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RESEARCH ARTICLE

Altitudinal patterns of soil nematode community diversity and functional structure in the Boysun Mountains, Uzbekistan

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Abstract

Mountain ecosystems provide natural gradients for investigating biodiversity responses to environmental variation. This study examined the effects of altitude on the taxonomic diversity, trophic structure, and functional composition of soil nematode communities in the Boysun Mountains, southern Uzbekistan. Soil and rhizosphere samples associated with perennial plant communities were collected from four altitudinal zones (<800, 800-1500, 1500-2000, and >2000 m a.s.l.), yielding a total of 128 samples. Nematodes were extracted using modified Baermann, flotation, and decantation techniques and identified to species level using morphological and morphometric characteristics. A total of 102

nematode species belonging to two classes, seven orders, and numerous trophic and colonizer-persister (c-p) groups were recorded. Tylenchida, Rhabditida, and Dorylaimida were the dominant orders. Bacterivores represented the most diverse trophic group (35.2% of all species), followed by ectoparasitic plant feeders (22.5%). The c–p structure was dominated by CP-2 (42.1%) and CP-3 (30.4%) taxa. Nematode community composition varied markedly along the altitudinal gradient, with high-elevation communities characterized by a greater proportion of plant-parasitic and persister taxa, whereas lower elevations were increasingly dominated by bacterivorous colonizers. Diversity indices revealed a unimodal pattern, with maximum Shannon, Simpson, and richness values occurring at intermediate elevations (800-2000 m). Jaccard similarity analysis indicated strong species turnover along the gradient, with communities above 2000 m forming a distinct assemblage. These findings demonstrate that altitude is a major driver of soil nematode diversity and functional organization in the Boysun Mountains and highlight the value of nematodes as sensitive indicators of soil ecosystem condition, food-web structure, and ecological stability in mountain environments.

Keywords
Soil nematodes, biodiversity, trophic structure, mountain ecosystems, soil food web

Introduction

Nematodes are among the most abundant and ubiquitous multicellular organisms on Earth, inhabiting virtually every terrestrial and aquatic ecosystem, from deserts and grasslands to forests, wetlands, and extreme environments (Procter 1990; Yeates 2010). Their remarkable ecological adaptability enables them to occupy a wide range of habitats and trophic niches, making them one of the most diverse and functionally important groups of soil fauna. Owing to their high abundance, short generation times, and sensitivity to environmental changes, soil nematodes have been extensively used as bioindicators of ecosystem condition and soil health (Bongers and Ferris 1999; Ritz and Trudgill 1999; Bhusal et al. 2014).

Soil nematodes play a fundamental role in regulating ecosystem processes. Through their interactions with bacteria, fungi, plant roots, and other soil organisms, they contribute to the decomposition of organic matter, nutrient mineralization, carbon cycling, and energy transfer within soil food webs (Neher 2001; Ferris et al. 2001). Different trophic groups – including bacterivores, fungivores, herbivores, omnivores, and predators – occupy distinct positions within the soil food web and collectively influence ecosystem functioning and stability. Consequently, the taxonomic composition and functional structure of nematode communities provide valuable insights into soil ecological conditions and environmental disturbances (Bongers and Ferris 1999; Ferris et al. 2001).

Mountain ecosystems are characterized by pronounced environmental gradients over relatively short geographical distances, making them ideal natural laboratories for studying biodiversity patterns and ecosystem responses to changing environmental conditions (Körner 2007). Among the various environmental factors operating in mountain landscapes, altitude is particularly important because it in-

fluences temperature, precipitation, vegetation composition, soil development, and nutrient availability. These factors collectively shape belowground communities and ecological processes (Körner 2007; Sundqvist et al. 2013). Soil nematodes are especially responsive to such environmental gradients because their distribution and community structure are strongly linked to soil physicochemical properties, vegetation characteristics, and resource availability (Neher 2010). Numerous studies have demonstrated that altitudinal gradients significantly influence the abundance, diversity, and functional composition of soil nematode communities. However, the direction and magnitude of these responses remain inconsistent across regions and ecosystems. Several studies have reported a decline in nematode abundance and diversity with increasing elevation, primarily due to lower temperatures, reduced primary productivity, and slower decomposition rates at higher altitudes (Afzal et al. 2021; Chen et al. 2024). In contrast, other investigations have documented increasing diversity patterns along elevational gradients (Kergunteuil et al. 2016), while some studies have observed unimodal or irregular distribution patterns driven by local environmental conditions (Dong et al. 2017). These contrasting findings suggest that the effects of elevation on nematode communities are context-dependent and mediated by multiple interacting factors. Among the principal drivers influencing nematode assemblages along altitudinal gradients are soil organic matter, humus accumulation, fungal biomass, vegetation composition, microclimatic conditions, and soil physicochemical characteristics (Traunspurger et al. 2017; Afzal et al. 2021; Kashyap et al. 2022). Changes in plant communities across elevations can alter the quantity and quality of organic inputs to the soil, thereby affecting resource availability for microbial communities and the nematodes that depend upon them. Similarly, variations in temperature and moisture regimes influence decomposition processes, nutrient cycling, and trophic interactions within soil food webs, ultimately shaping nematode community structure and ecosystem functioning (Wardle et al. 2004; Sundqvist et al. 2013).Despite increasing interest in soil biodiversity along environmental gradients, most studies investigating nematode diversity have been conducted in temperate forests, tropical ecosystems, and arid landscapes (Wu et al. 2022; Chen et al. 2024). In contrast, mountain ecosystems of Central Asia remain relatively understudied, particularly with respect to the taxonomic and functional organization of soil nematode communities. This lack of information limits our understanding of belowground biodiversity patterns and the ecological mechanisms governing soil food webs in this biogeographically important region (Dong et al. 2017). Furthermore, nematode communities provide a valuable tool for assessing soil ecosystem stability. Despite increasing research on the effects of environmental factors on living organisms and their physiological processes in Central Asia, including Uzbekistan (Nurmatova et al. 2025; Rakhmonov et al. 2026), the application of biological indicators for ecological monitoring has remained limited.

