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RESEARCH ARTICLE OPEN ACCESS

An Innovative Framework Fosters Practical Application of Nematode-Based Indices in Soil Health Assessment

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Keywords: bioindicators | community ecology | ecosystem functions | soil biological indicator | soil food web

ABSTRACT

Nematodes are versatile bioindicators of the soil food web in both agricultural and natural ecosystems. Multiple nematode-based indices (NBIs), derived from morphological, life history and community traits, provide invaluable information on various aspects of soil health. However, a standardised approach is required to explicitly link NBIs to the soil health concept. Moreover, unifying all NBIs into a single quantitative index could offer a more comprehensive and straightforward bioindicator for soil health. The ecological foundations for individual NBIs have been well established, but a single standardised bioindicator for soil microfaunal communities including nematodes, remains absent. Here, we integrated existing knowledge on NBIs into an innovative framework for quantitatively assessing soil health and ecosystem functions. Moreover, we propose a new Nematode Soil Health (NSH) index which summarises all NBIs into a single quantitative bioindicator. The framework was tested with five case datasets covering different soil types, depths, land uses and seasonal variations. Results for Datasets 1 and 2 indicated no significant difference in NSH values among soil types (Ferrosol, Chromosol and Vertosol) but significantly greater NSH in topsoil compared to subsoil layers. Dataset 3 revealed that soil amendments with fauna significantly increased the NSH index compared to defaunated soils, supporting the role of soil faunal communities in maintaining soil health. The NSH index (in Dataset 4) was also significantly higher in perennial pastures than annual croplands and exhibited (in Dataset 5) seasonal variation, with higher values in spring compared to autumn. Although this framework requires further calibration, testing and standardisation on more nematode community datasets, it could be combined with quantitative estimations or graphical representations of NBIs to provide additional information relevant to soil health conditions. The NSH index has the potential to foster the practical application of NBIs in soil health assessment programs, enhancing their adoption by practitioners and farmers.

1 | Introduction

There are several definitions for soil health from different perspectives (Acton and Gregorich 1995; Doran and Safley 1997; Doran and Zeiss 2000; Bünemann et al. 2018; Lehmann et al. 2020; Fierer et al. 2021; Janzen et al. 2021). However,

core concepts of all these definitions include the ability of a living soil to perform multiple ecosystem functions and services (Bünemann et al. 2018; Larkin 2015), and in a broader sense, soil health encompasses the functionality, vitality and sustainability of soil systems (Janzen et al. 2021). The vitality component of soil considers it as a living system with connective processes

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Summary

- Nematode-based indices (NBIs) are aggregated in a single bioindicator
- The Nematode Soil Health (NSH) index is a quantitative indicator based on nematode community
- The NSH index scores showed high correlations with nutrient cycling variables
- The proposed framework fosters practical application of NBIs in soil health

mediated in the context of the soil food web including microorganisms and fauna (Potapov et al. 2022). As soil biota play a central role in soil functioning, involving biological indicators greatly improves the assessment of soil health in different ecosystems (Bünemann et al. 2018).

Nematodes occur across multiple trophic levels in the soil food web, ranging from primary consumers to specialist predators (Herren et al. 2020; Potapov et al. 2022), offering a good option to examine ecological questions and understand the mechanisms underlying sustainability in agricultural or natural ecosystems (du Preez et al. 2022; Neher 2010). Therefore, nematodes have been recognised as a highly ranked bioindicator of soil health (Ferris and Bongers 2009; Neher 2001). The functional roles of nematodes in ecosystems can be inferred from a famous quotation by Cobb (1915), who speculated that the location of various plants and animals would be understandable by exploring their nematode associations. Nielsen's (1949) work was a milestone in the ecological studies of soil nematodes, providing a nematode classification scheme based on their feeding habits. Paramonov (1962) defined two functional groups of nematodes—'pararhizobes' (occupy the rhizosphere and may damage plants) and 'dyssaprobies' (consume detritus phase but may enter healthy plant tissues). Feeding habit subsequently was used as a character for the grouping of plant and soil nematodes by Wasilewska (1971) and Yeates (1971), the latter acting as a trigger point for a long-lasting plan with essential feeding groups of nematodes defined: plant feeders (herbivores), hyphal feeders (fungivores), bacterial feeders (bacterivores), predators and omnivores (Bongers and Bongers 1998; Yeates 1979; Yeates et al. 1993).

Building upon the *r*- to *K*-strategies in other animals, Bongers et al. (1989) proposed the colonisers to persisters (c-p) scale for nematode communities (Figure 1). This framework resulted in the introduction of the maturity index (MI) (Bongers 1990; Bongers et al. 1991), and MI relative indices, including the maturity index 2–5 (MI 2–5), plant parasitic index (PPI) and sigma maturity index (\sum MI) (Bongers et al. 1995; Korthals et al. 1996; Yeates 1994). Functional guilds (Bongers and Bongers 1998) and additional functional indices, including enrichment index (EI), structure index (SI), channel index (CI) and basal index (BI) (Ferris et al. 2001), further expanded applications of the nematode-based indices (NBIs) in research. Visual presentations of NBIs such as c-p triangles (de Goede et al. 1993), weighted faunal profile (Ferris et al. 2001) and metabolic footprints (MFs; Ferris 2010), as well as the online NBI calculation website NINJA (Sieriebriennikov et al. 2014; <https://shiny.wur.nl/ninja/>), have facilitated the application of NBIs in ecological studies.

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The development of NBIs incorporating morphological (e.g., body size and biomass), life history (e.g., reproductive rate and lifespan) and community (e.g., abundance and predator/prey rate) traits has accelerated the application of nematodes as biological indicators of soil quality (e.g., Ferris, Griffiths, et al. 2012; Ferris, Sánchez-Moreno, et al. 2012; Herren et al. 2020). Since the 1990s, NBIs have been widely applied at a global scale, providing invaluable information on various aspects of soil food web dynamics (Bongers 1990; du Preez et al. 2022; Ferris 2010; Ferris et al. 2001; Yeates 1994). The application and utility of NBIs were revisited and redefined recently with a robust framework developed for addressing research questions and hypotheses relevant to ecosystem functions and services, or environmental and anthropogenic impacts on soil food webs (du Preez et al. 2022).

A standardised approach is essential to specifically link NBIs to the soil health concept that is particularly applicable to end-users such as practitioners and farmers. Indicators should present and manage complex information in a simple and clear manner (Turbé et al. 2010), thus integrating all NBIs into a single quantitative index may provide a more comprehensive and accurate representation of soil health. For example, a single quantitative index was developed for all mesofaunal communities in soil ecosystems by Parisi (2001), which summarises 25 microarthropod groups into the eco-morphological index (EMI) and has been refined over time (Parisi et al. 2005; Menta et al. 2018). This index has been widely applied in different ecosystems, including agricultural lands, grasslands, degraded soils and urban soils (Menta et al. 2018; FAO 2020) and is now recognised as a standard index for measuring soil mesofauna in Europe (Menta et al. 2018). Similarly, all macrofaunal communities can be combined into a single general indicator of soil quality (GISQ), developed by Velasquez et al. (2007) and subsequently improved (Velasquez and Lavelle 2019) and evaluated for use as a standard global indicator of soil quality (Lugo et al. 2024). This GISQ can measure changes in soil health related to agricultural practices and provide a bottom-up procedure for evaluating ecosystem functions and services (Lugo et al. 2024).

