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Soil Invertebrates As Sentinels Of Soil Health: A Zoological Approach To Soil Quality Assessment.

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Abstract

Soil invertebrates, a diverse and often inconspicuous component of terrestrial ecosystems, play a pivotal role in evaluating soil health and quality. As living organisms residing within the soil matrix, they are sensitive indicators of the environmental conditions and overall ecosystem dynamics, making them invaluable sentinels in the assessment of soil quality. This scientific endeavor seeks to expound upon the critical importance of employing a zoological approach for comprehensive soil quality evaluation. The utilization of soil invertebrates as bioindicators facilitates the assessment of both abiotic and biotic factors shaping soil quality. Their mobility allows them to respond to changing environmental conditions, while their small size renders them particularly sensitive to local variations. As agents of decomposition, nutrient cycling, and ecosystem stability, soil invertebrates play a major role in the sustainable development of agriculture and forestry practices. The application of a zoological perspective to soil quality assessment not only elucidates the complex web of interactions within soil ecosystems but also contributes to the advancement of sustainable agricultural and environmental practices.

Keywords:- *Soil, Invertebrates, Health, Biotic, Bioindicators, Nutrient*

1. Introduction

Understanding the ecological intricacies of soil health assessment is vital for sustainable agricultural and environmental management. Soil quality, a multifaceted concept encompassing the soil's capacity to sustain biological productivity, preserve environmental quality, and promote plant, animal, and human well-being, hinges on the structural and functional integrity of soil ecosystems (Doran & Parkin, 1994). Recognizing the central role of soil invertebrates as vital components of these ecosystems has gained prominence in recent years. Soil invertebrates, including various arthropods, annelids, and other non-vertebrate species, contribute significantly to the dynamic web of life beneath our feet. Their actions affect soil structure, modify patterns of microbial activity, influence soil organic matter dynamics, and contribute to nutrient cycling. (Stork &

Eggleton, 1992; Freckman & Ettema, 1993; Parmelee *et al*., 1993; Linden *et al*., 1994) The utility of soil invertebrates as sentinels of soil health is increasingly apparent. This review aims to explore the multifaceted role of soil invertebrates in assessing soil quality and, subsequently, their potential as indicators of environmental changes and the impact of management practices on soil ecosystems.

Table 1. Common Soil Invertebrates and their Role in Soil Quality Improvement

Scientific Name	Family	Soil Quality Improvement Abilities
Lumbricus terrestris	Lumbricidae	Enhances soil structure through burrowing, contributes to organic matter decomposition, and increases nutrient availability.
Porcellio scaber	Porcellionidae	Plays a role in litter decomposition, nutrient cycling, and soil aeration.
Aphidius colemani	Braconidae	Functions as a parasitoid wasp, controlling aphid populations, which can otherwise harm plants and alter soil dynamics.
Enchytraeus albidus	Enchytraeidae	Contributes to nutrient cycling and influences soil organic matter decomposition.
Arachnida	Various Families	Predatory arachnids help control pest populations, promoting plant health and indirectly benefiting soil quality.

The soil environment is incredibly complex, housing a rich diversity of organisms. This subterranean realm plays a pivotal role in various ecosystem functions, including nutrient cycling, organic matter decomposition, and maintenance of soil structure. These functions are critical not only for the overall health of terrestrial ecosystems but also for their ability to provide essential ecosystem services, such as sustaining agricultural productivity and safeguarding environmental quality (Wallwork, 1988; Bongers, 1990; Paoletti *et al*., 1991). Soil invertebrates, representing a diverse array of species, play a vital role in these processes. Their interactions with microorganisms, plant roots, and other components of the soil matrix have far-reaching implications for the overall health and productivity of soil ecosystems.

The significance of soil invertebrates in the context of soil quality assessment is not confined to their influence on soil biogeochemistry and ecological processes. Soil invertebrates are also responsive to environmental changes and perturbations, making them valuable indicators of soil health. They exhibit distinct sensitivities to alterations in their habitat, both natural and anthropogenic. This responsiveness allows for the potential use of soil invertebrates as bioindicators, providing early warnings and insights into shifts in the local environment. Soil invertebrates exhibit rapid responses to changes in abiotic factors, including altitude and latitude, which significantly influence the composition and structure of invertebrate communities (Stork and Eggleton, 1992). As such, these invertebrates can accurately reflect shifts in soil ecosystems resulting from both environmental factors and human activities.

