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Quantitative Analysis of Diversity and Spatial Heterogeneity of Ground-Level Habitat Microstructures in an Old Temperate Forest

Quantitative Analyse der Diversität und räumlichen Heterogenität bodennaher Habitat-Kleinstrukturen in einem alten temperierten Wald

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Schlüsselbegriffe: Waldkleinstrukturen im Wald, Biodiversitätsschutz, Totholz, Ameisenhügel, kleinräumige Habitatmerkmale, Belgrader Wald, strukturelle Komplexität

Abstract

Ground-level habitat microstructures are critical yet overlooked drivers of forest biodiversity, offering resources for diverse forest organisms. While canopy gaps, tree-related microhabitats (TreMs), and coarse woody debris are widely studied, small-scale features such as ground-level dead wood, micro-pools, and topographic irregularities remain poorly documented in Türkiye. This study presents the first systematic, plot-based quantitative assessment of such features in the ancient Belgrade Forest, a historically protected woodland near Istanbul. 40 randomly selected 10×10 m plots were surveyed across 5,400 ha, assessing seven microstructure categories: dead wood elements (logs, snags, stumps), perennially wet micro-pools, mounds, depressions, branch/brash piles, stone piles, and ant mounds. Frequencies were evaluated using a standardized four-tier scale. Results revealed severe microhabitat simplification. Ecologically valuable dead wood (≥10 cm) occurred in only 7.5% of plots; smaller snags (<10 cm) appeared in 25%. Micro-pools were nearly absent (2.5%), large

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mounds (>50 cm) were rare (5%), and deep depressions (>50 cm) were scarce (7.5%). Branch/brash piles and ant mounds each occurred in <10% of plots. Stumps (≥10 cm) were widespread (82.5%), but excluded from the ecological rating due to anthropogenic origin. No category reached "High" status; most were "Low" or "Very Low." Shannon's H′ ranged from 2.05 to 2.31; Simpson's index (1–D) ranged from 0.82 to 0.86, indicating no spatial dominance. Jaccard similarity (mean = 0.31) reflected high spatial heterogeneity. Principal Component Analysis (PCA) results demonstrated that no individual structural element exerted a dominant effect; rather, small structural elements contributed to forest habitat heterogeneity along different axes, providing relatively modest but complementary contributions. Rarefaction curves plateaued near 12 types, confirming sampling sufficiency. Chi-square ($\chi^2 = 321.0$, df = 39, $p < 0.001$) and Kruskal–Wallis tests (H = 10.35, p = 0.016) indicated significant variation in frequency and richness.

These findings highlight the scarcity of essential microhabitats for saproxylic insects, amphibians, and other taxa, even in a legally protected forest, demonstrating that passive conservation alone cannot maintain ecological integrity. By focusing on ground-level microstructures (distinct from TreMs), this study reveals a structurally degraded but spatially heterogeneous mosaic. Restoration should prioritize dead wood enrichment, perennial micro-pools, and fine-scale topography, implemented proactively in historically protected forests such as Belgrade forest, once safeguarded under imperial edicts but now ecologically simplified. Similar degradation patterns may occur in other peri-urban forests such as Berlin's Grunewald, Vienna's Wienerwald, and Paris's Bois de Boulogne. Thus, Belgrade Forest provides an instructive model for biodiversity-oriented forest policy and restoration, emphasizing recognition, protection, and artificial creation of ground-level habitat microstructures. To our knowledge, this is the first systematic forest inventory worldwide focusing specifically on these features, addressing a gap in forest biodiversity monitoring.

Zusammenfassung

Bodennahe Habitat-Kleinstrukturen sind entscheidende, jedoch oft übersehene Faktoren der Waldbiodiversität, da sie essenzielle Ressourcen und ökologische Nischen für zahlreiche Waldorganismen bereitstellen. Während Kronenlücken, baumbezogene Mikrohabitate (TreMs) und grobes Totholz intensiv erforscht sind, sind kleinräumige Strukturen wie bodennahes Totholz, Kleinstgewässer und feinskalige topographische Merkmale in der Türkei kaum dokumentiert. Diese Studie liefert die erste systematische, stichprobenbasierte quantitative Erhebung solcher Strukturen im historischen Belgrader Wald bei Istanbul. In 40 zufällig ausgewählten 10×10 m-Plots auf 5.400 ha wurden sieben Kategorien erfasst: Totholzelemente (liegend, stehend, Stümpfe), permanent nasse Kleinstgewässer, Erhebungen, Vertiefungen, Reisig-/Gehölzhaufen, Steinhaufen und Ameisenhügel. Die Bewertung erfolgte anhand einer standardisierten vierstufigen Skala. Die Ergebnisse belegen eine starke Vereinfachung der Habitatstruktur: Ökologisch wertvolles Totholz (≥10 cm) kam nur in 7,5 % der Flächen vor, kleinere stehende Totholzelemente (<10 cm) in 25 %. Kleinstgewässer waren fast abwesend (2,5 %), große Erhebungen (>50 cm) waren selten (5 %), tiefe Vertiefungen (>50 cm) traten in 7,5 % der Plots auf. Reisighaufen und Ameisenhügel lagen jeweils unter 10 %. Baumstümpfe (≥10 cm) waren mit 82,5 % weit verbreitet, wurden jedoch aufgrund anthropogener Herkunft nicht in die ökologische Bewertung einbezogen. Keine Kategorie erreichte den Status „hoch"; die meisten lagen bei „niedrig" oder „sehr niedrig". Der Shannon-Index (H') lag zwischen 2,05 und 2,31, der Simpson-Index (1–D) zwischen 0,82 und 0,86. Der mittlere Jaccard-Index betrug 0,31 und wies auf eine hohe räumliche Heterogenität hin. Die Ergebnisse der Hauptkomponentenanalyse (PCA) zeigten, dass kein einzelnes Strukturelement einen dominanten Einfluss ausübte; vielmehr trugen kleine Strukturelemente entlang verschiedener Achsen zur Heterogenität der Waldlebensräume bei, wobei sie relativ geringe, jedoch komplementäre Beiträge leisteten. Seltenheitskurven zeigten eine Sättigung bei etwa 12 Strukturen. Chi-Quadrat- ($\chi^2 = 321{,}0$; df = 39; p < 0,001) und Kruskal-Wallis-Tests (H = 10,35; p = 0,016) bestätigten signifikante Unterschiede. Diese Ergebnisse verdeutlichen den Mangel an essenziellen Mikrohabitaten für saproxyle Insekten, Amphibien und andere Waldarten – selbst in einem gesetzlich geschützten Gebiet. Der Fokus auf bodennahe Habitat-Kleinstrukturen (ökologisch und methodisch klar von TreMs abzugrenzen) zeigt ein strukturell degradiertes, aber räumlich heterogenes Mosaik. Prioritäre Maßnahmen sollten die Anreicherung von Totholz, die Anlage dauerhafter Kleinstgewässer und feinskaliger Reliefstrukturen umfassen. Ähnliche Defizite finden sich in anderen stadtnahen Wäldern wie dem Grunewald (Berlin), dem Wienerwald (Wien) und dem Bois de Boulogne (Paris). Der Belgrader Wald kann somit als Modell für biodiversitätsorientierte Forstpolitik und kontextsensitive Wiederherstellung dienen. Soweit bekannt, handelt es sich um die erste systematische Waldinnenraum-Inventur weltweit, die gezielt auf bodennahe Habitat-Kleinstrukturen fokussiert.

1 Introduction

Biodiversity conservation is essential for sustainable forest management, with habitat diversity playing a key role. Recently, the focus has shifted to small-scale "ground-level habitat microstructures" (*e.g.*, dead wood, branch piles) embedded within larger habitats. These structures create diverse ecological niches, enhancing forest heterogeneity and integrity. Studies show that microstructures vary widely (from ant mounds and rock piles to perennial water bodies) and support species diversity beyond what their physical size would suggest (König & Chevillat, 2017; Naturnetz, 2017). They provide critical ecosystem services such as nesting, feeding, and sheltering. Their spatial arrangement and quality are vital for biodiversity at both stand and landscape scales (Meister, 2007).

In forest ecology, it is important to distinguish between ground-level habitat microstructures (German: *Kleinstrukturen im Wald*) and tree microhabitats (German: *Baummikrohabitate or Dendromikrohabitate*). Ground-level microstructures are features located at or near the forest floor, such as mounds, stone piles, branch piles, and wet depressions. These often result from abiotic factors and animal activity, and are largely independent of individual tree traits. By contrast, tree microhabitats (TreMs) are features directly linked to living or standing dead trees—such as cavities, bark loss, epiphytes, exposed heartwood, or dendrotelms. Examples include woodpecker cavities, mould-filled trunk hollows, broken branches, and root buttress cavities (Kraus *et al.*, 2016). These structures serve as crucial substrates or shelters for various forest organisms, with their occurrence influenced by tree species, size, and forest age (Višnjić *et al.*, 2025).