A wide range of living soil inhabitants from microorganisms (e.g., fungi and bacteria) to fauna (e.g., nematodes, mites, collembola and earthworms) have been accepted as indicators for measuring soil biological properties depicting soil or plant health (Bünemann et al. 2018). Compared to microorganisms, soil fauna occupy higher trophic levels in the food web, so they play roles as accumulators of physicochemical and biological properties of their food resources (Briones 2018; Potapov et al. 2022). Furthermore, they have a longer generation time and thus show more stable and predictable responses temporally. Among soil fauna, nematodes have been evaluated as a highly ranked bioindicator showing good potential for measuring soil health (Neher 2001; Ferris and Bongers 2009; Ferris, Griffiths, et al. 2012). A soil health bioindicator based on nematodes can be superior to those based on mesofauna (e.g., EMI) or macrofauna (e.g., GISQ) due to several key advantages. Nematodes are found almost in every soil with high diversity and functional trophic groups, which respond quickly and meaningfully to changes

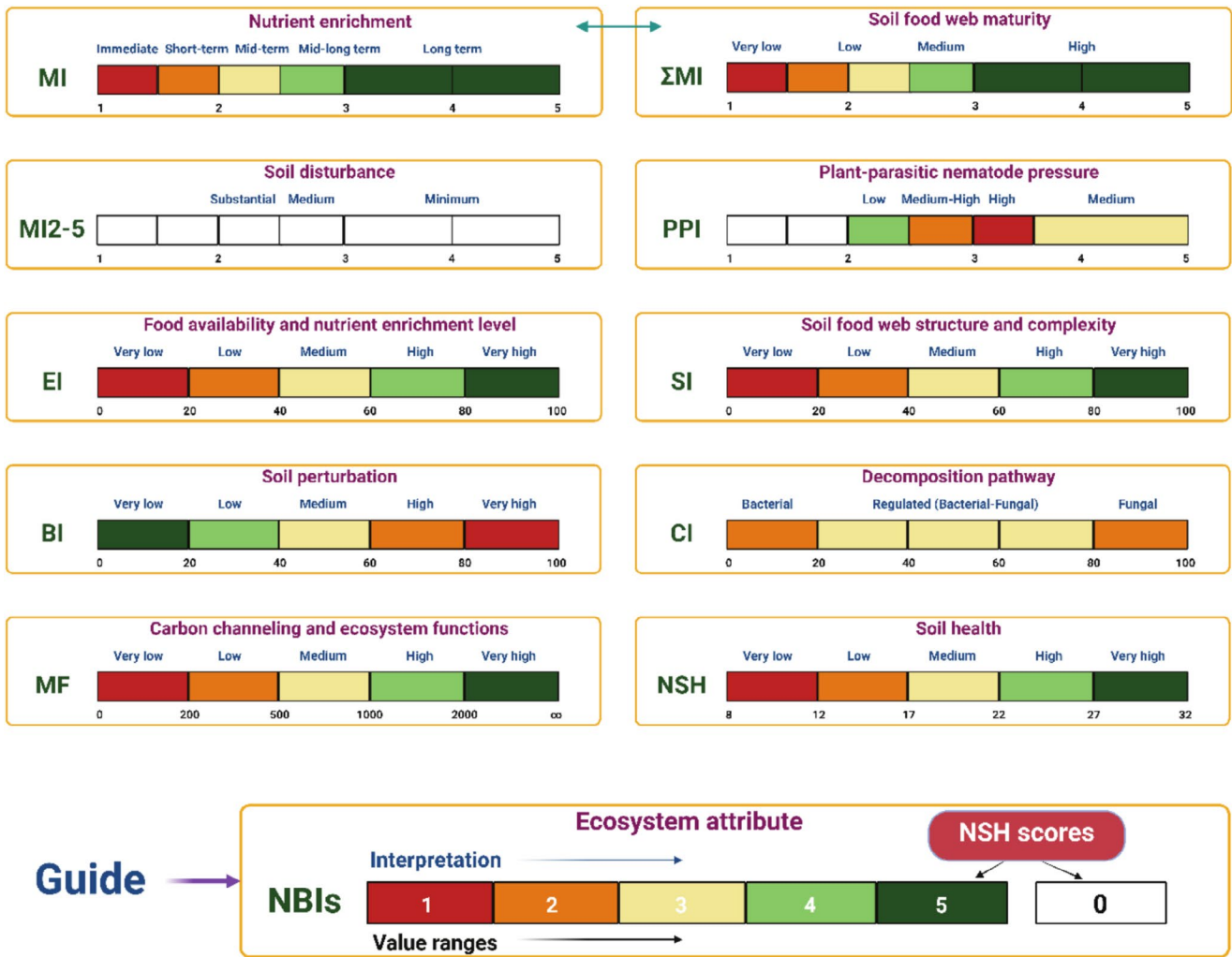


FIGURE 1 | A proposed framework using nematode-based indices (NBIs) that directly link the interpretation of soil health to the Nematode Soil Health (NSH) index. NBIs' value ranges are modified from du Preez et al. (2022). NBIs includes maturity index (MI), sigma maturity index (Σ MI), maturity index 2–5 (MI2–5), plant parasitic index (PPI), enrichment index (EI), structure index (SI), basal index (BI), channel index (CI) and composite metabolic footprint (MF). MF is the total abundance of the whole nematode assemblage based on 100 g dry soil; relevant biomass groups are as follows: (1) < 140 μ g; (2) 140–350 μ g; (3) 350–700 μ g; (4) 700–1400 μ g; and (5) > 1400 μ g. MI and Σ MI may be used alternatively. Colour coding is relevant to the NSH scores, with red representing the lowest score and dark green indicating the highest score.

in soil conditions, but mesofauna and macrofauna may not be present in certain soils, show slower responses or sometimes be less sensitive due to their mobility and escaping the changing factor. Moreover, nematodes represent multiple trophic levels in the soil food web and therefore, their relevant indicators provide more detailed insights into ecological processes in soil ecosystems (Ferris et al. 2001; du Preez et al. 2022).

Currently, no single standard indicator exists for measuring microfaunal communities, including nematodes. The basic information required for developing such an indicator is present in NBIs, which incorporate not only diversity but also life history and community traits. Although community composition (proportions of trophic groups or functional guilds) is important to link soil biodiversity to ecosystem functions (Ferris 2013), maintaining high abundance of trophic levels is equally essential for a multifunctional productive ecosystem (Larkin 2015; Soliveres et al. 2016). Further steps are needed to integrate existing knowledge of NBIs into a framework that aligns more closely

with the concept of soil health, and finally, to synthesise those indices into a single bioindicator which can score and classify given soils into categories based on their soil health condition. In this article, we propose the nematode soil health (NSH) index for consolidating all NBIs into a single quantitative bioindicator and aim to upgrade NBIs to a more applicable framework for the concept of soil health.

2 | Materials & Methods

2.1 | Datasets and Soil Sampling

Five datasets were used to test the new framework and the NSH index (Supporting Information 1). Datasets 1 and 2 were prepared based on the extracted nematodes from soil samples collected from two different sites (Table 1; Supporting Information 1) and used to test the effect of soil type and soil depth in the proposed framework during the present study. For Dataset 1, three sites

TABLE 1 | Physicochemical attributes of the soils used for testing nematode soil health (NSH) index during the present study.

Attribute Treatments ^a	Unit	Dataset 1			Dataset 2		
		Ferrosol	Chromosol	Vertosol	0–10 cm	10–20 cm	20–30 cm
pH (1:5 Water)	—	6.5	5.6	5.8	5.4	4.7	4.8
pH (1:5 CaCl ₂)	—	5.9	5.0	5.0	4.6	3.9	4.0
EC	ds/m	1.1	1.1	1.2	1.1	0.6	0.4
NO ₃ ⁻ -N	mg/kg	63	77	62	35.2	13.6	9.2
NH ₄ ⁺ -N	mg/kg	4.6	4.6	3.3	8.5	1.9	1.4
Potentially mineralisable N	mg/kg	—	—	—	44.4	2.6	1.3
Colwell P	mg/kg	49	40	33	22.8	11.6	5.3
P buffer index	—	140	69	110	116	188	198
Ca	Cmol(+)/kg	12	5.3	6.3	4.1	0.94	0.47
K	Cmol(+)/kg	1.7	1.3	1.0	0.84	0.30	0.27
Mg	Cmol(+)/kg	3.1	1.2	5.1	1.9	0.65	0.66
Na	Cmol(+)/kg	0.04	0.02	0.67	0.16	0.09	0.08
CEC	Cmol(+)/kg	16.5	7.9	13.0	7.73	7.28	6.37
S	mg/kg	6.8	8.1	9.9	6.3	4.3	4.0
Organic C	%	1.88	1.72	1.84	6.68	3.34	1.22
Texture	—	Clay	Clay loam	Clay	Sandy loam	Clay loam	Clay
Silt–clay–sand%		19–42–39	18–24–58	19–41–40	—	—	—
Land use		Wheat	Wheat	Natural grass		Remnant bush	

^aTreatments for Dataset 1 are soil types, and for Dataset 2 are soil depths. Values are the average of 4 and 5 replicates in Datasets 1 and 2, respectively.

in the Dookie campus of the University of Melbourne (36°23' S, 145°43' E) were sampled in August 2024 to test the effect of soil type (Table 1). The sites represented by Ferrosol, Chromosol and Vertosol soil types according to the Australian soil classification (Isbell 2021). In each site, a 50 × 50 m plot in the centre of the field was selected. Four composite samples, each consisting of 15 cores, were taken randomly from the selected area up to 10-cm-depth by a 5-cm-diameter soil corer from each site. In total, 12 samples were collected: 3 soil types × 4 replicates.

