculture. However, this view overlooks their varied roles as well as their functions within the different soil ecosystems. This paper summarizes the existing literature on the ecological functions of PPNs by using a trait-based ecological approach. The varied ways in which their feeding modes, life history, host specificity, and other factors impact soil food webs, rhizosphere interactions, and nutrient cycles are evaluated. The need to use multidimensional functional diversity index to establish the link between the structure of PPN communities and functioning of ecosystems is highlighted in the paper. The role of PPNs informational value in assessing soil health, especially in the context of agricultural intensification and climate change, is examined. The importance of taxa integration for accurate trait-function link is also discussed in the paper. The study concludes that considering PPNs as functional components of agroecosystems rather than just pests can contribute to the sustainable management of nematodes and their application in ecological research.

Keywords: *Plant-parasitic nematodes, functional diversity, agro-ecosystems, soil food web, integrative taxonomy, soil health etc.*

Introduction

Redefining the Role of Plant-Parasitic Nematodes

Plant-parasitic nematodes (PPNs) represent a varied range of organisms that dwell in soil, harming plant roots and tissues, thus leading to high agricultural production losses all over the world (Jones, *et al.*, 2013). Traditionally, research on PPNs has been predominantly done from the perspective of pest management, focusing on damage assessment, economic thresholds, and control of pests using chemicals (Perry and Moens, 2011). Even though this approach has improved the effectiveness of crop protection strategies, it has limited the ability to interpret PPNs from a broader ecological perspective in soil systems.

Nevertheless, soil ecology considers nematodes to be one of the components of soil food webs, participating in energy transfers and biogeochemical processes thanks to their interaction with plants and microorganisms (Yeates, *et al.*, 1993; Ferris, *et al.*, 2001). The idea of functional diversity has developed recently and is regarded as an essential

principle for establishing the relationship between biodiversity and ecosystem functioning (Tilman, 2001). However, as a rule, the concept of functional diversity has been applied to free-living nematodes, while PPNs have often been placed in one category.

In addition to the adverse influence on crops, PPNs bring about changes in the rhizosphere dynamics, the process of root exudation, and the interaction of plants with microorganisms (Ferris, *et al.*, 2001; Wardle, *et al.*, 2004). Nowadays, agricultural production has moved towards the application of biological indicators to ensure soil sustainability (Doran and Zeiss, 2000; Lehmann, *et al.*, 2020). Therefore, the implementation of the concept of functional diversity of nematodes into such frameworks allows reassessing the significance of PPNs in a systemic (soil-plant) context.

This review aims to summarize the existing research devoted to functional diversity of PPNs and placement of this concept in the framework of agroecology and soil health.

Knowledge Gaps and Novel Contributions

Although there has been much research on plant-parasitic nematodes (PPNs) as pests of agriculture, their functional diversity has not been adequately synthesized in an ecosystem framework. The majority of soil food web models classify PPNs in one trophic group, which fails to show significant diversity in feeding behavior, host preference, survival strategies and ecological interactions (Yeates, *et al.*, 1993; Ferris, *et al.*, 2001). Moreover, trait-based approaches, which have been widely applied to plants and free-living soil organisms, have hardly been comprehensively applied to the study of plant-parasitic nematodes (Díaz and Cabido, 2001; Tilman, 2001).

Another major gap is the limited linking of taxonomy and ecosystem function. Although many PPN taxa are included in cryptic species complexes, it is common to make functional conclusions at a genus level (Subbotin, *et al.*, 2010). Without integrative taxonomy using morphological, molecular and ecological features, the relationship between traits and function may be misrepresented (De Ley, *et al.*, 2005). The contribution of this review is in:

- a. Synthesizing functional trait categories across major groups of PPNs;
- b. Explicitly linking these traits with soil ecosystem processes and soil health parameters;
- c. Providing a trait-based framework for sustainable management of nematodes in agroecosystems.

Materials and Methods: Literature Search and Review Strategy

In order to maintain transparency and reproducibility, the conducted review followed a structured literature synthesis procedure. The search for the literature was performed in Web of Science, Scopus, Google Scholar, and CAB Abstracts for the period between 1990 and 2024. The following search terms were combined:

“Plant-parasitic nematodes,” “functional diversity,” “trait-based ecology,” “agroecosystems,” “soil food web,” “soil health indicators,” “integrative taxonomy,” and “climate change.”