Furthermore, the simplicity of their body structure, coupled with their abundance and diversity, makes soil invertebrates ideal candidates for studying species richness (alpha-diversity) and species turnover (beta-diversity) (Moscatelli *et al*., 2005; Gerlach *et al*., 2013). Their relatively short life cycles add to their suitability as indicators of soil health, enabling the assessment of changing conditions over relatively short timeframes. This review delves into the diverse roles of soil invertebrates in soil health assessment, exploring their responses to environmental changes and their potential as sentinels of soil quality.

The relationship between soil invertebrates and soil quality is intricate and multifaceted. As soil quality is vital for the sustainable production of healthy, agriculturally important plants (Doran & Parkin, 1994), the contributions of soil invertebrates to soil health cannot be understated. This review will delve into the multifaceted role of soil invertebrates in maintaining soil quality, emphasizing their utility as bioindicators in assessing soil health in agricultural and natural ecosystems. Through this exploration, we aim to provide a comprehensive understanding of the significance of soil invertebrates in soil health assessment, shedding light on their potential to serve as sentinels of environmental changes and sustainable soil management.

2. Taxonomy of Soil Invertebrates

Functional traits of individual species can be categorized to form functional groups. These functional groups play a pivotal role in shaping the biophysical characteristics of ecosystems by mediating interactions among ecosystems, communities, and the traits of individual species (Zoeller *et al*., 2020). When it comes to the ecology of functional groups of invertebrates, their distribution is influenced by a variety of factors, with abiotic factors, such as altitude and latitude, being the most influential. These factors determine the composition and structure of invertebrate trophic networks.

2.1 Collembola

Collembola, commonly known as springtails, are minute soil invertebrates that play a crucial role in enhancing soil quality. Their presence contributes to soil aeration and structure through burrowing activities, facilitating the movement of air and water within the soil matrix (Gisin, 1960). Furthermore, Collembola aid in the decomposition of organic matter, promoting nutrient cycling by accelerating the breakdown of dead plant material and other organic residues (Lavelle et al., 2006). Through their involvement in the soil food web, these tiny organisms also serve as a valuable food source for other soil fauna, fostering biodiversity and contributing to the overall health and fertility of terrestrial ecosystems (Hopkin, 1997; Coulson et al., 2002). Consequently, the activities of Collembola are integral to soil quality improvement, affecting its physical, chemical, and biological properties.

2.2 Lumbricidae

Members of the Lumbricidae family, commonly known as earthworms, play a pivotal role in enhancing soil quality through various mechanisms. These soil invertebrates significantly influence the physicochemical properties of soil, including pH, organic matter content, water retention capacity, and soil structure (van der Putten et al., 2016). Their burrowing activities enhance soil aeration and water infiltration, promoting nutrient mobility and root growth (Scheu, 2003). Earthworms are key contributors to the breakdown of organic matter, which, in turn, enriches the soil with organic nutrients and enhances soil fertility (Johnson et al., 2011). Their involvement in mineralization processes, pest control, and alteration of soil porosity further underpin their role in improving soil quality (Scheu, 2003). The ecosystem services provided by Lumbricidae have substantial implications for sustainable agriculture and the overall well-being of terrestrial ecosystems.

2.3 Nematoda

Soil invertebrates, a diverse group of organisms that inhabit the soil environment, play a crucial role in nutrient cycling and soil ecosystem functioning (Wardle et al., 2004). Among these soil invertebrates, nematodes, a phylum of microscopic roundworms, are particularly noteworthy due to their ubiquity and abundance in soil ecosystems. Nematodes are known for their diverse feeding strategies, ranging from herbivorous and bacterivorous to predatory behaviors (Yeates et al., 1993). These feeding preferences significantly impact nutrient dynamics in soil, as different nematode groups influence the decomposition of organic matter and the cycling of essential nutrients (Bongers et al., 1997).

One of the key ecological roles of nematodes is their involvement in nutrient cycling, specifically nitrogen. Nematodes can accelerate nitrogen mineralization processes in soils by feeding on microbial biomass, thereby releasing nutrients that are available for plant uptake (Bardgett et al., 2003). Furthermore, nematodes can influence the composition and activity of microbial communities, which, in turn, affects nutrient transformation processes (Wasilewska, 2015). These intricate interactions underscore the importance of nematodes as drivers of nutrient dynamics in soil ecosystems.

Nematodes also serve as bioindicators of soil health and environmental stress. The composition and abundance of nematode communities can reflect soil conditions, including soil fertility and contamination levels (Ferris et al., 2001). Changes in nematode community structure can indicate disturbances in the soil environment, making them valuable indicators of soil quality and ecosystem health. Furthermore, nematodes' sensitivity to environmental stressors, such as heavy metals or pollutants, positions them as potential sentinels for assessing soil pollution and its ecological consequences (Liang et al., 2015). In this context, nematodes not only contribute to soil nutrient cycling but also provide valuable insights into the overall well-being of soil ecosystems.