For Dataset 2, samples were taken up from a remnant vegetation site (Table 1) with grasslands and Eucalyptus trees in Broomfield, Victoria, Australia (37°42' S, 143°89' E) in July 2023. Soil from three depths of the site was collected from 0 to 10, 10 to 20 and 20 to 30 cm depths. For each depth, five soil samples were transferred directly as undisturbed blocks 38 × 28 × 10 cm to polyethylene boxes to preserve soil structure. In total, 15 samples were collected: 3 soil depths × 5 replicates.

Site description, sampling plan, treatments and methodology for Dataset 3 have already been discussed as Experiment 3 in Ghaderi et al. (2025). In total, 72 samples were analysed: 3 time points × 4 soil depths × 2 fauna levels × 3 replicates (Supporting Information 1). For Dataset 4, samples were taken from pastures and canola fields from the Dookie campus of the University of Melbourne (36°23' S, 145°43' E) in August 2024. For each crop, three sites were selected, and soil cores were taken from five 1 × 1 m plots. A composite sample from each

plot was considered as a replicate, and a total of 30 samples were collected: 2 crops × 3 sites × 5 replicates. Information for Dataset 5 is according to Čerevková et al. (2024), consisting of 165 samples collected from grasslands and forests during spring, summer and autumn seasons in 2017 and 2018 (Supporting Information 1).

2.2 | Nematode Extraction and Community Analysis

Nematodes were extracted from 100 g of soil by using the Whitehead tray method (Whitehead and Hemming 1965) after 72 h incubation at room temperature. The resultant suspension was passed through a 500 mesh (25 μm apertures) sieve, and nematodes were collected from the above sieve into a 50 mL polyethylene container. Final volume of suspension containing nematodes was adjusted to 20 mL. A 5 mL aliquot was transferred to a counting slide, and nematodes were identified under ×40 magnification of an inverted Axiolab 5 light microscope (Zeiss). Nematode abundance was expressed per 100 g of soil.

Nematodes were identified to the family or genus level based on morphological characteristics and assigned to five common trophic groups: herbivores (plant-parasitic nematodes), bacterivores, fungivores, predators and omnivores using stoma and pharynx morphology (Yeates et al. 1993; Ferris 2010). Nematodes were also classified into functional guilds based on feeding habits

and c-p (coloniser–persister) groups (Bongers 1990; Bongers and Bongers 1998; Ferris et al. 2001). NBIs including MI, PPI, EI, SI, BI and CI were calculated in Excel spreadsheets to assess the soil food web status according to the procedure, which was already described in the literature (Ferris 2010, 2013; Sieriebriennikov et al. 2014; Sánchez-Moreno and Ferris 2018). NBIs and total abundance of nematodes were implemented in an innovative framework for estimating a novel bioindicator: NSH index.

2.3 | A Proposed Framework for Soil Health Assessment

The NSH index, like NBIs, builds on the concept that both the abundance and community composition of nematode functional groups (Bongers and Bongers 1998; Ferris et al. 2001) contribute to soil health. The fundamental approaches for estimating the NSH index are adapted from well-established approaches for NBIs, which are framed on the characterisation of trophic groups (Yeates et al. 1993), c-p classes (Bongers et al. 1989) and functional guilds (Bongers and Bongers 1998), as discussed in detail previously (Ferris et al. 2001; Ferris 2013; du Preez et al. 2022).

Nine common practical NBIs, representing the provision of soil ecosystem functions and services (du Preez et al. 2022), were considered as subindicators for the calculation of a synthetic quantitative indicator (Figure 1). Each index in the NBI toolset is presented by certain value ranges. Each value range was allocated an NSH score, with higher scores corresponding to better soil health conditions. The NBI ranges proposed by du Preez et al. (2022) have been modified here to explain different aspects of soil health. For most indices, including MI, Σ MI, MI 2–5, EI, SI and MFs, higher value ranges are indicative of better soil health. In contrast, for BI, higher value ranges indicate reduced soil health. For PPI, lower ranges (2.0–2.5) represent the highest soil health, intermediate ranges (2.5–3.0 and 3.0–3.5) reflect low soil health, and higher ranges (3.5–5.0) represent medium soil health. For CI, intermediate ranges indicate the highest level of soil health (see justifications for selecting NBIs, value ranges and scores in Section 4.2). The mathematical sum of all scores for different NBIs is expressed as a single number for the NSH index (Figure 1). A template for estimating NSH index as Excel spreadsheets could be found in Supporting Information 1.

2.4 | Validation of the NSH Index With Nematode Community Datasets

We used five datasets (as explained in Section 2.1) to test ecological hypotheses relevant to ecosystem functions and soil health. For Dataset 1, we hypothesised that, considering similar soil texture and comparable levels of nutrients in the soils, the NSH index shows non-significant differences among the soils. By using Dataset 2, we tested this hypothesis that the NSH index is higher in topsoil than subsoil in a natural soil from a remnant vegetation site due to higher biodiversity and more rich sources of carbon in topsoil. Dataset 3 was implemented for testing three hypotheses as the NSH index is as follows: (i) higher in the receptive soil amended with fauna (O+, A+, B+, C+) than defaunated soils (O–, A–, B–, C–); (ii) higher in the soil amended with litter (O) and topsoil (A) than with subsoils (B, C); and (iii) increases over

time ($T1 < T2 < T3$). The hypotheses implying higher NSH index in perennial pastures vs. annual agricultural fields (Dataset 4) and forests versus grasslands (Dataset 5) were also tested.

2.5 | Statistical Analysis

The differences between treatments were estimated using one-way (Datasets 1 and 2), two-way (Datasets 3 and 4) and three-way (Dataset 5) analysis of variance (ANOVA), followed by Tukey multiple-comparisons post hoc test. For Datasets 1 and 2, soil types (Ferrosol, Chromosol and Vertosol) and soil depths (0–10, 10–20 and 20–30 cm) were considered as factors, respectively. For Dataset 3, two factors were considered: (i) soil depth amendments with four levels including O (litter or organic horizon), A (0–10 cm), B (10–20 cm) and C (20–30 cm); and (ii) soil fauna with two levels including presence (fauna) and absence (defaunated). For Dataset 4, two factors were accounted for in analyses: (i) land use with two levels, including pasture and canola; and (ii) sites, including three different sites. For Dataset 5, three factors were defined as follows: (i) season with autumn, spring and summer levels; (ii) land use with forest and grassland as levels; and (iii) sampling year including 2017 and 2018. Spearman correlation coefficient (r) was also estimated between NBIs, NSH index and chemical variables relative to carbon, nitrogen and phosphorus cycling for Datasets 1 and 2. All statistical analyses were conducted by GraphPad Prism 10.3.1.

3 | Results

An innovative framework estimated a single bioindicator (NSH) for each soil sample based on NBIs' subindicators (Figure 1). Higher scores of the NSH index reflect better soil health, with a maximum score of 32 indicating optimal conditions when all NBIs reach the highest values for a given soil. Conversely, a decline in this score indicates a decrease in soil health (Figure 1). From soil food web perspective, while moving from lower to higher trophic levels, NSH scores are increased for most subindicators such as MI, MI2-5, Σ MI, EI, SI and MFs, but decreased for BI. While shifting decomposition from bacterial towards fungal pathway, NSH scores for CI are increased. When nematode community is dominated by plant-associated nematodes and ectoparasites, PPI indicates the lowest NSH scores. However, the scores are increased by dominating virus-vector ectoparasites and reach maximum by dominating the most dangerous endoparasitic nematodes (Figure 2).

