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Dominance concentration and litter-associated trait shifts in ground-active arthropod assemblages along a recreational-use gradient

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Abstract

Ground-active arthropods are sensitive to forest-floor habitat structure, but their responses to recreational use may not appear as simple declines in total captures. We examined ground-active arthropod assemblages along a recreational-use gradient in Zijin Mountain, Nanjing, eastern China, where nine observation sites were classified into high-use (HRD), moderate-use (MRD) and low-use (LRD) categories using a visual interpretation disturbance score. Arthropods were repeatedly sampled with pitfall traps from July to December, and vegetation cover, litter cover and litter thickness were measured to characterize habitat structure. Recreational-use categories differed mainly in litter-layer structure rather than broad vegetation cover: HRD sites had thinner litter and lower litter cover, whereas tree, shrub and herb cover did not differ significantly among categories. HRD sites showed the highest activity density, but lower rarefied taxon richness, Shannon diversity and Pielou's evenness, together with higher Berger–Parker dominance. Rank–abundance patterns and dominance metrics indicated that this high activity density reflected dominance concentration rather than a broad increase across taxa, with Formicidae accounting for nearly half of total abundance in HRD. By contrast, LRD had a more distributed abundance structure, with greater contributions from Blattodea, Gryllidae, Araneae and other intermediate-abundance taxa. Community composition differed among recreational-use categories, but sampling date explained a larger fraction of compositional variation, indicating strong seasonal turnover. HRD also had higher proportions of omnivorous and high-dispersal taxa and lower community-weighted body length, whereas LRD had higher proportions of detritivore-associated, predator-associated and low-dispersal taxa. These results suggest that ground-active arthropod assemblages along this recreational-use gradient differed mainly through dominance concentration, dominant-taxon

composition, litter-associated habitat context, functional-composition shifts and seasonal turnover, rather than through a simple reduction in total activity density. Maintaining litter cover and ground-layer heterogeneity may help sustain more even forest-floor arthropod assemblages in heavily visited forest patches.

Keywords: ground-active arthropods; recreational use; activity density; dominance concentration; litter layer; functional composition

1. Introduction

Ground-active arthropods are important components of forest-floor communities. They occupy multiple trophic and functional roles, including predation, detritus processing, herbivory, scavenging and soil-surface foraging. Their assemblages are shaped by microhabitat conditions near the ground surface, where litter depth, litter cover, understory structure, soil moisture and thermal buffering jointly determine shelter availability, resource distribution and movement pathways (Carvalho et al., 2020; Perry et al., 2018; Work et al., 2002). For this reason, ground-active and litter-dwelling arthropods have often been used to characterize forest-floor habitat change and disturbance responses, especially where direct measurements of ecosystem processes are difficult (Nardi et al., 2023; Perry et al., 2018).

Their responses to disturbance, however, are not necessarily expressed as simple increases or decreases in total abundance. Pitfall traps measure activity density, which integrates local abundance and movement activity, rather than absolute population density (Brown and Matthews, 2016; Work et al., 2002). A higher number of captured individuals can therefore reflect increased surface activity or the dominance of a few highly active taxa, rather than a larger or more intact assemblage. Consequently, evaluations of forest-floor arthropod responses should not rely only on total captures or observed richness. Standardized richness, evenness, dominance concentration, species–abundance structure and the identity of dominant taxa are also needed to determine whether higher activity density reflects a broadly distributed assemblage or the concentrated activity of a few dominant groups (Gotelli and Colwell, 2001; Matthews

and Whittaker, 2015; Svensson et al., 2012; van Klink et al., 2024).

Recreational use represents a common but spatially heterogeneous form of disturbance within forest patches. Repeated trampling, trail proximity, edge exposure and frequent human access can alter forest-floor environments by reducing vegetation cover, compacting surface soils, widening trails and modifying fine-scale habitat structure (Ballantyne and Pickering, 2015; Kissling et al., 2009). These effects may occur even when tree, shrub and herb cover do not decline synchronously. For ground-active arthropods, such ground-layer changes are likely to be important because the litter layer provides shelter from desiccation and temperature fluctuation, increases spatial heterogeneity, supplies detrital resources and supports interactions among detritivores, predators, omnivores and surface-active foragers (Ashford et al., 2013; Brousseau et al., 2019; Uetz, 1979; Wang et al., 2023). Thus, litter-layer structure may provide a key interface linking recreational use to arthropod assemblage structure.

Changes in litter quantity or continuity may also be reflected in functional composition. In litter-poor or more exposed sites, assemblages may become biased towards taxa with greater mobility, broader feeding habits or higher tolerance of disturbed ground conditions. By contrast, sites with more continuous litter cover may support more even abundance distributions and greater contributions from detritivore-associated, predator-associated, low-dispersal or larger-bodied taxa. Trait-based approaches are useful in this context because they link taxonomic composition to ecological strategies and can reveal community responses that are not captured by richness alone (Birkhofer et al., 2015; Cadotte et al., 2011; Wong et al., 2019). Feeding

guild, dispersal ability, vertical activity stratum and body size describe how taxa use resources, move through heterogeneous ground-layer habitats and respond to local environmental conditions (Brousseau et al., 2019; Pedley and Dolman, 2014; Rigal et al., 2018; Wong et al., 2019). Nevertheless, these summaries should be interpreted cautiously in community-level observational studies. Feeding guilds do not demonstrate realized trophic links, dispersal categories are often based on taxon-level ecological information and body-size patterns may reflect changes in dominant taxa as well as environmental filtering (Pedley and Dolman, 2014; Wong et al., 2019).

Seasonal turnover adds a further layer of complexity. Arthropod activity, reproduction, dispersal and overwintering behaviour often change markedly across seasons, and these changes can alter both alpha diversity and community composition. Repeated sampling is therefore necessary to distinguish persistent differences among recreational-use categories from temporal variation associated with seasonal transitions. Several responses are possible. Recreational-use categories may differ consistently in activity density and dominance structure across the sampling period. Alternatively, assemblage differences may become more evident during particular seasonal windows if litter-associated microhabitats vary in their buffering capacity. Community composition may also show stronger temporal turnover than average differentiation among use categories (Nardi et al., 2023; Thorn et al., 2020; Uetz, 1979).

Despite increasing interest in arthropod responses to forest disturbance, relatively few studies have integrated activity density, standardized diversity, dominance structure, dominant-taxon composition, functional composition, litter-layer variables and

seasonal turnover within the same recreational-use gradient. This gap limits our ability to determine whether high-use forest-floor habitats support fewer arthropods overall, or whether they support assemblages with higher activity density but stronger dominance concentration and altered functional composition. It also limits the interpretation of recreational-use gradients within large forest patches, where recreational access, litter structure, spatial position and seasonal dynamics may covary. Studies of urban and fragmented systems further suggest that ground arthropod assemblages may show taxonomic and functional shifts under altered habitat structure and isolation, but local forest-floor processes within large forest patches remain less resolved (Piano et al., 2020; Wang et al., 2023; Xu et al., 2024).

To address this gap, we investigated ground-active arthropod assemblages along a recreational-use gradient in Zijin Mountain, Nanjing, eastern China. Zijin Mountain is a large forest patch embedded within a densely urbanized region, but our study was designed as an observational gradient within one forest patch rather than as a landscape-scale urbanization study. We classified nine observation sites into high-use (HRD), moderate-use (MRD) and low-use (LRD) recreational-use categories using a visual interpretation disturbance score based on proximity to roads or recreational trails, proximity to built facilities, exposure to edges or open spaces, and tourist accessibility. We then measured tree, shrub and herb cover, litter cover and litter thickness, and repeatedly sampled ground-active arthropods using pitfall traps from July to December. We therefore interpret the study in terms of associations among recreational-use category, litter-layer structure and arthropod assemblage patterns.

We addressed three main questions. First, do recreational-use categories differ mainly in litter-layer structure rather than broad vegetation cover, and are these habitat differences associated with variation in ground-active arthropod assemblages? We expected HRD sites to have thinner litter and lower litter cover, whereas vegetation-cover variables would show weaker or less consistent differences among categories. Second, do activity density, standardized diversity, evenness, dominance structure, dominant-taxon composition and community composition differ along the recreational-use gradient and across sampling dates? We expected HRD sites to show higher activity density but lower standardized diversity and evenness if pitfall captures were concentrated in a few dominant taxa, and we expected sampling date to contribute strongly to temporal variation in assemblage structure. Third, do feeding-guild composition, dispersal ability, vertical activity strata and community-weighted body size differ among recreational-use categories and align with litter-layer variables? We expected LRD sites with greater litter cover to support more even assemblages, higher contributions from detritivore-associated and predator-associated taxa, lower dominance concentration and larger community-weighted body size.