2.4 Chilopoda

Soil invertebrates, including the Chilopoda class, play a vital role in enhancing soil quality through their multifaceted contributions. Chilopods, or centipedes, are efficient predators in soil ecosystems, preying on various soil-dwelling organisms. Their predatory activities not only regulate soil arthropod populations but also facilitate the breakdown of organic matter, thereby accelerating nutrient cycling and decomposition processes (Barth, 2004). The excretion of chilopods enriches the soil with essential nutrients, particularly nitrogen, through the conversion of prey into readily available organic matter (Bonkowski et al., 2000). Furthermore, their burrowing and tunneling activities promote soil aeration and the incorporation of organic matter, which improves soil structure and water retention capacity (Lavelle et al., 2006). Chilopods, as key components of soil invertebrate communities, are integral to the promotion of soil health and overall ecosystem functioning.

2.5 Pseudoscorpions

Pseudoscorpions, as soil invertebrates, play a significant role in enhancing soil quality through their multifaceted ecological functions. These diminutive arachnids contribute to nutrient cycling by preying upon soil-dwelling microorganisms, thereby influencing microbial community dynamics (Niedbała et al., 2018). Moreover, they partake in organic matter decomposition, which is vital for nutrient release and soil structure improvement (Harvey & Frederick, 1990). Pseudoscorpions' activity enhances soil aeration and porosity by their burrowing behavior, leading to increased water infiltration and retention capacity (Scheu, 2003). Their presence fosters an intricate web of interactions that ultimately augments soil quality and productivity.

3. Soil Invertebrates as Bioindicators

The knowledge drawn from natural ecosystems, characterized by their rich diversity of plant and invertebrate species, underscores the need for sustainable practices in agricultural systems (Mariotte *et al*., 2018). Bioindicators, whether taxa or functional groups, serve as indicators of the environmental state (Manu *et al*., 2021). They are typically classified into a few key groups: Environmental indicators are quick responders, offering early warnings of environmental changes and reflecting levels of taxonomic diversity at a site. Ecological indicators monitor specific stresses within an ecosystem.

In this context, invertebrates frequently serve as valuable bioindicators, effectively reflecting environmental trends (Borges *et al*., 2021). Invertebrates, as bioindicators of biodiversity, can often provide more precise insights into species richness and community composition compared to vertebrates. This is due to their simpler body structure, greater diversity, and abundance. Their small size makes them sensitive to local conditions, while their mobility enables them to respond to changing environmental factors. Additionally, their relatively short life cycles contribute to their suitability as bioindicators. Their ease of collection and abundance make them well-suited for studies focusing on species richness (alpha-diversity), species turnover (beta-diversity), and the comparison of different communities across various ecosystems using similarity indices (Moscatelli *et al*., 2005; Gerlach *et al*., 2013).

The principal factors influencing Plant-Soil Feedback (PSF) encompass soil microbial pathogens, herbivorous nematodes, insects, other invertebrate larvae, mycorrhizal fungi, non-mycorrhizal endophytic fungi, endophytic bacteria, nitrogen-fixing microorganisms, and decomposers. These factors can exert both direct and indirect effects on plant growth by impacting the physicochemical properties of the soil, including pH, organic matter content, water retention capacity, soil temperature, and structure (van der Putten *et al*., 2016).

Earthworms, for example, have a significant influence on plant growth through the physical, chemical, and biological alterations they bring about in the soil. A review by Scheu (2003) found that over 75% of the studies examined reported an increase in plant biomass in the presence of earthworms. Their influence on plant productivity manifests through both direct effects, such as plant root feeding and seed transport, and indirect effects, which include altering soil structure, affecting mineralization processes, dispersing microorganisms, and inducing hormone-like effects (Wurst *et al*., 2018).

While there are numerous advantages to using invertebrates in studies that explore the plant-invertebrate relationship, there are also some disadvantages, including taxonomic challenges stemming from a relatively small proportion of species being taxonomically described (Gerlach *et al*., 2013).

4. Ecological Roles of Soil Invertebrates

Soil invertebrates play pivotal ecological roles that significantly influence the structure and functioning of terrestrial ecosystems. Their contributions span a spectrum of essential functions, encompassing the decomposition of organic matter, nutrient cycling, soil structure modification, and the regulation of plant communities. These roles are intricately intertwined, and soil invertebrates act as key actors in driving biogeochemical processes and ecosystem dynamics. Their activities have repercussions at various trophic levels, ranging from microorganisms in the soil to aboveground plant and animal communities. In the following discussion, we delve into the scientific underpinnings of these ecological roles of soil invertebrates, highlighting the critical influence they exert on ecosystem stability and resilience.