The NSH index was evaluated across five diverse datasets to assess its sensitivity and reliability in capturing soil health dynamics across different contexts, including soil types, depths, land uses, biological amendments and seasonal variations. ANOVA results for all datasets are presented in Supporting Information 2. For Dataset 1, the NSH index scores ranged from 18 to 22 and showed no statistically significant differences among the three soil types (Figure 3a; Table S1). These intermediate scores suggest moderate soil health conditions across all types. The practical implication here is that under uniform management and comparable physicochemical conditions, soil type alone may not significantly affect biological soil health. Thus, soil management practices could be prioritised over soil

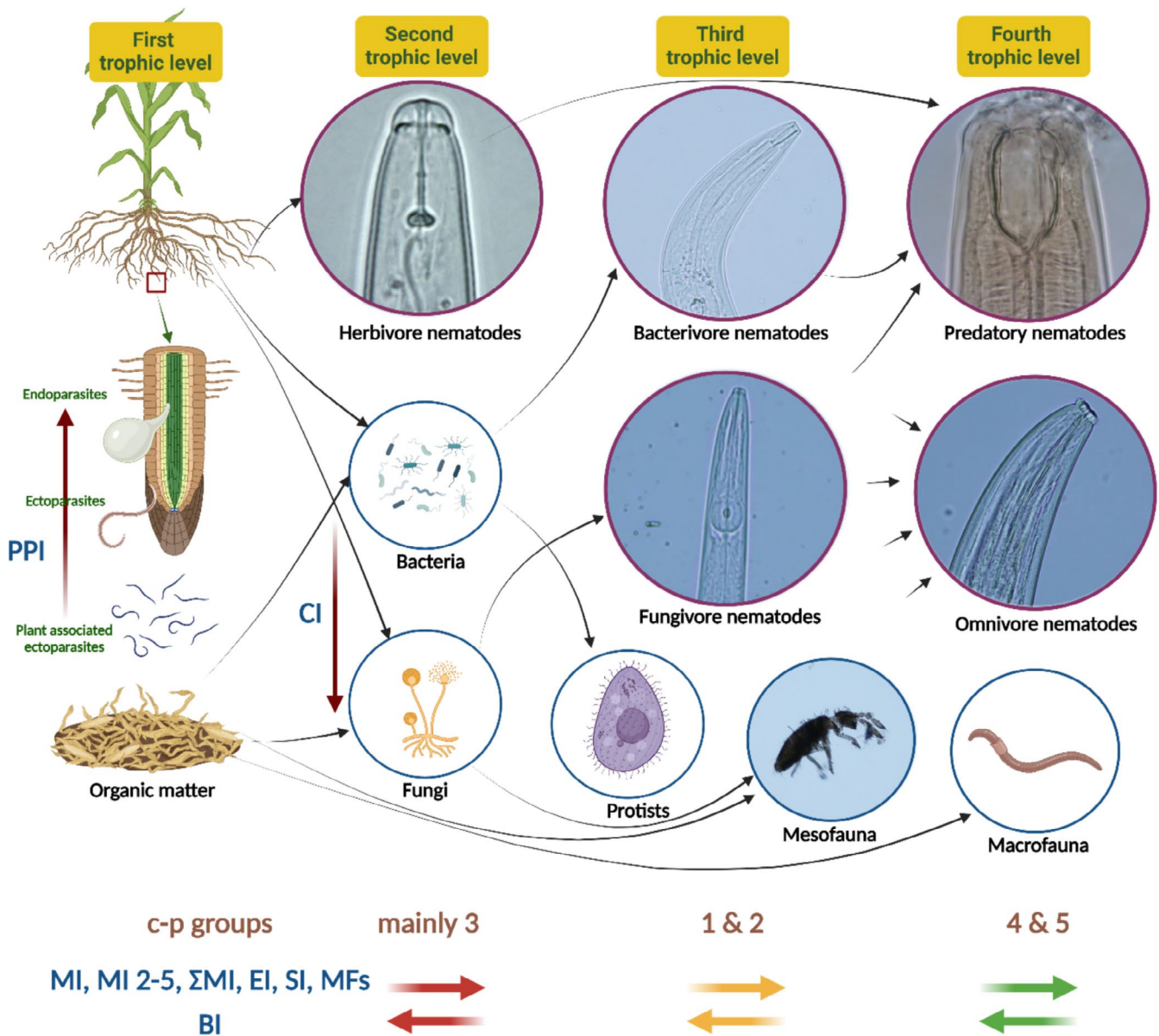


FIGURE 2 | A diagram of the soil food web demonstrating the functional roles of nematode trophic groups in soil ecosystems. Changes of the coloniser-persister (c-p) groups and nematode-based indices (NBIs) in the soil food web are also illustrated. NBIs shown include BI: Basal Index; CI: Channel Index; EI: Enrichment Index; MI: Maturity Index; MFs: Metabolic footprints; PPI: Plant-Parasitic Index; SI: Structure Index. Green, yellow and red arrows for NBIs at the bottom indicate high, intermediate and low scores for soil health, respectively.

classification for enhancing biological function in such cases. For Dataset 2, significantly higher NSH scores were observed in the topsoil (21–27; $p=0.003$) compared to subsoil layers (Figure 3b; Table S2). These findings validate the NSH index's sensitivity to vertical gradients in biological activity, with higher scores reflecting richer organic matter, active root zones and greater microbial and nematode biodiversity in surface layers. For Dataset 3, fauna-enriched amendments resulted in significantly higher NSH scores (two-way ANOVA, $p < 0.001$), especially at early (T1) and later (T3) stages for organic (O) and topsoil (A) layers. Additionally, NSH values increased significantly over time in most treatments (two-way ANOVA, $p < 0.001$) (Figure 3c; Table S3). These results confirm the pivotal role of soil fauna in restoring or enhancing soil health, especially in degraded or defaunated systems. For dataset 4, perennial pastures exhibited significantly higher NSH scores than

annual croplands (two-way ANOVA, $p < 0.001$), reflecting more stable and mature soil food webs in these systems (Figure 3d; Table S4). Higher scores in pasture systems are associated with greater proportions of omnivores and predators, indicators of complex and resilient ecological networks. This has clear implications for land management: integrating perennial cover or rotational grazing systems may enhance soil biological health and long-term sustainability. For Dataset 5, although no significant differences were found between land uses or across years, seasonal effects were evident (three-way ANOVA, $p < 0.01$), with spring samples consistently showing higher NSH scores than autumn (Figure 3e; Table S5).

For Dataset 1, the NSH index showed significant correlation with nematode abundance and nitrate (NO_3^-) concentration in soil (Figure 4). For Dataset 2, it indicated strong relationships