2. Materials and methods

2.1 Study area and recreational-use classification

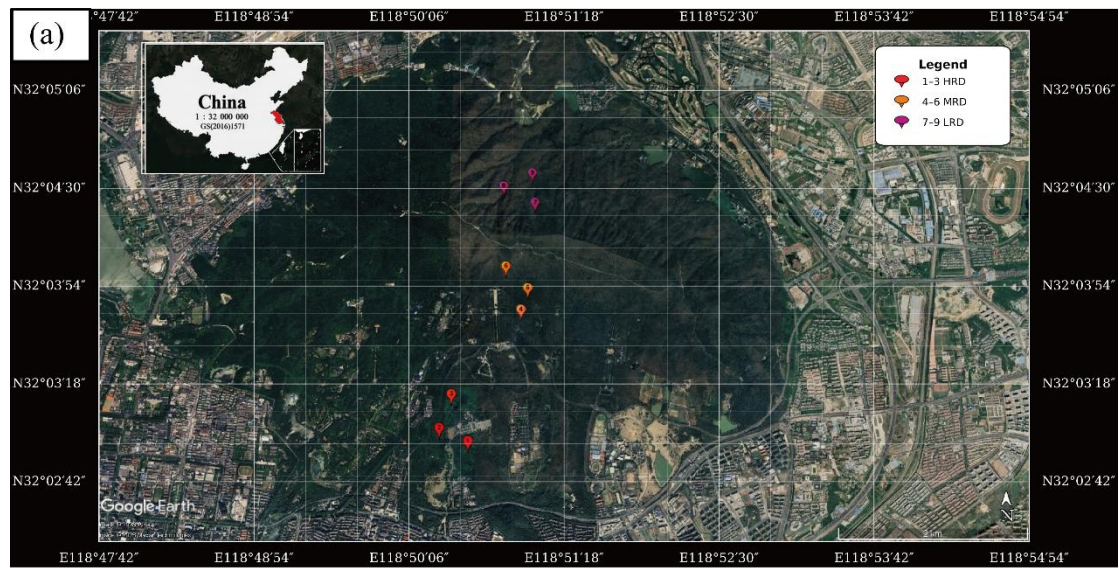
This study was conducted in Zijin Mountain, Nanjing, Jiangsu Province, eastern China. Zijin Mountain is a large forested mountain patch embedded within the urban

landscape of Nanjing. It covers 3,008.8 ha, of which approximately 2,107.6 ha is forested, with a forest canopy closure of 0.75–0.80. The highest peak reaches 448.9 m a.s.l. The area has a mean annual temperature of approximately 15.7 °C, a mean annual precipitation of approximately 1,021 mm and a frost-free period of approximately 237 d. The dominant soil types are yellow-brown soil and yellow-cinnamon soil. The vegetation occurs in the transition zone between warm-temperate deciduous broad-leaved forest and mid-subtropical evergreen broad-leaved forest, with evergreen–deciduous broad-leaved mixed forest representing the zonal vegetation.

We selected nine observation sites within Zijin Mountain to represent an existing gradient of recreational use. Site selection was based on preliminary field reconnaissance, the spatial arrangement of trails and built facilities, accessibility conditions and logistical feasibility. Ground-layer habitat variables were measured independently after site establishment and were not used to classify recreational-use categories or to construct the VIDS. To make the classification of recreational-use intensity transparent and repeatable, we constructed a visual interpretation disturbance score (VIDS) using satellite imagery, site-location information and field reconnaissance. Recreational use and trampling can modify vegetation and soil conditions in frequently visited habitats (Kostrakiewicz-Gierałt et al., 2022), and spatial variables such as roads, built-up environments, infrastructure and human activity intensity are commonly used to characterize anthropogenic disturbance pressure (Ballantyne et al., 2014; Venter et al., 2016; Mu et al., 2022). The VIDS incorporated four components: proximity to visible roads or recreational trails, proximity to scenic buildings or recreational

facilities, exposure to forest edges or open recreational spaces, and tourist accessibility. Each component was scored from 0 to 3, with higher scores indicating greater potential recreational pressure. The four component scores were summed and standardized to a 0–1 scale.

According to the VIDS and field reconnaissance, the nine sites were classified into three recreational-use categories: high-use sites (HRD; sites 1–3), moderate-use sites (MRD; sites 4–6) and low-use sites (LRD; sites 7–9). Sites 1–3 were close to roads, trails or areas with frequent tourist activity, whereas sites 7–9 were farther from major roads and core recreational areas and had lower potential recreational access according to the VIDS. The abbreviations HRD, MRD and LRD are used throughout the manuscript to denote recreational-use categories, not experimentally manipulated disturbance treatments.



(b)

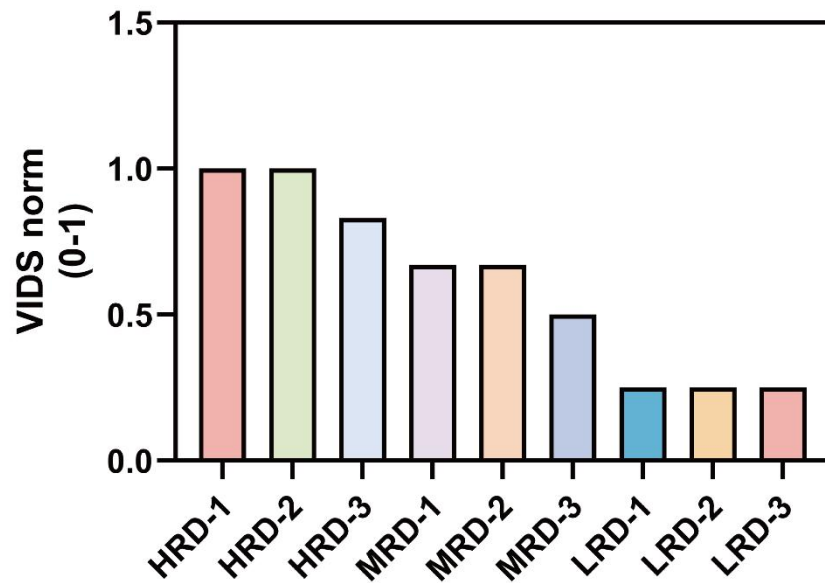


Fig. 1 Spatial distribution of sampling sites and visual interpretation disturbance scores in Zijin Mountain, Nanjing. a, Spatial distribution of the nine observation sites along the recreational-use gradient. Sites 1–3 were assigned to the high-use category (HRD), sites 4–6 to the moderate-use category (MRD), and sites 7–9 to the low-use category (LRD). The basemap was derived from Google Earth. The inset in the upper-left corner shows the location of Jiangsu Province within China. b, Standardized visual interpretation disturbance scores for each observation site (VIDSnorm, 0–1). VIDS was

derived from manual interpretation of satellite imagery and field information and integrated four components: proximity to visible roads or recreational trails, proximity to scenic buildings or recreational facilities, exposure to forest edges or open spaces, and tourist accessibility. Higher values indicate greater potential recreational use.

2.2 Spatial sampling design

Within each recreational-use category, three observation sites were used as independent site-level replicates, resulting in nine observation sites in total. The minimum distance between any two sites was greater than 500 m, and each site covered an area of more than 2 ha. The observation site, rather than the sampling point or individual trap, was treated as the independent spatial replicate for comparisons among recreational-use categories.

Four sampling points were established within each observation site, resulting in 36 sampling points in total. The sampling points were used to characterize within-site heterogeneity in arthropod activity and ground-layer habitat conditions. Adjacent sampling points within the same site were separated by 25 m. To reduce strong local edge effects, sampling points were placed within the interior part of each observation site and more than 100 m from the nearest visible forest edge, road or open recreational space where site geometry allowed.

At each sampling point, five pitfall traps were installed in a cross-shaped arrangement, with one trap placed at the centre and the other four traps placed 1 m from the central trap. Captures from the five traps within each sampling point were pooled before analysis. Thus, pitfall traps were treated as subsamples used to improve capture

precision at the sampling-point scale, not as independent replicates of recreational-use category.

2.3 Collection of ground-active arthropods

Ground-active arthropod assemblages were surveyed using pitfall traps. At each sampling point, five pitfall traps were installed using 450 ml plastic cups as collecting containers. The rim of each cup was level with the soil surface, and drainage holes were made in the upper part of the cup wall to reduce sample loss caused by rainfall. Each trap contained 50 ml of bait solution, prepared from vinegar, sugar, alcohol and water at a mass ratio of 2:1:1:20. Traps were left in the field for 7 d before retrieval. The collected samples were transported to the laboratory and preserved in 75% ethanol.

Arthropod sampling was conducted eight times. After each retrieval, samples were sorted, identified and counted. To ensure comparability among sampling units, a complete community abundance matrix was constructed. The matrix retained all combinations of sampling date, observation site and sampling point, and zero values were assigned to units in which a given taxon was not captured. According to the specific analytical objective, the data were organized into sampling point $\times$ date, site $\times$ date or site-level summary matrices.

2.4 Plant structure and ground-layer habitat survey

To assess the potential effects of plant structure and ground-layer microhabitats on ground-active arthropod assemblages, understory habitat structure was surveyed at each sampling point. Habitat surveys were conducted within a 2 m diameter area centred on the central pitfall trap of each sampling point. Plant structure and litter variables were

recorded simultaneously within each observation site. The measured habitat variables included tree cover, shrub cover, herb cover, litter cover and litter thickness. For each observation site, the values measured at the four sampling points were averaged to obtain site-level habitat-structure metrics, which were then used in subsequent analyses relating habitat structure to arthropod community composition and community-structure metrics.

Univariate differences in plant and litter structure were analysed using site-level data, with three independent observation sites for each recreational-use category. Differences among HRD, MRD and LRD were tested separately for each habitat variable. To describe multivariate changes in plant and litter structure, principal component analysis (PCA) was further performed using standardized plant and litter variables, and the first two principal components were used to visualize multivariate habitat differentiation among recreational-use categories.

2.5 Community alpha diversity and temporal dynamics

For each sampling unit, we calculated activity density, observed taxon richness, Shannon diversity, Pielou's evenness and Berger–Parker dominance for ground-active arthropods. Activity density was calculated as the total number of arthropod individuals captured. Observed taxon richness was defined as the number of taxa captured. Shannon diversity and Pielou's evenness were used to describe taxonomic diversity and the evenness of individual distribution among taxa. Berger–Parker dominance was used to quantify the degree to which the assemblage was dominated by the most abundant taxon.

To evaluate the effects of recreational-use category, sampling date and their interaction on alpha-diversity structure, mixed-effects models were fitted. Activity density and observed taxon richness were count response variables and were analysed using generalized linear mixed models. Shannon diversity, Pielou's evenness and Berger–Parker dominance were continuous response variables and were analysed using linear mixed models. Category, Date and the Category $\times$ Date interaction were included as fixed effects, and sampling points nested within observation sites were included as random effects to account for repeated sampling and spatial nesting. Model significance was assessed using likelihood-ratio tests or Wald χ^2 tests.

