ORIGINAL PAPER

Habitat of two threatened short-tailed whip-scorpions (Arachnida: Schizomida) in the tropical Andes of Northern South America

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Abstract

Aim Schizomids are one of the less-known arachnid groups in terms of their natural history and ecology. However, due to their remarkable short-range endemic distribution, they may be vulnerable to climate change and habitat loss. In Colombia, although the national IUCN red list of threatened invertebrates has categorized species of schizomids as vulnerable (VU), this assessment was based on expert criteria. Therefore, information about the ecology of schizomids is critical for a more accurate reassessment of their conservation status. In this study, we describe the habitat of two species of *Surazomus* in endangered Andean tropical forests of Colombia after a sampling effort of 15.12 m^2 (n = 168 soil samples) and the collection of 6999 soil fauna individuals from the samples. We analyzed soil fauna communities associated with schizomids as well as different forest and environmental variables from permanent plots installed a decade ago in the *Sabana de Bogotá* region. Detailed information on climate, plant communities, and forest structure was obtained from these plots. Thus, we provide the first comprehensive habitat description of schizomids including both above- and belowground compartments. We found that each species lives in specific habitats with different soil fauna communities, suggesting a potential association between geographical fidelity and habitat conditions. This result could indicate that schizomids are highly sensitive to dramatic environmental changes, such as those experienced in the Andean region of Colombia.

Implications for insect conservation Our study is valuable for the future reassessment of the conservation status of schizomids in the country, particularly considering that the previous categorization was based on expert criteria. Since habitat conditions and soil fauna communities are species-specific, schizomids could be disproportionately vulnerable to climate change and human disturbances in the Colombian Andes.

Keywords Colombian Andes · Endemism · Forest structure · Microhabitat · Soil properties · Soil fauna communities

Introduction

The order Schizomida, commonly known as short-tailed whip scorpions, is one of the smaller arachnid groups (Harvey 2003) and currently comprises 386 species (14 fossils), 79 genera (eight fossils), and three families (one fossil) (World Schizomida Catalog 2022). Schizomids are small predators (2.0–12.5 mm) widely distributed in tropical and subtropical areas around the World. They are frequently found in different habitats, including forests, caves, and human-dominated landscapes such as botanical gardens, greenhouses, and crops. These habitats offer multiple micro-habitats, such as leaf-litter, soil, termite nests, rock crevices and rotten logs, which provide the necessary resources for maintaining their populations (Reddell and Cokendolpher 1995).