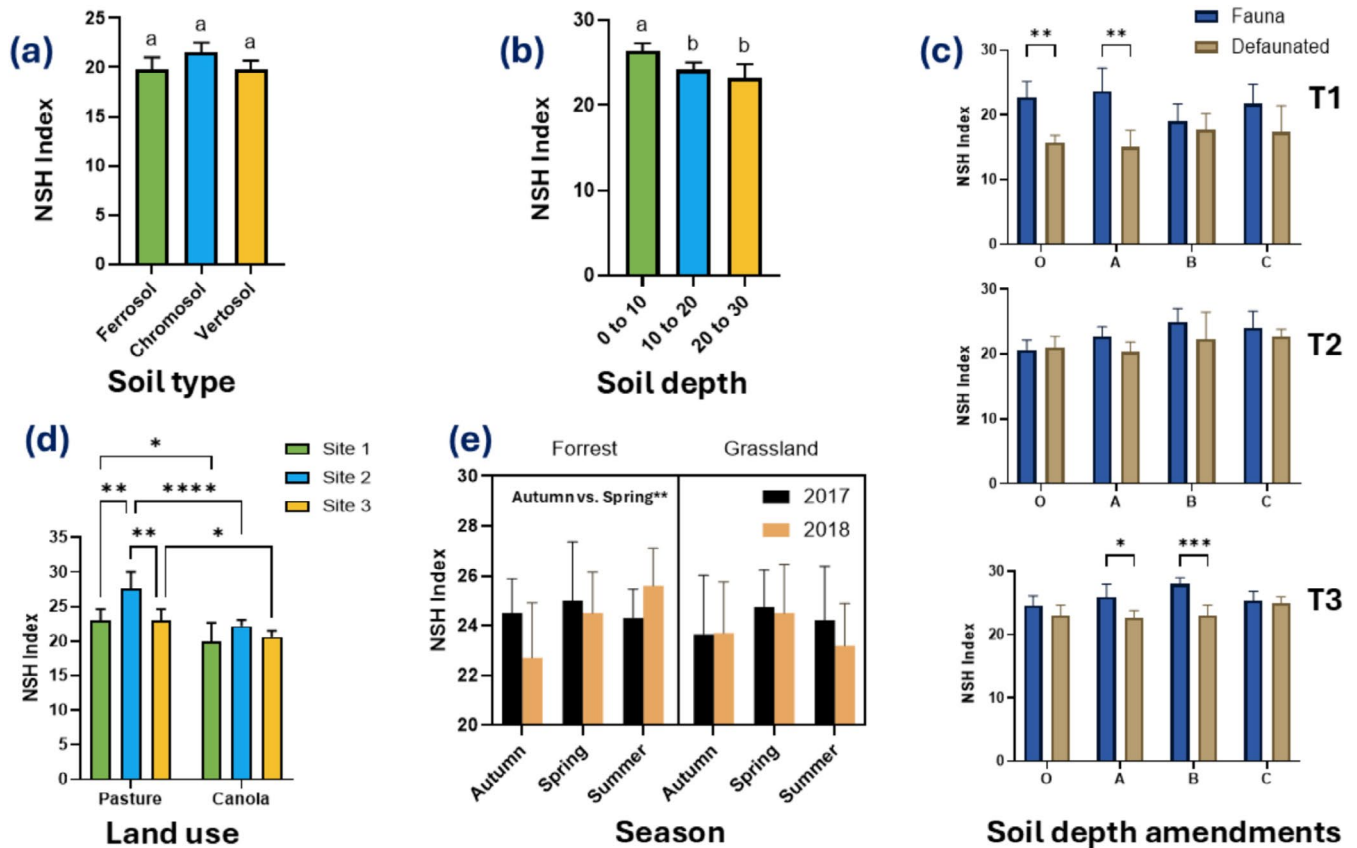


FIGURE 3 | Estimation of the Nematode Soil Health (NSH) index for different datasets including soil types (a), soil depths (b), soil depth amendments (c), land uses (d) and seasons and ecosystems (e). One-way (a, b), two-way (c, d) and three-way (e) ANOVA were implemented, followed by Tukey multiple comparisons test. Different letters indicate statistical significance based on ANOVA; *p* values are **** *p* < 0.001, *** *p* < 0.01 and * *p* < 0.05.

with certain NBIs like MI, SI, BI and nematode abundance, as well as with chemical variables such as organic C, labile C, NO_3^- , NH_4^+ , potentially mineralisable N and PO_4^+ concentrations in soil (Figure 4). In general, the NSH index showed moderate to strong positive correlations with key NBIs such as MI and SI, indicating that higher NSH scores are associated with more mature, structured and ecologically stable nematode communities. It also showed negative correlation with BI, suggesting that lower dominance of disturbance-tolerant taxa corresponds to better soil health. Moreover, it exhibited strong correlations with soil chemical properties like organic and labile carbon reflecting enhanced microbial activity and resource availability, with nitrate (NO_3^-), ammonium (NH_4^+) and potentially mineralisable nitrogen (PMN) indicating a link to nutrient cycling and fertility, and phosphate (PO_4^{3-}) relating to plant-available phosphorus and biological turnover.

4 | Discussion

4.1 | Practical Validation of the NSH Index With Nematode Community Datasets

The datasets revealed generally higher levels of soil health in the natural ecosystems (remnant bush, forests and grasslands) compared to the agricultural ecosystems (wheat and canola), in agreement with the literature (van den Hoogen et al. 2019; Girgan et al. 2020).

In Dataset 1, the NSH index did not show significant variation among the three soil types, indicating relatively uniform biological soil health across these classifications. This outcome aligns with our initial hypothesis but contrasts with previous findings that reported soil type as a key determinant of nematode community structure and function (Neher et al. 2005; Renčo et al. 2020). A plausible explanation for this discrepancy lies in the uniformity of physicochemical conditions across the sampled soils. All three soil types were derived from the same geographic region and subjected to similar agricultural management practices, such as crop rotation, fertilisation and irrigation regimes. These consistent external inputs may have overridden intrinsic soil type differences, leading to comparable nematode assemblages and, consequently, similar NSH scores.

In contrast, Dataset 2 revealed significant differences in NSH index scores among soil depths, underscoring the vertical heterogeneity of soil biological health. Topsoil samples (0–10 cm) displayed markedly higher NSH scores, reflecting more diverse and functionally complex nematode communities compared to subsoil layers. This observation is ecologically consistent with the stratified distribution of organic matter and microbial activity in undisturbed soils. The uppermost soil layer typically harbours greater concentrations of labile carbon and PMN, both of which fuel microbial processes and sustain a more abundant and trophically diverse nematode community (Delgado-Baquerizo et al. 2017; Liu et al. 2023). These conditions create

Dataset 1

	MI	PPI	EI	SI	BI	CI	Abundance	Organic C	NO ₃ ⁻	NH ₄ ⁺	PO ₄	PBI	NSH
MI	1.00	0.63*	-0.89***	0.79**	0.31	0.73**	-0.21	0.47	-0.06	0.21	0.41	0.47	-0.13
PPI	0.63*	1.00	-0.55	0.50	0.13	0.59*	-0.48	0.93***	-0.49	-0.03	0.44	0.93***	-0.45
EI	-0.89***	-0.55	1.00	-0.49	-0.60*	-0.92***	0.15	-0.47	0.06	-0.20	-0.41	-0.47	0.29
SI	0.79**	0.50	-0.49	1.00	-0.24	0.25	-0.37	0.35	-0.24	-0.08	0.11	0.35	0.06
BI	0.31	0.13	-0.60*	-0.24	1.00	0.66*	0.13	0.21	0.12	0.26	0.33	0.21	-0.49
CI	0.73**	0.59*	-0.92***	0.25	0.66*	1.00	-0.27	0.53	-0.18	0.10	0.35	0.53	-0.50
Abundance	-0.21	-0.48	0.15	-0.37	0.13	-0.27	1.00	-0.41	0.92***	0.82**	0.50	-0.41	0.59*
Organic C	0.47	0.93*	-0.47	0.35	0.21	0.53	-0.41	1.00	-0.50	0.00	0.50	1.00***	-0.55
NO ₃ ⁻	-0.06	-0.49	0.06	-0.24	0.12	-0.18	0.92***	-0.50	1.00	0.87**	0.50	-0.50	0.59*
NH ₄ ⁺	0.21	-0.03	-0.20	-0.08	0.26	0.10	0.82**	0.00	0.87**	1.00	0.87**	0.00	0.37
PO ₄	0.41	0.44	-0.41	0.11	0.33	0.35	0.50	0.50	0.50	0.87**	1.00	0.50	0.05
PBI	0.47	0.93*	-0.47	0.35	0.21	0.53	-0.41	1.00***	-0.50	0.00	0.50	1.00	-0.55
NSH	-0.13	-0.45	0.29	0.06	-0.49	-0.50	0.59*	-0.55	0.59*	0.37	0.05	-0.55	1.00

Dataset 2

	MI	PPI	EI	SI	BI	CI	Abundance	Organic C	NO ₃ ⁻	NH ₄ ⁺	PO ₄	PBI	PMN	NSH
MI	1.00	-0.34	-0.74**	0.63*	-0.61*	0.14	-0.40	-0.09	-0.30	-0.03	-0.11	-0.08	-0.19	-0.64*
PPI	-0.34	1.00	0.10	-0.17	0.16	0.36	0.00	-0.25	-0.19	-0.03	-0.06	0.30	0.04	0.03
EI	-0.74**	0.10	1.00	-0.17	0.16	-0.19	-0.10	-0.28	-0.23	-0.50	-0.33	0.29	-0.40	0.19
SI	0.63*	-0.17	-0.17	1.00	-1.00***	0.44	-0.84***	-0.60*	-0.74**	-0.62*	-0.59*	0.22	-0.60*	-0.84***
BI	-0.61*	0.16	0.16	-1.00***	1.00	-0.48	0.86***	0.62*	0.74**	0.64*	0.61*	-0.23	0.60*	0.84***
CI	0.14	0.36	-0.19	0.44	-0.48	1.00	-0.40	-0.55*	-0.32	-0.42	-0.49	0.39	-0.21	-0.44
Abundance	-0.40	0.00	-0.10	-0.84***	0.86***	-0.40	1.00	0.81***	0.87***	0.79***	0.78***	-0.46	0.67**	0.89***
Organic C	-0.09	-0.25	-0.28	-0.60*	0.62*	-0.55*	0.81***	1.00	0.88***	0.87***	0.95***	-0.80***	0.75**	0.77**
NO ₃ ⁻	-0.30	-0.19	-0.23	-0.74**	0.74**	-0.32	0.87***	0.88***	1.00	0.85***	0.85***	-0.61*	0.84***	0.85***
NH ₄ ⁺	-0.03	-0.03	-0.50	-0.62*	0.64*	-0.42	0.79***	0.87***	0.85***	1.00	0.89***	-0.65**	0.85***	0.66**
PO ₄	-0.11	-0.06	-0.33	-0.59*	0.61*	-0.49	0.78***	0.95***	0.85***	0.89***	1.00	-0.72**	0.77**	0.75**
PBI	-0.08	0.30	0.29	0.22	-0.23	0.39	-0.46	-0.80***	-0.61*	-0.65**	-0.72**	1.00	-0.62*	-0.46
PMN	-0.19	0.04	-0.40	-0.60*	0.60*	-0.21	0.67**	0.75**	0.84***	0.85***	0.77**	-0.62*	1.00	0.66**
NSH	-0.64*	0.03	0.19	-0.84***	0.84***	-0.44	0.89***	0.77**	0.85***	0.66**	0.75**	-0.46	0.66**	1.00