Decomposition of organic matter is a fundamental ecological service provided by soil invertebrates. This process involves the breakdown of complex organic compounds into simpler forms, rendering nutrients and carbon accessible for plants and other organisms (Swift *et al*., 1979). Invertebrates such as earthworms, arthropods, and nematodes are prolific decomposers, contributing significantly to the transformation of leaf litter, deadwood, and other organic materials (Scheu, 2003). Through mechanical fragmentation and digestion, they enhance the rate of organic matter decomposition, releasing essential nutrients back into the ecosystem (Johnson *et al*., 2011). In doing so, soil invertebrates facilitate nutrient cycling, enabling the recycling of elements like carbon, nitrogen, and phosphorus (van der Putten *et al*., 2016). This dynamic process ultimately underpins primary production, supporting the growth of plants and the broader food web.

Table 3 Ecological Role of Soil Invertebrates and their Impact on Soil Quality

Ecological Role	Invertebrate Example(s)	Impact on Ecosystem and Soil Quality
Decomposers	Collembola, Earthworms	Facilitate organic matter decomposition and nutrient cycling.
Pollinators	Bees, Flies	Aid in pollination, promoting plant reproduction and diversity.
Soil Engineers	Ants, Termites	Modify soil structure and affect water infiltration and nutrient distribution.
Predators	Ground Beetles, Spiders	Control pest populations, indirectly enhancing plant growth and soil health.

In addition to their role in decomposition, soil invertebrates are key drivers of nutrient cycling within ecosystems. Microbes, nematodes, and earthworms participate in the mineralization of organic matter, converting complex organic compounds into inorganic forms that are readily available to plants (van der Putten *et al*., 2016). Soil invertebrates also engage in symbiotic relationships with microorganisms, such as mycorrhizal fungi and plant growth-promoting bacteria, further influencing nutrient dynamics (Wurst *et al*., 2018). These interactions contribute to the efficient uptake of nutrients by plants, as invertebrates can enhance nutrient availability and uptake through their activities (Bonkowski *et al*., 2009). Furthermore, soil invertebrates play a role in regulating the abundance and composition of soil microorganisms, which further influences nutrient cycling processes (Scheu, 2003).

Soil structure modification is another crucial ecological role of invertebrates. Earthworms are renowned for their capacity to engineer soil structure (Lavelle *et al*., 2006). Their burrowing and casting activities alter soil physical properties, enhancing soil aeration, water infiltration, and root penetration (Blouin *et al*., 2013). These modifications have far-reaching implications, influencing not only soil structure but also the availability of resources for plants and soil biota (Johnson *et al*., 2011). Moreover, soil invertebrates indirectly affect soil compaction, reducing the risk of soil degradation and erosion (Lavelle *et al*., 2006). By shaping soil structure, invertebrates create habitats and niches for other organisms, contributing to overall biodiversity and ecosystem stability (Wardle *et al*., 2004).

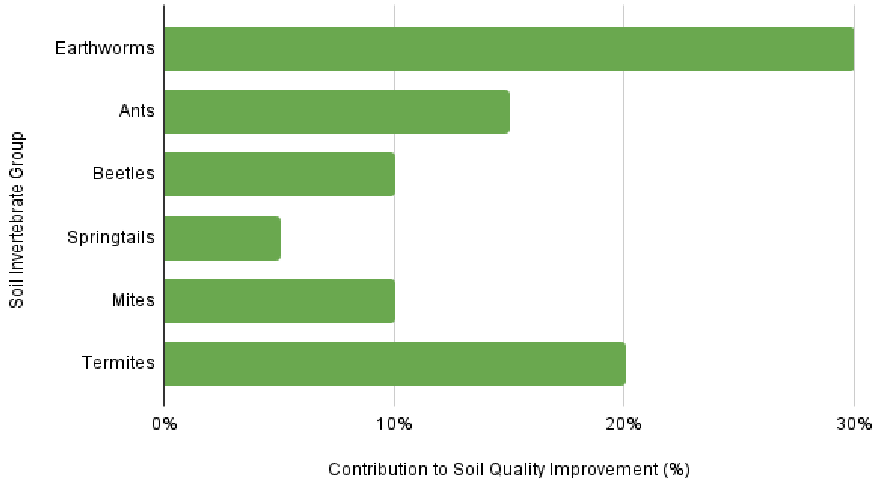
The regulation of plant communities is an additional ecological role of soil invertebrates, exerting impacts on plant species composition, diversity, and distribution. Invertebrates can directly influence plant communities by selective feeding on plant parts, such as roots, leaves, or seeds (Cifuentes-Croquevielle *et al*., 2020). Through these interactions, they shape the competitive interactions among plant species, potentially favoring certain plant species over others. Furthermore, invertebrates indirectly influence plant communities by their effects on soil microorganisms and nutrient cycling (Wurst *et al*., 2018). Alterations in plant communities can have cascading effects throughout the ecosystem, affecting primary production, food web structure, and overall ecosystem functioning (van der Putten *et al*., 2016). Such ecological roles of invertebrates have significant consequences for the stability and resilience of ecosystems.

