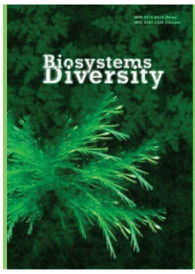

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Soil nematodes as a monitoring tool of bioenergy crop production management: The case of *Miscanthus giganteus* cultivation on different soil types

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The cultivation of bioenergy crops helps produce energy sources for industrial and domestic needs with a zero carbon footprint, which is very attractive in the context of efforts to prevent global climate change. However, this creates certain difficulties in terms of competition for agricultural land with crops used to satisfy human needs and produce food. One potential solution is the use of unproductive abandoned land disturbed by open-pit mining and marginal land contaminated with toxic substances for growing bioenergy crops. The subject of the study was to investigate the influence of soil type on nematode communities and related indicators in the cultivation of bioenergy crops for biofuel production in different geographical areas. A solution to the issue of the role of nematode communities in the hierarchical organisation of bioenergy crop management, which includes tactical and strategic levels, is proposed. A total of 44 nematode genera representing different soil types were found in the studied ecosystems. The lowest abundance of communities was found in Chernozem and Glayic Podzols. The highest abundance was found on Arenosols, Haplic Podzols, and Stagnic Fluvisols. The herbivores were represented by 21 genera. The proportion of herbivorous species usually did not exceed 60% of the total number of nematodes. The representatives of the genus *Paratylenchus* were found in all the studied soils. The results of multidimensional scaling showed that four dimensions could be identified. Dimension 1 proved to be the most sensitive to changes in the trophic structure of the communities, which is largely due to changes in the role of herbivores in the community. Dimension 2 allowed us to differentiate Arenosols from all other soil types. This difference is explained by functional changes in the structure of the nematode community. The Arenosols community is distinguished by an increase in the enrichment index, which is a consequence of an increase in the proportion of semi-endoparasites. Dimension 3 made it possible to differentiate a group of soils, including Haplich Fluvioglacial, Stagnant Fluvioglacial and Haplic Fluvisols, Stagnic Fluvisols, and Haplic Podzols from Glayic Podzols. Glayic Podzols are characterised by an increased total number of the community, mainly due to parasitic nematodes, as evidenced by the increased level of the plant parasitism index. Dimension 4 was able to capture the specific characteristics of the black soil nematode communities. This soil type is characterised by a higher density of nematode communities, which is explained by a higher proportion of bacteriophages and ectoparasites. Growing bioenergy crops has two different aspects: tactical and strategic. The tactical aspect involves the production of biological energy sources. This aspect includes traditional methods of crop management, including elements of plant disease and pest control, to achieve maximum yield. Thus, the object of tactical management is the plant. In contrast, the strategic aspect is concerned with soil reclamation to restore its functions, thereby paving the way for the possibility of using such soils for food production. The object of strategic management is soil. The tactical aspect involves obtaining direct economic benefits from the extraction of energy raw materials. The strategic aspect involves the restoration of disturbed lands and the creation of preconditions for the restoration of their ecosystem services and their inclusion in food production. Nematode communities can provide information for monitoring processes at both the tactical and strategic levels. The risks of parasitic nematodes and plant diseases should be assessed at the tactical level of management. At the strategic level of management, nematode communities should be used to monitor trophic network assessment and the level of stress in the soil system.

Keywords: bioindication; abandoned lands; military influence; global climate change; energy security.

Introduction

In the global energy market, biofuel demands have grown due to concerns about the effects of climate change. Changes in agricultural land use and management for bioenergy may impact biodiversity and ecosystem services (Vera et al., 2022). However, the spread of biofuel crops has either resulted in the direct or indirect displacement of natural ecosystems, or in the utilization of degraded or marginal areas. The first causes direct habitat loss, whereas later it has typical agricultural consequences (such as soil and biotic pollution and water eutrophication). However, in some cases, biofuel crops might result in an increase in biodiversity compared to traditional agricultural crops (Immerzeel et al., 2014). Second-generation biofuel is made from non-food sources such as forestry and municipal waste, lignocellulosic energy crops, fast growing trees, and crop residues. Lignocellulose obtained from non-food bioenergy crops can help to promote the bio-economy by being used as a valuable resource in biorefineries to produce diverse bioproducts, bioenergy, and biochemicals for a variety of commercial purposes (Rathour et al., 2023). This will not only assist to stabilize the circular bioeconomy, but it will also help to minimize waste and greenhouse gas emissions (Stefanovska et al., 2022).

Miscanthus × giganteus Greef et Deu (M×g) has a high biomass yield and cellulose content compared to other lignocellulosic bioenergy crops (Kvak et al., 2018), making it a suitable feedstock for the generation of biofuels and value added bioproducts: fibers, insulating materials, paper, biochar (Pidlisnyuk et al., 2020). A triploid perennial grass that is sterile, is regarded as one of the most promising crops for second-generation biofuels. With their superior environmental profile and C-4 photosynthetic pathway, *Miscanthus* (silvergrass) species have the ability to decrease fertilizer run-off and leaching while simultaneously increasing soil carbon, and biodiversity. Planting of M×g on areas polluted by anthropogenic sources or marginal areas provides environmental and economic advantages, including remediation potential (Alasmary et al., 2021). The phytoremediation of such lands through the cultivation of energy crops is one of the proposed environmentally friendly solutions in line with the principles of bio economy. Additionally, M×g production has a great potential for C storage and high carbon sequestration efficiency due to long-term crop cultivation, huge biomass yield, and low fertilizer and water requirements (Winkler et al., 2020). Since M×g is a new crop that has only been cultivated at scale in the last two decades, its below ground biodiversity and ecosystem functioning have not been studied yet comprehensively. The role of plant parasitic nematodes as potential soil borne pathogens is still not clear (Mekete et al., 2011). Nematodes are part of the soil microfauna and represent approximately 80% of all multicellular animals in terrestrial ecosystems. They are vital for ecosystem functioning (van den Hoogen et al., 2019). Although nematodes are the most abundant and diverse animals on the planet, they lack representation in biodiversity research. Nematodes have adapted to nearly all soil environments, from the tropics to the poles (Rahbek, 2005), from agroecosystems to desert ecosystems and from micro aggregate to macro aggregate fractions (De Vries et al., 2013). Nematodes support ecosystem functions like primary productivity, decomposition, and general nutrient cycling because of their widespread distribution, varied feeding habits (such as bacterial and fungal feeders, plant and animal parasites, omnivores, and predators), and placement at different trophic levels (Gebremikael et al., 2016). Because nematodes have different feeding behaviour, life strategies, reproduction capacity and play a significant part in the soil food web, they function as an important indicator of ecosystem processes, including pollution, environmental disturbances, and climate change impact (Howard Ferris, 2010). The analysis of the nematode population (assemblage and feeding groups) over time represents an effective method for determining the impact of land use and management strategies on soil quality and function (Shokoohi, 2023). Because nematode communities are sensitive to environmental disturbances, such as changes in temperature and water availability, it is possible that human activity induced environmental changes impact nematode communities and modify plant-nematode interactions (Wilschut & Geisen, 2021). Changes in nematode community composition in response to global change can occur both directly and indirectly. For example, through the changes in plant community composition (Liang et al., 2020). A recent long-term grassland research project found that adjustments in nematode populations can continue for many years, highlighting the importance of understanding how modifications in the nematode community in response to global change affect plant performance (Pidlisnyuk et al., 2022). At the local level, a variety of global change factors affect nematode communities in natural systems. Furthermore, nematode indices can be used to assess ecosystem nutrient condition (enriched vs. depleted), soil food web structure (complexity vs. simplicity), and the rate at which organic matter decomposes (slower fungal vs. faster bacterial) (Bongers & Ferris, 1999).