As a result, nearly [insert number] publications were identified. After removing duplicates, a thorough examination of titles and abstracts was performed.

Inclusion criteria:

- Studies investigating ecological, functional, or taxonomic issues of PPNs
- Research performed in agricultural or maintained ecosystems
- Publications in peer-reviewed journals or academic books

Exclusion criteria:

- Studies only investigating chemical control effectiveness without any ecological analysis
- Non-peer-reviewed reports

The publications were organized in categories:

- I. Classification of functional traits,
- II. Soil food web analysis,
- III. Soil health evaluation,
- IV. Integrative taxonomy, and
- V. Climate change effects and intensification aspects.

The analysis of the literature was done qualitatively in order to establish a conceptual framework which ties together the PPN functional traits and ecosystem processes.

Functional Diversity in Nematology: Conceptual Background

Functional diversity pertains to the diverse features that affect organisms' interactions with their surroundings and the processes of ecosystem (Díaz & Cabido, 2001). The traditional approach in nematology centers on the feeding guilds and the life cycle features, for instance, colonizer – per sister (C-P) schemes in case of free-living nematodes, which is informative about species' reactions to disturbance and ecological stability (Yeates, *et al.*, 1993; Bongers & Bongers, 1998).

Plant-parasitic nematodes are generally regarded as one trophic category in soil food web models. Nevertheless, PPNs differ quite substantially in terms of their functional characteristics, for example, way of feeding, host range, mobility, reproduction, and tolerance to stress (Perry and Moens, 2013). It is important to recognize the functional diversity of PPNs to better understand their ecological roles other than damaging plants.

Functional Trait Framework of Plant-Parasitic Nematodes

Feeding Strategies and Root Interaction Niches

PPNs can be classified into ectoparasites, semi-endoparasites, migratory endoparasites, and sedentary endoparasites, which showcase different functional approaches (Wyss, 2002). The ectoparasitic group, represented by *Xiphinema spp.*, feeds externally and causes indirect involvement in root development, while sedentary endoparasites, represented by *Meloidogyne* and *Heterodera spp.*, create feeding sites for long periods of time and can influence the plant's physiology.

Life-History Strategies and Functional Trade-offs

The differences in life history diversity lend PPN its unique functional role. While fast generational species may readily exploit favorable environmental conditions, the longer lasting species that possess

survival adaptations, like cysts, help with population survivability and stability (Bongers and Bongers, 1998).

Host Specificity and Functional Specialization

The host range of PPNs is diverse, ranging from specific species to general species. The degree of host specificity affects the pattern of damage to crops, as well as the composition of plant community and biodiversity underground (Decraemer and Hunt, 2006).

Quantifying Functional Diversity of Plant-Parasitic Nematodes

Functional diversity can be determined through the use of multidimensional trait indices that measure different facets of community composition (Petchey and Gaston, 2006; Villéger, *et al.*, 2008). Although hardly used for plant-parasitic nematodes, there are some indices that can be used for trait-based PPN studies:

- **Functional richness (FRic):** Indicates how much functional trait space is filled by species found in the community.
- **Functional evenness (FEve):** Indicates how regularly species abundance is distributed across functional traits.
- **Functional divergence (FDiv):** Indicates the degree to which species abundance is distributed toward extreme trait values (Villéger, *et al.*, 2008).
- **Rao's quadratic entropy:** Combines species dissimilarity and their abundance to provide an estimate of functional diversity (Villéger, *et al.*, 2008).

The application of these indices to PPN communities allows for the evaluation of how traits of organisms are homogenized due to agricultural intensity and climate change (Tilman, 2001; Díaz and Cabido, 2001).

Plant-Parasitic Nematodes in Soil Food Webs and Ecosystem Processes

Even if PPNs obtain their energy directly from plants, they have a significant impact on microbes, nutrient-mineralizing processes, and root exudation patterns (Wardle, *et al.*, 2004). The injury done to the roots by PPNs can stimulate the activity of microbes and change local processes in the rhizosphere, thus making PPNs a part of soil food webs rather than categorizing them as simply the last pests.