The Boysun Mountains of southern Uzbekistan represent an ideal system for examining these questions because they encompass a wide altitudinal range, diverse vegetation types, and substantial variation in climatic and edaphic conditions. The

pronounced environmental heterogeneity across elevational zones provides an opportunity to investigate how nematode communities respond to changing ecological conditions and to evaluate the consequences of these changes for soil ecosystem functioning and stability.

Therefore, the present study aims to (i) characterize the taxonomic and ecological diversity of soil nematode communities associated with perennial plant communities across different altitudinal zones of the Boysun Mountains, (ii) examine the relationship between altitude and nematode community composition, trophic structure, and functional guilds, and (iii) assess soil ecosystem condition and stability using nematode-based ecological indicators. We hypothesize that increasing altitude will be associated with significant changes in nematode community composition and functional structure, leading to reduced abundance and diversity of higher trophic-level nematodes and consequent shifts in soil food-web organization and ecosystem stability.

Materials and methods

Study area

The study was conducted in the Boysun mountain region located in the Surkhandarya Province of southern Uzbekistan (Fig. 1). The Boysun Mountains form part of the southern branch of the Hissar-Alay mountain system and are characterized by pronounced altitudinal gradients, heterogeneous landscapes, and diverse vegetation communities. Elevation in the study area ranges from approximately 500 to over 3000 m above sea level, creating substantial variation in climatic and edaphic conditions. The climate of the region is sharply continental, with hot, dry summers and cold winters. Mean annual temperatures range from approximately 14–16 °C in the foothills to 8–10 °C at higher elevations. Annual precipitation varies between 300 and 600 mm, generally increasing with altitude. Most precipitation occurs during winter and spring, whereas summers remain relatively dry. Based on differences in elevation, vegetation cover, and environmental conditions, four altitudinal zones were selected along a continuous mountain transect: (i) foothill zone (<800 m a.s.l.), (ii) lower mountain zone (800–1500 m a.s.l.), (iii) mid-mountain zone (1500–2000 m a.s.l.), and (iv) high-mountain zone (>2000 m a.s.l.). These zones represent distinct ecological conditions and vegetation types, ranging from semi-desert and steppe communities at lower elevations to mountain meadows and shrub-dominated habitats at higher elevations. The pronounced environmental gradient makes the Boysun Mountains an ideal natural system for investigating patterns of soil nematode diversity and community structure along elevation.

Sampling locations

38°07'53.95"N 66°56'26.11"E, 38°08'18.26"N 67°02'33.42"E, 38°12'29.42"N 67°01'55.03"E, 38°16'14.99"N 67°01'23.27"E, 38°17'47.89"N 67°22'24.03"E, 38°11'34.85"N 66°58'22.11"E, 38°17'23.88"N 67°03'36.11"E, 38°18'47.23"N 67°16'35.06"E, 38°20'46.04"N 67°15'07.84"E, 38°20'51.75"N 67°15'32.44"E, 38°21'23.12"N 67°06'59.74"E, 38°24'23.96"N 67°10'19.60"E, 38°25'06.69"N 67°24'51.52"E, 38°27'05.49"N 67°28'50.80"E, 38°28'16.89"N 67°14'38.34"E, 38°30'11.75"N 67°14'46.43"E, 38°27'28.27"N 67°11'46.29"E, 38°32'22.15"N 67°39'26.32"E, 38°36'06.40"N 67°21'20.32"E.

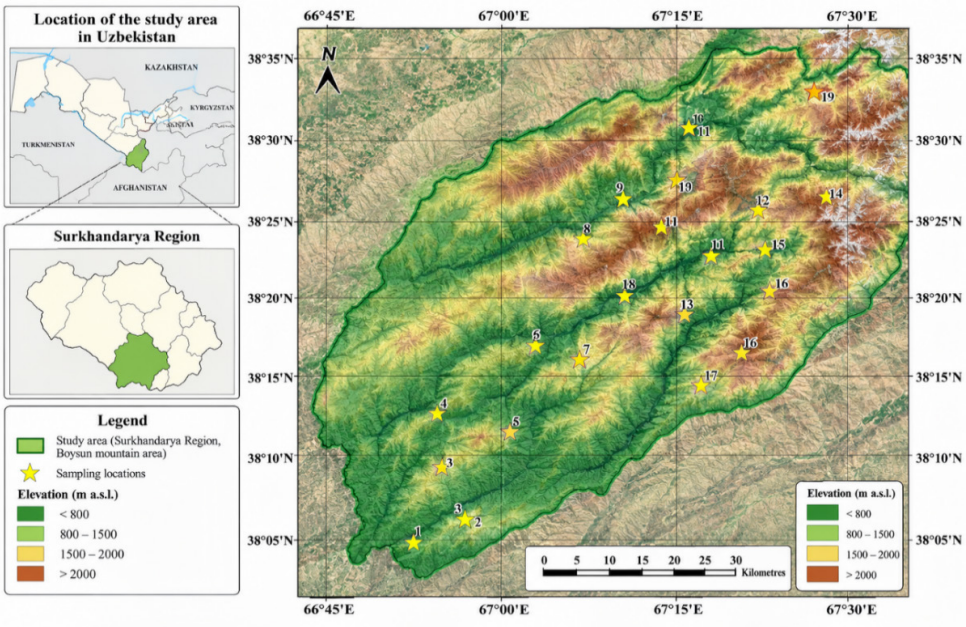

Figure 1. Study area.