In the temporal dynamic plots, each point represents the site-level mean for a given recreational-use category on a given sampling date, and error bars represent the standard error among the three independent observation sites within the same recreational-use category. Lines were used to show the temporal trajectory of each recreational-use category across the eight sampling dates.

2.6 Community ordination, PERMANOVA and dispersion analysis

To examine variation in community composition across recreational-use categories and sampling dates, the site $\times$ date community abundance matrix was first square-root transformed to reduce the influence of extremely dominant taxa on distance calculations. Bray–Curtis dissimilarities were then calculated among samples, and non-metric multidimensional scaling (NMDS) was used for visualization. In the NMDS ordination, each point represents one site $\times$ date community sample, colours indicate recreational-use categories, ellipses represent standard or confidence ellipses for each

recreational-use category, and diamonds represent the category-level community centroids.

To test whether community composition was associated with recreational-use category, sampling date and their interaction, PERMANOVA was performed on the Bray–Curtis dissimilarity matrix derived from square-root-transformed abundance data. The model included Category, Date and Category $\times$ Date. Because PERMANOVA results can be influenced by differences in within-group dispersion, betadisper analysis was further used to calculate the distance of samples to their group centroids and to test whether multivariate dispersion differed among recreational-use categories. PERMANOVA and betadisper results were interpreted jointly to determine whether compositional differences reflected centroid differentiation rather than changes in within-group variability alone.

In addition, to visualize temporal shifts in community composition, community centroids were calculated in the NMDS coordinate space for each Date $\times$ Category combination and were connected in chronological order. Arrows indicate the direction of temporal change. This analysis was used to assess whether community trajectories over the half-year sampling period were consistent among recreational-use categories.

2.7 Dominance structure and dominant-taxon composition

To examine the dominance structure of ground-active arthropod assemblages under different recreational-use categories, arthropod abundances were first pooled across all observation sites, sampling dates and sampling points within each recreational-use category. Taxa were then ranked in descending order according to their

total abundance, and rank–abundance curves were constructed.

$$RA_{gk} = A_{gk} / \sum_{k=1}^K A_{gk} \times 100$$

where A_{gk} is the total abundance of taxon k in recreational-use category g , and $\sum_{k=1}^K A_{gk}$ is the total abundance of all taxa within that recreational-use category.

To visualize the composition of dominant taxa, the 15 taxa with the highest total abundance across all samples were selected, and their relative abundances in HRD, MRD and LRD were calculated and displayed as a heatmap. In addition, the 10 most abundant taxa were used to generate a stacked composition plot, with all remaining taxa pooled as “Others”.

To avoid the absence of error estimation caused by simple aggregation at the recreational-use category scale, the cumulative contributions of the Top 1, Top 3 and Top 5 dominant taxa were calculated at the observation-site level. For each observation site, arthropod abundances were first pooled across all sampling dates and sampling points. Taxa were then ranked in descending order according to their abundance, and the proportional contribution of the 1, 3 and 5 most abundant taxa to the total number of individuals at that site was calculated as:

$$C_{s,m} = \sum_{r=1}^m as(r) / \sum_{k=1}^K ask \times 100, \quad m = 1, 3, 5$$

where $as(r)$ is the abundance of the taxon ranked r at observation site s , and $\sum_{k=1}^K ask$ is the total abundance of all taxa at that site. Three independent observation-site values were retained for each recreational-use category. Differences among recreational-use categories were tested using exact permutation ANOVA, with the Kruskal–Wallis test used as a sensitivity analysis.

2.8 Functional composition, dispersal ability, vertical activity strata and community-

weighted body size

To assess whether functional structure differed among recreational-use categories, taxa were assigned to functional categories based on ecological function and trait information. Feeding guilds were classified as primary consumers, detritivore-associated taxa, predator-associated taxa, omnivores, parasitoids and others. For each recreational-use category, the relative abundance of each feeding guild was calculated as the total abundance of that guild divided by the total abundance of all arthropods within the corresponding recreational-use category. The classification scheme covered all 62 arthropod taxa included in the main analysis; therefore, the category “Others” had a value of zero in this study.

Dispersal ability was classified into three categories according to taxon-level activity and mobility: low dispersal, intermediate dispersal and high dispersal. Vertical activity strata were classified according to the main activity space of each taxon, including ground-dwelling or surface-active, ground–vegetation interface, vegetation-associated, soil-associated and arboreal-associated taxa. The relative abundances of these categories were calculated at the recreational-use category scale and visualized using stacked bar plots.

To further evaluate the overall body-size structure of the assemblage, we calculated community-weighted mean body length (CWM body length). CWM body length was calculated at the observation-site level, with all sampling dates and sampling points pooled within each site before analysis. It was calculated as:

$$\text{CWMs} = \sum_{k=1}^K \text{psk} \times \text{Lk}$$

where psk is the relative abundance of taxon k at observation site s , and Lk the

mean body length of that taxon. Each recreational-use category contained three observation-site values. Differences in CWM body length among recreational-use categories were tested using one-way ANOVA, followed by Tukey's HSD test for multiple comparisons. Because each recreational-use category contained only three independent observation sites, the observation site was treated as the statistical unit when interpreting CWM body length, and neither sampling points nor individual pitfall traps were treated as independent replicates.

2.9 Correlations between habitat variables and community-structure metrics

To further link habitat context with community-structure responses, correlations were calculated between recreational-use intensity, plant/litter variables and arthropod community-structure metrics. The explanatory variables included VIDSnorm, litter thickness, litter cover, tree cover, shrub cover, herb cover and plant habitat PC1. The response metrics included activity density, Shannon diversity, Pielou's evenness, Berger-Parker dominance, Top 5 contribution, omnivore proportion, high-dispersal proportion and CWM body length.

Correlation results were displayed using a heatmap, in which colours indicate the direction and strength of correlations, and values within cells indicate correlation coefficients. Significance marks were used to indicate different significance levels. This analysis was used to identify which habitat variables showed consistent associations with changes in diversity, evenness, dominance concentration, functional composition and body-size structure.

In addition, to visualize the relationships between litter structure and selected

community-structure metrics, scatterplot regressions were performed for litter thickness against Pielou's evenness and Berger–Parker dominance. Points represent site $\times$ date samples, colours indicate recreational-use categories, and an overall linear regression line was fitted to show the general association across all samples. Shaded areas indicate 95% confidence intervals. This analysis was used only to characterize statistical associations between habitat variables and community-structure metrics, rather than to support strict causal inference.

2.10 Figure preparation and data output

All figures were generated using cleaned empirical data. Composition plots, point plots, heatmaps, ordination plots and variation-partitioning plots were produced in Python and exported as 600 dpi PNG, 600 dpi TIFF and vector PDF files. Statistical outputs, figure-input data and intermediate calculation tables were retained as Excel or CSV files for supplementary materials and result verification. Statistical significance was shown only when the corresponding statistical test had been performed. Descriptive composition plots were not annotated with significance marks to avoid interpreting proportional differences as statistically tested differences. All statistical analyses were performed in R, whereas final figure rendering was conducted in Python.

3. Results

3.1 Recreational-use categories differed mainly in litter-layer structure rather than broad vegetation cover

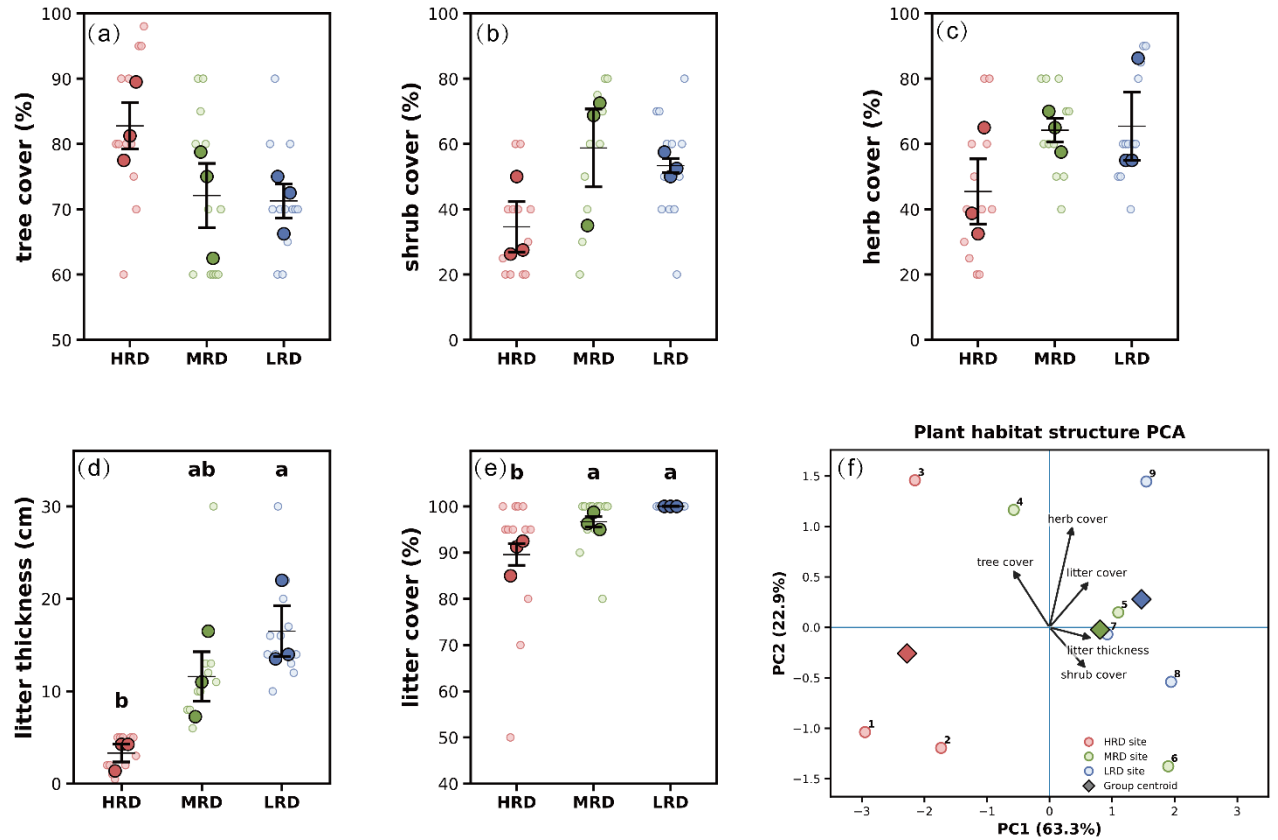


Fig. 2 Plant and litter habitat structure under different recreational-use categories in Zijin Mountain, Nanjing. a–f, Tree cover (a), shrub cover (b), herb cover (c), litter thickness (d), litter cover (e) and PCA ordination of plant and litter habitat structure (f) across high-use (HRD), moderate-use (MRD) and low-use (LRD) sites. In a–e, pale open circles show raw sampling-point-level values, dark filled circles show site-level means, and error bars indicate s.e.m. based on three independent sites per category. Different letters denote significant differences among categories ($P < 0.05$). In f, points represent independent sites, diamonds represent group centroids, and arrows show the loading directions of habitat variables on the first two PCA axes.

