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Distribution and abundance of a soil centipede, *Tygarrup nepalensis* Shinohara, 1965 (Mecistocephalidae: Geophilomorpha: Chilopoda) in a moist temperate forest in Northwest Himalaya

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Abstract

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This study investigates the distribution of the soil centipede, *Tygarrup nepalensis* (Order Geophilomorpha), in the moist temperate forest of the Northwest Himalayas, located in Himri, District Shimla, Himachal Pradesh, India. Centipedes were collected using a standardized 25 × 25 cm quadrat sampling method. We examined the influence of various environmental and edaphic parameters on its populations across different forest areas (north, northeast, southwest facing aspects). The north aspect exhibited higher density due to more favourable soil conditions, including higher phosphorus and organic carbon, which supported larger populations of detritivore earthworms, likely prey for *T. nepalensis*. These findings underscore the role of microhabitat characteristics in shaping centipede distribution and highlight implications for forest management strategies aimed at conserving soil biodiversity and enhancing forest productivity. Our results indicate that average soil moisture levels (25.8% to 30.5%) are conducive to the habitat requirements of *T. nepalensis*, which thrives in moist environments. Notably, population densities varied significantly, with lower density in the northeastern aspect, correlated with reduced soil phosphorus concentrations and increased acidity.

Keywords

centipedes, ecology, edaphic parameters, geophilomorphs, Northwest Himalayas, temperate forest

Introduction

Centipedes play a crucial role as top invertebrate predators in various habitats, such as soil, litter and dead wood. They are generally classified into four ecomorphological groups, corresponding to the centipede orders: soil and cave-dwelling Geophilomorpha, surface and litter-dwelling Lithobiomorpha and Scolopendromorpha, and wall-dwelling Scutigeromorpha (Lin and Wiegand, 2014). To evaluate the habitat of the endangered tree species Taxus contorta Griff. under the Indian National Mission on Himalayan Studies (NMHS), extensive sampling of soil macroinver

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tebrates was conducted in the moist temperate forests of the northwest Himalayas. The results revealed significant populations of soil centipedes, identified as *Tygarrup nepalensis* (Shinohara, 1965) of the family Mecistocephalidae and order Geophilomorpha. Geophilomorphs can be distinguished from other centipede groups by their elongated and slender bodies, which usually possess between 27 and 191 pairs of legs, and antennae with 14 segments (Minelli and Golavatch, 2013). Additionally, they are blind and primarily inhabit soil, preying on various invertebrates, including earthworms, enchytraeids, millepedes, snails, collembolans, diplurans, as well as larvae of dipterans and beetles Adis et al., 1996).

The genus *Tygarrup*, widespread mainly in Southeast Asia, includes 15 species, with *T. diversidens* (Silvestri, 1919), *T. nepalensis*, and possibly *T. poriger* (Verhoeff, 1937) occurring in the Himalayan Biodiversity Hotspot (Bonato et al., 2011; Bonato et al., 2016). One of the species *T. javanicus* Attems, 1929, originally described from Java and native to Southeast Asia, has