Sampling design

Sampling was carried out during the growing season across the four altitudinal zones of the Boysun Mountains. Representative perennial plant species, including *Rumex* spp., *Centaurea* spp., *Eremurus* spp., *Ferula* spp., *Allium* spp., *Glycyrrhiza* spp., *Plantago* spp., and *Inula* spp., were selected for rhizosphere sampling. Within each altitudinal zone, 16 sampling points were established along a single transect while maintaining comparable slope and aspect conditions to minimize topographic variability. Adjacent sampling points were separated by approximately 40–50 m to ensure spatial independence. At each sampling point, rhizosphere soil and associated plant material were collected. In total, 128 samples (soil and plant material

combined) were obtained across the four altitudinal zones. Soil samples were collected from the upper 0–20 cm layer using a soil auger. Approximately 500 g of soil was collected from each sampling point, homogenized, and cleared of stones, roots, and other debris. Samples were transported to the laboratory within 48 h and stored at 4 °C until processing. For nematode extraction, 100 g subsamples were taken from the homogenized soil.

Nematode extraction

Nematodes were extracted from soil and plant samples using the modified Baermann funnel technique following Van Bezooijen (2006). Soil and root samples were placed on tissue-supported sieves in water-filled funnels and incubated for 14-15 h to facilitate nematode migration into the water column. To improve the recovery of larger and less mobile nematodes, a flotation and decantation procedure was additionally employed (Coyne et al. 2018). Briefly, 10-20 g of soil was suspended in water within 300-500 ml containers and thoroughly agitated. The suspension was allowed to settle briefly, after which the supernatant containing suspended nematodes was decanted into a separate container. This process was repeated five to six times. Recovered nematodes were heat-killed and fixed in 4% formalin solution. For permanent slide preparation, specimens were processed through a glycerine-alcohol (1:1) solution for 18-20 h to enhance transparency and facilitate morphological examination. Both temporary and permanent mounts were prepared, with permanent slides mounted in glycerine-gelatin medium.

Identification and functional classification

Microscopic observations were conducted using MBI-1, MBI-3, AS ONE SL-700-LED, and Micromed MC-2-ZOOM Digital light microscopes. Nematodes were identified to the lowest possible taxonomic level based on morphological and morphometric characters using standard identification keys (Matveeva et al. 2018). Identification of members of the order Tylenchida was further verified using the diagnostic keys of Siddiqi (2000). Taxonomic nomenclature and classification followed the system proposed by Hodda (2022). Identified nematodes were assigned to trophic groups according to the classification of Yeates et al. (1993), which categorizes taxa as bacterivores, fungivores, herbivores (plant parasites), omnivores, and predators. Plant parasites were subdivided into ectoparasites, migratory endoparasites and sedentary endoparasites. Nematodes were classified according to the colonizer–persister (c–p) scale of Bongers (1990). Taxa were assigned to five categories (c-p 1 to c-p 5) based on reproductive potential, life cycle characteristics, and sensitivity to environmental disturbance (Bongers and Bongers 1998). Lower c-p classes (c-p 1 and c-p 2) comprise opportunistic colonizers that rapidly exploit disturbed habitats, whereas higher c-p classes (c-p 4 and c-p 5) consist of persister taxa characterized by longer life cycles, lower reproductive rates, and high sensitiv-

ity to environmental perturbation. Consequently, the relative abundance of higher c-p groups is widely used as an indicator of ecosystem maturity and environmental stability (Franco et al. 2021).

Soil physicochemical analyses

Soil pH was determined in a 1:2.5 soil-to-water suspension using a calibrated digital pH meter (FE20K, Mettler-Toledo) (Fig. 2A). Soil organic matter (humus) content was measured using the Tyurin wet oxidation method, whereby organic carbon is oxidized using potassium dichromate and the excess dichromate is back-titrated with ferrous sulfate solution. Humus content was subsequently calculated according to standard procedures (Fig. 2B).

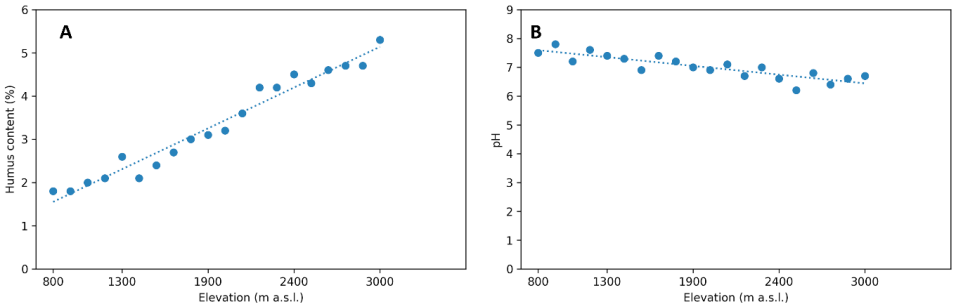

Figure 2. Variation in soil pH and humus content along the elevational gradient. (**A**) Changes in soil humus content across elevations ranging from 800 to 3000 m a.s.l. Humus content exhibited an increasing trend with altitude. (**B**) Changes in soil pH along the same elevational gradient, showing a gradual decline with increasing altitude.

Nematode community and statistical analyses

The taxonomic and ecological characteristics of nematode communities were assessed using a suite of diversity and ecological indices. Community diversity was evaluated using the Shannon-Wiener diversity index (H′), Simpson diversity index, Margalef richness index, and Menhinick richness index (Konopiński 2020). In addition, nematode maturity and ecosystem condition were assessed using the Maturity Index (MI) based on the c-p classification system of Bongers (1990).

Results

A total of 102 nematode species associated with perennial plants and their rhizosphere soils were recorded from the Boysun Mountains. These species belonged to two classes, Adenophorea (37 species) and Secernentea (65 species). Within Adeno-

phorea, the order Dorylaimida was the most diverse, comprising 20 species, while the remaining species were distributed among Triplonchida, Mononchida, Monhysterida, and Araeolaimida. Secernentea was represented by Tylenchida (33 species), Rhabditida (23 species), and Aphelenchida (9 species). Overall, Tylenchida, Rhabditida, and Dorylaimida constituted the dominant nematode groups in the studied communities (Fig. 3).