Recreational-use categories differed mainly in litter-layer structure. They did not show a synchronous decline in tree, shrub and herb cover. One-way ANOVA based on site-level means showed no significant differences among HRD, MRD and LRD sites

in tree cover ($F = 2.838$, $P = 0.1357$; Fig. 2a), shrub cover ($F = 2.335$, $P = 0.1778$; Fig. 2b) or herb cover ($F = 1.705$, $P = 0.2592$; Fig. 2c). Tree cover tended to be higher in HRD sites, whereas shrub cover tended to be lower in HRD than in MRD and LRD sites, but neither pattern was statistically significant.

By contrast, litter-layer variables differed significantly among recreational-use categories. Litter thickness increased along the sequence $HRD < MRD < LRD$ ($F = 8.506$, $P = 0.0177$; Fig. 2d). Tukey's HSD test showed that litter thickness was significantly higher in LRD than in HRD sites ($P = 0.0153$), whereas MRD did not differ significantly from either HRD or LRD. Litter cover also differed significantly among categories ($F = 12.868$, $P = 0.0068$; Fig. 2e). HRD sites had lower litter cover than both MRD ($P = 0.0344$) and LRD sites ($P = 0.0061$), while MRD and LRD did not differ significantly ($P = 0.3199$).

The PCA showed a similar pattern of habitat differentiation (Fig. 2f). PC1 and PC2 explained 63.3% and 22.9% of the total variation, respectively, together accounting for 86.2% of the variation in plant and litter habitat structure. HRD sites were mainly positioned on the negative side of PC1, whereas MRD and LRD sites were generally shifted towards the positive side. The positive direction of PC1 was associated mainly with litter thickness, litter cover and shrub cover, whereas tree cover was oriented towards the negative side of PC1. Thus, habitat differences among recreational-use categories were expressed primarily as thinner litter and lower litter cover in HRD sites, rather than as broad vegetation-cover change.

3.2 High-use sites had higher activity density but lower standardized diversity and

evenness

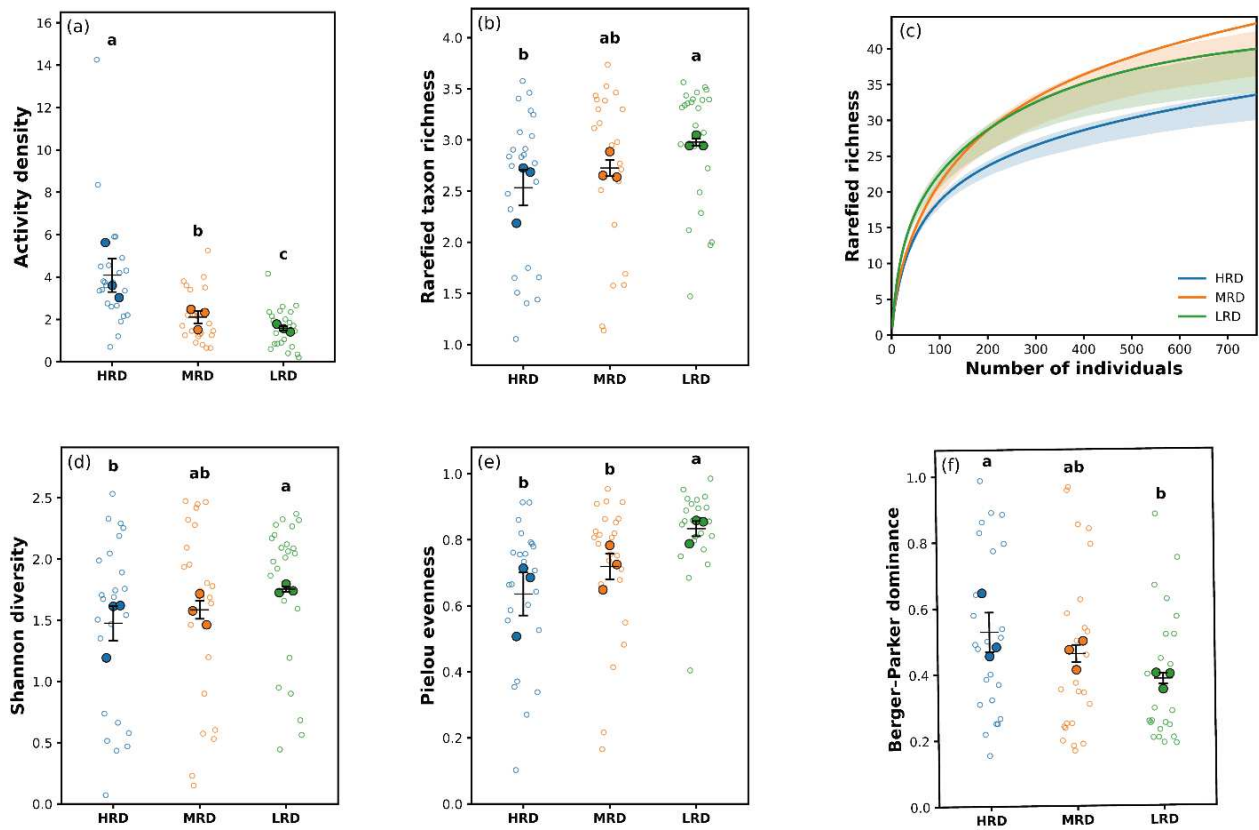


Fig.3 Alpha-diversity responses of ground-active arthropods across recreational-use categories. a–f, Activity density (a), rarefied taxon richness (b), individual-based rarefaction curves (c), Shannon diversity (d), Pielou’s evenness (e) and Berger–Parker dominance (f) across high-use (HRD), moderate-use (MRD) and low-use (LRD) sites. In a, b and d–f, pale open circles show observation-site $\times$ sampling-date means, dark filled circles show observation-site means averaged across sampling dates, and error bars indicate s.e.m. based on three independent observation sites per category. Different letters denote significant pairwise differences among categories based on estimated marginal means. Activity density was analysed using a negative binomial generalized linear mixed model; rarefied taxon richness and Shannon diversity were analysed using linear mixed models; and Pielou’s evenness and Berger–Parker dominance were

analysed using linear mixed models after logit transformation. Recreational-use category was included as a fixed effect, while sampling date and spatial nesting were controlled for. In c, curves represent individual-based rarefaction based on pooled abundance data for each recreational-use category, and shaded areas indicate 95% bootstrap quantile intervals.

Activity density and alpha-diversity metrics differed in contrasting directions among recreational-use categories. Activity density differed significantly among HRD, MRD and LRD sites (Wald $\chi^2 = 50.010$, $P < 0.0001$; Fig. 3a). HRD sites had the highest activity density, followed by MRD and LRD sites, with all pairwise comparisons being significant. Thus, HRD sites did not show reduced pitfall captures; they showed the highest activity density per sampling unit.

However, higher activity density did not correspond to higher standardized richness. Rarefied taxon richness differed significantly among recreational-use categories (Wald $\chi^2 = 11.940$, $P = 0.0026$; Fig. 3b). LRD sites had significantly higher rarefied taxon richness than HRD sites, whereas MRD sites were intermediate and did not differ significantly from either HRD or LRD. Individual-based rarefaction curves showed the same pattern: at a common number of individuals, rarefied richness in HRD was generally lower than that in MRD and LRD (Fig. 3c). Because HRD had more captured individuals, rarefaction was needed to compare richness at a standardized abundance level.

Shannon diversity also differed significantly among recreational-use categories (Wald $\chi^2 = 6.833$, $P = 0.0328$; Fig. 3d). LRD sites had significantly higher Shannon

diversity than HRD sites, whereas MRD sites were intermediate. Pielou's evenness showed a similar direction of change. It was highest in LRD sites and was significantly higher there than in both HRD and MRD sites (Wald $\chi^2 = 17.535$, $P = 0.0002$; Fig. 3e). These results show that the higher activity density in HRD was not accompanied by a more even distribution of individuals among taxa.

Berger–Parker dominance showed the opposite pattern to Pielou's evenness. It was highest in HRD sites and lowest in LRD sites, with HRD being significantly higher than LRD (Wald $\chi^2 = 8.479$, $P = 0.0144$; Fig. 3f). Overall, HRD sites combined high activity density with lower rarefied richness, lower Shannon diversity, lower Pielou's evenness and higher Berger–Parker dominance. By contrast, LRD sites had lower activity density but higher standardized richness, diversity and evenness, together with lower dominance. This contrast provided the basis for the rank–abundance and dominant-taxon analyses presented below.