Changes in land use and related land cover transformations are widely recognized as an important driver of global environmental degradation (Lambin et al., 2001). Nematodes are a model of soil fauna that can help us understand how soil biodiversity reacts to changes in land use. Variations in soil conditions caused by land-use changes promote microbial carbon cycling which likely also affects soil nematode communities in biofuel systems given that nematodes feed on soil microorganisms (Wang et al., 2022). Climate factor can be interrelated with land use impact on biodiversity. Temperature, for example, increases nematode diversity in resource-rich soils while decreasing it in resource-poor soils, with the latter often affecting intensively managed soils (Siebert et al., 2020). As demonstrated by other terrestrial species, the impacts of climatic factors may exacerbate those of land-use changes. Effects of land-use changes consequently are likely to negatively impact soil nematodes. Variations in soil conditions due to land-use changes drive microbial carbon cycling. The complex alterations in the nematode population were caused mostly by land use, with high seasonal dynamics, whereas future climate had a smaller influence. The high nematode numbers linked with changed climatic conditions and intensive land usage were caused by increasing densities of opportunists and potential plant pathogens (plant feeders). This correlated with a less diversified and less organized group, implying less ability to endure environmental stress. These deteriorated soil food web scenarios pose a hazard to ecosystem function, emphasizing the necessity of management methods that protect belowground species (Sprunger et al., 2023). Globally, a number of specific studies have demonstrated that environmental factors, such as ecosystem type and its properties (Nielsen et al., 2014), soil type and its properties (Renčo et al., 2020), vegetation (Dietrich et al., 2021) and the interaction of these factors affects the degree of species diversity of soil nematode assemblages or the abundance of nematode communities (Matlack, 2001). The type of soil influences the variety of nematode species present in the soil as well as the growth potential of the host plants (Jones, 1975). Agricultural practices in bioenergy cropping systems have a tremendous impact on the soil ecosystem, impacting both its physical and biological features. Previous studies found that the nematode community can be used as suitable indicator of soil health under different agricultural practices during cultivation of M×g in marginal and contaminated land (Alasmary et al., 2021). The diversity of nematode communities varies according to geographical location due to variation in ecological and edaphic factors. In terrestrial soil ecosystems, nematodes constitute a significant proportion of the microfauna, yet there is a paucity of knowledge regarding the ecological and edaphic factors regulating their population distribution, particularly in soil under production of bioenergy crops, including *Miscanthus × giganteus*. More research is needed to understand the impact of various bioenergy cropping methods on biotic communities to determine which ecological and edaphic factors (soil type and properties) may drive its abundance and functional diversity.

The subject of the study was to research the effect of soil type on the nematode community and their associated indices in M×g cropping for biofuel production at distinct geographical areas. The answer to this question will help to solve the issue of the role of nematode communities in the hierarchical organisation of bioenergy crop management, which includes tactical and strategic levels.

Materials and methods

Sampling locations. Soil nematodes were studied in M×g plantations of 3–8 years of cultivation in varied soils representing the distant geographic zones: Arenosols (Chojnice, Poland), Glayic Cambisols (Dolyna, Ukraine), Cambisoils (Chomutov, Czech Republic), Chernozem (Kalynivka, Ksaverovka, Kurakhove, Szepetivka, Veremyivka, Ukraine), Stagnic Fluvisols (Rumia, Poland), Haplic Fluvisols (Poznan, Starograd, Poland), Haplic Podzols (Iwonicz, Poland), Glayic Podzols (Batyeva gora, Ukraine), Podzols (Kyiv, Ukraine), Harney (Kansas, USA) (Table 1).

Table 1
Soil types and coordinates of sampling locations

Location	Geographical coordinates	Type of soil
Chojnice, Poland	53.66′ N, 17.6′ E	Cambic Arenosols
Rumia-Rekowo	49.85′ N, 22.72′ E	Eutric Fluvisols
Poznań, Poland	52.43′ N, 16.90′ E	Haplic Uvisols
Starogard, Poland	54.62′ N, 17.23′ E	Stagnic Luvisols
Iwonicz, Poland	49.79′ N, 21.79′ E	Haplic Podzols
Batyeva Gora,Kyiv, Ukraine	50.29′ N, 30.57′ E	Glayic Podzoluvisols
Chomutov, Czech Republic	50°27′ N, 13°23′ E	Cambisoils
Dolyna, Ukraine	48.58′ N, 23.54′ E	Glayic Cambisols
Ksaverivka, Ukraine	50.44′ N, 30.43′ E	Chernozem
Kalynivka, Ukraine	50.17′ N, 27.02′ E	Cherozem
Veremyivka, Ukraine	49.0′ N, 32.91′ E	Chernozem
Kurakhove, Ukraine	47.96′ N, 37.26′E	Chernozem
Shepetivka, Ukraine	54.62′ N, 17.23′E	Chernozem
Flint Hills, USA	39°11′ N, 96°35′ W	Harney

Nematode isolation from soil and identification. The nematodes were isolated from soil using a modification of the Baermann technique (Whitehead & Hemming, 1965). Plant samples were placed in trays lined with a plastic mesh. The plastic mesh bottom was covered with a single sheet of tissue paper. Approximately 50 g of the collected soil samples were put in tissue paper and spread in a thin and homogeneous layer before gently pouring tap water over the soil.After 24 hours the suspension collected in the plastic tray was put over a fine screen (400 mesh sieve) to concentrate it before identification. Water was added to the trays and the procedure was repeated after 48 h to ensure the efficiency of maximum extraction of nematodes from the soil. The suspension with isolated nematodes was stored in glass containers. The nematodes were then subjected to thermal killing with 6% formalin (90 °C), fixed with water, and passed through a series of glycerol-ethanol solutions before being stored on slides in anhydrous glycerol. The isolated nematodes were then transferred to a fixation plate containing S1 solution (20 mL of 96% ethanol, 1 mL of glycerol and 79 mL of distilled water). The dishes were placed in a desiccator with a thin coating of 96% ethanol and transferred to an incubator set to 40 °C. Using a micropipette, the S1 solution was withdrawn after 16–24 hours under the dissecting microscope, and the S2 solution (93 mL of 96% ethanol and 7 mL glycerine) was added later. After two hours, the fixation dish was returned to the incubator, with two drops of dried glycerine added. The fixation cup was left for 24 hours to let the alcohol evaporate. It was then placed in a desiccator with silica gel to evaporate the final remnants of water. The nematodes were now ready for mounting on slides. Initially, 100 individual nematodes were found in each sample. Paraffin sections of nematodes on slides were prepared using the paraffin ring method. Morphological traits were used to identify nematodes. Each nematode taxon was classified into five trophic categories based on their life features and dietary preferences: plant parasites, bacterivores, fungivores, omnivores and predators.