Functional Diversity of PPNs and Soil Health Assessment

Soil health is described as the capacity of soil to work as a living system that ensures plant

productivity, environmental quality, and ecosystem resilience (Doran and Zeiss, 2000; Lehmann, *et al.*, 2020). The current frameworks of soil health note biological parameters, as well as physical and chemical ones, and acknowledge soil biodiversity as an important regulator in ecosystem functioning. Nematodes are considered to be effective bioindicators due to their different roles in the trophic pyramid and sensitive reaction to environmental changes (Ferris, *et al.*, 2001; Neher, 2001).

Plant-parasitic nematodes (PPNs) have always been considered harmful organisms, but examining them from a functional characteristics angle may give one a better insight into their role in nature. Their feeding style, host specificity, reproductive ability, and survival strategies (e.g., cyst formation), can indicate the intensity of soil management practices, cropping systems, and disturbance regimes (Yeates, *et al.*, 1993; Bongers and Bongers, 1998). It has been observed that a prevalence of short-living opportunistic groups, may show that soil has undergone some disturbances, while balanced functional groups indicate the stability of the ecosystem.

PPN functional characteristics also indirectly affect soil processes critical for soil health. Depth of penetration into the roots and feeding place formation influence carbon allocation in the rhizosphere, and the emission of root products, and contribute to changing of microbial communities and mineralization process (Wardle, *et al.*, 2004). The survival mechanisms enable nematodes to live for the longer period contributing to stability of population and facilitating the processes of plants-soils feedback (Ferris, *et al.*, 2001).

If one incorporates functional diversity indices such as functional richness (FRic) and functional divergence (FDiv) into soil health assessment it will enable to enhance diagnostic abilities of assessments beyond simple measurements of quantity (Villéger, *et al.*, 2008). Observing the changes of PPN characterization under the agricultural intensification and climate change can serve as an early-warning signs of imbalance occurring in agroecosystem (Dutta and Phani, 2023; Tsiafouli *et al.*, 2014). Thus, trait-based soil health framework allows to consider PPNs as not only harmful, but also meaningful ecological elements of soil ecosystem.

Integrative Taxonomy as a Prerequisite for Functional Interpretation

Proper identification of species is critical for an accurate assessment of functional diversity. Numerous economically relevant genera of PPN have

cryptic species complexes, which cannot be easily identified relying solely on morphology (Subbotin, *et al.*, 2010). Integrative taxonomy, that synthesizes morphological, molecular and ecological data has become important for the correct correlation of species identity and functional traits (De Ley, *et al.*, 2005).

Misidentification is likely to confuse functional traits and generate incorrect conclusions about diversity-function relationships in agroecosystems, which rely heavily on proper diagnoses.

Effects of Climate Change and Agricultural Intensification

It is believed that climate change will have a major impact on various plant-nematode relationships since it will modify the way nematodes reproduce, survive as well as manifest their virulence and location. Increased temperatures and the concentration of higher CO₂ levels in the air will contribute to speeding up the life cycle of nematodes while also changing their ability to infect hosts, thus leading to more serious nematode infections on plants (Chakraborty and Newton, 2011; Dutta and Phani, 2023). It can be said that these changes will provide the homogenization function of the agroecosystems and reduce trait variation which can lead to lower ecosystem resilience (Tilman, 2001; Tsiafouli, *et al.*, 2014).

This means that it is crucial to observe changes in functional trait composition and not only species abundance to identify the ecological changes of the agricultural ecosystem caused by global warming.

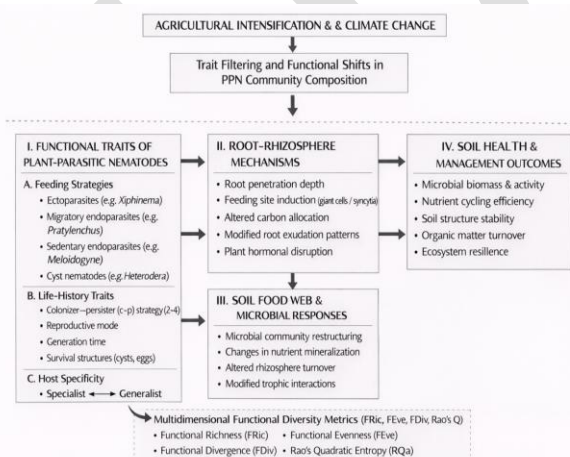


Figure 1. The theoretical framework explains how the evolution of land use in agriculture and climate change affects filtering of traits and changes in the functional composition of the PPN community. Functional characteristics influence the processes in the root-

rhizosphere ecosystem and soil food web, which affects soil health. The functional diversity index provides data on the ecosystem's responses.