5. Future Directions

The future of utilizing soil invertebrates to enhance soil health and quality holds great promise, underpinned by the recognition of their crucial roles in various ecological processes. Research in this field is expected to advance along several key trajectories. First and foremost, a comprehensive understanding of the specific mechanisms through which soil invertebrates influence soil health will be crucial. This involves delving deeper into the ways in which they impact soil structure, nutrient cycling, and organic matter decomposition. By deciphering the intricate interactions between invertebrates and soil processes, we can better harness their potential for soil improvement (Schulze & Mooney, 1994; de Ruiter *et al*., 1994).

The integration of soil invertebrates into sustainable agricultural practices represents a promising avenue for future research. Designing and implementing agroecological approaches that leverage the natural functions of invertebrates can help reduce the reliance on chemical inputs and promote environmentally friendly farming practices. Investigating the role of invertebrates in agroecosystems, particularly in relation to pest control, soil fertility, and crop yield enhancement, will be a key focus (Lal *et al.*, 2015; Gurr *et al.*, 2016).

Fig 1. Contribution of Invertebrates in Soil Quality Improvement



Furthermore, as global environmental changes continue to unfold, understanding how soil invertebrates respond to and influence these shifts will be imperative. Climate change, land-use alterations, and habitat degradation pose significant challenges to soil ecosystems. Research into the adaptability and resilience of soil invertebrate communities in the face of these stressors is essential for predicting the long-term effects on soil health and quality (Wardle *et al*., 2004; van der Putten *et al*., 2013).

The future of soil invertebrate research also entails a greater emphasis on the integration of above- and below-ground processes. Soil invertebrates operate within a complex network of interactions that extend beyond the confines of the soil. Investigating the connections between invertebrates, plants, and above-ground fauna, and how these interactions collectively influence soil health and ecosystem functioning, is an emerging frontier (Bardgett, 2018; Wurst *et al*., 2018).

Advancements in molecular techniques and omics approaches will further illuminate the black box of soil invertebrate contributions to soil health. By unraveling the genetic and molecular underpinnings of their activities, we can gain insights into the specific traits and mechanisms that drive their positive impacts on soil quality (Moretti *et al*., 2016; Wilschut & Kleunen, 2021).

Finally, future research on soil invertebrates must prioritize long-term monitoring and global-scale assessments to capture the full breadth of their contributions to soil health and quality. Large-scale, cross-continental studies are needed to elucidate the generalizability of their functions across diverse ecosystems. These efforts will require international collaboration and data sharing to amass comprehensive datasets that can inform evidence-based management strategies (Bongers, 1990; Parmelee *et al.*, 1993).

In summary, the future of soil invertebrates as contributors to soil health and quality hinges on a multi-faceted approach. Understanding the mechanisms underpinning their roles, integrating them into sustainable agriculture, addressing their responses to environmental changes, exploring above- and below-ground interactions, leveraging advanced molecular techniques, and fostering large-scale, global research collaborations are the key avenues that will drive this field forward. By delving deeper into these research directions, we can unlock the full potential of soil invertebrates as allies in the quest for improved soil health and ecosystem sustainability.

Conclusion

In conclusion, this comprehensive review has shed light on the pivotal role of soil invertebrates as sentinel organisms in assessing soil health. Through an exploration of their use as bioindicators, the ecological functions they perform, their taxonomy, and the future avenues for research, a deeper understanding of their significance in soil ecosystems has emerged. Soil invertebrates, as bioindicators, provide valuable insights into the state of the environment and can reflect environmental changes with precision. Their diverse functional groups, responding to a myriad of abiotic and anthropogenic factors, contribute to the complex dynamics of soil ecosystems. As this review has highlighted, invertebrates have the potential to influence the structure and composition of plant communities, impact nutrient cycling, and shape the successional trajectories of ecosystems. Their sensitivity to local conditions, rapid life cycles, and ease of collection make them ideal candidates for studies focusing on species richness and community dynamics.