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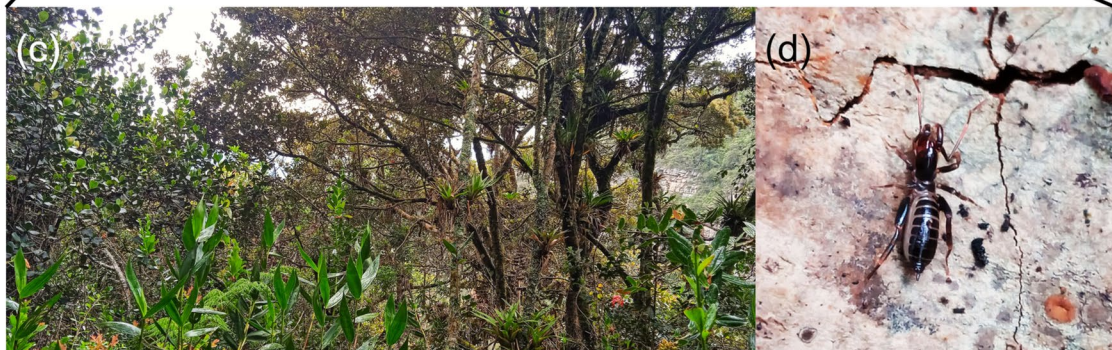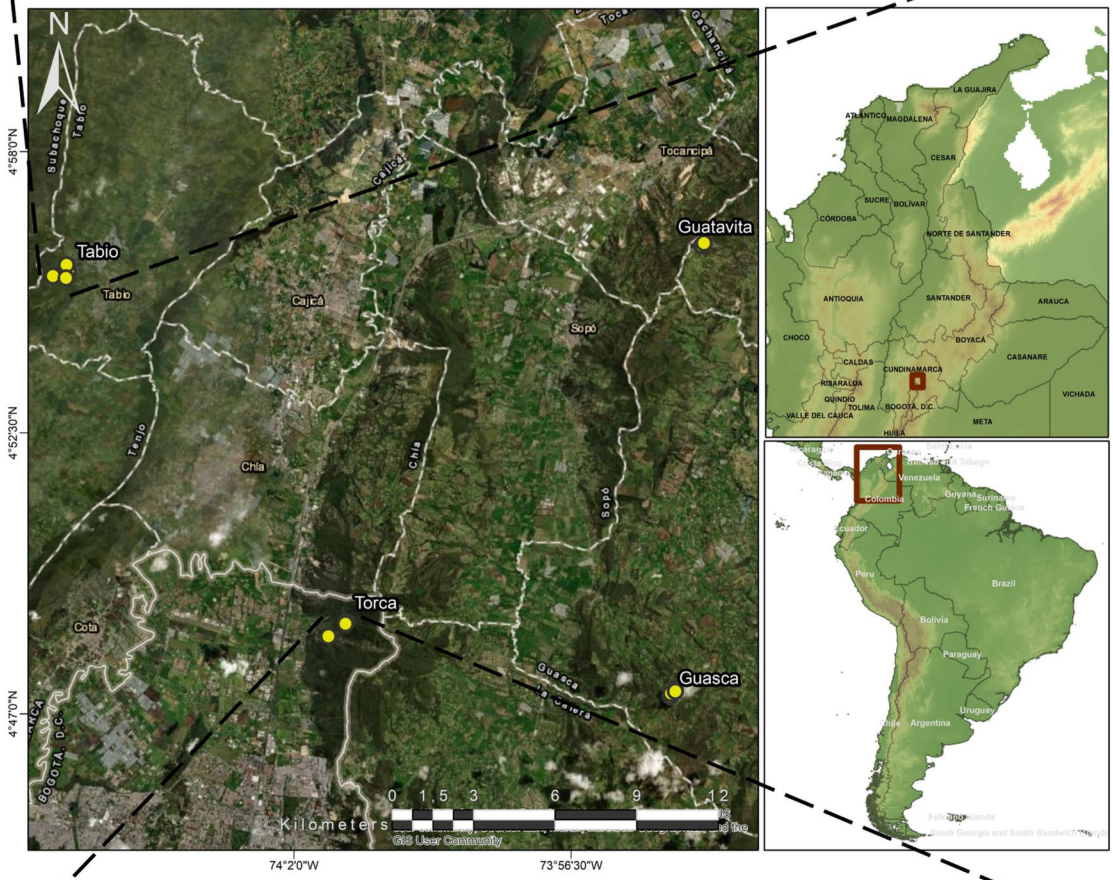4 Division of Invertebrate Zoology, American Museum of Natural History, New York, USA

◄Fig. 1 Species of *Surazomus* and their habitats in the *Sabana de Bogotá* region (Cundinamarca, Colombia). **a** Forest in Tabio; **b** female of *Surazomus* sp. over *Dapnhopsis caracasana* litter; **c** forest in Torca (Bogotá); **d** female of *Surazomus sturmi* over *Clusia multiflora* litter. The yellow circles on the map indicate the locations of the 14 permanent plots where soil fauna sampling took place. (Color figure online)