3.3 Dominance concentration was mainly associated with Formicidae in high-use sites

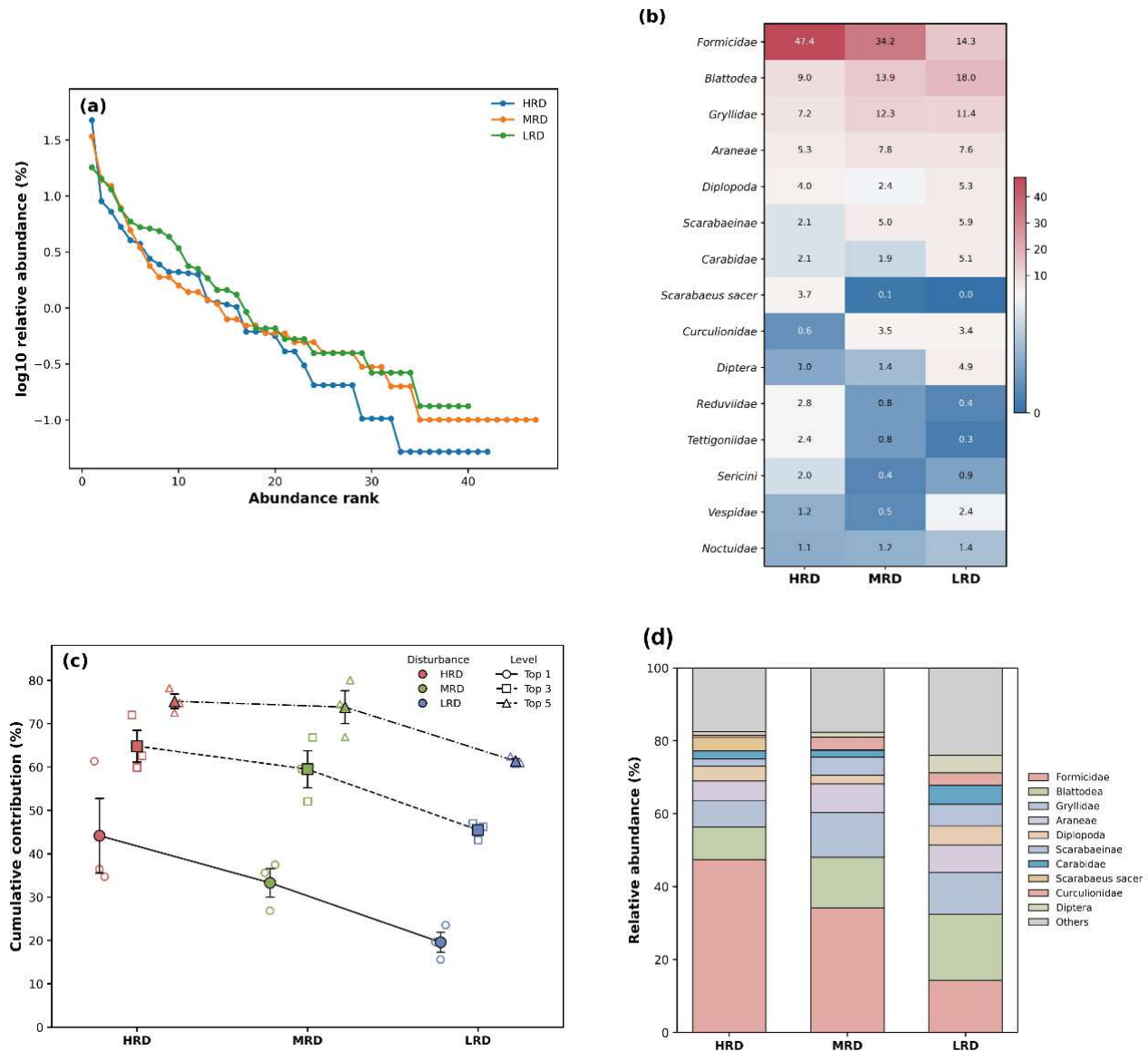


Fig. 4 Species–abundance structure and dominant-taxon composition among recreational-use categories. a–d, Rank–abundance curves (a), heatmap of the 15 most abundant taxa (b), cumulative contributions of the Top 1, Top 3 and Top 5 dominant taxa at the site level (c) and relative-abundance composition of the 10 most abundant taxa (d) across high-use (HRD), moderate-use (MRD) and low-use (LRD) sites. In a, abundances were pooled within each recreational-use category, taxa were ranked by total abundance, and the y axis shows $\log_{10}(\text{relative abundance (\%)} + 0.001)$. In b, cell values indicate relative abundance (%). In c, open circles show independent sites, and

filled circles and error bars show means $\pm$ s.e.m. based on three sites per category. In d, taxa outside the top 10 were pooled as “Others”.

The taxon–abundance structure differed among recreational-use categories. The HRD rank–abundance curve had a higher front end and declined more steeply than the LRD curve (Fig. 4a). By contrast, the LRD curve was flatter. This pattern was consistent with the lower Pielou’s evenness and higher Berger–Parker dominance observed in HRD sites, and indicated that individuals in HRD were concentrated in fewer dominant taxa.

Dominant-taxon composition showed the same contrast (Fig. 4b,d). Formicidae was the most abundant group in HRD, accounting for 47.45% of total abundance. Its relative abundance declined to 34.19% in MRD and 14.34% in LRD. By contrast, Blattodea reached its highest relative abundance in LRD (18.03%), compared with 13.90% in MRD and 8.98% in HRD. Gryllidae also contributed more in MRD (12.29%) and LRD (11.45%) than in HRD (7.21%). Araneae showed a similar but weaker pattern, increasing from 5.31% in HRD to 7.80% in MRD and 7.63% in LRD. Several other taxa, including Carabidae, Diptera and Scarabaeinae, also made greater relative contributions in LRD than in HRD.

Site-level dominance metrics supported this pattern (Fig. 4c). The Top 1 contribution was highest in HRD ($44.17 \pm 8.60\%$) and lowest in LRD ($19.60 \pm 2.30\%$). The same direction was observed for the Top 3 and Top 5 contributions, which were higher in HRD and MRD than in LRD. Permutation ANOVA detected significant differences among recreational-use categories for Top 1 ($F = 5.06$, $P = 0.018$), Top 3 (F

= 9.08, $P = 0.018$) and Top 5 contributions ($F = 9.97$, $P = 0.029$). Kruskal–Wallis tests showed the same direction but weaker statistical support. Overall, the higher activity density in HRD was expressed mainly as stronger Formicidae dominance, whereas LRD had a more distributed abundance structure involving multiple dominant and intermediate-abundance taxa.

3.4 Alpha-diversity metrics showed strong temporal variation across the sampling period

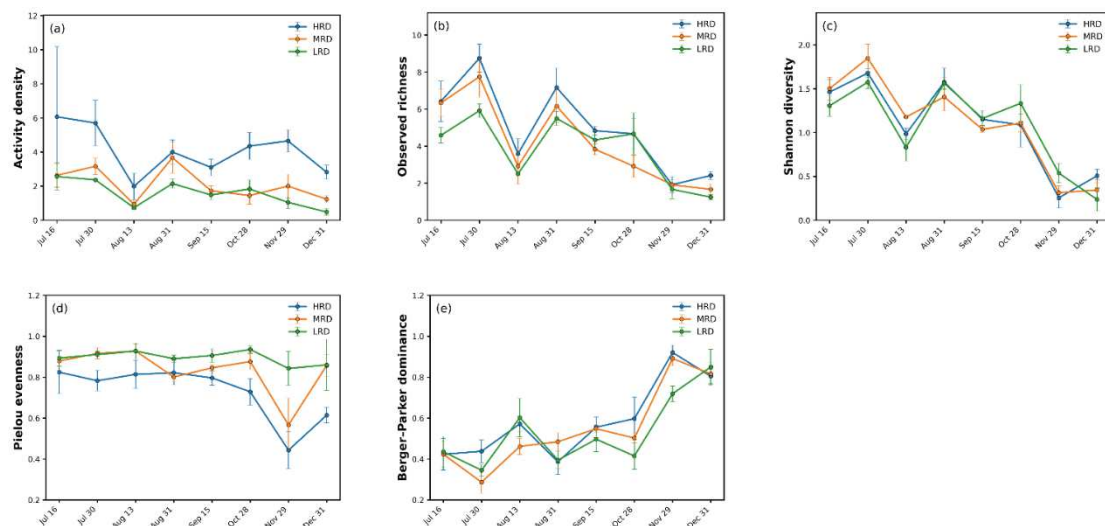


Fig. 5 Temporal dynamics of activity density, alpha diversity and dominance structure of ground-active arthropods. a–e, Temporal variation in activity density (a), observed taxon richness (b), Shannon diversity (c), Pielou’s evenness (d) and Berger–Parker dominance (e) across eight sampling occasions from July to December in high-use (HRD), moderate-use (MRD) and low-use (LRD) sites. Points represent mean values of the three independent observation sites within each recreational-use category on each sampling date, error bars indicate s.e.m., and lines show temporal trajectories. Effects of recreational-use category, sampling date and their interaction were tested

using mixed-effects models that accounted for the spatially nested sampling structure.

Alpha-diversity and dominance metrics varied markedly across the July–December sampling period. Activity density, observed taxon richness and Shannon diversity were generally higher during the summer sampling dates and declined towards late autumn and early winter (Fig. 5a–c). By contrast, Berger–Parker dominance tended to increase during the later sampling dates (Fig. 5e). Pielou’s evenness also varied through time, but its temporal trajectories differed more clearly among recreational-use categories than those of observed richness and Shannon diversity (Fig. 5d).

Mixed-effects models confirmed significant date effects for all five metrics. Activity density was affected by both recreational-use category and sampling date, but not by their interaction (Category: Wald $\chi^2 = 7.371$, $P = 0.0251$; Date: Wald $\chi^2 = 25.028$, $P = 0.0008$; Category $\times$ Date: Wald $\chi^2 = 20.370$, $P = 0.1189$). Thus, activity density differed among categories and changed through time, but did not show a significant category-dependent temporal trajectory.