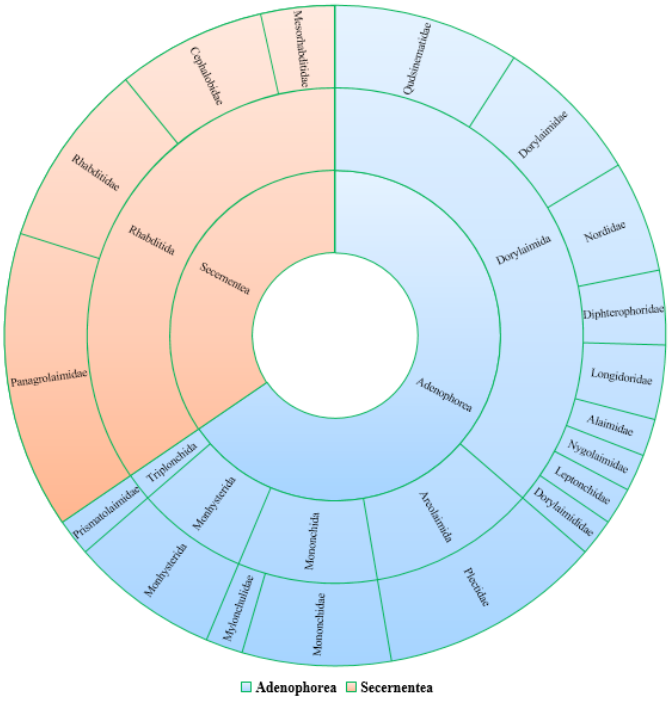

Figure 3. Hierarchical taxonomic composition of nematodes from the Boysun Mountains showing the distribution of classes, orders, and families. Blue sectors represent Adenophorea and orange sectors represent Secernentea.

Trophic and C-p composition

Based on trophic classification, the 102 nematode species identified in the Boysun Mountain biocenoses were assigned to five ecological groups: bacterivores, fungivores, predators, omnivores, and plant parasites. Plant-parasitic nematodes were further divided into ectoparasites, migratory endoparasites, and sedentary endoparasites. Bacterivores represented the largest trophic group, comprising 36 species (35.2% of the total fauna). Ectoparasitic plant feeders were the second most diverse group with 23 species (22.5%), followed by fungivores and omnivores, each represented by 13 species (12.7%). The remaining trophic groups were less diverse, containing between 2 and 9 species (Fig. 4). The identified nematode species were

distributed among all five colonizer–persister groups, although their representation varied considerably. The CP-2 group was the most abundant, comprising 43 species (42.1%), followed by CP-3 with 31 species (30.4%). The remaining groups were represented by 6–12 species each, with CP-1 showing the lowest contribution, accounting for only 6 species (5.8%) of the total fauna (Fig. 5).

Altitudinal variation in nematode community composition

The composition of nematode communities varied along the altitudinal gradient, with differences becoming more evident at the family and genus levels than at higher taxonomic ranks (Fig. 6). Families such as Aphelenchoididae, Qudsinematidae, Dorylaimidae, and Mononchidae showed a gradual decline in species richness from higher to lower elevations, whereas Cephalobidae increased in representation toward lower altitudes. Plectidae was absent above 2000 m but was represented by 5-7 species in the lower zones. In contrast, Anguinidae was consistently represented across all altitudinal zones. The 1500–2000 m zone supported the highest family and genus diversity, whereas the foothill zone (<800 m) contained the lowest number of species (59 species). Genera characteristic of higher elevations, including *Eudorylaimus* Andrássy, 1959, *Clarkus* Jairajpuri, 1970, and *Enchodorella* Khan, 1964, progressively declined with decreasing altitude and were absent from the foothill zone. Similarly, *Aphelenchoides* Fischer, 1894 and *Ditylenchus* Filipjev, 1936, which were widespread in the upper zones, became less diverse and abundant at lower elevations. The 800–1500 m zone exhibited the greatest compositional overlap, containing representatives of all genera recorded in the Boysun Mountains. Several species showed broad ecological amplitudes and occurred throughout the entire altitudinal gradient, including *Aphelenchoides parietinus* (Bastian, 1865) Steiner, 1932, *Aphelenchus avenae* Bastian, 1865, *Chiloplacus symmetricus* (Thorne, 1925) Thorne, 1937, *Diphtherophora communis* de Man, 1880, *Ditylenchus* spp., *Helicotylenchus multicinctus* (Cobb, 1893) Golden, 1956, *Mesoanguina picridis* (Kirjanova, 1944) Chizhov & Subbotin, 1985, *Pratylenchus* spp., *Tylenchorhynchus cylindricus* Cobb, 1931, and *Xiphinema basiri* Siddiqi, 1959 (Fig. 6).

Functional groups along the altitudinal gradien

The distribution of ecological groups varied considerably along the altitudinal gradient (Fig. 7). At elevations above 2000 m, plant-parasitic nematodes dominated the community, comprising 15 ectoparasitic and 10 endoparasitic species, whereas bacterivores were represented by only four species. In the 1500–2000 m zone, the richness of plant parasites remained relatively stable, while bacterivores increased markedly. Predator richness showed no change between the high- and mid-altitude zones, with six species recorded in each. At intermediate elevations (800–1500 m), omnivorous and predatory nematodes declined in species richness, whereas bacterivores increased substantially. In the foothill zone (<800 m), overall species

richness decreased further, with the most pronounced reduction observed among ectoparasites. Predators were represented by a single species, *Mononchus truncatus* Bastian, 1865, while bacterivores became the dominant ecological group, accounting for 54.2% of the community.