The vast majority of schizomids show remarkable geographical fidelity (Clouse et al. 2017) and are only known from single localities (type localities) or a few close localities. Thus, most of them have been considered short-range endemic taxa, a category for species distributed in < 10,000 km^2 (Harvey 2002). In consequence, schizomids may be especially vulnerable to climate change and habitat loss. Although some progress has been made regarding their systematics (e.g., Monjaraz-Ruedas et al. 2016; Clouse et al. 2017), paleontology (e.g., Magnussen et al. 2022), and morphology (e.g., Kallal et al. 2022), little is known about the natural history and ecology of these arachnids. For example, the behavior has been studied in only three species (Sturm 1958, 1973; Kraus and Beck 1967; Oliveira and Ferreira 2014), a handful of predators and preys of schizomids have been reported (Armas and Melic 2015; Armas and Moreno-González 2021), and the knowledge on reproductive biology is restricted to isolated observations of brooding (Giribet and Moreno-González 2021).

Our understanding about the ecology of South American schizomids is particularly reduced, despite occupying several ecosystems from sea level to upper Andean montane forests (Armas 2010). Available ecological contributions have mainly focused on the abundance and phenology of Amazonian schizomid communities (Adis et al. 1999, 2001). Nonetheless, there are no studies dealing with the co-occurrence of schizomids and other edaphic invertebrate communities, as well as the variables that modulate their habitat preference. In fact, most of the habitat characterizations available of schizomids consist of simple descriptions without a methodology to evaluate the biotic and abiotic conditions where schizomids live.

In turn, this lack of knowledge on the ecology of schizomids hampers the conservation efforts to protect them, which is particularly critical in the Andes of Northern South America. This region has experienced a legacy of large-scale deforestation that has triggered a pervasive habitat fragmentation, leaving isolated patches of old-growth forests (Etter et al. 2008). This is particularly evident in the *Sabana de Bogotá* region, where less than 30% of its original forest cover remains (Etter et al. 2021), and where an endemic schizomid species, *Surazomus sturmi,* is distributed (Kraus 1957). Due to this pervasive habitat loss, the national IUCN red list of threatened invertebrates has categorized *S. sturmi* as vulnerable (VU) (Flórez and Cepeda 2007). Nonetheless, this assessment was based on expert criteria and, therefore, information about the ecology of this species is critical for a more accurate assessment of its conservation status. Understanding the ecology of schizomids is also crucial for recommending management and land use strategies that support the conservation of these organisms. On the other hand, very few sampling efforts have been conducted in the peri-urban forest of the *Sabana de Bogotá* region, where other undescribed species of *Surazomus* are distributed.

In this paper, we characterized the habitat of two threatened *Surazomus* species from the Eastern Andes of Colombia, thus providing new information about environmental conditions, co-occurrence with other soil fauna, and forest attributes derived from long-term monitoring of permanent plots.

Methods

Our study took place in the Eastern Colombian Andes along a successional forest gradient in the Cundiboyacense high plains at elevations ranging from 2685 to 3140 m. The Andean region covers 24.5% of the Colombian territory (Etter and Wyngaarden 2000) and is the most populated region in the country, accounting for 70% of total population (DANE 2005). In this region, a set of 36 20 m × 20 m and eight 50 m × 50 m permanent plots were established starting in 2013 in five municipalities (Guasca, Guatavita, Tabio, San Francisco, and Soacha) and in peri-urban areas around Bogotá (Torca), the capital of Colombia, to monitor carbon cycling and biodiversity (both functional and taxonomic) in the long-term (Fig. 1). The plots are placed on private properties/reserves and encompass secondary and mature forests based on their structural attributes (i.e., basal area, tree height, tree density) and species composition (see Hurtado-M et al. 2021; Castillo-Figueroa et al. 2023). We established a successional gradient along the plots using the aboveground biomass from allometric equations as a proxy of forest recovery (Castillo-Figueroa et al. 2023).