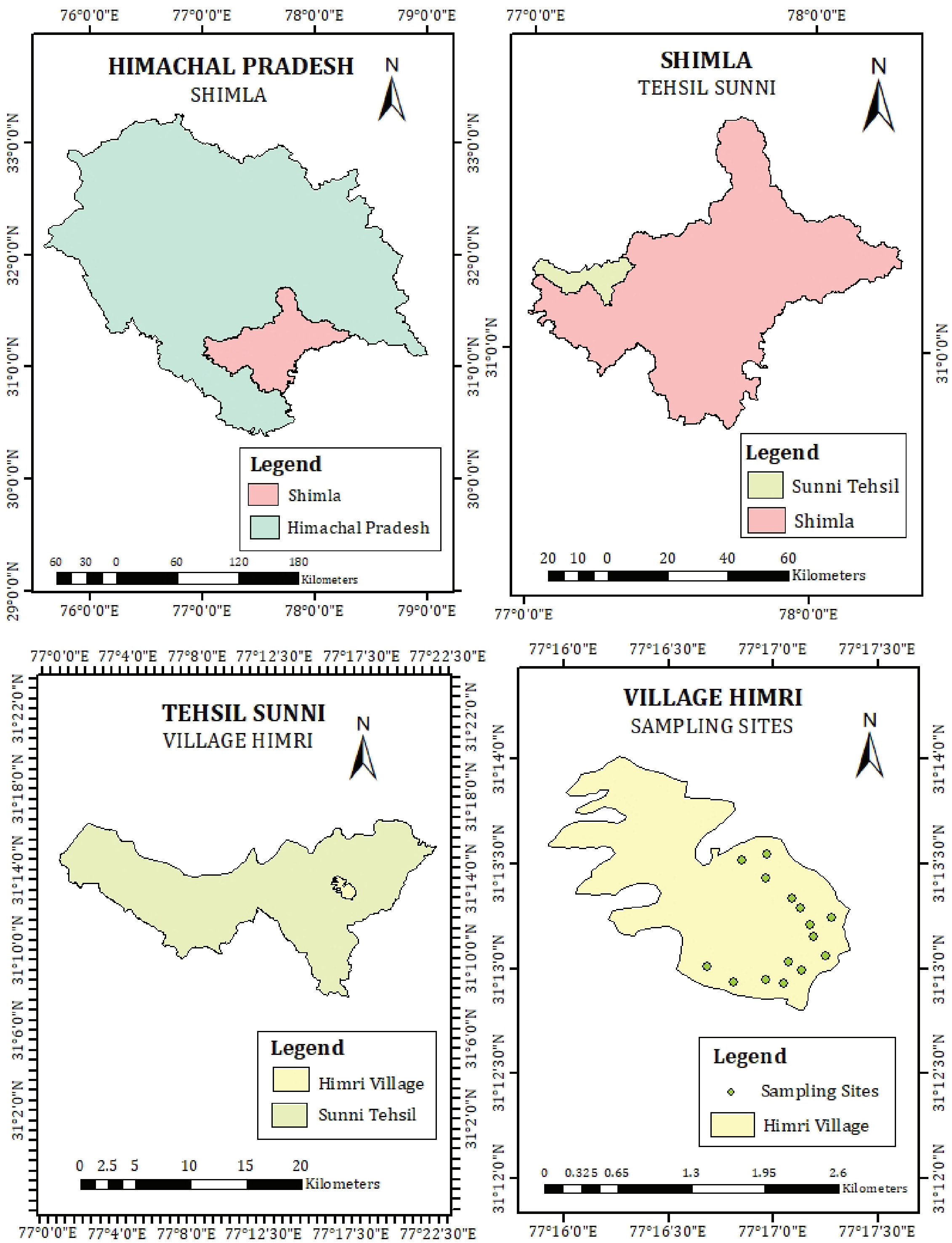

Fig. 1. Study area map showing sampling sites.

spread to various parts of the world, most likely due to anthropogenic activities. It has been extensively introduced into some European greenhouses (Bonato et al., 2011; Damasiewicz and Leśniewska, 2020). Its distribution now spans from Seychelles to the Hawaiian Islands (Tuf et al., 2018). Other species in the genus have more localized distributions: *T. muminabadicus* (Titova, 1965) – Tajikistan; *T. anepipe* (Verhoeff, 1939) – Mauritius; *T. crassignathus* (Titova, 1983) – Cambodia; *T. daliensis* (Chao, Lee, Yang & Chang, 2020) – Yunnan; *T. griseoviridis* (Verhoeff, 1937) – Peninsular Malaysia; *T. intermedius* (Chamberlin, 1914) – Guyana; *T. malabarus* (Chamberlin, 1944) – Java; *T. quelpartensis* (Paik, 1961) – South Korea; *T. singaporiensis* (Verhoeff, 1937) – Singapore, Cambodia and Peninsular Malaysia; *T. takarazimensis* (Miyosi, 1957) – Shoto; *T. triporus* (Titova, 1983) – Cambodia.

Several studies have emphasized the crucial role of soil centipedes in maintaining ecosystem stability by controlling populations of coexisting organisms such as collembolans, dipteran larvae, and earthworms (Klarner et al., 2017; Ion and Murariu, 2023). Nevertheless, specific investigations into the diet and feeding behavior of *Tygarrup* species are still lacking. According to Voigtlander (2011) and Ivask et al. (2019), knowledge on centipedes' community structure, species diversity and dynamics can be used to assess habitat quality and predict likely changes in an ecosystem, as well as formulate measures for its conservation.