This study specifically focuses on ground-level habitat microstructures, aiming to assess their frequency, distribution, and ecological condition within a protected forest ecosystem. Emphasizing this distinction helps prevent terminological confusion and *highlights* the research's novelty in Turkish forest science. Moreover, both ground-level microstructures and TreMs share overlapping ecological functions; for example, epiphyte-rich TreMs (such as moss-covered bark and lichen patches) provide nesting materials and microclimatic refuges, similar to forest floor features like dead wood and stone piles (Višnjić *et al.*, 2025). Recognizing these differences while acknowledging functional overlaps is crucial for developing precise ecological and methodological frameworks for biodiversity-oriented forest management.

Microstructure types and functions vary with forest and site conditions (Ammer & Utschick, 1984). Systematic inventories are essential for understanding this variability and guiding conservation efforts (LWF, 1996). Ideally, microstructures should form interconnected networks rather than isolated patches, with dead wood and branch piles distributed evenly across stands to support diverse organisms (Krüsi & Schütz, 1994; Harmon *et al.*, 1986; Schiegg, 1998). Dead wood is among the most ecologically valuable microstructures, providing microclimate regulation, foraging opportunities, shelter, and breeding sites (Carey & Johnson, 1995; Dueser & Shugart, 1978). Approximately 20% of forest fauna depend on dead wood, which supports a wide range of niches across various stages of decomposition (Heinrich, 1997). Its long decay process is critical for faunal succession, and its removal results in biodiversity loss (Speight, 1989). Recommended levels are 5–10 m^3 per hectare, or approximately 5% of stand volume (Ammer, 1991; Jedicke, 1995; Möller, 1994). However, Belgrade Forest falls below these thresholds (Arslan, 2011), consistent with studies on *Castanea sativa* vitality and regeneration in the area (Çevikayak, 2022).

Beyond dead wood, other structures such as ant mounds and small, permanent water-filled depressions also play vital ecological roles. Red wood ants contribute to biological regulation and serve as a food source for many bird species. In Central Europe, approximately 70 insect species and nearly 150 plant species depend on ants; however, ant populations are declining, necessitating urgent conservation action (Erlbeck *et al.*, 1998). Similarly, small depressions and ephemeral pools provide crucial breeding and foraging habitats for amphibians and aquatic invertebrates (Meister, 2007; SVS, 2006).

Although forest conservation is well integrated into some forestry traditions, biodiversity remains a secondary focus in many regions. Kırca (2009) highlighted how urbanization and land-use change around Belgrade Forest fragment habitats and disrupt ecological connectivity, negatively impacting green space continuity and key ecosystem processes. Between 1974 and 1977, biotope mapping in Bavaria identified the need for systematic documentation of ecologically valuable forest features, emphasizing microstructures that require tailored survey methods and dedicated funding. Pilot studies in the Bavarian National Park demonstrated that combining stand data, microstructure inventories, and faunal observations yielded the most comprehensive assessments. These studies recommended integrating microstructures into forest planning—a practice that has since been widely adopted (Ammer & Utschick, 1990).

A dense network of microstructures (such as rock piles, branch piles, small depressions, dead wood, ephemeral pools, and ancient meadows) helps counter habitat fragmentation by enhancing structural complexity and providing refugia for specialist species (BirdLife Switzerland; Glatzel, 1999; Müller *et al.*, 2008). Further studies, including the Jurapark Aargau brochure and Switzerland's WIN-Wieselnetz program, highlight branch piles and dead wood as critical shelters and breeding sites for mammals, reptiles, amphibians, and invertebrates. Even a few well-placed microstructures can support essential ecological functions across trophic levels (Müri, 2012). Seemingly untidy roadside features, such as dead wood intertwined with *Urtica* spp., also serve as important refugia; for instance, the Kars lizard utilizes such habitats, while structurally rich forest edges support bird species like the cuckoo. These microstructures are applicable across both moist and dry environments (including gardens, farms, and schoolyards), and several field manuals provide guidance on their restoration and design (SVS, 2016). BirdLife Switzerland brochures offer practical instructions for constructing microstructures, estimating costs, and designing habitat networks. European conservation initiatives, such as KARCH (the Swiss Amphibian and Reptile Conservation Programme, CSCF), emphasize urgent priorities like dry-stone walls, shrub hedgerows, and stone piles to enhance habitat quality and connectivity.

Despite international agreements such as the Rio Convention and relevant national legislation, biodiversity loss caused by anthropogenic habitat destruction remains a critical issue (Schramm, 1999). As Wilson (1992) emphasized, Earth's biological diversity is its greatest marvel. Forest structural elements (canopy gaps, dead wood, and forest edges) combined with ground-level microstructures enhance the habitat complexity essential for species survival. Despite the ecological importance of ground-level habitat microstructures, no systematic research has yet been conducted on these features within forest ecosystems. Belgrade Forest (a legally protected and relatively well-forested area near Istanbul) is increasingly exposed to anthropogenic pressures, which may threaten the integrity of such microhabitats.

This study aims to provide the first comprehensive assessment of the diversity, condition, and spatial heterogeneity of ground-level habitat microstructures in Belgrade Forest. Specifically, its objectives are:

(i) to identify and classify microstructure types, including both commonly observed elements (*e.g.*, dead wood, canopy gaps, branch and brash piles) and localized formations shaped by site-specific ecological and geomorphological conditions (e.g., ant mounds, ephemeral pools, stone piles);
(ii) to evaluate their ecological quality using standardized criteria such as structural integrity, ecological functionality, spatial continuity, and visibility;
(iii) to analyze spatial patterns in terms of isolation, connectivity, and biodiversity-support potential; and
(iv) to determine silvicultural and conservation priorities by identifying structurally degraded areas and proposing targeted restoration actions (*e.g.*, dead wood enrichment, creation of branch and brash piles, and protection of moist depressions and ant mounds).

While earlier research (*e.g.*, Ibáñez & Schupp, 2002) has explored microhabitats and forest floor ecology, this study is among the first to systematically inventory and analyze the diversity and spatial heterogeneity of ground-level habitat microstructures within the interior of a temperate forest. Moreover, it advocates for the recognition, preservation, and creation of similar microstructures in other peri-urban forests (particularly those surrounding European cities) to enhance biodiversity beyond the local scale. As such, the study informs regional conservation strategies and contributes scalable, nature-based forestry solutions for urban–ecological contexts.

2 Materials and Methods

2.1 Study Site Description

Belgrade Forest, covering approximately 5,400 ha on the Çatalca Peninsula near Istanbul (28°54'–29°00' E, 41°09'–41°12' N), comprises the Bentler and Kurtkemeri Forest Management Units (Tüfekcioğlu, 2013). The forest is situated within the Marmara Region's Çatalca Peninsula Forest Growth Region, with elevations ranging from 40 to 240 m (Kantarcı, 1980). The underlying geology consists of Paleozoic Carboniferous and Tertiary Pliocene formations, characterized by diverse sediments that result in heterogeneous soils: shallow brown forest soils over schist and deeper pseudogley soils on Neogene deposits (Yönelli, 1986; Kantarcı, 1980). Geomorphologically, the area is a gently sloping peneplain facing the Bosphorus, characterized by broad ridges, plateaus, and deep valleys (Irmak, 1940). Seasonal and permanent streams drain northwards into the Kağıthane Stream. Historical waterworks, including the Karanlık

Reservoir and several dams, have regulated Istanbul's water supply (OAP, 1949). The soils are primarily non-calcareous podzols rich in organic matter, shaped by erosion and runoff processes (Kantarcı, 1980). The region's humid mesothermal climate, classified according to Thornthwaite, is characterized by mild summer water deficits, a strong maritime influence, and high summer humidity (~80%) due to its proximity to the sea (2–10 km) (Tanoğlu *et al.*, 1961; Kantarcı, 1980). The annual mean temperature ranges between 12 and 13°C, with precipitation levels of 1000–1200 mm; the growing season lasts approximately 7.5 months (Rubner, 1934). Throughfall accounts for 75.4% of precipitation during leaf-on periods and 82.7% during leaf-off periods, underscoring the forest's hydrological buffering capacity (Özhan *et al.*, 2011). Vegetation contributes to water retention, while topography and parent material influence local microclimates (Kantarcı, 1980).

The forest is dominated (~75%) by *Quercus species* (*Q. frainetto*, *Q. petraea*, *Q. robur, Q. cerris*), along with *Acer campestre*, *Alnus glutinosa*, *Carpinus betulus*, *Castanea sativa*, *Corylus avellana*, *Fagus orientalis*, *Fraxinus angustifolia*, *Populus tremula*, *Salix alba*, *Salix cinerea*, *Sorbus torminalis*, *Tilia tomentosa*, and *Ulmus minor* (Çolak *et al.*, 2013; Saatçioğlu, 1954; Yaltırık, 1966). The forest falls within the optimal range for *Quercus* species, between the Castanetum and Fagetum phytogeographical zones (Walter, 1956; Zetnik, 1961; Kantarcı, 1980).