Observed taxon richness and Shannon diversity were associated mainly with sampling date. Date had significant effects on observed richness (Wald $\chi^2 = 86.035$, $P < 0.0001$) and Shannon diversity (Wald $\chi^2 = 118.760$, $P < 0.0001$), whereas neither recreational-use category nor Category $\times$ Date was significant for either metric. These results indicate that temporal variation in observed richness and Shannon diversity was stronger than the average difference among recreational-use categories.

Pielou’s evenness and Berger–Parker dominance showed a different pattern. For Pielou’s evenness, sampling date and Category $\times$ Date were significant (Date: Wald χ^2

= 67.332, $P < 0.0001$; Category $\times$ Date: Wald $\chi^2 = 27.508$, $P = 0.0165$), whereas the main effect of recreational-use category was not significant (Wald $\chi^2 = 1.076$, $P = 0.5839$). Berger–Parker dominance showed the same statistical structure, with significant effects of Date and Category $\times$ Date (Date: Wald $\chi^2 = 96.742$, $P < 0.0001$; Category $\times$ Date: Wald $\chi^2 = 24.083$, $P = 0.0448$), but no significant main effect of category (Wald $\chi^2 = 0.026$, $P = 0.9873$). Overall, temporal turnover was a prominent component of alpha-diversity variation, while recreational-use categories differed most consistently in activity density and in the seasonal trajectories of evenness and dominance.

3.5 Community composition showed moderate differentiation among recreational-use categories and strong seasonal turnover

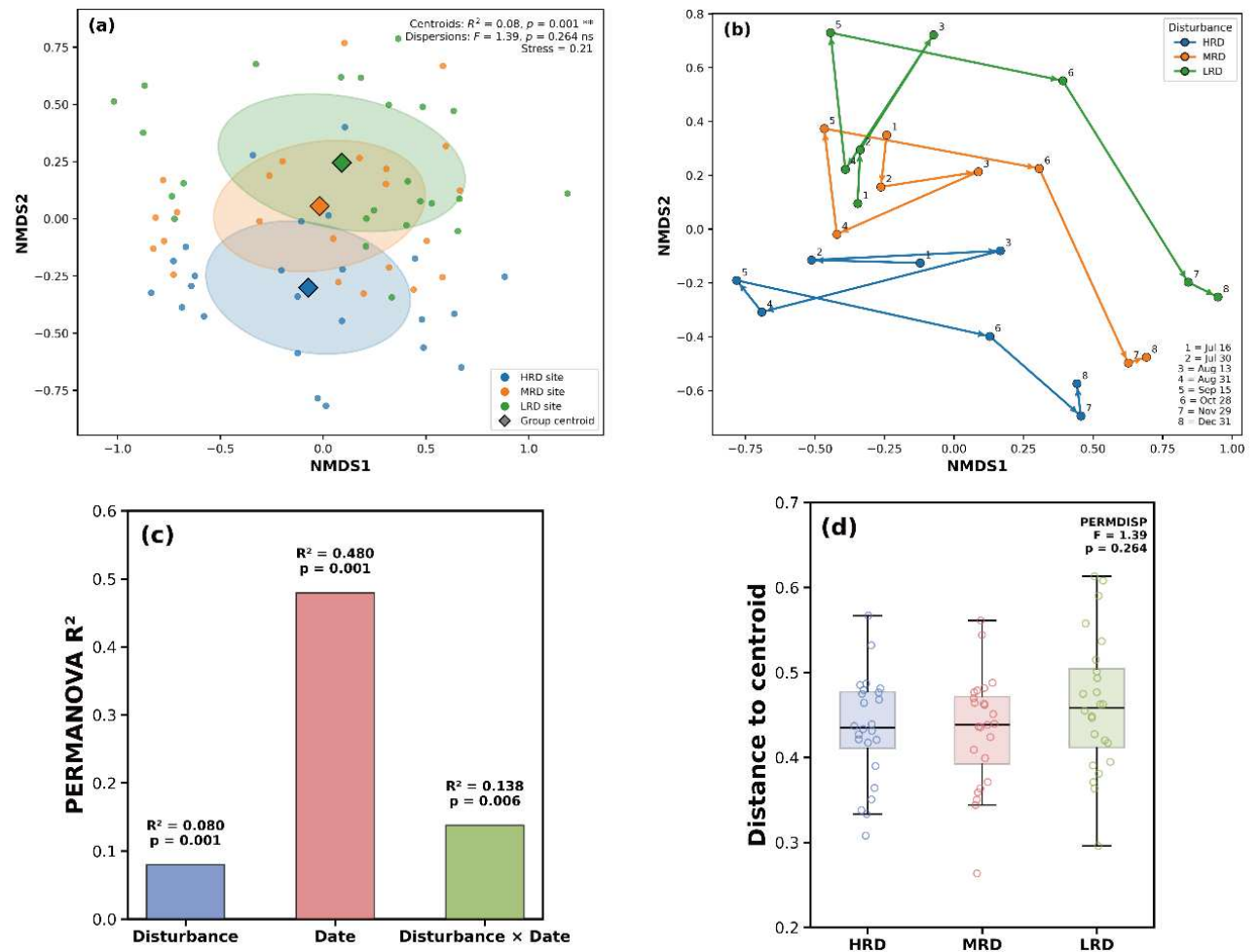


Fig. 6 Community composition of ground-active arthropods across recreational-use categories and sampling dates. a–d, NMDS ordination based on square-root-transformed abundance data and Bray–Curtis dissimilarity (a), temporal centroid trajectories in NMDS space (b), PERMANOVA R^2 values for community compositional variation (c) and within-group multivariate dispersion based on betadisper / PERMDISP (d) across high-use (HRD), moderate-use (MRD) and low-use (LRD) sites. In a, points represent site × date samples, colours indicate recreational-use categories, ellipses show standard ellipses, and diamonds indicate category-level centroids. NMDS stress = 0.212. In b, numbers indicate sampling-date order, and lines show temporal trajectories from July to December. In c, bars show the variation

explained by recreational-use category, sampling date and their interaction. In d, values represent the distance of each site $\times$ date sample to its recreational-use category centroid.

Ground-active arthropod community composition differed among recreational-use categories and changed substantially across sampling dates (Fig. 6a,b). In the NMDS ordination, HRD, MRD and LRD samples occupied partly different regions of ordination space, with category centroids separated along the main compositional gradients (Fig. 6a). Temporal centroid trajectories further showed that assemblages shifted from July to December in all three recreational-use categories, but the direction and magnitude of these shifts differed among HRD, MRD and LRD sites (Fig. 6b).

PERMANOVA confirmed significant compositional differences among recreational-use categories. Recreational-use category explained 8.0% of the total variation in community composition ($R^2 = 0.080$, $F = 6.301$, $P = 0.001$; Fig. 6c). Sampling date explained a larger fraction of compositional variation ($R^2 = 0.480$, $F = 10.841$, $P = 0.001$), indicating pronounced seasonal turnover across the July–December sampling period. The interaction between recreational-use category and sampling date was also significant ($R^2 = 0.138$, $F = 1.555$, $P = 0.006$), showing that seasonal compositional trajectories differed among recreational-use categories.

The site-blocked PERMANOVA sensitivity analysis produced the same pattern of significance, with recreational-use category, sampling date and their interaction all remaining significant. Multivariate dispersion did not differ significantly among categories (PERMDISP: $F = 1.386$, $P = 0.264$; Fig. 6d), indicating that the compositional differences detected by PERMANOVA were not attributable to

differences in within-category dispersion. Overall, community composition varied consistently with both recreational-use category and sampling date, with seasonal turnover accounting for the largest share of explained compositional variation.