For a long time, the study of centipede ecology has been relatively sparce. Nonetheless, the past two decades have seen significant progress in ecological research on European soil centipedes (Ion and Murariu, 2023). However, there remains a notable gap in similar studies for the Himalayan region, which is the focus of our current research. Recognized as a critical area for the development of a comprehensive biological database and the study of ecological indicators of environmental changes, this region is integral to the National Mission for Sustaining the Himalayan Ecosystem, an initiative by the Government of India aimed at addressing global climate change. Accordingly, our present study seeks to fill the existing research gap by enhancing our understanding dynamics of soil centipedes in the Himalayan moist temperate forests, particularly *Taxus* stands.

Materials and methods

Study site

The study was conducted in a moist temperate forest with naturally regenerating stands of *Taxus contorta* at Himri (31.1421°N, 77.4795°E; altitude 2,200–2,400 m) in Sunni forest division of Shimla District, Himachal Pradesh (Fig. 1). The selection of Himri forest area (556.03 hectares) was based on the data from the HP State Forest Department about the presence of regenerating *Taxus contorta* population. The area experiences an average annual rainfall of 2,000 mm, along with average annual minimum and maximum temperatures of 7 °C and 19 °C, respectively.

Centipede sampling

Based on preliminary field surveys, three areas where *T. contorta* was present in the tree canopy were selected for study. These areas represented north, northeast, and southwest-facing geographical aspects with varying vegetation compositions (Table 1). Centipedes were collected twice each year during 2020–2022: in Autumn (November 2020 and 2021) and in Spring (March 2021 and 2022). The occurrence of *T. contorta* and other selected plants were marked with a Garmin eTrex 10 Global Positioning System (GPS) receiver with ±5 m accuracy by following the protocol as recommended by Tropical Soil Biology Fertility Program for the sampling of soil macroinvertebrates (SWIFT and Bignell, 2001).

A total of 57 plots, each measuring 5 × 5 m^2, were selected randomly for sampling in three different geographical aspects (24 in the north, 24 in the northeast, and 9 in the southwest). The smaller number of plots in the southwest was because of the smaller area of *Taxus* canopy. An online Random Number Generator app was used to lay out the plots. Within each plot, three soil monoliths, each measuring 25 cm by 25 cm in area and

Table 1. Aspect-wise vegetation composition (%) in moist temperate forest at Himri, District Shimla, Himachal Pradesh

Plant community (%)	North	Northeast	Southwest
Aesculus indica (Wall. ex Cambess) Hook.	0.16	–	–
Cedrus deodara (Roxb. ex D. Don) G. Don	27.26	5.21	0.36
Picea smithiana (Wall.) Boiss.	3.48	6.92	5.05
Pinus wallichiana A. B. Jacks.	9.98	13.48	10.47
Quercus floribunda Lindl. ex A. Campus	21.23	50.46	8.12
Quercus leucotrichophora A. Campus	0.16	2.55	63.17
Quercus semecarpifolia Sm.	11.72	–	10.10
Rhododendron arboretum Sm.	0.47	1.64	–
Quercus dilatate A. Kem.	4.60	2.55	0.18
Rhododendron barbatum Wall. ex G. Don	7.92	1.64	0.9
Taxus contorta Griff	7.92	14.39	0.18
Populus ciliate Wall. ex Royle	5.07	1.09	–
Millettia pinnata (L.) Panigrahi	–	–	1.26
Pyrus pashia Buch.-Ham. ex D. Don	–	–	0.18

30 cm in depth were extracted to collect centipedes. The monoliths were carefully hand-sorted to retrieve centipedes, which were subsequently preserved in 70% ethanol for further laboratory analysis. The term “monolith” refers to a core of soil, a concept widely employed in the sampling of soil macroinvertebrates (Valdez et al., 2020).

Environmental and edaphic parameters

On-site data collecting involved measurement of various factors in the field. A Spherical Crown Densiometer was used to evaluate the canopy cover of the trees, a steel scale to estimate litter thickness, and an iButton Temp Logger to record soil temperature. Rainfall, air temperature and humidity data were sourced from ERA5 through Elistar Geomatics, Delhi.