FIGURE 4 | Correlation analysis based on Spearman correlation coefficient (r) between nematode-based indices (NBIs), soil chemical properties relative to nutrient cycling and nematode soil health (NSH) index. Significant differences are presented as follows: '***' < 0.001, '**' < 0.01, '*' < 0.05.

a more dynamic and interconnected soil food web, enhancing nutrient mineralisation and contributing to improved soil health as indicated by higher NSH scores.

Amendments containing soil faunal communities (Dataset 3) resulted in higher levels of the NSH index in the receptive soil compared to defaunated amendments, in line with the importance of soil faunal communities for transferring ecosystem functions (e.g., nutrient cycling and plant-nematode suppression) from natural to agricultural soils (Wubs et al. 2016; Ghaderi et al. 2025). Moreover, improving soil health conditions over time is most likely linked to increasing maturity and structure of the soil food web as an outcome of the beneficial free-living nematode populations (Ghaderi et al. 2025). Compared

to annual field crops, perennial pastures (Dataset 4) generally supported higher biodiversity with higher ratios of omnivores and predators (Ferris et al. 2001; van den Hoogen et al. 2019), ultimately yielding higher NSH scores.

In contrast to our initial hypothesis, Dataset 5 revealed no significant difference in NSH index scores between forest and grassland ecosystems. However, the similar NSH scores observed in both ecosystems suggest that grasslands in this context maintained equally diverse and structured nematode communities. This could be attributed to the relatively stable and diverse vegetation cover in grasslands, which fosters consistent organic inputs and supports a wide array of trophic groups. Both ecosystems exhibited high EI and SI values, indicating

well-developed food web networks with ample energy flow and trophic complexity. Importantly, significant seasonal differences were detected within the dataset, with NSH index scores being consistently higher in spring compared to autumn. This variation is likely driven by a combination of abiotic factors that influence nematode activity and community composition across seasons. During spring, warmer temperatures and increased soil moisture generally enhance microbial and faunal activity, promoting the proliferation of trophic groups such as bacterivores and fungivores. These groups, in turn, fuel higher trophic levels, such as omnivores and predators, contributing to a more structured and functionally rich nematode community. Additionally, seasonal dynamics in labile carbon and nitrogen availability, key resources for microbial and nematode metabolism, further influence the responsiveness of the soil biota to environmental cues (Huo et al. 2021). Another contributing factor may be the seasonal vertical migration of nematodes, particularly in forest ecosystems. During warmer or drier periods (e.g., late summer and autumn), nematodes may move to deeper soil layers in search of more favourable microhabitats, reducing their detectability in the topsoil where sampling typically occurs (Verschoor et al. 2001). This behavioural plasticity, while ecologically adaptive, can introduce sampling bias and affect temporal comparisons of surface soil communities.

4.2 | Key Conceptual Evidence for Validating the NSH Index

The NSH index is a composite indicator consisting of multiple subindicators (NBIs) relevant to nematode functional diversity and community composition. Validating the NSH index, therefore, requires assessment of NBIs in soil and their ecological interpretation (Figure 1).

The MI family, including MI, Σ MI and MI 2–5, is an indicator of environmental disturbance from perturbations. While MI accounts for only free-living nematodes, Σ MI is calculated based on both plant-parasitic (herbivores) and free-living nematodes in the community (Ferris 2013; du Preez et al. 2022). MI 2–5, similar to MI but excluding c-p 1 nematodes, is used for indicating perturbations unrelated to nutrient enrichment and has proven to be particularly useful in measuring soil pollution levels (Korthals et al. 1996). Low values of MI and Σ MI (<2.5) indicate immediate nutrient enrichment, such as fertilisation (Ferris et al. 2001), which could be considered a feature of soil health condition indicating improved nutrient status (Figure 1). However, these low values also indicate a simple soil food web characterised by high disturbance, low maturity, minimum structure connectance and limited energy flow between trophic levels. Low values for the MI family may indicate a primary successional stage, for instance, after soil fumigation (Bongers and Bongers 1998) or indicate ‘hot moments’ (Briones 2018). In contrast, higher values for the MI family indicate a mature and well-structured soil food web with higher complexity and enhanced ecosystem functions, indicating a high-level soil health condition. Only MI was included for the NSH index calculation, as Σ MI and MI 2–5 are not widely applied by nematode ecologists (du Preez et al. 2022), possess similar ecological interpretation and could be used alternatively. MI 2–5 is generally applicable

for monitoring of soil ecosystems to heavy metal pollutants (Korthals et al. 1996; Ferris 2010).

The PPI evaluates the complexity of the plant-parasitic nematode community. Lower value ranges (2.0–2.5) indicate the dominance of ectoparasitic nematodes, such as Tylenchidae and Paratylenchidae nematodes, with minimal to moderate damage to plants (allocated high NSH score). Intermediate PPI values (2.5–3.5) indicate high pressure of herbivory risk due to the dominance of semi(endo) plant-parasitic nematodes (e.g., *Meloidogyne*, *Heterodera* or *Pratylenchus*), which generally show higher economic impacts on plant yield (Karsen et al. 2013; Turner and Subbotin 2013; Duncan and Moens 2013) (Figure 1); therefore, they get the lowest NSH score. Higher PPI values (>3.5) represent the dominance of longidorid (family Longidoridae) and trichodorid (family Trichodoridae) nematodes, which are both ectoparasitic nematodes, but they pose a greater level of risk than other ectoparasites due to their longer stylets and ability to transport plant viruses (Decraemer and Geraert 2013), and they get intermediate NSH scores.

The EI is an indicator of food availability and nutrient enrichment in soil (Ferris et al. 2001; du Preez et al. 2022). Higher EI ranges are associated with improved soil health, although they do not necessarily indicate sufficient plant-available nutrients, as immobilisation by microorganisms often dominates the soil food web (Chen and Ferris 2000). In complex soil food webs, nutrient enrichment is assumed to be immobilised by microorganisms or consumed by plants (Whalen et al. 2013). Soil fauna (including nematodes) play a pivotal role in providing additional nutrient resources for plants through bioturbation and grazing on microorganisms (Coleman et al. 2024; Angst et al. 2024) and in this way increase nutrient enrichment, leading to higher EI values.

Higher ranges of the SI indicate a well-structured soil food web characterised by high maturity, complexity and connectance. A structured food web indicates either abundant food nutrient resources or the recovery of soil food web from a stressed condition (Ferris et al. 2001). In structured food webs, the abundance of nematodes in c-p classes 3–5 increases, indicating enhanced predator–prey relationships and multiple trophic interactions, finally resulting in environmental stability and homeostasis (Ferris et al. 2001; Ferris, Griffiths, et al. 2012; du Preez et al. 2022). Structure indicator taxa are susceptible to stress and disturbance, and therefore, the nematodes most abundant in stressed and disturbed soils are tolerant basal taxa in the c-p 2 group, resulting in increased BI values (Ferris et al. 2001). Therefore, BI can be considered as an informative indicator of a diminished food web, indicating conditions such as limited food availability, extreme or unfavourable environmental conditions, or different levels of contamination (Ferris et al. 2001; du Preez et al. 2022).

The CI measures the relative abundance of fungal and bacterial communities in the soil food web to determine the active decomposition pathway (Ferris et al. 2004). When recalcitrant organic material is available, bacterial activity is increased, and bacterivore nematodes become more abundant. When complex organic material is available, the abundance of fungivore

nematodes is increased due to a higher level of fungal activity (Ferris et al. 2001; du Preez et al. 2022). The CI index has been updated to broaden the range of regulated bacterial-fungal pathways, to account for multi-channel feeding and dominance of omnivory in soil food webs (Bradford 2016; Wood and Bradford 2018).