The colonizer-persister (C-P) structure of nematode communities also exhibited clear altitudinal variation (Fig. 8). Across all altitudinal zones, CP-2 and CP-3 groups were predominant, although their relative proportions differed. Higher elevations supported a greater proportion of persister taxa, whereas lower elevations were characterized by an increasing contribution of colonizer groups, reflecting shifts in community composition along the altitudinal gradient. At elevations above 2000 m, CP-3 dominated (43.6%), and higher CP groups (CP-4 and CP-5) were also well represented (36.3%), while CP-1 was rare. At 1500–2000 m, CP-2 (39.7%) and CP-3 (32%) were dominant, with CP-4 and CP-5 contributing 24.3%. In the 800–1500 m zone, CP-2 (46.9%) and CP-3 (28.5%) remained dominant, whereas CP-4 and CP-5 were less represented. In the foothill zone (<800 m), CP-2 dominance increased further (52.5%), while CP-4 and CP-5 were rare.

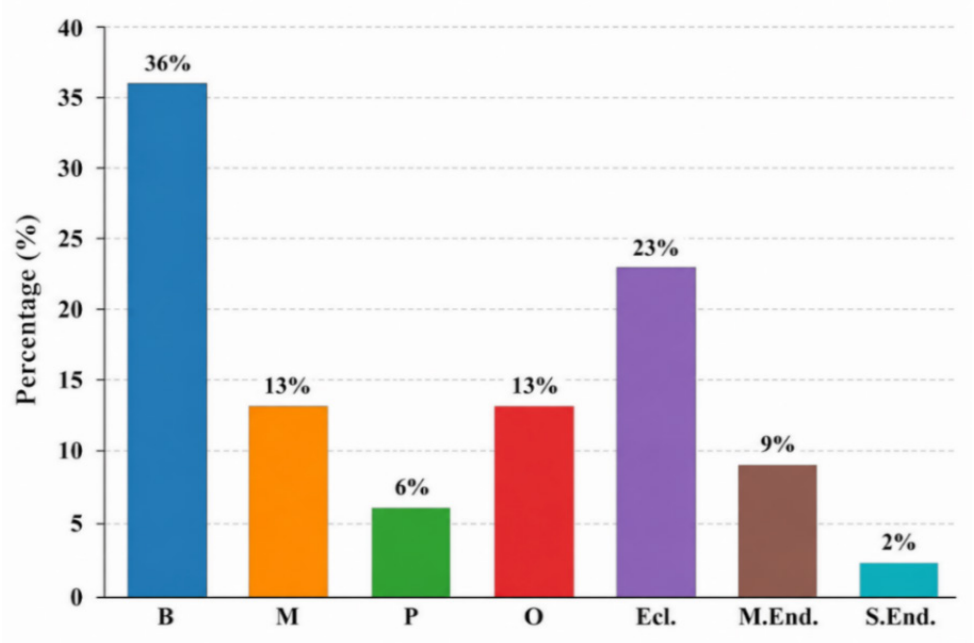

Figure 4. Relative percentage (%) of nematode ecological groups in the Boysun Mountain biocenoses. B = bacteriotrophs, M = mycophages, P = predatory nematodes, O = omnivores, Ect. = ectoparasites, M. End. = migratory endoparasites, and S. End. = sedentary endoparasites. Values represent percentages of the total recorded species.

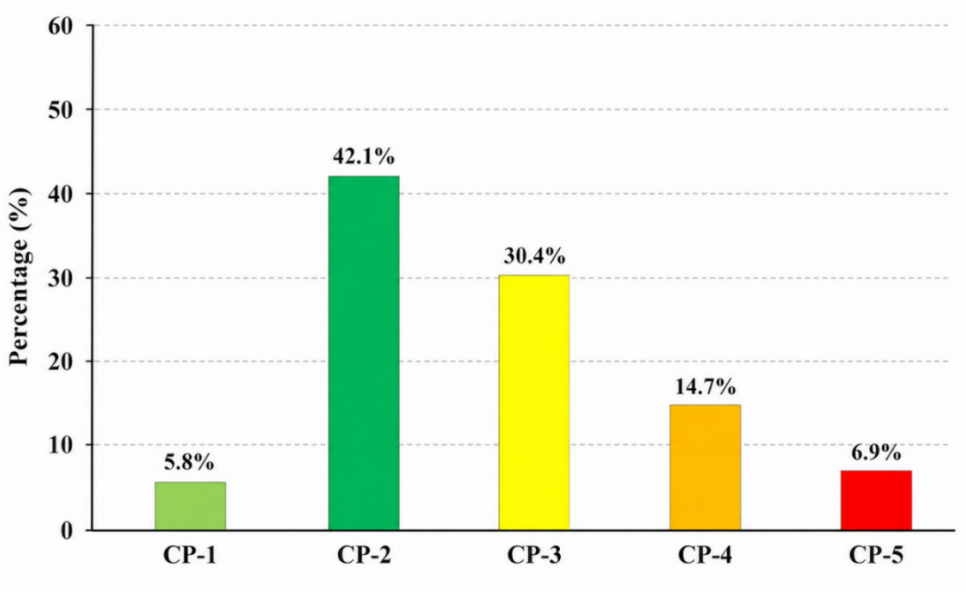

Figure 5. Relative percentage (%) of nematode species belonging to different colonizer–persister (C-P) groups in the Boysun Mountain biocenoses.