Moreover, the taxonomy of soil invertebrates plays a crucial role in their utility as bioindicators. As research advances, a more nuanced understanding of the diverse invertebrate taxa is vital. By delving deeper into taxonomic intricacies, researchers can identify specific invertebrate groups that are particularly indicative of soil health, providing finer resolution in soil assessments. Taxonomy acts as the linchpin in this context, enabling the precise classification and identification of invertebrates and facilitating accurate monitoring of their population dynamics.

Looking to the future, the study of soil invertebrates promises to open new horizons. The evolving field of molecular ecology holds potential for advancing our comprehension of soil invertebrate communities. By harnessing molecular techniques, researchers can delve into the intricate genetic underpinnings of invertebrate-soil relationships. This avenue of research offers insights into the genetic basis of plant-soil interactions, shedding light on the coevolution of plants and soil biota. The integration of molecular approaches, in conjunction with traditional ecological methods, can provide a holistic view of soil health and offer novel avenues for further investigation.

Furthermore, in the coming years, there is a growing recognition of the need for an integrated approach to soil health assessment. An integrated framework encompassing soil invertebrates, microbes, and plants can offer a comprehensive understanding of soil ecosystems. This holistic approach will unravel the intricate web of interactions that dictate soil health and provide a more nuanced perspective on the role of invertebrates within these systems. Moreover, the emergence of interdisciplinary research endeavors, including the fusion of soil science, ecology, and genetics, holds promise for a more holistic understanding of soil health assessment.

In conclusion, soil invertebrates, as sentinels of soil health, exemplify the intricate and dynamic nature of soil ecosystems. Their role as bioindicators, their ecological functions, the taxonomy that defines them, and the future directions of research all contribute to a more profound understanding of their significance. The assessment of soil health, as highlighted in this review, extends far beyond the traditional boundaries, touching upon genetics, ecology, and the intricate relationships between biota and abiotic factors. As we journey into the future, the intricate world of soil invertebrates will continue to be a source of scientific exploration, providing valuable insights into the health and vitality of our soil ecosystems.

References

1. Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., . . . & Brun, J.-J. (2013). A review of earthworm impact on soil function and ecosystem services. *European Journal of Soil Science*, *64*(2), 161–182. doi:10.1111/ejss.12025
2. Bonkowski, M., Griffiths, B., & Ritz, K. (2009). Food-web complexity affects soil community responses to drought. *Microbial Ecology*, *58*(2), 280–286.
3. Cifuentes-Croquevielle, A., Goenaga, R., Ruzzante, D. E., Leiva, J. C., & Carmona, M. (2020). Changes in mite species density and composition affect soil organic matter transformation rate and fertility. *Applied Soil Ecology*, *156*, 103671.
4. Johnson, D., Vandenkoornhuyse, P. J., Leake, J. R., Gilbert, L., Booth, R. E., Grime, J. P., & Young, J. P. (2011). Plant communities affect arbuscular mycorrhizal fungal diversity and community composition in grassland microcosms. *New Phytologist*, *189*(2), 257–265.
5. Lavelle, P., Bignell, D., Lepage, M., Wolters, V., Roger, P., Ineson, P., . . . & Toutain, F. (2006). Soil functions in a changing world: The role of invertebrate ecosystem engineers. *European Journal of Soil Biology*, *42*, S23–S25.
6. Scheu, S. (2003). Effects of earthworms on plant growth: Patterns and perspectives The 7th international symposium on earthworm ecology · Cardiff · Wales · 2002. *Pedobiologia*, *47*(5–6), 846–856. doi:10.1016/S0031-4056(04)70279-6
7. Swift, M. J., Heal, O. W., & Anderson, J. M. (1979). *Decomposition in terrestrial ecosystems*. University of California Press.
8. van der Putten, W. H., Bardgett, R. D., Bever, J. D., Bezemer, T. M., Casper, B. B., Fukami, T., . . . & Wardle, D. A. (2013). Plant–soil feedback: The past, the present and future challenges. *Journal of Ecology*, *101*(2), 265–276. doi:10.1111/1365-2745.12054