Trait-Based Management and Conceptual Framework

Reframing PPN in a functional diversity context opens new possibilities for the development of trait-based management strategies. Rather than an indiscriminate targeting of species, management may concentrate on regulating the most dominant functional traits using crop diversification, promoting soil organic amendments, and applying biological control methods; thus, promoting system resilience.

This approach provides a new perspective on plant parasitic nematodes as functional elements of agroecosystems rather than pests. Functional traits of these nematodes affect root interactions, which in turn influence the rhizosphere microbial communities and nutrient-cycling processes (Wardle, *et al.*, 2004). All the aforementioned interactions lead to changes in soil health indicators such as organic matter turnover, microbial biomass, and resilience of a system (Doran and Zeiss, 2000; Ferris, *et al.*, 2001). Trait-based monitoring allows for the implementation of effective management strategies based on regulation of the dominant functional groups instead of blind suppression.

Future Research Directions

Future studies need to adopt functional traits analysis in conjunction with molecular taxonomy, long-term monitoring, and ecosystem modeling. Such effort would enhance predictive ability regarding the PPN dynamics in a changing environment and support sustainable agriculture.

Conclusion

Nematodes that consume plants are a diverse group of organisms in soil ecosystems that fulfills many ecological roles, not all of which relate to damage of crops. The combination of trait-based ecology and integrative taxonomy together makes a powerful tool for relating diversity to ecological functioning. Connecting the traits of plant-parasitic nematodes with processes in soil and soil health indicators is the focal point of this article that makes an important step towards changing pest-based practices into ecological approach. Future studies should concentrate on using functional indices, molecular biology tools, and long-term monitoring.

Table 1. Functional Trait Classification of Major Plant-Parasitic Nematode Groups in Agroecosystems

Functional Group	Example Genera	Feeding Strategy	Host Specificity	Life Strategy (c-p)	Ecological Effect	Management Implication
Ectoparasites	<i>Xiphinema</i> , <i>Longidorus</i>	External root feeding	Moderate–broad	Generally associated with intermediate to higher c–p values (3–4)	Root tip damage, virus transmission	Crop rotation, resistant varieties
Migratory Endoparasites	<i>Pratylenchus</i>	Intracellular migration	Broad	Typically associated with lower to intermediate c–p values (2–3)	Root lesion formation, secondary infection	Organic amendments
Sedentary Endoparasites	<i>Meloidogyne</i>	Feeding site induction (giant cells)	Broad	Commonly associated with lower c–p values (2) reflecting opportunistic strategy	Altered root physiology, altered carbon allocation in the rhizosphere	Resistant cultivars
Cyst Nematodes	<i>Heterodera</i> , <i>Globodera</i>	Syncytium formation	Narrow–moderate	Generally associated with intermediate c–p values (3) due to persistent survival structures	Long-term soil persistence	Crop rotation cycles

Note: The functional classification has been taken from studies done by Yeates, *et al.*, (1993), Ferris, *et al.*, (2001) and Perry and Moens (2013). The colonizer–persister (c–p) scale is based on life-history characteristics outlined by the work of Bongers and Bongers (1998) and is approximate for the plant-parasitic nematodes.

Table 2. Linking Functional Traits of Plant-Parasitic Nematodes to Soil Ecosystem Processes.

Functional Trait	Mechanistic Role	Affected Soil Process	Ecosystem Outcome
Root penetration depth	Alters carbon deposition zone	Rhizosphere microbial turnover	Modified nutrient mineralization
Feeding site formation	Alters plant hormonal balance	Root exudation profile	Microbial restructuring
Survival structures (cysts/eggs)	Long-term persistence	Temporal stability	Ecosystem stability or susceptibility to disturbance
Host specificity	Selective plant suppression	Plant community composition	Below-ground diversity shifts

Note: Trait–ecosystem linkages synthesized from Wardle, *et al.*, (2004); Doran and Zeiss (2000); Ferris, *et al.*, (2001).