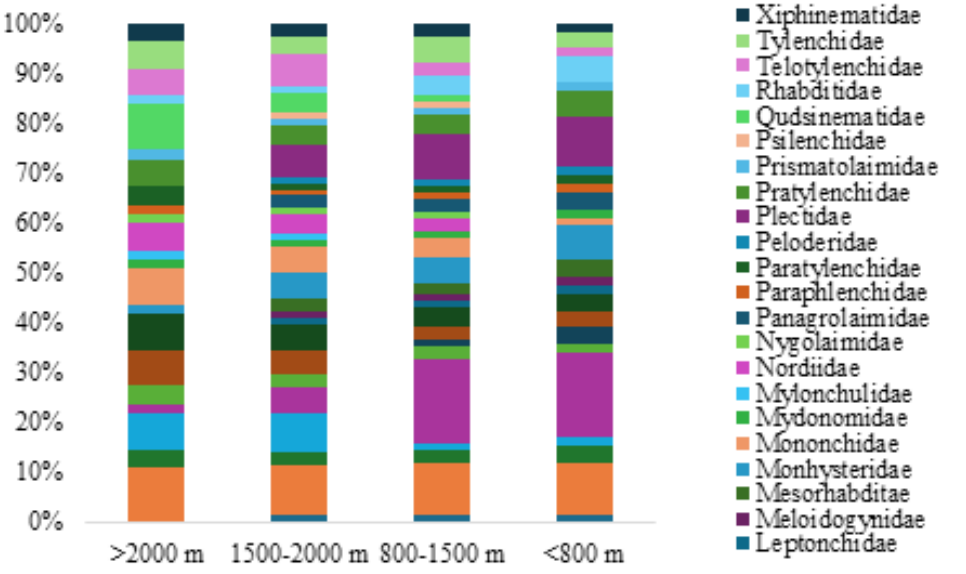

Figure 6. Relative contribution (%) of nematode families across four altitudinal zones of the Boysun Mountains (>2000 m, 1500–2000 m, 800–1500 m, and <800 m). Community composition varied along the elevational gradient, with shifts in the relative representation of major nematode families. Percentages are based on the total number of species recorded within each altitudinal zone.

Figure 7. Relative abundance of nematode ecological groups across four altitudinal zones in the Boysun Mountains. B = bacterivores, M = mycophages, O = omnivores, P = predators, Ect. = ectoparasites, and End. = endoparasites.

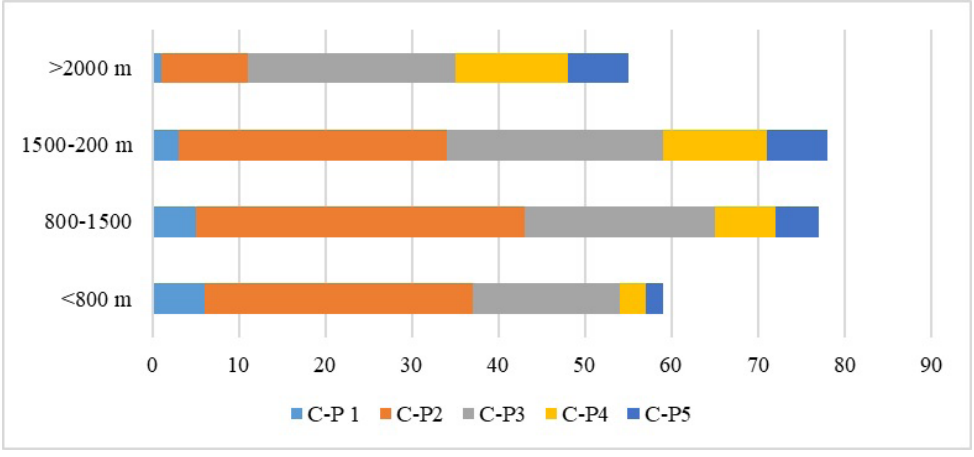

Figure 8. Distribution of colonizer–persister (C-P) groups (CP-1 to CP-5) of nematode communities across four altitudinal zones in the Boysun Mountains. Stacked bars represent the number of species belonging to each C-P group within each altitudinal zone. CP-2 and CP-3 groups predominated across all elevations, while the relative contribution of CP-1, CP-4, and CP-5 groups varied along the altitudinal gradient.

Diversity

Diversity indices varied along the altitudinal gradient, with overall diversity generally highest at 800–1500 m. Simpson's diversity (0.9765), Shannon diversity (4.074), and Menhinick richness (1.792) reached their maximum values in this zone, indicating a more diverse and evenly distributed nematode community. The Margalef index, which primarily reflects species richness, was slightly higher at 1500–2000 m (10.16) than at 800–1500 m (10.11). In contrast, the lowest values of all diversity indices were observed above 2000 m, suggesting reduced species richness and diversity at higher elevations. Diversity declined slightly again below 800 m, although values remained higher than those recorded at elevations above 2000 m (Fig. 9).

Diversity indices based on species presence-absence varied along the altitudinal gradient, with the highest values generally recorded at intermediate elevations (800–1500 m and 1500–2000 m). The >2000 m zone exhibited the lowest diversity and richness, while values declined again in the foothill zone (<800 m), indicating a peak in nematode diversity at mid-elevations (Fig. 9).

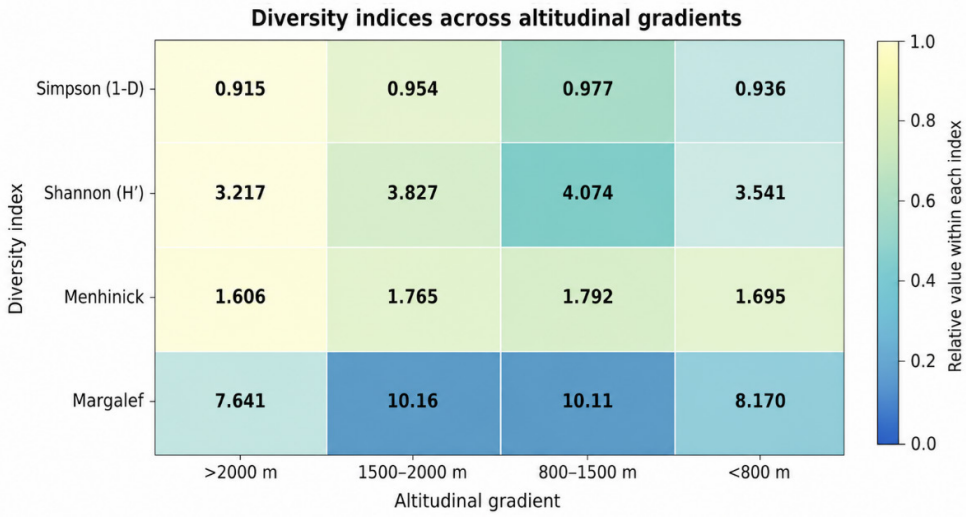

Figure 9. Diversity indices of soil nematode communities across four altitudinal zones in the Boysun Mountains.