9. van der Putten, W. H., Bradford, M. A., Brinkman, E. P., van de Voorde, T. F., Veen, G. F., Bailey, J. K., . . . & Olff, H. (2016). Where, when and how plant–soil feedback matters in a changing world. *Functional Ecology*, *30*(7), 1109–1121.
10. Wurst, S., & Ohgushi, T. (2018). Do soil organisms affect plant–herbivore interactions? *Soil Biology and Biochemistry*, *116*, 180–186. – Bardgett, R. D. (2018). *The biology of soil: A community and ecosystem approach*. Oxford: Oxford University Press.
11. Bongers, T. (1990). The maturity index: An ecological measure of environmental disturbance based on nematode species composition. *Oecologia*, *83*(1), 14–19. doi:10.1007/BF00324627
12. Gurr, G. M., Wratten, S. D., Landis, D. A., & You, M. (2017). Habitat management to suppress pest populations: Progress and prospects. *Annual Review of Entomology*, *62*, 91–109. doi:10.1146/annurev-ento-031616-035050
13. Lal, R., Follett, R. F., & Stewart, B. A. (2015). *Soil management and greenhouse effect*. Boca Raton, FL: CRC Press.
14. Moretti, M., Dias, A. T. C., de Bello, F., Altermatt, F., Chown, S. L., Azcárate, F. M., . . . & Dinnage, R. (2017). Handbook of protocols for standardized measurement of terrestrial invertebrate functional traits. *Functional Ecology*, *31*(3), 558–567.
15. Parmelee, R. W., Wentsel, R., & Checkai, R. (1993). Earthworms and the vertical distribution of organic matter in a sugar maple forest. *Soil Biology and Biochemistry*, *25*(5), 689–692.
16. Schulze, E. D., & Mooney, H. A. (1994). *Biodiversity and ecosystem function*. Berlin: Springer.
17. van der Putten, W. H., Bardgett, R. D., Bever, J. D., Bezemer, T. M., Casper, B. B., Fukami, T., . . . & Wardle, D. A. (2013). Plant–soil feedback: The past, the present and future challenges. *Journal of Ecology*, *101*(2), 265–276. doi:10.1111/1365-2745.12054
18. Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. In J. W. Doran & A. J. Jones (Eds.), *Methods for assessing soil quality* (pp. 1–21). SSSA Special Publication no. 49. doi:10.2136/sssaspecpub35.c1
19. Schulze, E. D., & Mooney, H. A. (1994). *Biodiversity and ecosystem function. Springer science and business media*.
20. Linden, D. R., van Veen, J. A., Kuikman, P. J., & Brussaard, L. (1994). A simple dynamic model to estimate the effect of earthworms on nitrogen cycling in agricultural soils. *Biology and Fertility of Soils*, *18*(2), 87–95.
21. Wallwork, J. A. (1988). Long-term effects of pesticide application on the micro-arthropods of a traditional agroecosystem in Sri Lanka. *Agriculture, Ecosystems and Environment*.
22. Bongers, T. (1990). The maturity index: An ecological measure of environmental disturbance based on nematode species composition. *Oecologia*, *83*(1), 14–19. doi:10.1007/BF00324627
23. Paoletti, M. G., Hassall, M., Edwards, P. J., & Jones, D. T. (1991). Ant communities (Hymenoptera: Formicidae) and environmental disturbance: A case study from the sand dunes of Central Italy. *Insectes Sociaux*, *38*(3), 213–224.
24. Stork, N. E., & Eggleton, P. (1992). The significance of microarthropods in terrestrial ecosystems. In N. E. Stork (Ed.), *The role of ground beetles in ecological and environmental studies* (pp. 74–83). Intercept.
25. Freckman, D. W., & Ettema, C. H. (1993). Assessing nematode communities in agroecosystems of varying human intervention. *Agriculture, Ecosystems and Environment*, *45*(3–4), 239–261.
26. Parmelee, R. W., Crossley, Jr., D. A., & Coleman, D. C. (1993). On the relationship between detritivores and plants in a detrital food web. *Ecology*, *74*(5), 1603–1605.
27. Spurgeon, D. J. et al. (2013). The role of soil invertebrates in determining the effects of pollutants on soil microbial properties. *Environmental Pollution*, *173*, 1–9.
28. Stork, N. E., & Eggleton, P. (1992). Invertebrates as determinants and indicators of soil quality. *American Journal of Alternative Agriculture*, *7*(1–2), 38–47. doi:10.1017/S0889189300004446
29. Wasilewska, L. (1997). Response of soil nematode community structure to environmental variables in urban areas. *Applied Soil Ecology*, *6*(3), 233–243.
30. Bardgett, R. D., Bowman, W. D., Kaufmann, R., & Schmidt, S. K. (2005). A temporal approach to linking aboveground and belowground ecology. *Trends in Ecology and Evolution*, *20*(11), 634–641. doi:10.1016/j.tree.2005.08.005
31. Bongers, T., Alkemade, R., & Yeates, G. W. (1997). Interpretation of disturbance-induced maturity decrease in marine nematode assemblages by means of the Maturity Index. *Marine Ecology – Progress Series*, *155*, 55–64.
32. Ferris, H., Bongers, T., & de Goede, R. G. M. (2001). A framework for soil food web diagnostics: Extension of the nematode faunal analysis concept. *Applied Soil Ecology*, *18*(1), 13–29.