Historically, Belgrade Forest has been protected for centuries due to its hydrological importance, with legal safeguards dating back to the Byzantine and Ottoman periods, including the 1733 firman issued by Sultan Mahmud I that prohibited logging under severe penalties. The forest played a key role in Istanbul's water supply through monumental aqueducts and water systems. After forest management was assigned to the Forestry School in 1924, the area became a model forest for research and education. Officially designated a "Preserved Forest" in 1953, forestry operations between the 1950s and 1970s emphasized uniformity and productivity, resulting in the removal of dead wood and simplification of stand structures (Kırca *et al.*, 2013). Since then, recreational use, urban pressures, and weak enforcement of conservation measures have further degraded microhabitats such as coarse woody debris, snags, and wet depressions (Arslan, 2011; Kırca *et al.*, 2013).

2.2 Selection of sampling plots, plot design, and data collection

This study was conducted in Belgrade Forest to assess the occurrence and ecological condition of ground-level habitat microstructures. Sampling plots were surveyed across the Belgrade Forest, covering approximately 5,400 hectares. To capture the spatial heterogeneity of the forest ecosystem, sampling plots were systematically distributed across distinct sections of the forest (Figure 1).

First, a 400×400 meter grid was overlaid onto the study area using topographic maps and GIS tools, resulting in the identification of 175 potential sampling points across the forest landscape. Although the term "random selection" is often used, the actual sampling method followed a tessellation-stratified random approach. That is, a systematic grid was first applied to ensure spatial coverage, and randomization was then applied within this grid to select 40 plots. This hybrid approach allowed for both spatial evenness and statistical robustness. Furthermore, a minimum distance of 500–1,000 meters was maintained between plots to avoid clustering and reduce spatial autocorrelation. This arrangement enabled representative sampling across a wide range of site conditions and forest compartments.

Regarding plot size, a field-based pretest was conducted to evaluate the detection efficiency of different plot dimensions. The 5×5 m plots were found to be too small to reliably capture diverse and dispersed microstructures, while 20×20 m plots were unnecessarily large and inefficient given the focus on fine-scale elements. As a result, 10×10 m plots (100 m^2) were selected as optimal. This dimension allowed for accurate measurement of all ground-level habitat microstructures (including those spatially discrete or irregular in form) while maintaining consistency with European forest structure inventory practices.

Although our focus lies on ground-level microstructures rather than canopy or tree-related features, the spatial layout of the sampling plots followed standardized approaches designed to capture habitat fragmentation and microclimatic gradients, as recommended by recent landscape-scale assessments (Višnjić *et al.*, 2025). Within each plot, all detectable ground-level habitat microstructure types were recorded based on their frequency, dimensions, and visual detectability. Presence or absence data were first documented for each feature, followed by the compilation of detailed measurements into a master dataset. This enabled a systematic analysis of the spatial distribution, size classifications, and ecological significance of each ground-level habitat microstructure type.

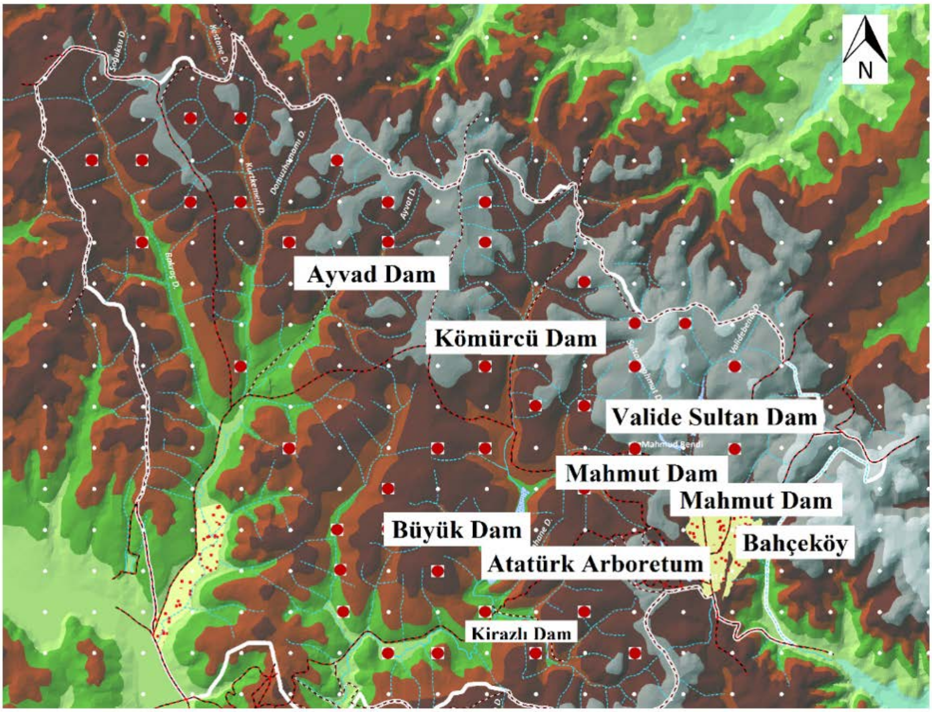

Figure 1: Spatial distribution of the 40 ground-level habitat microstructure sampling plots (red dots) in Belgrade Forest, Istanbul. The base map displays elevation gradients, illustrating the forest's moderately hilly terrain (light blue: 5-25 m; light green: 25-50 m; green: 50-75 m; dark orange: 75-100 m; brown: 100-150 m; dark grey: 150-200 m; light grey: 235-260 m). Sampling plots follow a systematic grid-based layout established using topographic maps and GIS tools. The base map was generated by Abbas Şahin based on forest management plans covering the years 2012-2022.

Abbildung 1: Räumliche Verteilung der 40 Stichprobenflächen für bodennahe Habitat-Kleinstrukturen (rote Punkte) im Belgrader Wald, Istanbul. Die Hintergrundkarte zeigt Höhenstufen und veranschaulicht das mäßig hügelige Gelände des Waldes (hellblau: 5-25 m; hellgrün: 25-50 m; grün: 50-75 m; dunkelorange: 75-100 m; braun: 100-150 m; dunkelgrau: 150-200 m; hellgrau: 235-260 m). Die Stichprobenflächen folgen einem systematischen, topografischen und GIS-gestützten Rasterdesign. Die Kartenbasis wurde von Abbas Şahin auf Grundlage der Forsteinrichtungspläne für die Jahre 2012-2022 erstellt.

This study aimed to assess the diversity and ecological condition of ground-level habitat microstructures (hereafter, microstructures) within Belgrade Forest, Istanbul. Recognizing their heterogeneity and ecological significance, a broad definition was adopted to encompass small-scale, discrete, or linear structural features embedded within the forest matrix. The classification was informed by established literature and regional biodiversity guidelines (Verein biodivers, 2022; Liechti, 2003; Meister, 2007).

Due to the absence of inventory-based assessments for such features in Türkiye, a tailored protocol was developed by adapting Central European methodologies (Labiola, 2016; Labiola, 2023). Structure types and measurement criteria followed established European frameworks, employing a classification approach similar to that of Ammer and Utschick (1990). Both natural and anthropogenic microstructures, such as branch piles, were included in line with Swiss recommendations, which emphasize their composition, size, and maintenance practices (SVS, 2006; Labiola, 2016). A structured inventory form was created by modifying survey methods from previous studies (Meister, 2007; SVS, 2006).

Identified forest-edge and interior microstructures included lying and standing dead wood, ant mounds, branch piles, soil and stone accumulations, unvegetated patches, depressions, wet corridors, small streams, and micro-pools-features widely recognized for their ecological importance (Dueser & Shugart, 1978; Liechti, 2003; Fuhrer *et al.*, 2008; WWF, 2020; Rossier *et al.*, 2021; Meister, 2007). These elements (especially dead wood, soil and stone accumulations, stumps, and mound structures) contribute significantly to forest habitat heterogeneity and species richness (Meister, 2007). Table 1 provides a detailed overview of these structural types, their ecological roles, and key references, while Figure 2 presents a schematic representation.

The classification and measurement of the seven microstructure types were based on comprehensive ecological and methodological frameworks (Dueser & Shugart, 1978; Fuhrer *et al.*, 2008; FVA, 2016; WWF, 2020; Rossier *et al.*, 2021). Ant mound evaluations adhered to inventory and ecological guidelines highlighting their indicative role in structural complexity (Punttila & Kilpeläinen, 2009; Meijer, 2020; Dewes, 2006; Meister, 2007). Branch piles were assessed following European biodiversity and forest management recommendations, with emphasis on their structural characteristics and importance for fauna (Castillo-Escrivà *et al.*, 2018; Aldridge *et al.*, 2020; Wieselnetz, 2009; Virginia Department of Forestry, 2015; Meister, 2007).