Based on the Jaccard similarity index, a comparison of nematode communities from different altitudes revealed that a unique community was formed in biocenoses above 2000 meters, while communities from 800-1500 meters and below 800 meters had the highest similarity (Fig. 10).

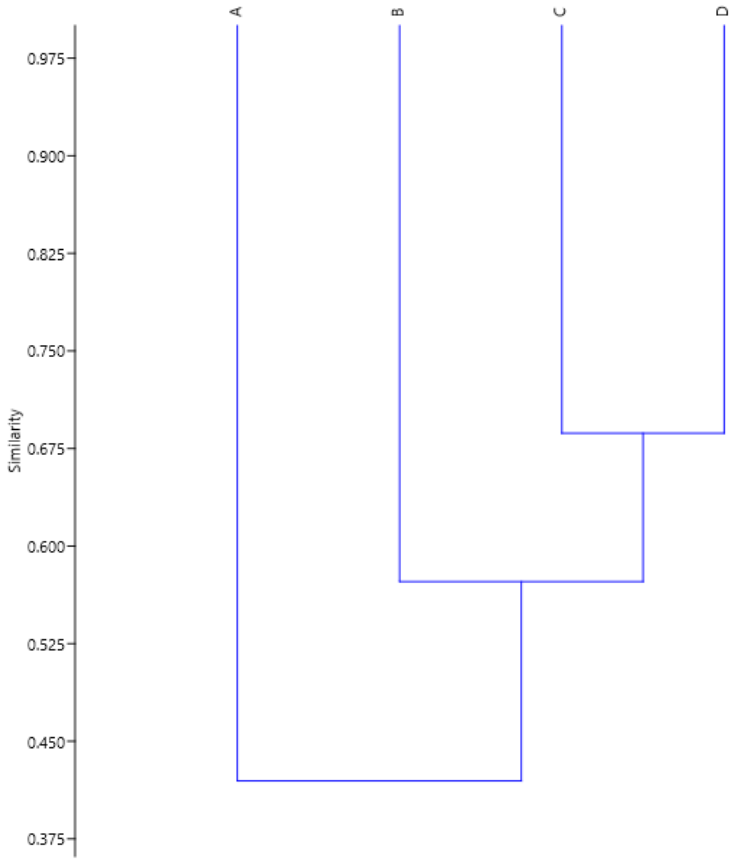

Figure 10. Jaccard similarity index. A – >2000 m, B –1500-2000 m; C – 800-1500 m; D – <800. (UPGMA method, bootstrap values >80%).

Discussion

The present study demonstrates that soil nematode communities of the Boysun Mountains exhibit considerable taxonomic and functional complexity and respond strongly to variation in altitude. The recorded fauna comprised 102 species representing diverse trophic and colonizer–persister (c–p) groups, reflecting a well-developed soil food web and a broad range of ecological functions. The dominance of the orders Tylenchida, Rhabditida, and Dorylaimida indicates the simultaneous importance of plant-based energy channels, microbial decomposition pathways, and higher trophic interactions within the studied ecosystems. Similar community structures have been reported from other mountain ecosystems where nematode assemblages are shaped by interactions among vegetation, soil properties, and climatic conditions (Ferris et al. 2001; Bongers and Ferris 1999; Kambarov et al.

2025). The nematode community of the Boysun Mountains showed broad taxonomic similarity to that previously reported from the nearby Western Zarafshan Range (Narzullayev 2022), indicating a common regional faunal background. Nevertheless, several distinct differences were identified. Notably, the genera *Coomansus* Jairajpuri & Khan, 1977, *Enchodelus* Thorne, 1939, *Enchodorella* Khan, 1964, *Heteroanguina* Chizhov, 1980, *Ironus* Bastian, 1865, *Macrolaimus* Maupas, 1900, *Psilenchus* de Man, 1921, and *Scutylenchus* Jairajpuri, 1971 were recorded in the Boysun Mountains but were not reported from the Western Zarafshan Range, suggesting regional differences in nematode community composition and highlighting the unique faunal characteristics of the Boysun mountain ecosystem.

The predominance of Tylenchida highlights the importance of plant–nematode interactions in the rhizosphere environments of the Boysun Mountains. Members of this order are primarily plant-associated and depend directly on root systems for survival and reproduction (Siddiqi 2000). The widespread occurrence of herbivorous taxa across all altitudinal zones suggests that perennial vegetation provides a relatively stable resource base throughout the mountain gradient. At the same time, the substantial representation of Dorylaimida and Mononchida, which include many omnivorous and predatory taxa, indicates the presence of structurally complex food webs and relatively mature soil ecosystems (Ferris and Bongers 2006). Such higher trophic groups are generally associated with stable environments because of their longer life cycles and greater sensitivity to disturbance (Bongers 1990; Ferris et al. 2001). Although altitude did not markedly alter the composition of major taxonomic groups, clear shifts were observed at the family and genus levels. This pattern suggests that broad taxonomic categories may mask ecologically meaningful responses to environmental gradients, whereas finer taxonomic resolution better reflects habitat filtering and species-specific adaptations. Similar observations have been reported from alpine and temperate mountain ecosystems where environmental gradients primarily influence community composition through species replacement rather than changes in higher-level taxonomy (Kergunteuil et al. 2016; Dong et al. 2017). The decline of families such as Dorylaimidae, Qudsinematidae, Mononchidae, and Aphelenchoididae toward lower elevations, together with the increasing representation of Cephalobidae and Plectidae, reflects a shift from communities dominated by persister and omnivorous taxa to those characterized by opportunistic bacterivorous species.