Ecological indexes calculation. The ratio of a specific genus to the total number of nematodes and their corresponding c-p values were used to determine the maturity index (MI) for FLNs and the plant parasite index (PPI) for herbivores (Bongers, 1990). A number of indicators of the complexity and organization of the soil food web were calculated (Ferris et al., 2001). The parameters listed below were chosen for this situation: the channel index (CI) based on rapidly growing bacterivores and fungivores with c-p values of 1 or 2, the basal index (BI) based on rapidly growing bacterivores and fungivores with a c-p value of 2, the enrichment index (EI), which was thought to be a sign of conditions that favour rapidly growing bacterivores, and the structure index (SI), which correlated with the development of an ecosystem made up of nematode genera with c-p values between 3 and 5. In addition, the relative abundance of nematode functional guilds (trophic and c-p groups) was calculated. The SI, which is a weighted average of the proportion of sensitive predatory and omnivorous nematodes, is a measure of the complexity of the soil food web as a result of soil disturbance. The CI is the ratio of fungivores to bacterivores and represents the predominance of fungi-mediated organic matter decomposition. The BI is based on the prevalence of general opportunist nematodes and implies basal, disturbed soil food web conditions. The EI is predicated on the presence of enrichment opportunist nematodes and suggests fast, bacterially induced organic matter breakdown (Ferris et al., 2001). The scatter plot of SI vs EI values, separated into four quadrants, has been proposed as a method for classifying the soil food web into four distinct states: structured, mature, degraded, and disturbed (Ferris et al., 2001). NINJA: Nematode Indicator Joint Analysis used to calculate the ecological indices (Sieriebriennikov et al., 2014).

Statistical analysis. The calculation of descriptive statistics, as well as cluster, factor, discriminant, and ANOVA analyses were conducted with the assistance of Statistica 10.0 software (Statsoft). The multidimensional scaling was performed using the vegan library for Project R. A variety of data preprocessing procedures are available for multidimensional scaling, and the procedure can be performed on distance matrices calculated from different metrics. The corresponding distance index should have a high rank order of similarity with the gradient separation for multidimensional scaling. The rank correlation coefficient was used to compare the distance indices with the gradient division based on the functional indicators of the nematode community. From the multitude of potential combinations of preliminary data transformation methods and distances between species in the community, we selected the one that yielded the highest rank correlation with the functional index matrix. The optimal number of measurements for the final solution was determined based on the sharp decrease in stress and differential stress.

Results

A total of 44 genera of nematodes were identified within the ecosystems under study, representing a range of soil types (Table 2). The abundance of communities varied from 241.2 ± 18.3 to 587.7 ± 33.6 individuals per sample (Table 2). The lowest abundance of communities was found in the Chernozem and Glayic Podzols (Planned comparison F = 82.4, P < 0.001). The highest abundance of was found in the Arenosols, Haplic Podzols, and Stagnic Fluvisols (Planned comparison F = 36.9, P < 0.001). The communities in other soils occupied a transitional position in terms of total abundance. Herbivores were revealed to be represented by 21 genera. This trophic group ranged from 39.4 ± 1.6% to 86.6 ± 2.7% of the total abundance of the community. The proportion of herbivores was usually not higher than 60% of the total community in the group of soils consisting of Arenosols, Glayic Cambisols, Podzols (Pb), and Harney (Planned comparison F = 363.6, P < 0.001). The proportion of herbivores was typically above 70% in other soils.

Table 2

Taxonomic composition of nematode communities of soil types and their abundance (ind./sample, mean ± st. deviation)

Genus	Arenosols	Glayic Cambisols	Cambisols	Chernozem	Stagnic Fluvisols	Haplic Fluvisols	Haplic Podzols	Glayic Podzols	Podzols (Pb)	Harney
Amplimerlinius	–	1.5 ± 0.3	1.0 ± 0.0	4.1 ± 1.3	–	8.3 ± 1.3	0.5 ± 0.2	3.6 ± 1.1	–	–
Bitylenchus	117.0 ± 3.7	63.0 ± 14.8	4.0 ± 0.8	16.3 ± 2.0	84.6 ± 7.5	60.8 ± 8.3	101.9 ± 3.7	8.9 ± 3.1	9.7 ± 0.9	–
Criconema	–	–	–	–	7.3 ± 1.4	2.7 ± 0.4	–	2.6 ± 0.9	–	–
Criconemoides	–	–	–	–	5.6 ± 1.6	5.4 ± 1.2	–	–	–	–
Geocenamus	–	1.0 ± 0.0	13.1 ± 1.1	–	–	–	–	–	–	12.6 ± 1.3
Longidorus	23.3 ± 3.7	–	–	1.0 ± 0.4	54.7 ± 8.0	2.7 ± 0.6	7.3 ± 2.3	–	–	1.6 ± 0.3
Merlinius	7.7 ± 1.0	9.3 ± 0.7	23.1 ± 2.7	9.4 ± 3.6	23.3 ± 4.6	–	57.6 ± 10.4	25.7 ± 4.0	19.3 ± 2.0	25.2 ± 2.3
Mesocriconema	–	16.5 ± 1.9	–	10.2 ± 3.1	5.3 ± 1.0	10.3 ± 1.4	2.2 ± 0.7	4.7 ± 0.8	1.2 ± 0.2	–
Paralongidorus	–	–	–	0.3 ± 0.1	–	–	–	–	–	–
Paratrichodorus	20.3 ± 1.1	–	–	–	19.6 ± 1.4	15.1 ± 3.0	–	–	–	–
Paratrophurus	–	–	0.6 ± 0.3	–	–	–	–	–	–	0.6 ± 0.3
Paratylenchus	41.0 ± 0.9	37.5 ± 1.9	28.3 ± 2.6	28.9 ± 8.0	28.3 ± 7.9	26.1 ± 6.6	62.4 ± 17.2	14.2 ± 1.4	36.3 ± 4.9	28.3 ± 2.6
Sauertylenchus	–	12.5 ± 1.7	–	–	–	14.3 ± 2.5	–	–	20.5 ± 2.5	–
Scutylenchus	–	11.2 ± 1.9	–	24.1 ± 4.1	25.0 ± 1.9	23.9 ± 2.1	–	18.5 ± 4.2	8.9 ± 1.1	–
Trichodorus	–	10.8 ± 0.8	–	1.3 ± 0.7	12.4 ± 0.6	2.7 ± 0.7	0.6 ± 0.2	–	10.0 ± 1.9	–
Xiphinema	3.8 ± 0.7	12.2 ± 1.6	–	10.9 ± 1.8	19.4 ± 2.1	5.7 ± 0.5	3.8 ± 1.3	13.8 ± 3.6	–	–
Cephalenchus	–	1.7 ± 0.3	–	25.1 ± 2.6	11.3 ± 1.3	12.7 ± 0.8	–	15.2 ± 4.0	1.5 ± 0.1	–
Hoplotylus	–	–	–	–	–	–	2.6 ± 0.4	–	1.0 ± 0.0	–
Pratylenchus	29.0 ± 1.9	16.8 ± 0.8	58.6 ± 4.1	13.4 ± 2.8	37.6 ± 4.6	26.3 ± 2.7	15.2 ± 2.0	19.8 ± 2.0	29.9 ± 2.4	58.9 ± 4.1
Helicotylenchus	44.7 ± 1.9	16.0 ± 2.2	28.5 ± 2.8	24.5 ± 3.7	71.1 ± 7.1	56.9 ± 6.0	130.0 ± 13.1	–	50.3 ± 5.7	28.7 ± 2.8
Rotylenchus	19.3 ± 0.6	84.3 ± 10.6	–	38.1 ± 2.4	12.3 ± 3.6	31.2 ± 2.5	64.6 ± 14.0	67.0 ± 5.2	36.7 ± 5.5	–
Acrobeles	–	–	–	–	–	–	–	–	18.1 ± 0.5	–
Acrobeloides	–	–	16.2 ± 2.2	–	–	–	–	–	–	16.1 ± 2.1