Topographic depressions and micro-mounds were evaluated based on studies of pit-and-mound dynamics and their influence on soil processes and biodiversity (Barker Plotkin *et al.*, 2017; Liang *et al.*, 2023). Stone accumulations were assessed following conservation typologies that highlight their abiotic functions as thermal refuges and habitat shelters (KARCH, 2011; Völkl *et al.*, 2007; Kühne *et al.*, 1999; Merkblatt für ökologisch wertvolle Steinhaufen, 2017; Labiola, 2023; WWF, 2020; Meister, 2007). Dead wood protocols were derived from both classical and contemporary sources, emphasizing position, decay class, and diameter (Swanson *et al.*, 1976; Ranius *et al.*, 2003; Norden *et al.*, 2004; Lipan *et al.*, 2008; Atıcı *et al.*, 2008). Wet micro-pools were included based on hydrological and faunal studies illustrating their significance for small-scale water retention and habitat diversity (Dueser & Shugart, 1978; Meister, 2007).

All microstructures were recorded by type, spatial location, and visible condition across 40 systematically selected 10×10 m plots. The structures were categorized into seven main types, summarized in Table 1 and visually conceptualized under the forest canopy in Figure 2. A four-tier frequency-based system classified their occurrence as Very Low (0–24%), Low (25–50%), Moderate (51–75%), and High (76–100%), enabling a spatially explicit assessment of habitat quality, ecological integrity, and structural diversity. This approach provides a foundation for restoration planning.

Diversity assessment relied on presence/absence data, expressed as percentage occurrence (% occurrence)—the proportion of plots in which a given structure was found. This metric avoids distortions from per-hectare extrapolations that can misrepresent spatially aggregated features in heterogeneous stands. Therefore, % occurrence was considered the most ecologically robust and comparable metric.

Measurement criteria were carefully defined to include both naturally occurring and anthropogenically introduced analogs. Thresholds for inclusion (*e.g.*, size, height, distinctiveness) were derived from ecological literature and practical conservation applications. This ensured consistency in evaluating features regardless of origin and supported future monitoring or restoration interventions.

Dead wood assessment

Dead wood was evaluated in three forms: lying dead wood (logs), standing dead wood (snags), and naturally formed stumps; each further classified by diameter as <10 cm or ≥10 cm (see Table 1). Lying dead wood included fallen trunks and large branches, with diameters measured at the midpoint. Standing dead wood was measured at breast height (1.3 m). Only naturally formed stumps were included.

Coarse woody debris with a diameter ≥10 cm provides complex habitats, particularly for saproxylic species (Atıcı *et al.*, 2008, and others). Fine woody debris (<10 cm) has limited ecological impact but was included to allow for a comprehensive assessment (Dueser & Shugart, 1978).

Stone piles assessment

Natural or ecologically retained stone piles were classified into two height categories: low (0–50 cm) and high (>50 cm), with anthropogenic structures excluded (see Table 1). These features serve as thermal refuges and shelters for reptiles, small mammals, and invertebrates (Fuhrer *et al.*, 2008; Rossier *et al.*, 2021) and align with known ecological management typologies (WWF, 2020).

Branch and brash pile classification

Dead wood piles were classified by origin (anthropogenic (resulting from forest management) or natural (resulting from canopy fall)) and by height: small (≤50 cm) or large (>50 cm) (see Table 1). This classification is consistent with forestry guidelines

(Virginia Dept. of Forestry, 2015). Although relatively small, these piles have high microhabitat value (Rossier *et al.*, 2021).

Perennially wet micro-pools assessment

Perennially wet micro-pools were classified by diameter as small (≤1 m) or large (>1 m). Only naturally formed depressions retaining water year-round were included (see Table 1). These are important breeding and shelter sites for amphibians and moisture-dependent species (Calhoun *et al.*, 2014).

Microtopography assessment

Natural mounds and depressions were classified by size: small/shallow (0–50 cm) or large/deep (>50 cm) (see Table 1). This classification reflects their role in influencing soil heterogeneity and habitat diversity (Liang *et al.*, 2023).

Ant mounds assessment

Formica ant mounds were classified by visibility: distinct or indistinct, with only natural formations included (see Table 1). Ant mounds increase habitat complexity and support diverse insect communities (Fuhrer *et al.*, 2008).

Table 1: Structural classification, ecological functions, and key references of ground-level habitat microstructures.

Tabelle 1: Strukturklassifikation, ökologische Funktionen und zentrale Literaturquellen bodennaher Habitat-Kleinstrukturen.

	Category-Subcategory	Structural Criteria	Ecological Role	Key References
Dead wood	Lying dead wood (logs)	Diameter at breast height (cm) ≥ 10 Diameter at breast height (cm) < 10	Dead wood is a keystone structural component of forest ecosystems, offering microclimatic buffering, foraging sites, breeding and sheltering spaces, and supporting billions of ecological niches across various decay stages; its absence can lead to significant biodiversity loss, especially among saproxylic species.	Carey & Johnson (1995); Dueser & Shugart (1978); Heinrich (1997); Speight (1989); Ammer (1991); Jedicke (1995); Möller (1994); Atıcı *et al*. (2008)
	Standing dead wood (snags)	Diameter at breast height (cm) ≥ 10 Diameter at breast height (cm) < 10		
	Stumps (natural origin): Remnant tree bases formed by natural processes	Diameter (cm) ≥ 10 Diameter (cm) < 10		
	Stumps (human-induced): Formed by anthropogenic tree cutting	Diameter (cm) ≥ 10 Diameter (cm) < 10		
Wet microhabitats	Perennially wet micro-pools (small) Perennially wet micro-pools (large)	Diameter (m) ≤ 1 Diameter (m) > 1	Perennially wet micro-pools provide key breeding, shelter, and foraging habitats for amphibians and aquatic invertebrates, supporting moisture-dependent forest biodiversity.	Dueser & Shugart (1978); Meister (2007); SVS (2006); Calhoun *et al*. (2014); Brooks & Hayashi (2002)
Microtopography	Mounds - small Mounds - large	Height (cm) 0–50 Height (cm) > 50	Mounds and depressions enhance soil heterogeneity and microhabitat diversity by shaping moisture and temperature conditions essential for ground-dwelling species.	Dueser & Shugart (1978); Barker Plotkin *et al*. (2017); Meister (2007); Liang *et al*. (2023)
	Depressions - shallow Depressions - deep	Depth (cm) 0–50 Depth (cm) > 50		
Branch and brash piles	Brash piles (management-originated) - small Brash piles - large	Height (cm) 0–50 Height (cm) > 50	Branch and brash piles offer essential shelter, foraging, and overwintering sites for small mammals, reptiles, amphibians, and invertebrates, enhancing microhabitat availability in structurally simplified forests.	Meister (2007); Rossier *et al*. (2021); Müri (2012); Castillo-Escrivà *et al*. (2018); Aldridge *et al*. (2020)
	Branch piles (natural)- small Branch piles (natural)- large	Height (cm) 0–50 Height (cm) > 50		
Ant mounds	*Formica* spp. mounds – indistinct *Formica* spp. mounds – distinct	Structural form: non-distinct Structural form: distinct/visible	Ant mounds contribute to habitat complexity, support diverse insect communities, aid seed dispersal, and serve as prey sources for birds and small mammals.	Meister (2007); Fuhrer *et al*. (2008); Punttila & Kilpeläinen (2009); Meijer (2020); Dewes (2006); FVA (2016)
Stone piles	Natural (naturally retained or clustered stones)- small Natural- large	Height (cm) 0–50 Height (cm) > 50	Stone piles act as thermal refuges and hiding places, supporting reptiles, small mammals, and invertebrates while enhancing microclimatic and structural diversity in forest habitats.	Meister (2007); Fuhrer *et al*. (2008); Rossier *et al*. (2021); KARCH (2011); Völkl *et al*. (2007); Dölle *et al*. (2022); WWF (2020)
	Anthropogenic (artificial or relic stone structures)- small Anthropogenic- large	Height (cm) 0–50 Height (cm) > 50		

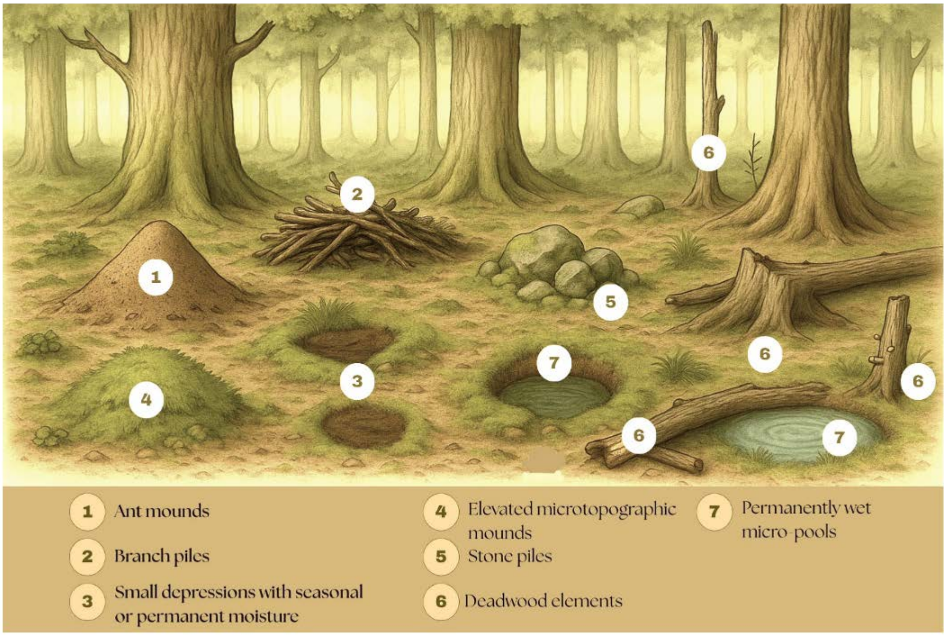

Figure 2: A schematic illustration of ground-level habitat microstructures occurring beneath the forest canopy. This figure is based on the original schematic by Meister (2007), with modifications to form and structure made by the authors for visual clarity.