MFs are estimators of the nematode community's contribution to carbon channelling (Ferris 2010). Given the centrality of carbon in ecosystems (Neher et al. 2004; Kopittke et al. 2022), MFs can predict the nematode community's contribution to ecosystem functions. Generally, a composite MF is calculated for the whole nematode community, but MFs specific to each trophic group can also be calculated (Ferris 2010; du Preez et al. 2022). The composite MF is reflective of the carbon budget in the whole nematode community, which integrates both biomass and abundance as key variables (Ferris 2010; van den Hoogen et al. 2019). Therefore, the abundance or biomass of nematodes can serve as alternative index of MFs in soil health assessment.

We used the estimation of abundance and biomass of nematode communities at a global scale (van den Hoogen et al. 2019) as a baseline for defining value ranges for MFs. Biomes such as tundra, boreal and broadleaf forests, which typically have high biodiversity (often exceeding 2000 nematodes per 100g dry soil), are assumed to represent healthy soils. Conversely, regions like Antarctic sites, hot deserts and flooded grasslands and Savannas, characterised by very low biodiversity (less than 200 nematodes per 100g dry soil), reflect poor soil health. Tropical dry forests (200–500 nematodes per 100g dry soil), grasslands (500–1000 nematodes per 100g dry soil) and coniferous forests (1000–2000 nematodes per 100g dry soil) reflect intermediate soil health conditions. Therefore, we considered five abundance groups for whole nematode assemblage (Figure 1) according to the ranges of different biomes at a global scale. Natural grasslands and forests are widely recognised as baseline ecosystems with higher soil health conditions when NBIs are implemented to study the effects of agricultural practices or environmental changes on soil health (Girgan et al. 2020).

MFs are usually presented in nematode indicator joint analysis (NINJA) as graphical shapes and quantitative values. However, abundance data should be presented in a standardised way (e.g., expressed per 100g dry soil) so that results from different studies are comparable. Here, we consider the same categories as abundance groups for the composite MF, but further standardisation will be needed in future to transform abundance data into MF data. Moreover, if we transform abundance data to biomass data, according to van den Hoogen et al. (2019), five relevant groups of total nematode assemblage biomass (per 100g dry soil) can be defined as: (i) < 140 µg; (ii) 140–350 µg; (iii) 350–700 µg; (iv) 700–1400 µg; and (v) > 1400 µg. Depending on data availability, either MF, abundance or biomass of the whole nematode assemblage could be used for calculation of the NSH index.

Considering the substantial development and use of NBIs during the last three decades (Bongers and Bongers 1998; Ferris et al. 2001; Ferris 2010; du Preez et al. 2022), there is a strong conceptual and practical background for using NBIs in soil

health research. Combining all the NBIs into a single quantitative indicator in a framework more relevant to the soil health concept provides a step forward in the description of soil biological health and nematode communities. The new framework could be combined with quantitative estimations or graphical representations of NBIs (e.g., c-p triangles, profile food webs and MFs) to provide additional information relevant to assessing soil health conditions.

4.3 | Potential Implications of Using the NSH Index for Soil Health Assessment

Given that only a small proportion of previous nematode community studies estimated all NBIs, and most research works tend to calculate certain NBIs like EI and SI (du Preez et al. 2022), it is difficult to use published data in the literature to validate the NSH, as it is an aggregated index based on all the NBIs. Nevertheless, the NSH index is still flexible enough to be calculated using a smaller number of NBIs if the same NBIs are measured and used for all comparisons between soil samples, treatments, sites or times in a research study. NSH estimations based on all NBIs, however, will provide a more comprehensive view of the nematode community composition with a more precise description of the soil health condition. In this new framework, the final consensus index (NSH) as well as its subindicators (NBIs) can be used as estimators of soil health because the NSH index is scored in ranges from 8 to 32, and each subindex from 1 to 5 regarding soil health condition. For the NSH index, scores < 15 indicate degraded soil health with low biodiversity and disturbed food webs, scores between 15 and 24 suggest moderate soil health, typical of systems with some ecological structure but still under stress or transition, and scores > 25 reflect well-functioning soils with diverse, structured food webs and strong ecosystem service delivery. These score ranges can be used as benchmarks in field-based soil health assessments to: (i) diagnose soil health status across different management zones; (ii) track restoration progress over time; (iii) compare land use impacts on biological function; and (iv) guide management decisions (e.g., organic amendment, reduced disturbance, crop diversification).

When considering the practical implications of the NSH index for soil health assessment, it becomes clear that this tool offers valuable real-world applications for farmers, land managers and agricultural consultants. For instance, farmers could use the NSH index to monitor the biological health of their soils under different cropping systems, such as comparing perennial pastures with annual cropping fields, to guide decisions on crop rotation, cover cropping or tillage intensity. A high NSH score could indicate that soil ecosystems are functioning well, allowing for the optimisation of inputs and reduced reliance on chemical fertilisers, while low scores may prompt targeted interventions such as compost application or the introduction of soil biota through inoculants. Land managers overseeing restoration projects could use the NSH index to track improvements in soil health over time, especially when rehabilitating degraded soils or converting land from conventional to regenerative practices. Additionally, the index could serve as a biological benchmark for certification programs

(e.g., organic or sustainable farming standards), helping to demonstrate soil stewardship and environmental responsibility to regulators and consumers alike. By translating complex nematode community data into a single, intuitive score, the NSH index enables more informed, evidence-based soil management at both the field and landscape levels.

Currently, we present the NSH index as a new measure and novel framework, though subsequent research studies are needed to further evaluate, calibrate and standardise the NSH index through implementation with real data on nematode community composition in soils, similar to the datasets used in the present study. One possible calibration could be adjusting the weighting of the NBIs for the final calculation of the NSH index as different NBIs may contribute to soil health in different degrees and not necessarily in the same way. However, it should be noted that all NBIs have already been estimated based on weighted abundances of nematode taxa or trophic groups (Ferris 2013). Moreover, we adjusted weights and value ranges for the subindicators to increase the sensitivity of the NSH index. Another improvement could be providing a more powerful justification of soil health categories to either support or modify the thresholds for the current grouping scheme. Furthermore, benchmarking NBIs and the NSH index requires comparisons of soil health within biomes of the same type, using well-characterised soils with information from chemical and physical indicators to support their designated soil health status as poor, medium or high. Finally, the NSH index should also be validated for a wide range of soil and ecosystem types to test its consistency in predicting soil health conditions.

Presently, NBIs are usually calculated based on traditional microscope-based observations using morphological characters to identify the nematodes within a community. Diagnostic morphological characters are sometimes unreliable (showing intraspecific variability) or unobservable (not easily distinguished), making microscope-based identification difficult, time-consuming and often unsuccessful at lower taxonomic levels (Knot et al. 2020). Alternative high-throughput approaches such as DNA metabarcoding can substantially help researchers in estimating NBIs in agricultural and environmental ecosystems (e.g., Geisen et al. 2018; Bongiorno et al. 2019). Despite substantial limitations still associated with metabarcoding techniques, they are increasingly improving our insight into nematode diversity and community composition (Griffiths et al. 2018; Bongiorno et al. 2019; Waeyenberge et al. 2019; Knot et al. 2020). It should be noted that, regardless of the morphological or metabarcoding approach used for calculating NBIs, these indices have several fundamental limitations in their use and interpretation. The current NBIs, while still informative and helpful, are not the whole picture of the nematode community framework because they are based on our rudimentary knowledge of the autecology of nematode taxa. Many groups of taxa, particularly free-living nematodes that are not associated with crop damage, are overlooked and poorly studied in aspects of their biology and ecology (du Preez et al. 2022). Another challenge for NBIs arises from the plasticity or unclear nature of feeding habits in certain nematode taxa. While distinct groupings of feeding habits have been used as the foundation of NBIs, some evidence blurs these distinctions and their functional significance, as indicated by the unification of energy channels (omnivory) being widespread in most soil food webs (Bradford 2016; Potapov et al. 2022).