3.6 Functional composition and body-size structure differed along the recreational-use gradient

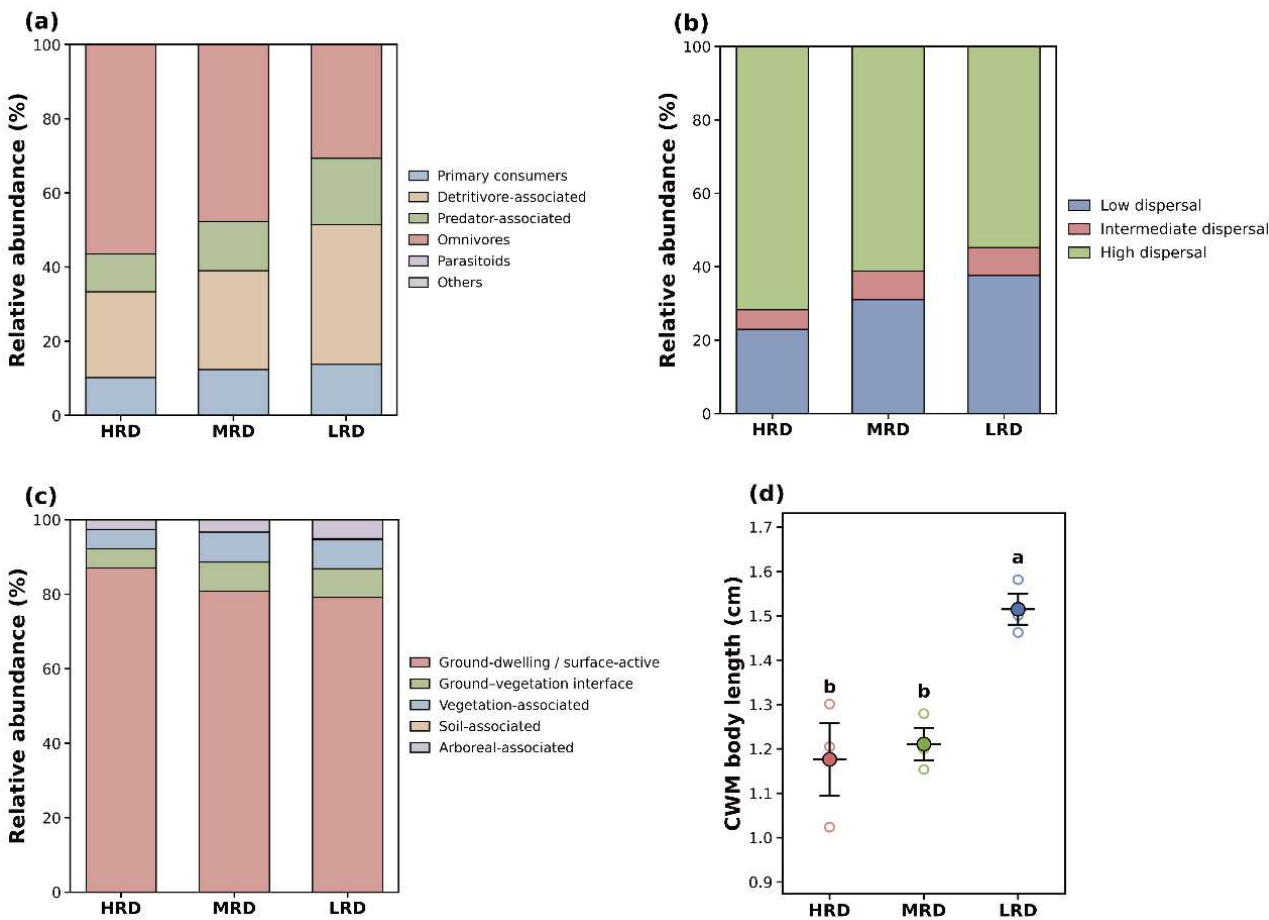


Fig. 7 Functional composition, dispersal ability, vertical activity strata and community-weighted body-size structure of ground-active arthropods across recreational-use categories. a–d, Relative-abundance composition of trophic functional groups (a), dispersal-ability categories (b), vertical activity strata (c) and community-weighted mean body length (d) across high-use (HRD), moderate-use (MRD) and low-

use (LRD) sites. In a, taxa were assigned to primary consumers, detritivore-associated taxa, predator-associated taxa, omnivores, parasitoids and others according to their dominant or mixed feeding habits. These categories represent feeding guilds or trophic functional groups, rather than strict trophic levels. In b, taxa were classified as low-, intermediate- or high-dispersal taxa. In c, taxa were classified according to their main vertical activity strata, including ground-dwelling or surface-active, ground–vegetation interface, vegetation-associated, soil-associated and arboreal-associated taxa. In d, community-weighted mean body length was calculated at the observation-site level, with all sampling dates and sampling points pooled within each site as one independent replicate. Open circles represent independent observation sites, and filled circles and error bars show means $\pm$ s.e.m. based on three observation sites per category. Different letters denote significant differences based on Tukey's HSD test.

Functional composition differed among recreational-use categories. Omnivores accounted for the largest proportion of the assemblage in HRD sites, reaching 56.38% of total abundance (Fig. 7a). This proportion declined to 47.67% in MRD and 30.66% in LRD. By contrast, detritivore-associated taxa increased from 23.16% in HRD to 26.66% in MRD and 37.63% in LRD. Predator-associated taxa showed the same direction, increasing from 10.20% in HRD to 13.28% in MRD and 17.89% in LRD. Primary consumers varied only slightly among categories, whereas parasitoids contributed little to the assemblage.

Dispersal-ability composition showed a parallel contrast (Fig. 7b). High-dispersal taxa accounted for 71.73% of total abundance in HRD, but decreased to 61.15% in

MRD and 54.74% in LRD. By contrast, low-dispersal taxa increased from 22.96% in HRD to 37.63% in LRD. Thus, HRD assemblages were characterized by a greater relative contribution of high-dispersal taxa, whereas LRD assemblages contained a larger contribution from low-dispersal taxa.

Vertical activity strata were dominated by ground-dwelling or surface-active taxa in all recreational-use categories (Fig. 7c). This group accounted for 86.94% of total abundance in HRD, 80.77% in MRD and 79.21% in LRD. Other strata contributed smaller proportions, but their relative contributions were generally higher in LRD than in HRD. Vegetation-associated taxa accounted for 5.15% of total abundance in HRD, 8.03% in MRD and 7.76% in LRD. Arboreal-associated taxa increased from 2.60% in HRD to 3.37% in MRD and 5.00% in LRD. Soil-associated taxa were absent from HRD and MRD samples and contributed 0.39% in LRD.

Community-weighted mean body length also differed significantly among recreational-use categories (Fig. 7d). LRD had the highest CWM body length (1.515 ± 0.035 cm), followed by MRD (1.211 ± 0.037 cm), whereas HRD had the lowest value (1.176 ± 0.081 cm). One-way ANOVA showed a significant category effect on CWM body length ($F = 11.312$, $P = 0.0092$). Tukey's HSD test indicated that CWM body length was significantly higher in LRD than in HRD ($P = 0.0118$) and MRD ($P = 0.0191$), whereas HRD and MRD did not differ significantly ($P = 0.8997$).

Overall, HRD assemblages had higher proportions of omnivorous and high-dispersal taxa, together with lower community-weighted body length. By contrast, LRD assemblages had higher proportions of detritivore-associated, predator-associated and

low-dispersal taxa, together with larger community-weighted body length. These patterns show that differences among recreational-use categories extended beyond taxon identity and dominance structure to functional composition and body-size structure.

3.7 Litter cover showed consistent associations with diversity, dominance and trait metrics

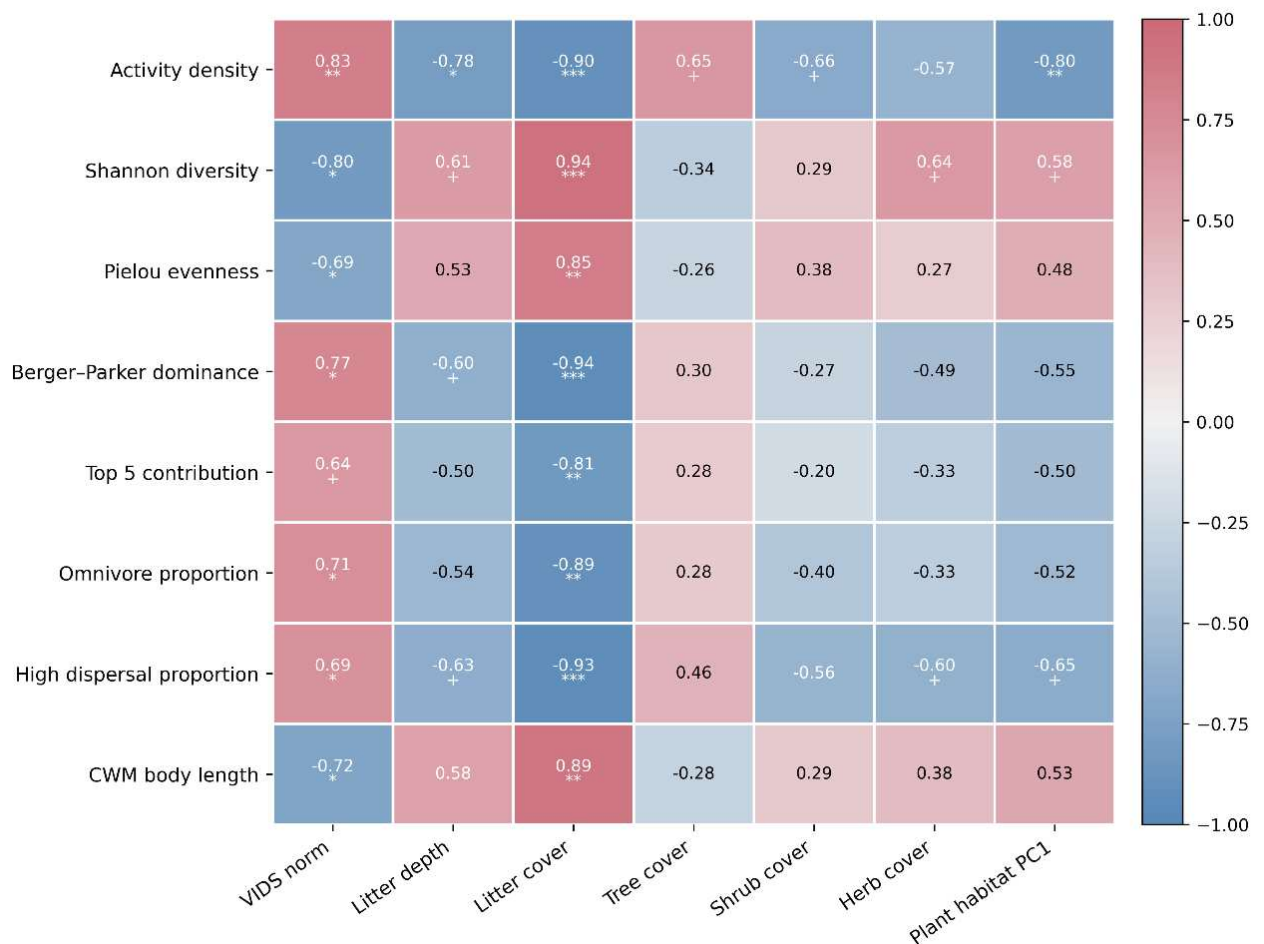


Fig. 8 Correlations between recreational-use intensity, habitat variables and community-structure metrics of ground-active arthropods. Colours indicate the direction and strength of correlations, with red denoting positive correlations and blue

denoting negative correlations ($n = 9$). Values within cells show correlation coefficients. Community-structure metrics include activity density, Shannon diversity, Pielou's evenness, Berger–Parker dominance, Top 5 contribution, omnivore proportion, high-dispersal proportion and community-weighted mean body length. Explanatory variables include VIDSnorm, litter thickness, litter cover, tree cover, shrub cover, herb cover and plant habitat PC1. Significance levels are indicated as + $P < 0.10$, * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$. VIDSnorm denotes standardized recreational-use intensity, and plant habitat PC1 denotes the primary composite axis of plant and litter habitat structure.