Abbildung 2: Schematische Darstellung bodennaher Habitat-Kleinstrukturen unter dem Kronendach des Waldes. Die Abbildung basiert auf dem Originalschema von Meister (2007), wurde von den Autoren in Form und Struktur überarbeitet zur besseren visuellen Darstellung.

2.3 Frequency-based assessment and classification of microstructure occurrence

Ground-level habitat microstructures were assessed using presence/absence data collected from systematically surveyed 10 × 10 m plots. For each microstructure type, occurrence was quantified as percentage presence (% occurrence), defined as the proportion of plots in which the feature was observed. This frequency-based metric enabled direct comparison across categories by representing their spatial distribution without the need for area-based conversions. Each microstructure was then assigned to one of four ecological occurrence classes: Very Low (0–24%), Low (25–50%), Moderate (51–75%), and High (76–100%). This classification provided an ecologically meaningful representation of relative abundance, particularly given the naturally patchy and clustered distribution of microhabitats in forest ecosystems. Frequency data were not converted into per-hectare estimates, as such transformations may produce inflated or misleading density values under spatial aggregation. In this framework, a

7.5% occurrence corresponds to detection in 3 of the 40 surveyed plots (10 × 10 m each). These values therefore represent detection frequency across discrete sampling units rather than absolute spatial density. Reporting results as percentage occurrence ensures a more accurate reflection of spatial heterogeneity, rarity, and ecological relevance across the forest landscape.

To evaluate structural heterogeneity in Belgrade Forest, diversity metrics and multivariate analyses were applied to presence/absence and frequency data from 40 plots (Table 1). Two complementary indices were calculated:

(i) Shannon's diversity index (H'), which accounts for both richness and evenness, and
(ii) Simpson's index of diversity (1–D), which is sensitive to dominance patterns among microstructures.

Shannon index values were interpreted following established ecological thresholds (Whittaker, 1972; Magurran, 2004), with <1.5 indicating low diversity, 1.5–3.5 moderate diversity, and >3.5 high diversity. Together, these indices provided a quantitative overview of the complexity and balance of the microhabitat assemblage described in Table 1.

To test whether microstructure distributions deviated from uniformity, a Chi-square (χ^2) test was conducted on presence/absence data, highlighting structural imbalance or rarity. Compositional similarity among plots was assessed using Jaccard coefficients, followed by hierarchical cluster analysis (Ward's linkage, Euclidean distance), which grouped plots into five distinct clusters based on shared microstructure composition.

Ten types of small structural elements with distinct characteristics were considered and classified into six categories:

(i) deadwood (lying dead wood, standing dead trees, stumps),
(ii) micro-topography (mounds, depressions),
(iii) branch piles (natural and management-related),
(iv) ant mounds,
(v) stone piles, and
(vi) wet micro-habitats.

Prior to analysis, all data were standardized. To identify underlying patterns, Principal Component Analysis (PCA) was performed using the correlation matrix to account for differences in measurement scales among variables. Components with eigenvalues >1 were retained for interpretation. Variable loadings were examined to identify which structural elements were most strongly associated with each component. In addition, a scree plot was used to evaluate the variance explained by the components, and a biplot was produced to visualize relationships between sample plots and structural elements.

Sampling sufficiency was evaluated by generating a rarefaction curve with 100 random permutations per subset size (1-40 plots). The results confirmed that the number of plots was sufficient to capture microstructure diversity.

Finally, to investigate spatial patterns, the 40 plots were grouped into four geographic units corresponding to forest management boundaries and physiographic zones. A Kruskal–Wallis test was then applied to compare microstructure richness across these units, testing whether variations in structural diversity were driven by landscape-scale factors or by localized conditions.

3 Results

A comprehensive structural assessment of ground-level habitat microstructures was conducted across 40 systematically surveyed plots in Belgrade Forest. The evaluation focused on dead wood, stumps, topographic features, moisture-related structures, and accumulation features (*e.g.*, stone or branch piles), providing a detailed ecological classification (see Table 2).

Table 2: Master table of identified ground-level habitat microstructures across all sample plots (n = 40). Colors indicate the frequency-based occurrence classification (High: dark green; Moderate: light green; Low: purple; Very low: orange).

Tabelle 2: Übersichtstabelle der erfassten bodennahen Habitat-Kleinstrukturen über alle Probeflächen (n = 40). Die Farben kennzeichnen die häufigkeitsbasierte Auftretensklassifikation (hoch: dunkelgrün; mittel: hellgrün; niedrig: lila; sehr niedrig: orange).

Category	Subcategory	Structural criteria	Number of plots	Total count	Frequency (%)	Classification
Dead wood	Lying dead wood (logs)	Diameter at breast height (cm) ≥ 10	3	3	7.5	Very low
		Diameter at breast height (cm) < 10	1	1	2.5	Very low
	Standing dead wood (snags)	Diameter at breast height (cm) ≥ 10	3	3	7.5	Very low
		Diameter at breast height (cm) < 10	10	19	25	Low
	Stumps (natural origin)	Diameter (cm) ≥ 10	0	0	0	Very low
		Diameter (cm) < 10	0	0	0	Very low
	Stumps (human-induced)	Diameter (cm) ≥ 10	33	99	82.5	High
		Diameter (cm) < 10	9	18	22.5	Very low
Wet micro-habitats	Perennially wet micro-pools (small)	Diameter (m) ≤ 1	1	1	2.5	Very low
	Perennially wet micro-pools (large)	Diameter (m) > 1	0	0	0	Very low
Micro-topography	Mounds - small	Height (cm) 0–50	20	25	50	Moderate
	Mounds - large	Height (cm) > 50	2	2	5	Very low
	Depressions - shallow	Depth (cm) 0–50	16	16	40	Low
	Depressions - deep	Depth (cm) > 50	3	3	7.5	Very low
Branch and brash piles	Brash piles (management-originated) - small	Height (cm) 0–50	4	8	10	Very low
	Brash piles - large	Height (cm) > 50	4	5	10	Very low
	Branch piles (natural)- small	Height (cm) 0–50	0	0	0	Very low
	Branch piles (natural)- large	Height (cm) > 50	2	2	5	Very low
Ant mounds	*Formica* spp. mounds – indistinct	Structural form: non-distinct	1	1	2.5	Very low
	Formica spp. mounds – distinct	Structural form: distinct/visible	0	0	0	Very low
Stone piles	Natural (naturally retained or clustered stones)- small	Height (cm) 0–50	0	0	0	Very low
	Natural- large	Height (cm) > 50	0	0	0	Very low
	Anthropogenic (artificial or relic stone structures)- small	Height (cm) 0–50	0	0	0	Very low
	Anthropogenic- large	Height (cm) > 50	0	0	0	Very low

Dead wood assessment

Dead wood components were evaluated across all surveyed plots, categorized by structural type (lying logs, standing dead wood, and stumps) and diameter classes (<10 cm and ≥10 cm), consistent with the framework described in Section 2.3. Summary data, including plot occurrence, total counts, frequency percentages, and ecological classifications, are presented in Table 2.

Lying dead wood (logs): Logs with diameters ≥10 cm were detected in only 3 plots (7.5% frequency), totaling 3 individuals, and were therefore classified as "Very low" occurrence (0–24%). Smaller logs (<10 cm) were even rarer, recorded in a single plot (2.5%) with 1 individual, also "Very low." These very limited frequencies indicate that lying dead wood contributes only marginally to habitat heterogeneity in the study area.

Standing dead wood (snags): Large snags (≥10 cm DBH) were equally scarce, present in 3 plots (7.5%), also classified as "Very low." By contrast, smaller snags (<10 cm DBH) were more common, recorded in 10 plots (25%) with 19 individuals, corresponding to the "Low" occurrence class. While individually offering limited habitat, their relatively higher frequency suggests a modest contribution to microstructural complexity, particularly for small-bodied or early successional species.