We sampled soil fauna communities in surface litter and in 30 cm × 30 cm × 5 cm depth samples in soils in 14 of the plots during four climatic seasons of 2022 (dry: Jan–Feb; wet: Apr–May; moderately dry: Jul–Aug; wet: Oct–Nov), as a part of a litter decomposition experiment. In this experiment, three litterbeds with a minimal distance of 5 m between them were installed per plot for a total of 42 experimental units (Castillo-Figueroa et al. in prep.). Three soil samples were collected near the litterbeds for each plot between 8:00 and 12:00, resulting in a total of 42 samples across the 14 plots and 168 samples spanning the four climatic seasons. We stored litter and soil samples in separate plastic bags to distinguish soil fauna from: (1) leaf-litter and (2) soil depth at 0–5 cm. In the lab, soil fauna was manually extracted and preserved in 70% ethanol. Taxonomic

identification was carried out with the help of experts, original descriptions, and with the existing identification keys for the region to achieve the best taxonomic resolution possible. We also conducted field trips in all the sites, during March 2023, to manually search for schizomids on the forest floor. In this field campaigns, two researchers (DCF and CCA) were looking for schizomids during 2 h in all the potential microhabitats they can inhabit within the 20 m × 20 m permanent plots such as leaf-litter, rock crevices, rotten logs, and soil. This comprised a total surface area of 5600 m² and 56 h of active searching. The individuals that we found in these field trips and in the litter and soil sampling, were used to analyze the relationships between environmental conditions and the presence of schizomids.

To characterize the microhabitat of schizomids, we installed TMS-4 dataloggers (TOMST, Czech Republic) in the center of each plot. We recorded temperature 15 cm above the soil surface, at the soil level, and at 8 cm depth, as well as soil volumetric water content every 15 min (Wild et al. 2019). To describe forest structure, we quantified canopy openness and Leaf Area Index (LAI), by taking hemispherical photographs (Canon Inc. EW-77 Fisheye Zoom Lens EF 8–15 mm 1:4 (Japan), which were then processed with Gap Light Analyzer (GLA version 2.0, https://www.caryinstitute.org/). Finally, litter depth was averaged from five random soil points within each sampling unit using a digital caliper (0.1 mm).

We performed a non-metric multidimensional scaling (NMDS) with the edaphic communities associated to the litter and soil samples where the species of *Surazomus* were found. This was complemented with an Analysis of Similarity (ANOSIM) based on 9999 permutations and a Similarity Percentage breakdown analysis (SIMPER) (Clarke 1993). All three analyses were performed using Bray–Curtis distance. To describe the habitat of *Surazomus*, we did a Principal Component Analysis (PCA) with the environmental variables associated to the samples where individuals of *Surazomus* were collected, including the manual samplings in the ground. In this PCA, we also incorporated pre-existing data from the permanent plots such as litter production, soil pH, bulk density, and litter decay (Tables S1, S2). Initially, we had 14 variables obtained from the permanent plots. However, we refined our selection by excluding highly correlated variables (rho > 0.7) and those considered less informative regarding the environmental and structural forests characteristics (Fig. S1). As a result, we performed a PCA with eight highly informative variables, providing a more accurate representation of the forest structure, edaphic characteristics, and climatic conditions associated with each species of *Surazomus*. In this PCA, data points were scaled by $1/\sqrt{d_k}$ and the biplot eigenvectors by $\sqrt{d_k}$ according to the correlation biplot of Legendre and Legendre (1998). To assess the suitability of PCA as a method for dimensionality reduction, Bartlett's test of sphericity was used (Bartlett 1951). This test evaluates the null hypothesis that the variables are not interrelated and, therefore, may not be suitable for a PCA. Rejection of this null hypothesis indicates a correlation among variables, thereby supporting the assumption required for PCA to be effective in capturing underlying patterns and reducing dimensionality. Lastly, we did pairwise comparisons in the microhabitat characteristics between the sites where the species of *Surazomus* were found through a *t* test. All the statistical analyses were performed in PAST 4.14 (Hammer et al. 2001) and JASP 0.18.1.0 (JASP TEAM 2023).