A total of 228 composite soil samples and an equal number of litter samples, each weighing 150 grams, were collected from each plot over two seasons each year. These samples were taken from the same sites used for centipede sampling. The soil and litter samples were analysed in the laboratory to assess various physicochemical properties using specific techniques: soil moisture by gravimetric method (Santhanam et al., 1989); litter moisture by Litter Moisture Content Monitoring method (Zhang and Tian, 2021); soil pH by using pH meter (Anderson and Ingram, 1993); electrical conductivity by using electrical conductivity meter (Rathore et al., 2023); organic carbon by Walkley and Black’s rapid titration method (Walkley and Black, 1934); available nitrogen by Kjeldahl method (Jackson, 1962); available potassium by Flame photometer method (Stanford and English, 1949); available phosphorus for acidic soil by Bray’s method (Bray and Kurtz, 1945).

Principal component analysis was used to assess the impact of litter and soil physicochemical variables, as well as environmental conditions, on centipede distribution and density.

Species identification

Centipedes were identified with the help of Lucio Bonato (University of Padova, Italy), a renowned authority on the taxonomy of global centipedes and the key of Shinohara (1965).

Results

Edaphic and environmental parameters

The northeast aspect exhibited the highest average levels of soil moisture content (30.5%), litter moisture (34.4%), soil organic carbon concentration (4.9%), and available nitrogen (475.9 kg ha^{-1}) over two seasons each year (Table 2). Comparatively, the north and southwest aspects showed marginally lower values. The northeast also had the greatest canopy coverage at 93.8%, followed by the southwest, while the north had the lowest at 90.9%. However, average litter thickness was highest in the southwest (1.9 cm), followed by the northeast (1.7 cm), with the north showing similar values.

The average soil pH ranged from 5.8 to 6.0, with the north and southwest showing the highest values and the northeast the lowest. Furthermore, average available phosphorus was greatest in the north (36.5 kg ha^{-1}), followed by the southwest (35.4 kg ha^{-1}), and lowest in the northeast (31.2 kg ha^{-1}).

The southwest recorded the highest average electrical conductivity (101.1 ppm) and average soil temperature (8.8 °C), followed by the north, while the northeast had the lowest values (77.4 ppm and 8.3 °C). Average available potassium was also the most abundant in the southwest

Table 2. *Tygarrup nepalensis densities* (ind. m^{-2}) and aspect wise soil & environmental parameters in a mixed temperate forest stand of *Taxus contorta* at Himri, District Shimla, Himachal Pradesh. D – Centipede density; RF – Relative frequency; n – No. of samples/monoliths; SM – Soil moisture; pH – potential of hydrogen; EC – Electrical conductivity; ST – Soil temperature; SOC – Soil organic carbon; AN – Available nitrogen; AP – available phosphorus; AK – available potassium; CA – Canopy; LT – Litter thickness; LM – Litter moisture

Density and environmental parameters	North aspect (Mean ± SE)	Northeast aspect (Mean ± SE)	Southwest aspect (Mean ± SE)
D (ind. m^{-2})	7.17 ± 2.09	2.39 ± 1.21	5.33 ± 2.81
RF (%)	19.79	10.42	22.22
No. of samples (n)	288	288	108
SM (%)	27.3 ± 3.09	30.5 ± 2.98	25.8 ± 2.93
Ph	6.0 ± 0.20	5.8 ± 0.18	6.0 ± 0.25
EC (ppm)	89.5 ± 6.88	77.4 ± 7.82	101.1 ± 7.51
ST (°C)	8.4 ± 3.71	8.3 ± 3.71	8.8 ± 3.90
SOC (%)	4.7 ± 0.32	4.9 ± 0.26	4.1 ± 0.19
AN (kg ha^{-1})	466.2 ± 9.10	475.9 ± 11.19	463.6 ± 9.08
AP (kg ha^{-1})	36.5 ± 2.35	31.2 ± 1.54	35.4 ± 1.73
AK (kg ha^{-1})	413.7 ± 17.98	404.3 ± 22.34	423.1 ± 15.39
CA (%)	90.9 ± 2.67	93.8 ± 1.17	91.3 ± 1.15
LT (cm)	1.7 ± 0.17	1.7 ± 0.13	1.9 ± 0.11
LM (%)	29.3 ± 4.26	34.4 ± 4.61	24.7 ± 3.79