Stumps: Large stumps (≥10 cm diameter) were highly prevalent, occurring in 33 plots (82.5%) with 99 individuals, representing a "High" occurrence class. Smaller stumps (<10 cm) were found in 9 plots (22.5%) with 18 individuals, classified as "Very low." Field observations confirmed that nearly all stumps originated from historic logging rather than natural tree fall. Most lay flat at ground level, lacking the vertical structure typical of natural snags. In line with the methodological approach, anthropogenically created stumps were excluded from subsequent ecological diversity analyses due to their limited structural and habitat value. Notably, no naturally formed stumps were observed in any plot.

Stone piles

Neither natural nor anthropogenic stone piles were recorded across any plots, leading to a "Very low" classification for all stone pile subcategories. This complete absence indicates that stone piles do not contribute to microhabitat diversity in Belgrade Forest (Table 2).

Branch and brash piles

Small brash piles (0–50 cm), typically originating from forest management, were detected in 4 plots (10%) with 8 total piles, while large brash piles (>50 cm) were similarly found in 4 plots (10%) with 5 piles, both classified as "Very low." Natural branch piles were nearly absent; small natural piles were not observed at all, and only 2 large natural piles (>50 cm) occurred in 2 plots (5%), also "Very low." These results demonstrate that anthropogenic debris dominates branch and brash accumulations, contributing minimally to the ground-level habitat heterogeneity.

Perennially wet micro-pools

Only one small micro-pool (≤1 m diameter) was found in a single plot (2.5% occurrence), with no large pools (>1 m) detected. Both fall under the "Very low" category, indicating a scarcity of permanent aquatic microhabitats that could support hydrophilic species, reflecting hydrological constraints or anthropogenic impacts on water retention.

Microtopographic features

Small mounds (0–50 cm height) were relatively common, recorded in 20 plots (50% frequency), classified as "Moderate," whereas large mounds (>50 cm) were rare (2 plots, 5%, "Very low"). Shallow depressions (0–50 cm depth) appeared in 16 plots (40%, "Low"), while deeper depressions (>50 cm) were scarce (3 plots, 7.5%, "Very low"). These patterns indicate moderate variability in fine-scale topography, with smaller features more prevalent and contributing to habitat complexity.

Ant mounds (Formica spp.)

Only one indistinct ant mound was documented (2.5%, "Very low"), with no distinct or large mounds detected, suggesting minimal influence of mound-building ants on microhabitat diversity in the area.

Synthesis of microstructure patterns and statistical analyses

As summarized in Table 2, Belgrade Forest exhibits a substantially degraded and simplified microhabitat structure. None of the categories reached the high classification, except for anthropogenic stumps, and most fell into the very low or low tiers. The most frequently observed features, such as small mounds and shallow depressions, have relatively low ecological impact. In contrast, structurally and functionally critical features (including coarse woody debris, wet micro-pools, and natural branch accumulations) were nearly absent. These results indicate a forest floor with limited ecological complexity, likely shaped by historical and ongoing management interventions.

Structural diversity was evaluated using Shannon's index (H′ = 2.05) and Simpson's index (1–D = 0.82), suggesting moderate richness and evenness but a fragmented composition. Jaccard similarity among plots was low (mean = 0.31), highlighting substantial heterogeneity. Cluster analysis identified five distinct structural plot groups (Figure 3).

The PCA results showed that the first four components explained 70.5% of the total variance (Table 3, Figure 4). PC1 (26.8%) was defined by lying dead wood, standing dead trees, stumps, and micro-topographic structures (mounds and depressions), indicating frequent co-occurrence within the same plots (Table 4). PC2 (19.7%) was associated with both natural and management-related branch piles, whereas stone piles were negatively loaded, suggesting that these elements tended to occur in different areas. PC3 (13.8%) reflected the distribution of ant mounds, while PC4 (10.2%) was linked to wet micro-habitats. The PCA biplot (Figure 5) showed that deadwood elements and micro-topographic structures clustered along the same axis, while branch piles were positioned separately. Ant mounds and wet micro-habitats, in contrast, occupied more independent dimensions. These findings reveal that small structural elements contribute to habitat heterogeneity in complementary but distinct ways.

The rarefaction curve plateaued at 12 structure types (Figure 6), confirming adequate sampling effort. A Chi-square test showed significant variation across plots ($\chi^2 = 321.0$, $df = 39$, $p < 0.001$). The Kruskal–Wallis test ($H = 10.35$, $p = 0.016$) indicated spatial heterogeneity among four geographic sectors.

The five structural clusters identified through hierarchical cluster analysis (Figure 3) reflected compositional differences in ground-level microhabitat structures among the 40 plots. Variation among clusters was primarily driven by differences in coarse woody debris (e.g., snags and logs), micro-topographic features (*e.g.*, small mounds and depressions), and moisture-retaining elements such as micro-pools. For example, Cluster A contained the highest proportion of small snags and mounds, while Cluster C was characterized by a near-total absence of dead wood and hydrological features. These contrasts likely reflect differences in past management intensity, natural disturbance regimes, and local geomorphological conditions.

Although environmental variables (*e.g.*, canopy cover, soil moisture, management history) were not explicitly recorded, the spatial arrangement of clusters suggests potential geographic patterns. A spatial overlay of cluster identity on the sampling plot map (not shown) indicated partial aggregation of structurally similar plots, particularly in the northwestern and southeastern sectors. This may point to landscape-scale drivers such as proximity to trails, slope position, or forest edge effects. A dedicated geospatial analysis incorporating environmental covariates is recommended for future research.

Overall, these findings suggest that while structural diversity exists, it is unevenly distributed and ecologically limited in scope. Restoration measures are urgently needed to increase the presence of naturally derived microstructures and enhance habitat complexity for forest-dwelling taxa.

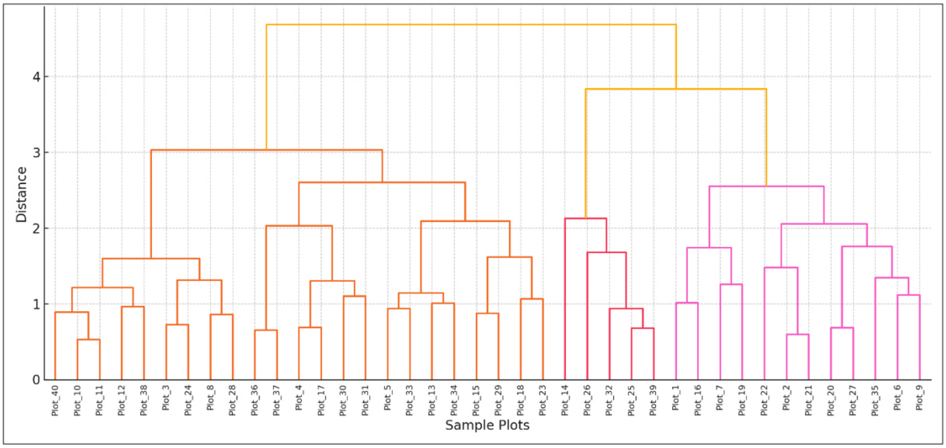

Figure 3: Jaccard dendrogram based on ground-level habitat microstructure composition. Hierarchical clustering of sample plots using the Jaccard similarity index derived from presence–absence data. Five distinct structural clusters were identified using Ward's linkage method, reflecting compositional divergence among plots.

Abbildung 3: Jaccard-Dendrogramm basierend auf der Zusammensetzung der bodennahen Habitat-Kleinstrukturen. Hierarchische Clusteranalyse von Probeflächen unter Verwendung des Jaccard-Ähnlichkeitsindex, abgeleitet aus Präsenz/Absenz-Daten. Fünf deutlich unterscheidbare Strukturcluster wurden mittels der Ward-Verknüpfungsmethode identifiziert und spiegeln die Unterschiede in der Zusammensetzung zwischen den Flächen wider.

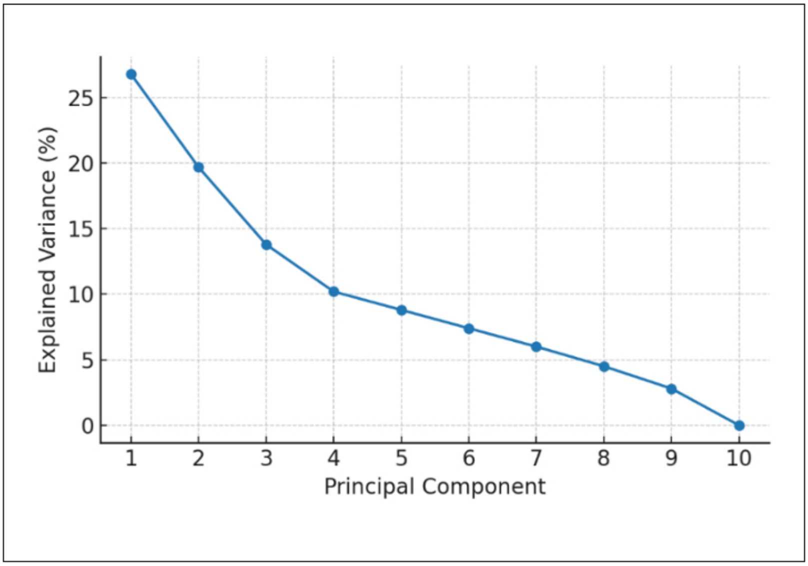

Figure 4: Scree plot showing explained variance by principal components.