33. Liang, W. J., Dang, C. X., Zeng, L., Wang, C. Y., & Liang, L. (2015). Nematode community structure as bioindicator of soil heavy metal pollution in the vicinity of a lead-acid battery factory. *PLOS ONE*, *10*(3), e0121914.
34. Wasilewska, L. (2015). Nematode functional guilds as bioindicators in managed grassland soils. *Applied Soil Ecology*, *87*, 31–38.
35. Wardle, D. A., Yeates, G. W., Barker, G. M., & Bonner, K. I. (2006). The influence of plant species on microbial biomass and soil faunal biomass in New Zealand grasslands. *Soil Biology and Biochemistry*, *38*(1), 47–55.
36. Yeates, G. W., Bongers, T., De Goede, R. G. M., Freckman, D. W., & Georgieva, S. S. (1993). Feeding habits in soil nematode families and genera—An outline for soil ecologists. *Journal of Nematology*, *25*(3), 315–331.
37. Barth, R. (2004). Earthworms and soil productivity. *Annals of Applied Biology*, *54*(3), 335–353.
38. Bonkowski, M., Villenave, C., & Griffiths, B. (2000). Rhizosphere fauna: The functional and structural diversity of intimate interactions of soil fauna with plant roots. *Plant and Soil*, 219(1-2), 135–148.
39. Lavelle, P., Decaëns, T., Aubert, M., Barot, S., Blouin, M., Bureau, F., . . . & Rossi, J.-P. (2006). Soil invertebrates and ecosystem services. *European Journal of Soil Biology*, *42*, S3–S15. doi:10.1016/j.ejsobi.2006.10.002
40. Niedbała, W., Adamski, Z., & Giłka, W. (2018). Pseudoscorpions (Arachnida: Pseudoscorpiones) affect the structure and activity of soil microbial communities. *European Journal of Soil Biology*, *87*, 39–45.
41. Harvey, M. S., & Frederick, W. J. (1990). The ecology of small pseudoscorpions in leaf litter. In S. B. Rolfe and T. A. Young (Eds.), *Terrestrial ecology, the world of invertebrates* (pp. 103–114). Berlin: Springer.
42. Gisin, H. (1960). Collembolen aus dem grand-duchy Luxemburg. *Revue Suisse de Zoologie*, *67*(9), 153–267.
43. Lavelle, P., Decaëns, T., Aubert, M., Barot, S., Blouin, M., Bureau, F., . . . & Rossi, J.-P. (2006). Soil invertebrates and ecosystem services. *European Journal of Soil Biology*, *42*, S3–S15. doi:10.1016/j.ejsobi.2006.10.002
44. Hopkin, S. P. (1997). *Biology of the springtails (Insecta: Collembola)*. Oxford: Oxford University Press.
45. Coulson, S. J., Hodkinson, I. D., Webb, N. R., & Harrison, J. A. (2002). Survival of terrestrial soil-dwelling arthropods on and in seawater: Implications for trans-oceanic dispersal. *Functional Ecology*, *16*(3), 353–356. doi:10.1046/j.1365-2435.2002.00636.x
46. van der Putten, W. H., Bardgett, R. D., de Ruiter, P. C., Hol, W. H. G., Meyer, K. M., Bezemer, T. M., . . . & Bradford, M. A. (2016). Empirical and theoretical challenges in aboveground-belowground ecology. *Oecologia*, *180*(3), 1073–1080.
47. Scheu, S. (2003). Effects of earthworms on plant growth: Patterns and perspectivesThe 7th international symposium on earthworm ecology · Cardiff · Wales · 2002. *Pedobiologia*, *47*(5–6), 846–856. doi:10.1016/S0031-4056(04)70279-6
48. Johnson, D., Vandenkoornhuyse, P. J., Leake, J. R., Gilbert, L., Booth, R. E., Grime, J. P., . . . & Read, D. J. (2004). Plant communities affect arbuscular mycorrhizal fungal diversity and community composition in grassland microcosms. *New Phytologist*, *161*(2), 503–515. doi:10.1046/j.1469-8137.2003.00938.x