Results and discussion

In three distinct seasons (dry: Jan–Feb, wet: Apr–Mar, wet: Oct–Nov), we found two species of *Surazomus* in the *Sabana de Bogotá* region: *Surazomus sturmi* (Kraus 1957) in Torca and an undescribed species of *Surazomus* in Tabio (Moreno-González in prep.). Both species could be readily identified based on the shape of the male flagella and female spermathecae, which are commonly used morphological characters for species distinction in Schizomida (Reddell and Cokendolpher 1995). After a sampling effort of 15.12 m² and 168 samples and the collection of 6999 soil fauna individuals from the samples, we found only five individuals of *S. sturmi* in Torca (4♀, 1♂) and six individuals of *Surazomus* sp. in Tabio (4♀, 2♂) (Fig. 1), representing the 0.16% of the total soil fauna community. Despite this, within the nine samples where schizomids were present, their relative abundance was 3.7% in Torca and 3.2% in Tabio (Table S3). The sex ratio of 4:1 females to males in Torca and 2:1 in Tabio is consistent with findings reported for other species of *Surazomus* (Adis et al. 1999, 2001), however, it is important to exercise caution when interpreting these sex ratios due to the relatively low number of schizomids collected in this study.

We found that habitat conditions and soil fauna communities are species-specific, which is consistent with the short-range distribution of schizomids (Harvey 2002). In the case of *S. sturmi*, our results show that they can be found mainly in old-growth forests with large trees that shed vast amounts of litter into the soil (Fig. 2a, Tables S1, S2). These forests are dominated by plant species with conservative leaf traits such as *Weinmannia tomentosa* L. f., *Clusia multiflora* Kunth, *Cavendishia nitida* (Kunth) A.C. Sm., and other Ericaceae species with thick leaves that decompose slowly. High litter production and slow decay rates likely explain the high litter depth on the forest floor and the thicker soil organic horizon (Figs. 2a, S2, Tables S1, S2). On the other hand, individuals of *Surazomus* sp. from Tabio were found in both old-growth and secondary forests, with higher soil temperatures ($t = 236.273$, $P < 0.001$, Cohen's $d = 1.193$),