Genus	Arenosols	Glayic Cambisols	Cambisols	Chernozem	Stagnic Fluvisols	Haplic Fluvisols	Haplic Podzols	Glayic Podzols	Podzols (Pb)	Harney
Cephalobus	–	–	12.1 ± 1.2	–	–	–	0.8 ± 0.3	–	17.6 ± 0.4	12.1 ± 1.2
Diplogaster	–	–	–	–	–	–	–	–	16.3 ± 0.3	–
Panagrolaimus	–	–	11.3 ± 1.3	–	–	–	–	–	–	11.7 ± 1.2
Plectus	–	1.0 ± 0.0	7.9 ± 1.1	–	–	–	–	–	–	7.9 ± 1.1
Cuticularia	–	–	–	–	–	–	–	–	12.1 ± 0.5	–
Rhabditis	–	–	10.2 ± 1.4	–	–	–	–	–	22.6 ± 0.9	9.6 ± 1.4
Aphelenchoides	122.2 ± 3.2	9.5 ± 1.2	22.9 ± 1.5	8.2 ± 1.6	20.8 ± 3.1	9.7 ± 3.2	34.0 ± 1.3	3.7 ± 0.6	19.8 ± 0.8	23.2 ± 1.5
Aphelenchus	115.2 ± 2.8	86.7 ± 12.9	63.6 ± 7.2	43.2 ± 8.3	99.1 ± 10.0	43.3 ± 11.7	103.3 ± 5.3	43.4 ± 3.5	25.0 ± 0.6	64.0 ± 7.1
Ditylenchus	–	–	26.0 ± 3.9	2.0 ± 0.5	–	–	0.5 ± 0.2	–	21.8 ± 0.6	28.3 ± 3.6
Filenchus	–	–	25.9 ± 2.2	–	–	–	–	–	25.9 ± 0.6	25.9 ± 2.2
Allodorylaimus	–	–	–	–	–	–	0.5 ± 0.2	–	6.2 ± 0.2	–
Dorylaimus	–	1.0 ± 1.0	21.0 ± 2.6	1.8 ± 0.4	–	–	–	–	–	20.5 ± 2.7
Enchodelus	–	1.0 ± 0.1	4.3 ± 0.6	–	–	–	–	–	–	2.9 ± 0.7
Mesodorylaimus	1.5 ± 0.2	–	6.5 ± 0.8	–	–	–	–	–	4.1 ± 0.1	6.4 ± 1.0
Aporcelaimus	–	–	–	–	–	–	–	–	8.3 ± 0.4	–
Clarkus	–	–	–	–	–	–	–	–	1.1 ± 0.0	–
Coomansus	–	–	4.1 ± 0.3	–	–	–	–	–	–	4.1 ± 0.3
Eudorylaimus	–	1.2 ± 0.2	11.6 ± 1.1	–	–	–	–	–	5.3 ± 0.3	11.8 ± 1.1
Iotonchus	–	1.0 ± 0.0	1.5 ± 0.1	–	–	–	–	–	–	1.5 ± 0.1
Mylonchulus	–	–	4.9 ± 0.5	–	–	–	–	–	1.1 ± 0.1	4.9 ± 0.5
Prionchulus	–	–	3.2 ± 0.3	–	–	–	–	–	–	3.2 ± 0.3

Table 3
Functional indices of nematode communities (mean value ± st. deviation)