Abbildung 4: Scree-Plot mit der durch die Hauptkomponenten erklärten Varianz.

Table 3: Principal components, eigenvalues, and explained variance (%).

Tabelle 3: Hauptkomponenten, Eigenwerte und erklärte Varianz (%).

Principal Component	Eigenvalue	Explained Variance (%)	Cumulative Variance (%)
PC1	2.68	26.8	26.8
PC2	1.97	19.7	46.5
PC3	1.38	13.8	60.3
PC4	1.02	10.2	70.5
PC5	0.88	8.8	79.3
PC6	0.74	7.4	86.7
PC7	0.60	6.0	92.7
PC8	0.45	4.5	97.2
PC9	0.28	2.8	100.0
PC10	0.00	0.0	100.0

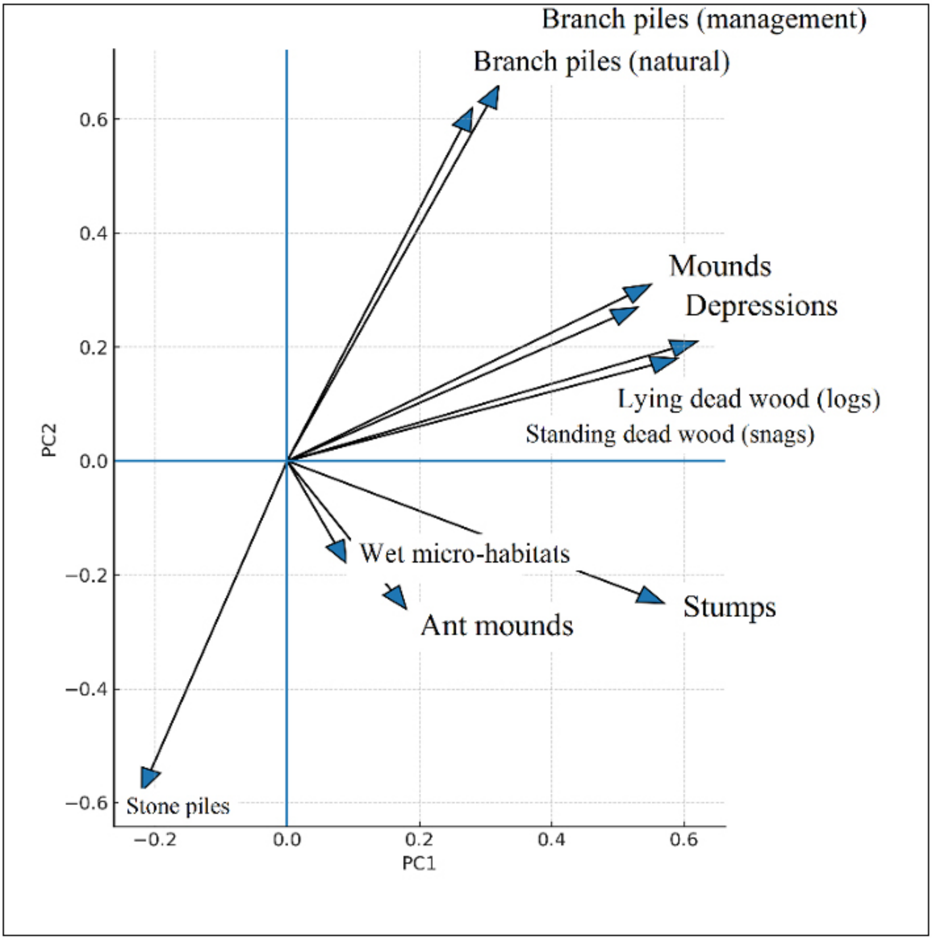

Figure 5: PCA biplot of sample plots and small structural elements (with arrows).

Abbildung 5: PCA-Biplot der Stichprobenflächen und kleinen Strukturelemente (mit Pfeilen).

Table 4: Variable loadings of small structural elements on principal components.

Tabelle 4: Variablenladungen der kleinen Strukturelemente auf die Hauptkomponenten.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Lying dead wood (logs)	0.62	0.21	-0.13	-0.31	0.40	-0.28	0.35	-0.32	-0.18	-0.10
Standing dead wood (snags)	0.59	0.18	0.26	-0.33	-0.41	0.38	-0.24	0.29	-0.19	0.21
Stumps	0.57	-0.25	0.19	0.42	-0.36	-0.22	0.44	-0.21	0.32	0.20
Mounds	0.55	0.31	0.40	-0.29	0.33	0.22	-0.27	0.39	-0.21	-0.28
Depressions	0.53	0.27	-0.38	0.22	-0.29	0.46	0.31	-0.25	0.28	-0.30
Brash piles (management)	0.32	0.66	0.18	0.25	0.42	-0.39	-0.29	0.24	-0.19	0.31
Branch piles (natural)	0.28	0.62	-0.22	0.44	-0.38	0.41	0.25	-0.35	0.29	-0.20
Ant mounds	0.18	-0.26	0.68	0.31	-0.33	-0.28	-0.22	0.38	0.24	0.36
Stone piles	-0.22	-0.58	0.29	-0.41	0.35	-0.31	0.42	0.20	-0.37	0.21
Wet micro-habitats	0.09	-0.18	-0.21	0.61	0.39	0.42	-0.36	0.28	0.27	-0.26

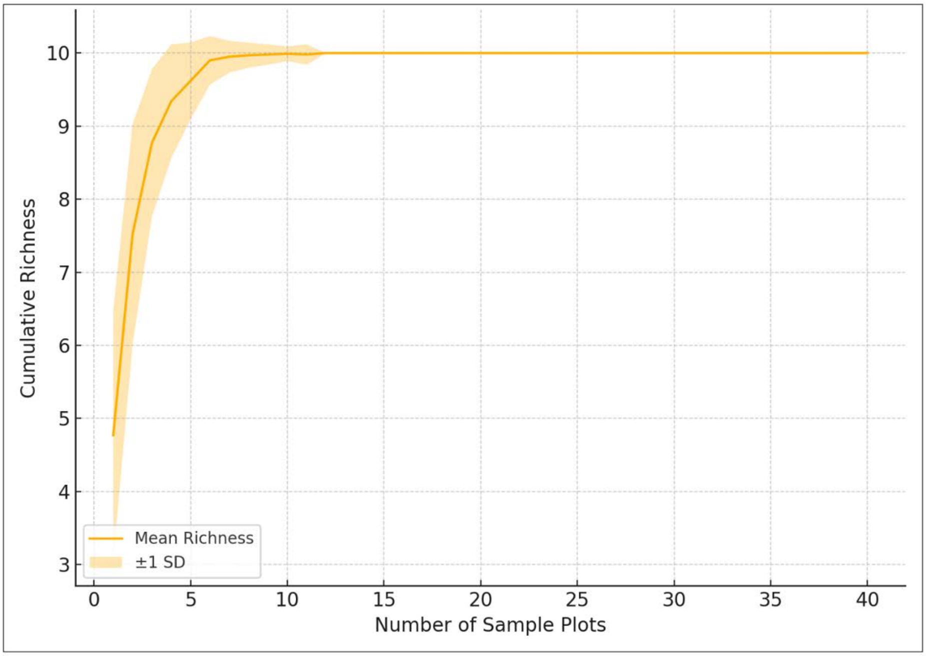

Figure 6: Rarefaction curve of ground-level habitat microstructure richness. Accumulated richness curve based on presence data from 1 to sample plots. The curve approaches an asymptote after approximately 12 sampling plots, suggesting that microhabitat richness was adequately captured and sampling effort was sufficient.

Abbildung 6: Rarefaktionskurve der Vielfalt bodennaher Habitat-Kleinstrukturen. Akkumulationskurve der erfassten Strukturvielfalt basierend auf Präsenzdaten aus 1 bis Probeflächen. Die Kurve nähert sich nach etwa 12 Probeflächen einem Plateau an, was darauf hindeutet, dass die Vielfalt der Mikrostrukturen ausreichend erfasst und der Stichprobenumfang angemessen war.

4 Discussion

4.1 Structural degradation and spatial patterns of microhabitats

This study, conducted in the Belgrade Forest, assessed the presence, spatial distribution, and structural diversity of ground-level habitat microstructures. Preliminary analyses revealed significant structural degradation. A Chi-square test on ground-level habitat microstructure frequencies showed significant variation across plots ($\chi^2 = 321.0$, df = 39, $p < 0.001$), indicating clustering of certain types and the absence of others. This spatial heterogeneity was supported by low Jaccard similarity coefficients (mean = 0.31, range = 0.11–0.67), and hierarchical clustering grouped plots into five structural categories.