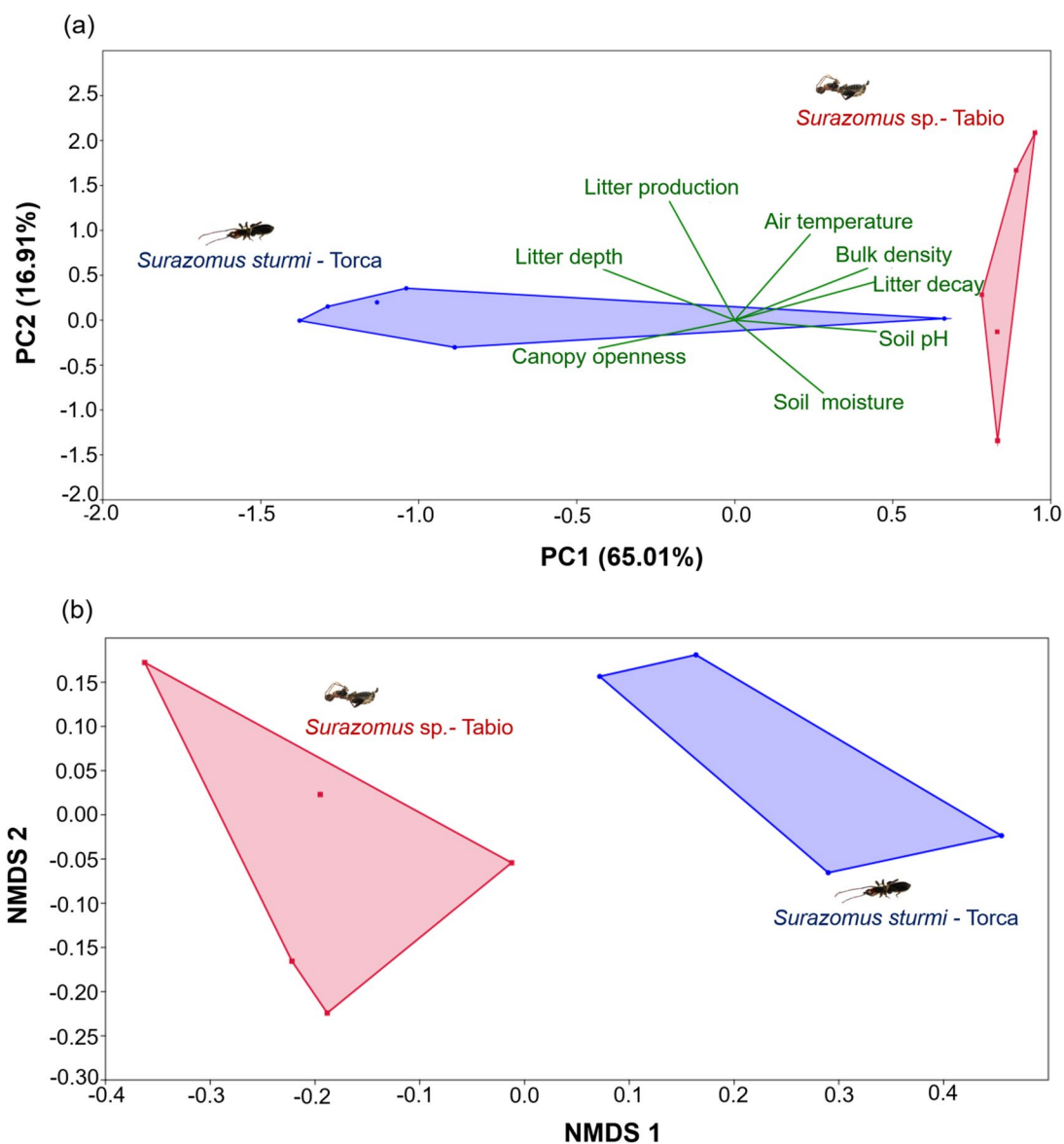
Fig. 2 Habitat characteristics and soil fauna communities associated to each *Surazomus* species. **a** Principal Component Analysis (PCA) of 14 *Surazomus* sampled and eight environmental characteristics associated to them (green arrows) including air temperature (°C), soil moisture (%), soil pH, bulk density (g/cm³), canopy openness (%), litter depth (cm), litter decay (% mass loss), and litter production (Ton C ha⁻¹ year⁻¹). The first two principal components accumulate 81.92% of total variation. Barlett's sphericity test indicates strong relationships among the variables (Chi-square = 235.24, df = 28, P < 0.0001), supporting their suitability for the PCA. Loading plots are depicted in Fig. S2. **b** Non-metric multidimensional scaling (NMDS) of soil fauna communities where *Surazomus* were found. The number of dimensions was set to 3 (k = 3), however we represent dissimilarity in a two-dimensional space to highlight differences between soil fauna communities associated to each *Surazomus* species. Stress = 0.15. In both PCA and NMDS, crimson squares depict *Surazomus* sp. from Tabio, while blue dots correspond to *S. sturmi* from Torca. In the NMDS, squares and dots correspond to nine soil samples (five in Tabio and four in Torca), in which we found 11 individuals of *Surazomus* species (six in Tabio and five in Torca). (Color figure online)

decay rates (t = 2.491, P = 0.014, Cohen's d = 0.349), and soil moisture (t = 69.100, P < 0.001, Cohen's d = 0.349) than in Torca (Fig. 1, Table S1). Forests in Tabio are dominated by more acquisitive plant species such as *Cedrela montana* Moritz ex Turcz., *Daphnopsis caracasana* Meisn., *Miconia squamulosa* (Sm.) Triana and *Croton bogotanus* Cuatrec.