Variable	Arenosols	Glayic Cambisols	Cambisols	Chernozem	Stagnic Fluvisols	Haplic Fluvisols	Haplic Podzols	Glayic Podzols	Podzols (Pb)	Harney
Total number, ind	545.0 ± 3.8	395.7 ± 24.9	409.0 ± 22.8	257.6 ± 21.1	528.1 ± 28.4	355.1 ± 29.1	587.7 ± 33.6	241.2 ± 18.3	430.7 ± 14.1	407.4 ± 21.7
Total biomass, mg	0.5 ± 0.1	0.3 ± 0.1	1.2 ± 0.1	0.2 ± 0.1	1.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	1.0 ± 0.1	1.2 ± 0.1
Maturity Index	2.0 ± 0.1	2.1 ± 0.1	2.5 ± 0.1	2.1 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.4 ± 0.1
Maturity Index 2-5	2.0 ± 0.1	2.1 ± 0.1	2.6 ± 0.1	2.1 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.4 ± 0.1	2.5 ± 0.1
Sigma Maturity Index	2.6 ± 0.1	2.8 ± 0.1	2.6 ± 0.1	2.7 ± 0.1	3.1 ± 0.1	2.9 ± 0.1	2.7 ± 0.1	2.8 ± 0.1	2.5 ± 0.1	2.6 ± 0.1
Plant Parasitic Index	3.1 ± 0.1	3.0 ± 0.1	2.8 ± 0.1	2.8 ± 0.1	3.3 ± 0.1	3.0 ± 0.1	2.9 ± 0.1	3.0 ± 0.1	2.9 ± 0.1	2.8 ± 0.1
Channel Index	100.0 ± 0.1	100.0 ± 0.1	64.9 ± 2.0	100.0 ± 0.1	100.0 ± 0.1	100.0 ± 0.1	100.0 ± 0.1	100.0 ± 0.1	31.5 ± 0.6	65.2 ± 2.2
Basal Index	49.4 ± 0.1	46.3 ± 0.7	26.3 ± 1.3	45.3 ± 1.3	50.0 ± 0.1	50.0 ± 0.1	49.8 ± 0.1	50.0 ± 0.1	23.4 ± 0.2	27.4 ± 1.2
Enrichment Index	50.0 ± 0.1	49.7 ± 0.1	55.6 ± 0.6	50.0 ± 0.1	50.0 ± 0.1	50.0 ± 0.1	49.8 ± 0.1	50.0 ± 0.1	69.8 ± 0.3	55.6 ± 0.7
Structure Index	2.5 ± 0.4	14.5 ± 2.3	58.7 ± 2.5	15.7 ± 4.0	–	–	1.6 ± 0.5	–	48.8 ± 0.6	56.9 ± 2.4
Composite footprint	120.6 ± 9.1	81.0 ± 4.6	210.4 ± 17.0	56.9 ± 3.4	217.3 ± 23.2	63.2 ± 3.2	93.6 ± 7.0	50.3 ± 5.8	192.2 ± 5.1	208.7 ± 18.0
Enrichment footprint	20.4 ± 0.5	9.2 ± 1.3	37.3 ± 3.8	5.2 ± 0.8	9.7 ± 1.8	5.0 ± 1.4	12.7 ± 0.6	4.5 ± 0.3	69.6 ± 2.0	36.7 ± 3.8
Structure footprint	0.5 ± 0.1	8.7 ± 5.8	148.7 ± 14.5	10.0 ± 2.1	–	–	0.4 ± 0.1	–	83.3 ± 3.4	144.4 ± 14.8
Herbivore footprint	99.7 ± 9.5	62.8 ± 2.9	14.4 ± 0.9	41.7 ± 4.1	207.6 ± 21.6	58.3 ± 2.6	80.4 ± 6.8	45.8 ± 5.7	33.1 ± 2.2	17.7 ± 1.1
Fungivore footprint	20.4 ± 0.5	9.2 ± 1.3	14.0 ± 1.3	5.2 ± 0.8	9.7 ± 1.8	5.0 ± 1.4	12.7 ± 0.6	4.5 ± 0.3	9.4 ± 0.3	14.4 ± 1.2
Bacterivore footprint	–	0.3 ± 0.1	33.3 ± 3.7	–	–	–	0.1 ± 0.1	–	66.4 ± 2.0	32.1 ± 3.7
Predator footprint	–	2.3 ± 0.1	24.3 ± 1.5	–	–	–	–	–	76.6 ± 3.3	24.4 ± 1.5
Omnivore footprint	0.5 ± 0.1	6.5 ± 5.6	124.4 ± 14.9	10.0 ± 2.1	–	–	0.4 ± 0.1	–	6.7 ± 0.2	120.0 ± 15.2
Herbivores, % of total	56.2 ± 1.0	75.0 ± 2.3	39.9 ± 1.7	77.7 ± 3.5	81.4 ± 2.8	86.6 ± 2.7	75.9 ± 1.1	79.7 ± 1.3	50.9 ± 1.2	39.4 ± 1.6
Fungivores, % of total	43.5 ± 1.0	23.7 ± 2.2	31.8 ± 1.6	21.4 ± 3.4	18.6 ± 2.8	13.4 ± 2.7	23.9 ± 1.1	20.3 ± 1.3	22.2 ± 0.6	32.9 ± 1.4
Fungivores, % of free-living	99.4 ± 0.1	94.8 ± 0.8	52.0 ± 1.7	94.6 ± 1.6	100.0 ± 0.1	100.0 ± 0.1	99.0 ± 0.3	100.0 ± 0.1	45.1 ± 0.6	53.7 ± 1.5
Bacterivores, % of total	–	0.3 ± 0.1	13.2 ± 1.0	–	–	–	0.1 ± 0.1	–	20.6 ± 0.5	13.3 ± 1.0
Bacterivores, % of free-living	–	1.1 ± 0.2	20.9 ± 1.3	–	–	–	0.6 ± 0.2	–	42.1 ± 0.6	21.2 ± 1.3
Predators, % of total	–	0.6 ± 0.1	7.0 ± 0.7	–	–	–	–	–	3.8 ± 0.2	6.9 ± 0.6
Predators, % of free-living	–	2.3 ± 0.3	13.2 ± 1.7	–	–	–	–	–	7.7 ± 0.2	12.6 ± 1.4
Omnivores, % of total	0.3 ± 0.1	0.5 ± 0.2	8.1 ± 0.7	0.8 ± 0.2	–	–	0.1 ± 0.1	–	2.5 ± 0.1	7.4 ± 0.7
Omnivores, % of free-living	0.6 ± 0.1	1.8 ± 0.7	13.9 ± 1.3	5.4 ± 1.6	–	–	0.4 ± 0.1	–	5.1 ± 0.2	12.5 ± 1.2
Sedentary parasites, % of herbivores	–	–	–	–	–	–	–	–	–	–
Migratory endoparasites, % of herbivores	9.5 ± 0.5	5.8 ± 0.4	38.6 ± 2.7	6.5 ± 1.2	8.8 ± 1.1	8.6 ± 0.6	4.0 ± 0.4	10.3 ± 0.7	15.1 ± 1.2	38.5 ± 2.4
Semi-endoparasites, % of herbivores	20.9 ± 0.4	34.7 ± 3.9	17.7 ± 1.2	32.6 ± 1.8	19.7 ± 0.8	29.8 ± 2.4	42.8 ± 2.7	36.1 ± 2.5	37.8 ± 2.7	18.0 ± 1.3
Ectoparasites, % of herbivores	69.7 ± 0.6	59.0 ± 4.4	43.8 ± 2.3	43.1 ± 3.3	67.5 ± 1.8	57.2 ± 2.4	53.2 ± 2.4	45.3 ± 3.2	46.3 ± 2.5	43.5 ± 2.0
Epidermal/root hair feeders, % of herbivores	–	0.6 ± 0.1	–	17.8 ± 2.8	4.1 ± 0.9	4.4 ± 0.5	–	8.3 ± 1.9	0.7 ± 0.1	–
CP 1, % of free-living	–	–	7.7 ± 0.6	–	–	–	–	–	24.8 ± 0.4	7.7 ± 0.6
CP 2, % of free-living	99.4 ± 0.1	95.9 ± 0.7	65.2 ± 2.2	94.6 ± 1.6	100.0 ± 0.1	100.0 ± 0.1	99.6 ± 0.1	100.0 ± 0.1	62.4 ± 0.4	67.2 ± 2.0
CP 3, % of free-living	–	–	–	–	–	–	–	–	–	–
CP 4, % of free-living	0.6 ± 0.1	4.1 ± 0.7	27.1 ± 2.5	5.4 ± 1.6	–	–	0.4 ± 0.1	–	8.7 ± 0.3	25.2 ± 2.1
CP 5, % of free-living	–	–	–	–	–	–	–	–	4.0 ± 0.2	–
PP 2, % of herbivores	13.4 ± 0.3	13.3 ± 0.6	17.4 ± 0.8	29.2 ± 2.3	11.0 ± 2.0	12.4 ± 1.5	12.4 ± 2.6	16.0 ± 2.3	15.6 ± 1.3	17.7 ± 0.9
PP 3, % of herbivores	71.2 ± 1.2	78.9 ± 0.9	82.6 ± 0.8	64.0 ± 2.4	64.1 ± 1.0	78.6 ± 1.7	85.0 ± 2.5	77.6 ± 1.8	80.4 ± 1.7	81.2 ± 0.8
PP 4, % of herbivores	6.6 ± 0.3	3.7 ± 0.2	–	0.3 ± 0.2	7.5 ± 0.2	6.2 ± 1.2	0.1 ± 0.1	–	4.0 ± 0.6	–
PP 5, % of herbivores	8.8 ± 1.0	4.1 ± 0.5	–	6.5 ± 1.3	17.3 ± 2.1	2.8 ± 0.3	2.5 ± 0.4	6.4 ± 1.2	–	1.1 ± 0.3