Recreational-use intensity and litter cover showed opposite correlation patterns with community-structure metrics. VIDSnorm was positively correlated with activity density ($r = 0.83$) and showed positive associations with Berger–Parker dominance, Top 5 contribution, omnivore proportion and high-dispersal proportion (Fig. 8). By contrast, VIDSnorm was negatively correlated with Shannon diversity ($r = -0.80$), Pielou's evenness ($r = -0.69$) and CWM body length ($r = -0.72$). These correlations were consistent with the preceding results showing that HRD sites had higher activity density, stronger dominance and lower community-weighted body size.

Litter cover showed the reverse pattern. It was positively correlated with Shannon diversity ($r = 0.94$), Pielou's evenness ($r = 0.85$) and CWM body length ($r = 0.89$), but negatively correlated with activity density ($r = -0.90$), Berger–Parker dominance ($r = -0.94$), Top 5 contribution ($r = -0.81$), omnivore proportion ($r = -0.89$) and high-dispersal proportion ($r = -0.93$). Thus, sites with greater litter cover tended to have

more diverse and more even assemblages, larger community-weighted body length and weaker dominance concentration.

In addition, litter thickness showed broadly similar but weaker associations with most community metrics. Tree, shrub and herb cover showed weaker and less consistent relationships with community-structure metrics than the litter variables. Plant habitat PC1 was negatively correlated with activity density ($r = -0.80$) and showed positive associations with Shannon diversity, Pielou's evenness and CWM body length.

4. Discussion

This study showed a clear but non-linear assemblage response along the recreational-use gradient. HRD sites had higher activity density, but lower rarefied taxon richness, Shannon diversity and Pielou's evenness, together with higher Berger-Parker dominance. These patterns were accompanied by thinner litter, lower litter cover, stronger dominance concentration, higher relative abundance of omnivorous and high-dispersal taxa, and lower community-weighted body length. Community composition also differed among HRD, MRD and LRD sites, although sampling date explained a larger fraction of compositional variation than recreational-use category. Together, these results indicate that the main response of ground-active arthropods was not a uniform decline in total captures, but a shift in dominance structure, dominant-taxon composition, litter-associated habitat context, functional composition and seasonal trajectory.

The contrast between high activity density and lower standardized diversity is

central to this interpretation. Pitfall traps measure activity density rather than absolute population density, because captures depend on both local abundance and movement activity (Brown and Matthews, 2016; Spence and Niemelä, 1994; Work et al., 2002). Thus, high trap catches in HRD sites should not be interpreted as evidence for a larger or more intact assemblage. The rarefaction results showed that, at a comparable number of individuals, HRD sites had lower taxon richness than LRD sites. In addition, the lower Shannon diversity and Pielou's evenness, together with higher Berger–Parker dominance, showed that individuals were distributed less evenly among taxa in HRD. This explains why total capture abundance and assemblage evenness moved in opposite directions. It also reinforces the need to examine multiple components of biodiversity rather than relying only on total captures or observed richness (Gotelli and Colwell, 2001; Svensson et al., 2012). The rank–abundance curves and dominance-contribution metrics further showed that high activity density in HRD was associated with a steeper abundance hierarchy rather than a broad increase across many taxa. Species–abundance structure is therefore not an accessory result in this study; it is necessary for understanding why high capture abundance and low evenness occurred together (Matthews and Whittaker, 2015; van Klink et al., 2024).

The biological basis of this pattern was mainly related to dominant-taxon composition. Formicidae accounted for nearly half of the total abundance in HRD, whereas its relative contribution declined markedly in MRD and LRD. By contrast, LRD had greater relative contributions from Blattodea, Gryllidae, Araneae and several intermediate-abundance taxa. This means that the high activity density in HRD was not

generated by a balanced increase across the assemblage, but was mainly associated with strong Formicidae dominance. Ants are surface-active, socially organized and flexible in foraging strategy, and these characteristics can allow them to contribute disproportionately to pitfall catches under open, simplified or frequently disturbed ground-layer conditions (Andersen, 1995; Carvalho et al., 2020). However, the stronger conclusion from our data is not a species-level mechanism. It is a shift in dominance structure. HRD was characterized by a more concentrated abundance structure, whereas LRD retained a more distributed assemblage involving multiple dominant and intermediate-abundance groups.

Litter-layer differences provide the most direct habitat context for these assemblage patterns. HRD, MRD and LRD differed mainly in litter thickness and litter cover rather than in broad tree, shrub or herb cover. This distinction is important because the litter layer forms the immediate physical and resource matrix for many ground-active arthropods. It buffers temperature and moisture, provides refuges, supports detrital resources and mediates local interactions among detritivores, predators and omnivores (Hättenschwiler et al., 2005; Uetz, 1979; Wardle et al., 2004; Yang and Gratton, 2014). In this study, litter cover was positively associated with Shannon diversity, Pielou's evenness and community-weighted body length, but negatively associated with activity density, Berger–Parker dominance, Top 5 contribution, omnivore proportion and high-dispersal proportion. These correlations suggest that sites with more developed litter cover supported more even assemblages with broader representation of feeding and dispersal categories. By contrast, sites with reduced litter

cover were associated with stronger dominance concentration and a higher representation of mobile or generalist functional groups. Similar links between forest-floor disturbance, litter conditions and ground-dwelling arthropod composition have been reported in forest disturbance and litter-manipulation studies (Perry et al., 2018; Work et al., 2002).

This litter-associated pattern also helps explain the functional-composition results. HRD had higher proportions of omnivorous and high-dispersal taxa, whereas LRD had higher proportions of detritivore-associated, predator-associated and low-dispersal taxa, together with larger community-weighted body length. Such a shift is consistent with the idea that exposed or simplified ground-layer conditions may favour taxa with greater mobility, broader feeding habits or weaker dependence on continuous litter structure. Conversely, thicker and more continuous litter may provide more stable microhabitats and resources for detritus-associated, predator-associated and lower-dispersal taxa. Trait-based approaches are useful in this context because they connect taxonomic composition with ecological strategies and can reveal responses that are not captured by richness alone (Birkhofer et al., 2015; Cadotte et al., 2011; Wong et al., 2019). At the same time, these results should be treated as community-level functional summaries. Feeding guilds do not demonstrate realized trophic interactions, dispersal categories are based on taxon-level ecological information, and body-size patterns may partly reflect changes in dominant taxa such as Formicidae. Thus, the functional results are best interpreted as functional-composition shifts associated with the recreational-use gradient and litter-layer differences, rather than as direct measurements of

ecosystem functioning (Pedley and Dolman, 2014; Rigal et al., 2018; Wong et al., 2019).

The results can also be placed within a forest-floor food-web context, but the inference should remain at the assemblage-structure level. Litter is not only a habitat layer; it is also a resource base for detritus-associated arthropods and their consumers. Changes in litter continuity may therefore influence assemblage structure by modifying shelter availability, movement routes, detrital resource distribution and predator–prey encounter environments. Studies of litter-dwelling arthropods have shown that soil and litter conditions can be linked to trophic-group density and food-web organization in urban or managed landscapes (Wang et al., 2023), and forest-floor management can alter multi-trophic arthropod diversity through changes in litter, woody debris and vegetation structure (Košulič et al., 2021). Our results are consistent with this framework. However, they do not directly measure decomposition rates, predation rates, stable isotopes or energy fluxes. The present evidence therefore supports litter-associated shifts in dominance, feeding-guild representation and body-size structure, not direct changes in ecosystem process rates.

Seasonal turnover was another major component of assemblage variation. Sampling date explained a larger fraction of compositional variation than recreational-use category, and most alpha-diversity and dominance metrics changed significantly across the July–December sampling period. This indicates that differences among HRD, MRD and LRD were embedded within strong temporal dynamics rather than representing fixed contrasts among sites. Seasonal changes in temperature, moisture, litter input, plant phenology and arthropod life cycles can alter surface activity,

reproduction, dispersal and overwintering behaviour, thereby affecting pitfall captures and community composition. In addition, the significant interaction between recreational-use category and sampling date suggests that assemblages in HRD, MRD and LRD did not follow identical seasonal trajectories. Such temporal context is important because recreational-use-associated assemblage patterns may depend on background environmental conditions and species traits (Nardi et al., 2023; Thorn et al., 2020). Repeated sampling therefore strengthened the interpretation of this study by showing that recreational-use differences were superimposed on, and partly modified by, seasonal community turnover.

The scale of inference should be defined carefully. This study does not attempt to make a broad claim about landscape-scale urbanization. Instead, it identifies how forest-floor arthropod assemblage structure varied across local recreational-use contexts within a large forest patch. This scale is appropriate because the strongest habitat differences occurred at the forest-floor level: litter cover and litter thickness differed more clearly than canopy or understory cover, and these litter variables were consistently associated with dominance, evenness, functional composition and body-size structure. The spatially nested field-gradient design also means that HRD, MRD and LRD should be understood as integrated recreational-use and forest-floor habitat contexts. Within this framework, the consistent differences in dominance structure, dominant taxa and functional composition provide evidence that ground-active arthropod assemblages are sensitive to local ground-layer conditions associated with recreational use.

From a management perspective, the results suggest that forest-floor habitat structure deserves more attention in heavily visited forest patches. HRD sites did not simply contain fewer arthropods; they contained assemblages with higher activity density, stronger dominance concentration and greater contribution of omnivorous and high-dispersal taxa. This distinction matters because total captures alone may obscure lower standardized richness, reduced evenness and narrower representation of feeding and dispersal categories. Maintaining litter cover, reducing repeated off-trail trampling, limiting informal trail expansion and preserving ground-layer heterogeneity may help sustain more even and functionally broader ground-active arthropod assemblages. The conservation implication is therefore specific rather than overstated: recreational use within forest patches can coincide with changes in the litter-layer habitat interface, and these changes may be reflected in dominance concentration, dominant-taxon composition and functional-composition shifts in ground-active arthropod assemblages.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this

paper.

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