Table 3. Importance of Integrative Taxonomy in Functional Diversity Studies of Plant-Parasitic Nematodes

Taxonomic Resolution	Risk of Misinterpretation	Functional Consequence
Genus-level identification	Masks cryptic species	Underestimation of functional diversity
Morphology-only approach	Misidentification in species complexes	Incorrect ecological inference
Integrative taxonomy (morphology + molecular + ecology)	Accurate species delimitation	Reliable trait–function linkage

Note: Conceptual framework based on De Ley, *et al.*, (2005); Subbotin, *et al.*, (2010).

REFERENCES

- Bongers, T., and Bongers, M. (1998). Functional diversity of nematodes. *Applied Soil Ecology*, 10, 239–251.
- Chakraborty, S., and Newton, A.C. (2011). Climate change, plant diseases and food security. *Plant Pathology*, 60, 2–14.
- Decraemer, W., and Hunt, D.J. (2006). Structure and classification. In: *Perry and Moens (Eds.), Plant Nematology*. CABI.
- De Ley, P., et al., (2005). An integrated approach to nematode taxonomy. *Nematology*, 7, 1–17.
- Díaz, S., and Cabido, M. (2001). Vive la difference: plant functional diversity matters. *Trends in Ecology & Evolution*, 16, 646–655.
- Doran, J.W., and Zeiss, M.R. (2000). Soil health and sustainability. *Applied Soil Ecology*, 15, 311.
- Dutta, T.K., and Phani, V. (2023). The pervasive impact of global climate change on plant–nematode interaction continuum. *Frontiers in Plant Science*, 14, 1143889. <https://doi.org/10.3389/fpls.2023.1143889>
- Ferris, H., Bongers, T., and De Goede, R.G.M. (2001). A framework for soil food web diagnostics. *Applied Soil Ecology*, 18, 13–29.
- Jones, J.T., et al., (2013). Top 10 plant-parasitic nematodes in molecular plant pathology. *Molecular Plant Pathology*, 14, 946–961.
- Lehmann, J., Bossio, D.A., Kögel-Knabner, I., and Rillig, M.C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth and Environment*, 1, 544–553. <https://doi.org/10.1038/s43017-020-0080-8>
- Neher, D.A. (2001). Role of nematodes in soil health and their use as indicators. *Journal of Nematology*, 33(4), 161–168.
- Perry, R.N., and Moens, M. (2013). *Plant Nematology* (2nd ed.). CABI.
- Perry, R.N., and Moens, M. (2011). Introduction to plant-parasitic nematodes. In: *Perry & Moens (Eds.), Plant Nematology*.
- Subbotin, S.A., Mundo-Ocampo, M., and Baldwin, J. G. (2010). *Systematics of cyst nematodes (Nematoda: Heteroderinae), part a*. <https://doi.org/10.1163/ej.9789004162259.i-352>
- Tilman, D. (2001). Functional diversity. *Encyclopedia of Biodiversity*.
- Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., De Ruiter, P.C., Van der Putten, W.H., Birkhofer, K., Hemerik, L., De Vries, F.T., Bardgett, R.D., Brady, M.V., Bjornlund, L., Jørgensen, H.B., Christensen, S., Hertefeldt, T.D., Hotes, S., Gera Hol, W., Frouz, J., Liiri, M., Mortimer, S. R., Hedlund, K. (2014). Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biology*, 21(2), 973–985. <https://doi.org/10.1111/gcb.12752>
- Wardle, D.A., et al., (2004). Ecological linkages between above- and belowground biota. *Science*, 304, 1629–1633.
- Wyss, U. (2002). Feeding behaviour of plant-parasitic nematodes. *Annual Review of Phytopathology*, 40, 135–154.
- Yeates, G. W., et al., (1993). Feeding habits in soil nematode families. *Soil Biology and Biochemistry*, 25, 1701–1710.

CITATION OF THIS ARTICLE

Malti and Sharma, L. (2026). Functional Diversity of Plant-Parasitic Nematodes in Agro-ecosystems: From Crop Damage Paradigm to Ecosystem Functioning and Soil Health Frameworks, *Int. J. Agriworld*, 7 [2]: 44-49.