The representatives of the genus *Paratylenchus* were found in all studied soils. In Arenosols, Glayic Cambisols, Stagnic Fluvisols, Haplic Fluvisols, Haplic Podzols, the representatives of the genus *Bitylenchus* were dominant among ectoparasites. The representatives of the genus *Paratylenchus* were the most prevalent in Cambisols, Chernozem, Podzols (Pb), and Harney. The representatives of the genus *Merlinius* were dominant in Glayic Podzols. The proportion of ectoparasites among herbivores was found to range from 43.1 ± 3.3% to 69.7 ± 0.6 %. This trophic group was recorded in Arenosols, Glayic Cambisols, Haplic Fluvisols, Stagnic Fluvisols, which exhibited statistically significant higher levels than in other soil types (planned comparison F = 39.1, P < 0.001). The group of organisms known as epidermal/root hair feeders was represented by a single genus, *Cephalenchus*. The study revealed the presence of two genera of migratory endoparasites, with the genus being identified in all soil types examined. The proportion of migratory endoparasites among herbivores ranged from 4.0 ± 0.4% to 38.6 ± 2.7%. This index was highest in the Cambisols and Harney (planned comparison F = 307.7, P < 0.001). Semi-endoparasites were represented by the two genera (*Helicotylenchus* and *Rotylenchus*).

Among herbivores, the proportion of semi-endoparasites exhibited a considerable range, from 17.7 ± 1.2% to 37.8 ± 2.7%. The lowest proportion of semi-endoparasites among herbivores was observed in soils classified as the Arenosols, Cambisols, Harney, and Stagnic Fluvisols (Planned comparison F = 58.0, P < 0.001). The eight genera of bacterivores were represented. No representatives of bacterivores were identified in the following soil types: Arenosols, Chernozem, Stagnic Fluvisols, Haplic Fluvisols, and Glayic Podzols. In the ecosystems where representatives of this trophic group were identified, their abundance ranged from 0.1 ± 0.1% to 20.6 ± 0.5%. The fungivore group was represented by four genera, with *Aphelenchoides* and *Aphelenchus* being found in all ecosystems. Fungivores ranged from 13.4 ± 2.7% to 43.5 ± 1.0% of the total community. The largest proportion of the fungivore community was in Arenosols, Cambisols, and Harney (planned comparison F = 99.2, P < 0.001). Omnivores are represented by four genera, their number is not high and they were not found in some soil types. Predators were represented by seven genera, among which the most numerous were representatives of *Eudorylaimus*.

Table 4
Functional indices of nematode communities fitting
to the dimensions extracted after multidimensional scaling

Index	NMDS1	NMDS2	NMDS3	NMDS4	R^2	*P*-level
Maturity Index	0.49	0.40	–0.08	–0.77	0.77	0.001
Plant Parasitic Index	–0.65	0.26	–0.72	–0.03	0.26	0.001
Channel Index	–0.59	0.70	–0.22	–0.33	0.87	0.001
Basal Index	–0.84	0.44	–0.13	0.30	0.86	0.001
Enrichment Index	0.40	–0.85	0.20	0.30	0.80	0.001
Structure Index	0.89	–0.17	0.14	–0.39	0.88	0.001
Biomass	0.89	0.17	0.23	0.35	0.39	0.001
Abundance	0.05	–0.06	–0.47	0.88	0.36	0.001
Herbivores	–0.76	–0.15	–0.11	–0.62	0.91	0.001
Fungivores	0.29	0.49	0.00	0.82	0.73	0.001
Bacterivores	0.62	–0.52	0.21	0.54	0.86	0.001
Predators	0.76	0.06	–0.23	–0.60	0.82	0.001
Omnivores	0.79	0.51	0.28	–0.22	0.68	0.001
Migratory endoparasites	0.66	0.40	0.02	–0.64	0.88	0.001
Semi-endoparasites	–0.47	–0.82	–0.24	0.22	0.45	0.001
Ectoparasites	–0.28	0.13	–0.04	0.95	0.35	0.001
Epidermal/root hair feeders	–0.55	0.06	0.53	–0.64	0.42	0.001

Table 5
Ecological characteristics of nematode genera and their correlation with multidimensional dimensions