These compositional changes are likely driven by differences in temperature, moisture availability, and organic matter dynamics along the elevational gradient. Soil temperature is widely recognized as a major determinant of nematode distribution because it regulates microbial activity, decomposition processes, and metabolic rates (Wardle et al. 2004; Sundqvist et al. 2013). The occurrence of cold-adapted genera such as Eudorylaimus primarily at elevations above 2000 m supports previous findings that some dorylaimid taxa are particularly adapted to alpine and subalpine environments (Hoschitz and Kaufmann 2004). In contrast, the broad distribution of genera such as *Pratylenchus* Filipjev, 1936, *Aphelenchoides*, and *Ditylenchus*

across all elevations indicates high ecological plasticity and the ability to persist under a wide range of environmental conditions (Jones and Fosu-Nyarko 2014).

The trophic structure of the nematode community further highlights the influence of altitude on ecosystem functioning. Bacterivores constituted the most species-rich trophic group overall, indicating active microbial decomposition pathways and efficient nutrient cycling within the soil food web (Ferris et al. 2001). However, the relative abundance of trophic groups varied markedly across elevations. Plant-parasitic nematodes dominated high-altitude communities, whereas bacterivores progressively increased toward lower elevations and became dominant below 800 m. Such shifts likely reflect changes in resource availability and microbial activity. At higher elevations, low temperatures slow microbial growth and decomposition rates, limiting resources for bacterivorous nematodes despite increasing soil organic matter accumulation (Bakonyi et al. 2007; Choudhary et al. 2023). Consequently, only taxa adapted to cold conditions and slow nutrient turnover are able to persist. Similar patterns have been reported from mountain ecosystems in the Himalayas and the European Alps, where reduced microbial activity at high elevations results in simplified soil food webs (Afzal et al. 2021; Chen et al. 2024).

The observed diversity patterns provide further evidence that environmental conditions are most favorable at intermediate elevations. Shannon, Simpson, and Menhinick indices reached their highest values at 800–1500 m, whereas the Margalef index was slightly higher at 1500–2000 m. This difference reflects the distinct ecological information provided by these indices. The Margalef index primarily measures species richness, whereas the Shannon and Simpson indices incorporate both species richness and the evenness of species distribution. Therefore, the slightly higher Margalef value at 1500–2000 m indicates greater species richness, while the higher Shannon and Simpson values at 800–1500 m suggest a more even community structure and higher overall diversity. Together, these indices indicate that mid-elevation zones (800–2000 m) support the greatest nematode diversity, although different aspects of diversity peak in different altitudinal bands. This unimodal pattern is consistent with the mid-elevation diversity hypothesis, which predicts maximum species richness under intermediate environmental conditions where climatic constraints are less severe and resource availability is relatively high (Lomolino 2001; Dong et al. 2017). Mid-elevation zones in the Boysun Mountains likely provide optimal combinations of soil moisture, temperature, vegetation productivity, and organic matter turnover, enabling the coexistence of multiple trophic groups and ecological strategies. Similar mid-elevation diversity peaks have been documented for nematodes and other soil organisms across mountain ecosystems worldwide (Dong et al. 2017; Zhang et al. 2025). In contrast, the high-altitude zone (>2000 m) supported lower diversity and was characterized by a greater proportion of plant-parasitic and higher c-p taxa. Harsh environmental conditions, including low temperatures, a shorter growing season, and slower decomposition rates, act as strong environmental filters that limit species establishment and reduce trophic complexity (Körner 2007; Chen et al. 2024). Nevertheless, the substantial represen-

tation of CP-4 and CP-5 groups suggests relatively undisturbed conditions and high ecosystem stability. Persister taxa are generally associated with mature ecosystems because they are sensitive to environmental disturbance and require stable resource conditions for persistence (Bongers 1990; Bongers and Bongers 1998).

At lower elevations, particularly below 800 m, the dominance of CP-1 and CP-2 groups indicates a shift toward opportunistic life-history strategies. Colonizer taxa are characterized by rapid reproduction, short generation times, and high tolerance to environmental fluctuations (Bongers 1990). The predominance of these groups, together with the decline in predators and omnivores, suggests increased ecological disturbance and simplified food-web structure. Such patterns may result from greater anthropogenic influence, grazing pressure, reduced soil moisture, and increased temperature stress in foothill environments. Similar reductions in higher trophic-level nematodes under disturbed conditions have been widely reported and are often interpreted as indicators of declining ecosystem complexity and resilience (Ferris et al. 2001; Kashyap et al. 2022; Chen et al. 2024). The Jaccard similarity analysis further demonstrated that high-altitude communities were compositionally distinct from those occurring at lower elevations. This finding suggests strong environmental filtering and species turnover along the altitudinal gradient, a process frequently observed in mountain ecosystems where climatic and edaphic conditions change rapidly over relatively short spatial scales (Sundqvist et al. 2013; Kergunteuil et al. 2016). The greater similarity between the 800–1500 m and <800 m zones reflects the sharing of many widespread and ecologically tolerant taxa adapted to warmer conditions.

Overall, the results largely support the study hypothesis that altitude significantly influences nematode community composition and functional structure. Elevational variation was associated with pronounced shifts in trophic organization, c–p composition, diversity patterns, and community similarity. However, contrary to the original expectation of a universal decline in higher trophic-level nematodes with increasing altitude, omnivorous and predatory persister taxa remained relatively well represented at higher elevations. This suggests that altitude influences soil food-web organization not only through environmental stress but also through changes in ecosystem stability and disturbance regimes. Consequently, mountain ecosystems appear to support distinct but functionally structured nematode assemblages across different elevational zones.

In conclusion, altitude acts as a major ecological determinant of soil nematode community structure in the Boysun Mountains. The observed changes in taxonomic composition, trophic structure, diversity, and c–p organization reflect shifts in soil food-web functioning and ecosystem stability along the environmental gradient. These findings confirm the utility of nematode communities as sensitive bioindicators of ecological condition and provide valuable insights into the mechanisms regulating belowground biodiversity in mountain ecosystems.

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