Table 3. Number and seasonal densities of *Tygarrup nepalensis* (ind. m^{-2}) across different aspects in a mixed temperate forest stand of Taxus contorta at Himri, District Shimla, Himachal Pradesh

Seasons	North aspect		Northeast aspect		Southwest aspect	
	Total	Mean ± SE	Total	Mean ± SE	Total no.	Mean ± SE
Autumn (Nov, 2020)	114	25.33 ± 5.90	25	5.56 ± 2.80	17	9.78 ± 5.38
Spring (March, 2021)	4	0.89 ± 0.73	4	0.89 ± 0.56	5	3.56 ± 2.10
Autumn (Nov, 2021)	7	1.56 ± 1.02	12	2.67 ± 1.20	10	4.89 ± 1.80
Spring (March, 2022)	4	0.89 ± 0.73	2	0.44 ± 0.28	6	3.11 ± 1.96

(423.1 kg ha^{-1}), followed by the north (413.7 kg ha^{-1}), and lowest in the northeast (404.3 kg ha^{-1}).

Species diversity and abundance

A total of 210 centipede individuals were collected during the present study. These belonged exclusively to the *Tygarrup nepalensis*, a soil centipede of the family Mecistocephalidae and order Geophilomorpha. The findings in Table 2 show that the highest mean density of *T. nepalensis*, based on 684 samples collected over four seasons across two years, was observed in the north aspect (7.17 ind. m^{-2}) followed by the southwest (5.33 ind. m^{-2}) and lowest in the northeast (2.39 ind. m^{-2}). However, it was recorded more frequently in the southwest aspect (22.22%), followed by north (19.79%) and northeast aspect (10.42%). In comparison to the 11.43% relative density of *T. nepalensis* in Himri Forest, earthworms and beetle larvae, as potential prey, had relative densities of 65.32% and 9.42% respectively. Competitor ants comprised 10.13%.

Temporal variations across three forest aspects revealed that the autumn season, especially in 2020, recorded the highest total counts, with peak activity observed in the north aspect (Table 3).

Principal component analysis (PCA)

Principal component analysis (PCA) was performed across different aspects (north, northeast, southwest) to understand the influence of edaphic parameters on the density of *Tygarrup nepalensis* (Fig. 2). It revealed significant variability (PC1 = 90.82% variance) due to litter moisture, electrical conductivity and soil moisture. The reduced population on the northeast aspect was linked to higher soil moisture levels. A lesser degree of variability (PC2 = 9.18% variance) was observed across different aspects due to parameters such as available phosphorus and organic carbon and litter thickness. The high population density of *T. nepalensis* on the northern aspect appears to be indirectly influenced by the availability of phosphorus and soil organic carbon, which sustain populations of coexisting potential prey, such as earthworms and other detritivores. While research on the feeding behaviour of *Tygarrup* species has been largely neglected, studies on related geophilomorph taxa suggest a predatory diet that includes earthworms and other soil-dwelling invertebrates.

Discussion

The latest checklist of Indian centipedes lists 77 species, predominantly of the order Scolopendromorpha (75 species), with one species each of the orders Scutigeromorpha and Geophilomorpha (Sureshan, 2024). However, this list is incomplete, as it omits several species found in India, such as geophilomorphs reported by Bonato and