Genus	C-p class	P-p class	Feeding type	Mass, ug	MDS1	MDS2	MDS3	MDS4
Acrobeles	2	0	Bacterivores	0.64	0.27	–1.12	0.05	0.21
Acrobeloides	2	0	Bacterivores	1.26	0.70	0.60	0.23	0.42
Allodorylaimus	4	0	Omnivores	3.82	0.28	–1.09	0.02	0.22
Amplimerlinius	0	3	Herbivores – ectoparasites	1.06	–0.72	0.05	0.29	–0.76
Aphelenchoides	2	0	Fungivores	0.15	0.09	0.12	–0.22	0.06
Aphelenchus	2	0	Fungivores	0.22	–0.14	0.30	0.07	0.24
Aporcelaimus	5	0	Predators	76.65	0.31	–1.12	0.11	0.28
Bitylenchus	0	3	Herbivores – ectoparasites	0.36	–0.73	0.13	–0.48	0.24
Cephalenchus	0	2	Herbivores – epidermal/root hair feeders	0.12	–0.88	0.07	0.53	–0.64
Cephalobus	2	0	Bacterivores	0.27	0.51	–0.27	0.11	0.25
Clarkus	4	0	Predators	3.80	0.29	–1.10	0.02	0.19
Coomansus	4	0	Predators	6.32	0.81	0.47	–0.19	–0.48
Criconema	0	3	Herbivores – ectoparasites	0.66	–0.94	0.35	–0.12	–0.12
Criconemoides	0	3	Herbivores – ectoparasites	0.66	–0.96	0.08	–1.04	–0.33
Diplogaster	1	0	Bacterivores	1.89	0.29	–1.11	0.04	0.22
Ditylenchus	2	0	Fungivores	0.50	0.57	–0.12	–0.08	0.09
Dorylaimus	4	0	Omnivores	42.77	0.69	0.60	0.12	–0.28
Enchodelus	4	0	Omnivores	3.68	0.68	0.53	0.25	0.24
Eudorylaimus	4	0	Predators	3.19	0.69	0.12	–0.13	–0.38
Filenchus	2	0	Fungivores	0.10	0.57	–0.14	0.06	0.15
Geocenamus	0	3	Herbivores – ectoparasites	0.59	0.72	0.53	0.06	0.16
Helicotylenchus	0	3	Herbivores – semi–endoparasites	0.29	–0.10	–0.19	–0.40	0.00
Hoplotylus	0	3	Herbivores – migratory endoparasites	0.21	–0.06	–0.68	–0.25	0.45
Iotonchus	4	0	Predators	7.34	0.72	0.45	–0.10	–0.38
Longidorus	0	5	Herbivores – ectoparasites	16.39	–0.67	0.53	–0.80	0.00
Merlinius	0	3	Herbivores – ectoparasites	0.25	0.03	0.11	0.17	0.26
Mesocriconema	0	3	Herbivores – ectoparasites	0.50	–0.89	–0.10	0.10	–0.50
Mesodorylaimus	4	0	Omnivores	1.28	0.59	0.03	0.10	0.09
Mylonchulus	4	0	Predators	1.76	0.70	0.26	–0.19	–0.27
Panagrolaimus	1	0	Bacterivores	0.66	0.73	0.59	0.19	0.23
Paralongidorus	0	5	Herbivores – ectoparasites	21.97	–1.00	0.12	0.21	–0.97
Paratrichodorus	0	4	Herbivores – ectoparasites	0.75	–0.90	0.25	–0.90	–0.16
Paratrophurus	0	3	Herbivores – ectoparasites	0.32	0.68	0.38	–0.13	0.33
Paratylenchus	0	2	Herbivores – ectoparasites	0.06	–0.04	–0.09	0.03	–0.04
Plectus	2	0	Bacterivores	0.86	0.77	0.41	–0.17	–0.15
Cuticularia	1	0	Bacterivores	1.17	0.28	–1.13	0.09	0.24
Pratylenchus	0	3	Herbivores – migratory endoparasites	0.14	0.34	0.15	–0.03	–0.39
Prionchulus	4	0	Predators	11.59	0.81	0.49	–0.10	–0.48
Rhabditis	1	0	Bacterivores	7.50	0.45	–0.48	0.08	0.22
Rotylenchus	0	3	Herbivores – semi–endoparasites	0.87	–0.67	–0.18	0.47	–0.10
Sauertylenchus	0	3	Herbivores – ectoparasites	0.85	0.00	–0.94	0.20	0.21
Scutylenchus	0	3	Herbivores – ectoparasites	0.43	–0.67	–0.14	0.24	–0.39
Trichodorus	0	4	Herbivores – ectoparasites	1.01	–0.14	–0.73	0.10	0.18
Xiphinema	0	5	Herbivores – ectoparasites	5.52	–0.92	0.19	0.47	–0.52

The results of the multidimensional scaling analysis indicated that four dimensions could be extracted (Table 4). Dimension 1 was found to be the most sensitive to variation in the trophic structure of the communities, which was largely due to changes in the role of herbivores in the community. The decrease in the total proportion of herbivores in the community in Cambisols and Harney was compensated by an increase in migratory endoparasites. In Podzols (Pb), the total number of herbivores also decreased, but this decrease was compensated by an increase in the proportion of semi-endoparasites in the community.

In other soil types, the abundance and diversity of herbivores was high due to ectoparasites and epidermal/root hair feeders. Cambisols and Harney were characterised by higher values of the maturity index and community biomass. The Podzols (Pb) exhibited a higher value of the enrichment index, while other soil types demonstrated higher values of the basal and channel indices. The positive scores of Dimension 1 are marked by the predators (*Prionchulus* and *Coomansus*) and bacterivores (*Plectus* and *Panagrolaimus*), and the negative scores of this dimension are marked by the herbivores-ectoparasites (*Paralongidorus* and *Criconemoides*) (Table 5). The results of the study indicated that Dimension 2 was able to differentiate between Arenosols and all other soil types. This distinction is attributable to functional alterations in the structure of the nematode community. The Arenosols community is distinguished by an increase in the Enrichment Index, which is a consequence of an increase in the proportion of semi-endoparasites. Consequently, the Channel Index is observed to be lower in Arenosols in comparison to other soil types. The positive scores of Dimension 2 are marked by the bacterivores (*Acrobeloides* and *Panagrolaimus*) and omnivores (*Dorylaimus* and *Enchodelus*), and the negative scores of this dimension are marked by the bacterivores (*Cuticularia* and *Acrobeles*) and predators (*Aporcelaimus* and *Clarkus*). Dimension 3 enabled the differentiation of the group of soils comprising Haplic Fluvisols, Stagnic Fluvisols, and Haplic Podzols from Glayic Podzols. Glayic Podzols are distinguished by an elevated total number of the community, predominantly due to parasitic nematodes, as evidenced by the augmented level of the Plant Parasitic Index. Herbivore nematodes were the markers of both positive scores in Dimension 3 (*Cephalenchus* and *Xiphinema*) and negative scores (*Criconemoides* and *Paratrichodorus*). Dimension 4 was able to reflect the specific characteristics of the Chernozem nematode communities. This type of soil is distinguished by a higher density of nematode communities, which is attributed to a higher proportion of bacterivores and ectoparasites. The positive scores of Dimension 4 are marked by the bacterivores (*Acrobeloides* and *Cephalobus*), and herbivores (*Hoplotylus* and *Paratrophurus*), and the negative scores of this dimension are marked by the herbivores-ectoparasites (*Paralongidorus* and *Amplimerlinius*) and herbivores-epidermal/root hair feeders (*Cephalenchus*).