Interestingly, out of the 14 individuals collected (8♀, 3♂ from soil samples and 3♀ from manual samplings), 10 were found in the soil layer which was the microsite with higher mean temperature and lower variability (X = 12.39 °C, CV = 0.04) than surface (X = 12.06 °C, CV = 0.12) and air (X = 11.54 °C, CV = 0.22). Considering

that low temperatures in high Andean forests are common, especially at dawn, *Surazomus* may select warmer habitats at a certain depth in the soil, avoiding the exposure to cold air temperatures. This result is in agreement with Adis et al. (1999), who found a positive relation between temperature and abundance of *S. brasiliensis* in late successional lowland tropical forests. This suggests that *Surazomus* species actively search for microhabitats that improve thermoregulation, thus avoiding low thermal conditions of their environment. However, Adis et al. (2001) reported a decrease in the abundance of *S. mirim* and *S. rodriguesi* in the Amazon with increasing temperature in early successional forests, where atmospheric temperature is warm because of high canopy openness and solar radiation exposure. Due to the low number of individuals in each sample (1 to 2), we could not establish a correlation between temperature and schizomid abundance, even though 70% of the individuals were found in the soil layer, which displayed a higher mean temperature and higher thermal stability. Despite the very low local abundance of these arachnids, further studies are needed to determine whether mean temperature and its variability act as limiting factors in schizomid microhabitat preference.

The NMDS (Figs. 2b, S3) and the ANOSIM ($P = 0.008$, $R = 0.85$) indicated that *Surazomus.* sp. from Tabio and *S. sturmi* from Torca were associated with different soil fauna communities. Although some taxonomic groups were present only in one site, millipedes and mites were the most dominant groups in both sites (Tables S3, S4). According to the SIMPER analysis, species of millipedes (Trichopolydesmidae, Pseudonannolenidae), mites (Oribatida), isopods (Scleropactidae), pseudoscorpions (*Ideobisium* sp.), and diplurans (Campodeidae) accounted for 42.26% of the dissimilarity between the two edaphic communities (Table S4). It has been suggested that schizomids may prey on millipedes, cockroaches, symphylans, springtails, small worms, isopods, and even other schizomids (Humphreys et al.1989; Armas and Melic 2015); however, dietary analyses are required to confirm this statement. Centipedes, pseudoscorpions and spiders are also listed as potential natural enemies of schizomids (Armas and Moreno-González 2021), and they were found in the soil fauna communities but in low proportions (Tables S3, S4). Further research should analyze the interactions between these endangered schizomid species and other soil animals and its implications on soil food webs.

Schizomids are still understudied, and our basic understanding of their ecology remains limited. Besides our study, there are no detailed descriptions of their habitats including both above- and belowground compartments. Despite the limited number of individuals collected in this study, our findings suggest that the short-range distribution of schizomids may be associated with specific habitat conditions where they live, which could render them highly sensitive to dramatic environmental changes. However, further studies

with larger sampling areas that encompass more sites and individuals collected should address this issue. We hope this study could be useful in the reassessment of the conservation status of schizomids in Colombia and encourages more ecological investigations on these poorly studied soil arachnids.

Author contributions DCF conceived the study, collected and analyzed the data, wrote the paper, prepared the figures, reviewed and edited drafts of the manuscript. CCA collected data, wrote the paper, reviewed and edited drafts of the manuscript. JAM identified the schizomids, wrote the paper, reviewed and edited drafts of the manuscript. JMP wrote the paper, reviewed and edited drafts of the manuscript, and acquired funding.

Data availability The data and supplementary material that support the findings of this study are openly available in Open Science Framework repository at https://osf.io/y2qfs/ (Castillo-Figueroa 2023).

Declarations

Competing interests The authors declare no potential conflict of interest.

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