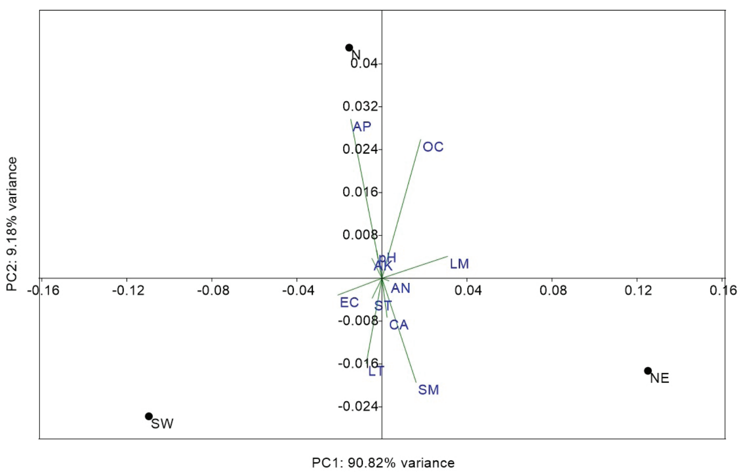

Fig. 2. Principal component analysis (PCA) showing centipede relationships with soil and climatic parameters. AP – Available phosphorus; OC – Soil organic carbon; pH – Potential of Hydrogen; AK – Available potassium; LM – Litter Moisture; AN – Available nitrogen; EC – Electrical conductivity; ST – Soil temperature; CA – Canopy; LT – Litter Thickness; SM – Soil moisture in different aspects (N – North; NE – Northeast; SW – Southwest) in moist temperate forest stand at Himri, District Shimla, Himachal Pradesh.

Minelli (2004) and lithobiomorphs recorded by Eason (1992) and Edgecombe (2001).

Although Geophilomorpha is the most diverse centipede group globally, its limited diversity in this country may be attributed to collection methods that predominantly focused on epigeic centipedes found beneath stones, logs, litter and bark. This approach often tends to overlook the deep soil-dwelling geophilomorphs as well as cave- and crevice-dwelling lithobiomorphs, which may explain their low diversity in India.

Geophilomorph communities in temperate forest soils exhibit remarkable diversity, with over 10 species co-existing at individual sites in the European Alps (Magnolini and Bonato, 2023; Petersen and Luxton, 1982; Bonato et al., 2017). The presence of a single species, *T. nepalensis*, from this group in the moist temperate forests of the Himalayas, where the current research was conducted, is particularly remarkable and intriguing. This may be attributed to the historical and specific climatic conditions of the study area, which was covered by glaciers during the last glacial maximum in the Western Himalayas (Srinivasan et al., 2013).

The present record of *T. nepalensis* from Himri is highly significant as it represents the first sighting of this species in the Indian Himalayan region. Previously, this species had only been recorded in the Nepal Himalaya, revealing a notable gap in its geographical distribution. This finding not only expands our knowledge of the species' range but also emphasizes the rich ecological diversity of the temperate zone within the Himalayan biodiversity hotspot. It is also noteworthy that another species in the *Tygarrup* genus, *T. diversidens* is found in the Himalayan region (Bonato and Minelli, 2004).

Spatial distribution of centipedes is shaped by a range of environmental factors, including habitat type, geography, altitude, soil composition, and microhabitat preferences (Blackburn et al., 2002). Additionally, centipedes have adapted to diverse ecological niches, which means their distribution can also be influenced by local environmental conditions (Druce, 2000; Eason, 1964; Balan and Sureshan, 2017).

Average soil moisture among different aspects of Himri forest ranged between 25.8% to 30.5%, which is suitable as habitat for *T. nepalensis*. According to Kula and Lazorik (2016), soil centipedes prefer moist sites with more than 25% soil moisture as these sites provide abundant moist resistant microbial food (Bardgett et al., 2005). Average litter moisture varied between 24.7% and 34.4%.

The lower average population density of *T. nepalensis* (2.39 ind. m^{-2}) in the northeastern aspect may be indirectly linked to reduced soil phosphorus concentrations (31.2 kg ha–1) and increased soil acidity (pH 5.8). These conditions are recognized for their adverse effects on detritivores such as earthworms, millipedes and Collembola, which serve as food source for soil centipedes (Ke et al., 2004; Geissen et al., 2007). However, the higher average population of *T. nepalensis* (7.17 ind. m^{-2}) on the north aspect appears to be due to the significant influence of increased available soil phosphorus (36.5 kg ha^{-1}) and organic carbon (4.7%). Soil organic carbon plays a vital role in supporting earthworm populations, as it serves as a crucial resource for their survival (Bartz et al., 2013; Singh et al., 2020a, 2020b). Furthermore, enhanced available phosphorus shows higher earthworms' activity and abundance (Vos et al., 2023).

The presence of well-established populations of *T. nepalensis* in the soil beneath both coniferous and broadleaf trees across different aspects of the Himri temperate forest indicates a wider distribution throughout the western Himalayan temperate region. This also points to a healthy ecosystem, as their presence could indicate good soil health. Understanding this can help in developing effective conservation strategies and land management practices to protect the temperate forest ecosystems in the Himalayas.

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