4.4 | Meeting Bioindicators Criteria by the Proposed Framework

Any indicator which is used for measuring any aspect of soil biodiversity needs to be meaningful, standardised, measurable and cost-efficient, while also meeting some other criteria, including policy-relevance, spatio-temporal coverage, understandability and accuracy (Turbé et al. 2010). The NSH index could be considered as a meaningful indicator because it recognises nematodes as indicator organisms, which are the most frequent multicellular eukaryotes in soil and have already proven as versatile bioindicators (Ferris and Bongers 2009; Ferris 2013; Waeyenberge et al. 2019). Moreover, the NSH index links nematodes to important ecosystem functions like nutrient cycling or to soil food web condition (Ferris et al. 2001; du Preez et al. 2022). Different subindicators of the NSH index can be measured in a routine, practical, affordable and standard way (Ferris 2013; du Preez et al. 2022); however, their estimation still needs some expertise and labour work, and their practical application for soil health assessments needs more standardisation and optimisation (Griffiths et al. 2018). Although the NSH index and NBIs present a dynamic and sensitive measure of biological soil health, they provide informative directions in response to different management practices in policy-relevant temporal and spatial scales (du Preez et al. 2022). For instance, NBIs have already been used successfully for monitoring nematode communities in organic production systems (Ferris, Sánchez-Moreno, et al. 2012; Landi et al. 2018) or different agricultural practices in more than 800 research works (du Preez et al. 2022). Nematode communities may be similar to microbial communities, which provide a temporally integrated metric of the variation with their high diversity able to be used to characterise many aspects of the soil environment (Fierer et al. 2021; Shi et al. 2024). Finally, the NSH index is simple to interpret, reduces complexity to an easily understood number and provides insight into soil biological health based on soil fauna, as opposed to many measures which examine microbial taxa or functional traits.

The new proposed framework meets the criteria of soil health indicators (Lehmann et al. 2020) as it is as follows: (i) highly relevant to soil health concept; (ii) sensitive to ecosystem changes; (iii) a cost-efficient and practical indicator; and (iv) informative for management. Four other criteria, including directional accuracy, quantified outcomes, functional form and a clear link to management, are recommended for a practical soil health indicator (Wood and Blankinship 2022). The directional change of the NSH index can be interpreted very clearly as high scores are related to a higher level of soil health, and lower scores reflect low levels of soil health conditions. Moreover, the NSH index quantifies the level of soil health in a range between 8 and 32, which can be used as a scoring measure for comparing different soils. The NSH index will be of most value, though when used to compare different soil samples within a soil type, land use or ecosystem. Any evaluation of soil health bioindicators, including the NSH index, needs to include soil chemical and physical data collection alongside biological data (Karlen et al. 2019; Lehmann et al. 2020; Fierer et al. 2021). However, functional forms of the NSH index, and the relationships between quantified outcomes of soil health with chemical and physical traits of soil, as well as with crop yield, need to be explored in future works. The NSH index and NBIs validation will help clarify

their use in agriculture to (1) describe soil health accurately and (2) link to management and policy purposes.

The NSH index represents a valuable alternative or complementary tool to existing soil health bioindicators, such as EMI for mesofauna (Parisi et al. 2005; Menta et al. 2018) and GISQ for macrofauna (Velasquez et al. 2007; Lugo et al. 2024). However, a significant limitation in comparative studies of these bioindicators is the absence of comprehensive datasets that simultaneously assess microfaunal, mesofaunal and macrofaunal communities using standardised methodologies. Without such integrated datasets, direct comparisons between these indicators remain challenging, preventing a holistic evaluation of their relative effectiveness in assessing soil health.

To address this gap, we strongly advocate for future research efforts aimed at developing standardised sampling and assessment protocols capable of capturing the diversity and functional roles of all soil faunal groups within the same dataset. By implementing consistent methodologies for estimating microfaunal, mesofaunal and macrofaunal communities, researchers will be able to conduct robust comparative analyses of the NSH index, EMI and GISQ. Such an approach would facilitate the refinement and optimisation of these bioindicators, enhancing their reliability and applicability in soil biodiversity and soil quality assessments. Ultimately, improving these indicators through rigorous comparative studies will lead to more accurate and comprehensive insights into soil ecosystem health, supporting sustainable land management and conservation strategies.

4.5 | Future Research Directions

To enhance the robustness and practical utility of the NSH index, future research should focus on its systematic calibration, validation and standardisation across a wider array of soil types, climates, land uses and management regimes. Calibration efforts could involve controlled experiments that manipulate key drivers of soil health, such as organic amendments, tillage intensity and crop diversity, to assess how the NSH index responds to known ecological changes. For example, factorial field trials incorporating both conventional and regenerative farming practices across contrasting soil textures (e.g., sandy vs. clayey) would allow researchers to evaluate the sensitivity and consistency of the NSH index under varied environmental conditions. Validation should also include long-term monitoring studies in natural and managed ecosystems, where NSH trends can be compared to independently measured ecosystem functions such as nutrient mineralisation, microbial activity, plant productivity or carbon sequestration. Furthermore, the refinement of index weighting schemes for individual NBIs should be guided by their relative ecological importance and predictive power in different systems. This may involve multivariate analyses (e.g., PCA, redundancy analysis or machine learning models) to determine which NBIs most strongly correlate with comprehensive measures of soil function. Weighting could also be adapted based on land use context; for instance, assigning greater importance to the MI and SI in degraded soils, where food web recovery is a priority, and to the EI or BI in highly fertilised or compacted soils.

Standardisation of the NSH index will require the development of benchmarks and reference ranges, ideally through the compilation of a large, publicly available database of NSH scores linked to metadata on soil physical, chemical and functional properties. This would enable the categorisation of soils into 'poor', 'moderate' or 'high' health classes based on evidence-driven thresholds. Benchmarking should be ecosystem-specific, acknowledging that healthy soils in grasslands, forests and croplands may exhibit different optimal NBI profiles. Collaborative efforts between soil ecologists, agronomists and land managers will be essential to test the NSH index under operational conditions and integrate it into decision-support tools, certification schemes and national soil monitoring frameworks. Ultimately, such advancements will ensure that the NSH index evolves into a standardised, adaptable, and policy-relevant bioindicator for guiding sustainable soil management.

5 | Conclusion

This study introduces an innovative framework for integrating NBIs into a single standardised bioindicator, the NSH index, offering a more comprehensive assessment of soil health. The framework validation was carried out using multiple datasets, which confirmed its robustness to effectively capture variations in soil biological health across different soil depths, land uses and ecosystems.

Key findings highlight the robustness of the NSH index in capturing soil health dynamics. The lack of significant differences among soil types suggests that, under similar management conditions, soil health may be influenced more by biological and chemical parameters than by soil classification alone. However, the significantly higher NSH values observed in topsoil (0–10 cm) compared to deeper layers (10–20 cm and 20–30 cm) confirmed the established understanding that topsoil harbours greater biological activity due to higher organic matter and nutrient availability. Soils amended with faunal communities exhibited significantly higher NSH values compared to defaunated soils, reinforcing the importance of soil biota in nutrient cycling and ecosystem function. The NSH index also effectively differentiated soil health between land uses by exhibiting higher values in perennial pastures compared to annual croplands, aligning with previous findings that pasture systems generally support more complex and resilient soil food webs. Furthermore, the NSH index captured seasonal shifts in nematode community dynamics. Strong correlations between the NSH index and key soil chemical variables, including organic C, NO_3^- and PO_4^{3-} , confirm its ecological relevance as an indicator of biological soil health. The observed relationships suggest that the NSH index not only reflects nematode community structure but also serves as a proxy for essential ecosystem functions such as nutrient mineralisation and soil organic matter dynamics.

The NSH index represents a significant advancement in soil health assessment by consolidating complex biological indicators into a single, interpretable metric. While further calibration across diverse soil types and ecosystems is needed, this framework provides a practical and scalable tool for researchers, land managers and policymakers. Future work

should refine the weighting of NBIs, expand validation efforts using molecular techniques and explore its integration into decision-support systems for sustainable soil management. By bridging ecological research with real-world applications, the NSH index has the potential to enhance soil health monitoring and inform management practices aimed at improving agricultural and environmental sustainability. This approach aims to provide a comprehensive and accessible method for assessing soil health, benefiting researchers, practitioners and farmers alike.

Author Contributions

Reza Ghaderi: conceptualization, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Helen L. Hayden:** conceptualization, investigation, methodology, validation, writing – review and editing. **Ramesha H. Jayaramaiah:** methodology, software, visualization, writing – review and editing. **Hang-Wei Hu:** investigation, validation, writing – review and editing. **Ji-Zheng He:** conceptualization, validation, writing – review and editing, supervision, resources, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.