Discussion

The cultivation of bioenergy crops allows the production of energy sources for industrial and domestic needs with a zero carbon balance, which is highly attractive in the context of measures to prevent global climate change. However, this presents a challenge in terms of competition for agricultural land with crops used to meet human needs and food. One potential solution is to utilise unproductive abandoned land, which has been disturbed by open-pit mining, and marginal land contaminated with toxic substances for growing bioenergy crops. The ongoing conflict in Ukraine has resulted in significant disruption to the country's agro-ecosystems, with toxic substances of military origin contaminating large areas of productive land (Falko & Zhukov, 2023). This will have a profound impact on food production in Ukraine in the coming decades. Therefore, the cultivation of bioenergy crops has two distinct aspects: tactical and strategic. The tactical aspect involves the production of biological energy sources. This aspect involves traditional crop management techniques, including elements of plant disease and pest control, to achieve maximum yield. Consequently, the objective of tactical management is the plant. In contrast, the strategic aspect concerns soil reclamation with the aim of restoring its functions, thereby paving the way for the possibility of using such soils for food production. The object of strategic management is the soil.

The diversity of nematode communities is identified as an important indicator of the state of agroecosystems and the course of organic matter transformation processes (Yeates & Bongers, 1999). Consequently, nematode communities can be a reliable source of information regarding the state of plants and the risks of developing diseases in bioenergy crops, as well as the dynamics of organic matter and the recovery of soil systems after disturbance. Parasitic plant nematodes act as pests and factors in the spread of plant diseases, and can significantly affect crop yields. Therefore, indicators of the state of parasitic nematode communities can be considered as a monitor of bioenergy crop management at the tactical level of management. This position is in line with the results that show the possibility of using plant parasitic nematodes as an indicator to assess progress in the remediation of solid waste landfills (Zapałowska et al., 2024). The enhancement of the soil system restoration is accompanied by a reduction in the plant parasite index (PPI) (Du Preez et al., 2022). The PPI for *Miscanthus* plantations in the different soil types is at a level that is typical for crops in the temperate zone (Villenave et al., 2001). This index indicates a high level of dynamism of nematode communities in soils with opposite moisture levels: in arid Arenosols and wet Stagnic Fluvisols. It should be noted that changes in the state of the parasitic component of the nematode community, which are marked by PPI, are accompanied by the structural transformations of the community as a whole (Skwiercz et al., 2022). This is evidenced by the positive correlation between PPI and Basal Index. Basal Index is a measure of the state of the food web, which is simplified due to stress or limitation of nutrient resources (Berkelmans et al., 2003). This correlation suggests the interpretation that due to the decrease in trophic resources of the soil system, the protective potential of *Miscanthus* plantations decreases, which makes it possible for pathogenic organisms to actively develop. PPI correlates negatively with the Structural Index, which indicates the number of trophic levels and the regulation capacity of the nematode community (Berkelmans et al., 2003). This connection explains the reasons that can lead to the development of parasitic nematodes in *Miscanthus* plantations. Obviously, a decrease in the regulatory potential of the ecological system creates conditions for the development of pathogens.

An important feature of soil nematodes is their connection with soil formation processes (Yeates & Bongers, 1999), which allows us to consider nematode communities in terms of monitoring soil restoration processes from a strategic perspective. Four dimensions were identified through the use of multidimensional scaling. Changes in the functional structure of the nematode population lead to differentiation, which accounts for the first two dimensions. While functional transformation is less significant for dimensions 3 and 4, they are responsive to modifications in the community structure. The main trend in the grouping's metamorphosis is the shifts caused mostly by fungivores and partially by herbivores. This pattern sets apart all other soil types from those with a comparatively lower herbivore population, such as Podzols, Cambisols, and Harney. The decrease in the abundance of herbivores is compensated by the growth of individual functional components of this trophic group. In Podzols, the population of semi-endoparasites is increasing, which is also accompanied by an increase in the enrichment index. In Cambisols and Harney, the number of migratory endoparasites is increasing, which is accompanied by an increase in the maturity index. It is the Podzols, Cambisols, Harney soil group that is characterized by a high level of the Maturity Index, while other soils functionally correspond to degraded conditions. This funding is in contradiction with previous researches indicating that Podzol soils have unique properties; their low nutrient content and poor drainage make them unsuitable for nematodes. Nematodes thrive in soils with more organic matter and greater moisture retention. The herbivores were found as the most distributed group in nematode community during M×g cultivation. This trend differentiates soils with a relatively lower number of herbivores (Podzols, Cambisols, Harney) from all others. The decrease in the total number of herbivores is compensated by the growth of individual functional components of this trophic group. In Podzols, the number of semi-endoparasites is increasing, whereas in Cambisoils and Harney, the population of migratory endoparasites is growing. These groups of herbivores are potential pathogens of Mxg. Further research is needed to determine the economic thresholds for species dominance of these groups and population dynamics on different soil types to provide M×g biomass production for conversion into bioenergy and high value-added bio-products as a pathway to bioeconomy development. The genus *Pratylenchus*, which ranks among the world list as having some of the most economically important harmful species, was found in all geographical areas. The type of soil significantly affected abundance and frequency of occurrence of genera *Pratylenchus*. This finding indicated that biomass yield loss might be expected during the upscaling of cultivation of *Miscanthus*×*giganteus* caused by the plant parasitic nematodes, potentially initiating the crop's damage.

Our results are in line with findings suggesting that functional groups of nematodes exhibit better indicator performance than individual nematode species (Sroczyńska et al., 2021). The functional groups are the most sensitive to soil types in agroecosystems. The nematode Maturity Index provides useful information about the direction of change in a particular soil. The Maturity Index can discriminate between well-functioning ecosystems and severely disturbed or stressed systems (Berkelmans et al., 2003). According to this indicator, the studied soils can be divided into two large groups: mature and sustainable plantations created at Cambisols and Harney and other plantations that are in the early stages of recovery under high stress conditions. This result is very important: *Miscanthus* plantations are able to trigger mechanisms for the restoration of degraded land and reduce the level of stress in the trophic chains of soil systems. It is worth noting that Harney soils are post-military soils that have been significantly negatively impacted by military activities (Alasmary et al., 2020). The high level of their restoration can be proved by using nematode communities as a monitor of strategic management of degraded and marginal lands.

Conclusion

Plantations of bioenergy crops are a factor in ensuring energy security and a tool for maintaining a high economic level of human development with a zero carbon balance, which is a prerequisite for preventing negative climate change. Bioenergy crops should be expanded on marginal and degraded lands to reduce competition with crops used for food production. Therefore, both the environmental and economic components of energy crops should be considered from a tactical and strategic perspective. The tactical aspect involves obtaining direct economic benefits from the production of energy raw materials. The strategic aspect involves the restoration of disturbed lands and the creation of preconditions for the restoration of their ecosystem services and their inclusion in food production. Nematode communities can provide information for monitoring processes at both the tactical and strategic levels. The risks of parasitic nematodes and plant diseases should be assessed at the tactical level of management. The assessment of the trophic network and the level of stress in the soil system should be monitored using nematode communities at the strategic level of management.

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