Diversity indices further underscored structural limitations. Shannon values ($H' = 2.05–2.31$) and Simpson indices ($1–D = 0.82–0.86$) indicated moderate diversity and evenness. Despite relatively balanced distributions within individual plots, ground-level habitat microstructures were scarce overall, pointing to reduced forest-scale complexity. Rarefaction analysis confirmed the presence of 12 microhabitat types across 40 plots. However, a Kruskal–Wallis test ($H = 10.35$, $p = 0.016$) revealed significant richness disparities, reinforcing spatial imbalance.

4.2 Legacy effects of historical management on microstructure diversity

The fragmentation and inconsistency of ground-level habitat microstructures are likely the result of historical forestry practices that prioritized timber production and aesthetic values over biodiversity. Mid-20th-century "clean management" practices, which removed dead wood and homogenized forest stands, contributed to the degradation of the forest floor. Although Belgrade Forest was once strictly protected due to its hydrological importance (functioning historically as a critical water catchment supplying reservoirs and aqueducts essential to Istanbul's urban water system) disturbances intensified after World War I and during the early Republican period, driven by firewood collection, mining, and infrastructure projects. Even with later restoration efforts, ground-level habitat microstructures remained neglected in forest management practices.

4.3 Current structural gaps and ecological functionality of microstructures

This reflects a departure from a long-standing legacy of ecological stewardship spanning the Byzantine, Ottoman, and early Republican periods. Once a sanctuary safeguarding Istanbul's water supply, Belgrade Forest now faces increasing urban pressure. Future restoration efforts must go beyond broad forest management approaches and incorporate microhabitat-scale interventions. Priority should be given to the reintroduction of dead wood, enhancement of topographic variation, and creation of wet micro-sites. Integrating ecological restoration with historical identity could position Belgrade Forest as a living example of heritage-based conservation.

Despite their ecological importance, none of the surveyed ground-level habitat microstructures received a "High" quality rating. Four out of eight types (including large logs, snags, micro-pools, and ant mounds) were found in fewer than 25% of plots, qualifying as "Very Low." Only microtopographic mounds achieved a "Moderate" frequency rating (50%). Features such as small depressions (40%) were more common, likely due to geophysical origins. In contrast, ecologically critical features (coarse dead wood, perennial micro-pools, and branch piles) were rare.

The combined evaluation of field observations and PCA results demonstrates that small structural elements play a multidimensional role in shaping forest habitat structure. PC1 (26.8%) represents a suite of elements (lying dead wood, standing dead trees, stumps, mounds, and depressions) that typically arise from natural deadwood dynamics and uneven terrain. These features contribute substantially to biodiversity by creating heterogeneous conditions, particularly important for saproxylic species. The co-occurrence of deadwood with topographic irregularities often generates diverse habitat configurations. For example, depressions beneath logs or standing snags provide ecological functions such as shelter and nesting opportunities for a wide array of organisms. PC2 (19.7%) highlights the ecological role of branch piles, formed either naturally or through management activities. However, these elements are frequently removed due to forestry operations or recreational use, resulting in a patchy distribution across the forest landscape. In contrast, stone piles, though less common, constitute distinctive microhabitats that remain ecologically separated from other structural elements. The absence of multiple structural elements within the same plots reflects the strong influence of human activity on forest ecosystems. Together, naturally occurring features and management-related structures create a complex mosaic, shaped by the interplay of ecological processes and anthropogenic interventions. Although relatively rare, PC3 (13.8%, ant mounds) and PC4 (10.2%, wet micro-habitats) represent highly specialized habitats. Their presence underscores the need to safeguard even infrequent structural elements, as they provide critical niches for specialized species. Overall, the findings suggest that conserving a single type of structural element is insufficient. At the local scale, the joint protection of deadwood and micro-topographic features is essential, whereas at broader scales, stone piles, branch piles, and other specialized habitats must also be preserved within a mosaic framework. Thus, sustainable forest management requires an integrative perspective that recognizes the ecological importance of both natural and management-derived structures.

4.4 Drivers of microstructure scarcity: anthropogenic and ecological factors

The near absence of branch and brash piles in the Belgrade Forest indicates a strong suppression of dead wood accumulation dynamics, despite their well-known role in biodiversity support, nutrient cycling, and microsite heterogeneity. For example, Castillo-Escrivà *et al.* (2018) showed that purposefully constructed branch piles in semiarid landscapes attracted frugivorous birds and enhanced seed rain, acting as restoration nuclei. In our study area, piles were rare, spatially limited, and always rated "Very low" in frequency, suggesting minimal habitat or restoration value.

In urban and peri-urban forests, public use pressure likely contributes to this scarcity: visitors may collect branches for firewood or inadvertently disturb piles, while forest management operations often remove or damage them during harvesting. Similar restoration approaches in Central European light-woodlands, such as brush piles for reptiles (Völkl *et al.*, 2007), illustrate how intentional design can enhance habitat diversity. Aldridge *et al.* (2020) found that most brush piles degraded within two years, losing essential interstitial space. Practical guidelines (Virginia Department of Forestry, 2015) recommend rot-resistant base logs, interlaced layers, and periodic renewal to maintain ecological function. According to Wieselnetz (2009), effective piles should include multiple layers, elevated bases, and internal cavities, reaching at least one metre in height. None of these attributes were observed in our plots, which likely limits their habitat value.

Stumps occurred in 82.5% of plots, meeting the "High" threshold but were excluded from assessment due to anthropogenic origin and low complexity. No naturally formed stumps were found. Logging stumps, typically low-cut and smooth, offer limited ecological value compared to naturally broken stumps with irregular forms and decay niches. Nevertheless, in managed forests lacking natural stump formation, elevated and structurally modified anthropogenic stumps could serve as provisional substitutes for fauna dependent on vertical dead wood. Coarse dead wood (≥10 cm) was present in only 7.5% of plots, and small snags (<10 cm) in 25%, indicating very low dead wood dynamics and a simplified forest floor. The absence of large, naturally formed logs and functional stumps suggests a structural deficit likely reducing microhabitat diversity. Dueser & Shugart (1978) demonstrated that stump and log density and arrangement strongly influence small mammal habitat use.

Water-retaining features were also scarce; only mounds and small depressions reached "Low" or "Moderate" ratings. This loss of microtopographic heterogeneity may affect fauna reliant on ground-level complexity. Arslangündoğdu (2010) documented 146 bird species in Belgrade Forest, with seasonal variation likely tied to such features. The few shallow depressions observed could offer seasonal water retention, consistent with Liang *et al.* (2023), who found that surface depressions delayed runoff and increased water storage. Similarly, Barker Plotkin *et al.* (2017) showed that pit–mound structures enhance soil processes and biodiversity, with their size strongly linked to tree diameter. Intensive silviculture and removal of large-diameter trees in the Belgrade Forest have reduced the frequency and scale of these features, a legacy effect noted by Barker Plotkin *et al.* (2017). Restoration aiming to develop old-growth traits should both promote large trees and protect existing pit–mound structures.

Perennial micro-pools were nearly absent in the Belgrade Forest, with only one small pool recorded across 40 plots (2.5%), indicating a major lack of hydrologically stable ground-level habitats. These features support amphibians and other moisture-dependent taxa as breeding and refuge sites, and their scarcity likely reflects limited microtopographic variability and anthropogenic impacts on water retention. Dueser & Shugart (1978) showed that even small differences in surface moisture and structure can shape forest-floor species distributions. Similarly, Brooks & Hayashi (2002) found that shallow or small ephemeral pools often fail to retain water long enough for amphibian breeding, suggesting that depressions in Belgrade Forest may fall below such hydroperiod thresholds. Weak morphometric–hydroperiod correlations in their study highlight the influence of broader hydrological processes on pool persistence.

This absence aligns with Calhoun *et al.* (2014), who stressed that loss of small aquatic habitats under land-use pressure reduces amphibian populations and resilience. Conservation planning should prioritise restoring such features to improve hydrological retention and habitat heterogeneity in urban and peri-urban forests. Retaining well-distributed large-diameter trees could help, as their natural fall would add dead wood and create pit–mound topography, enhancing forest structure.

Şahin (2022) reported similar human-linked ecological disturbances in riparian zones. Verein biodivers (2022) also emphasised that both quality and density of microstructures determine ecological function—both lacking in our plots, where 75% of sites had two or fewer functional types.

Stone piles were absent in all 40 plots, indicating both ecological degradation and historical land-use pressures typical of peri-urban forests. These small abiotic structures provide shelter, crevices, and thermally buffered zones for vertebrates and invertebrates (KARCH, 2011; Merkblatt für ökologisch wertvolle Steinhaufen, 2017; Rossier *et al.*, 2021). Central European habitat guidelines note their role as critical microhabitats for reptiles, amphibians, invertebrates, and small mammals (Merkblatt für ökologisch wertvolle Steinhaufen, 2017; Rossier *et al.*, 2021). Their absence likely reduces structural and functional heterogeneity.

The lack of old-growth trees (often responsible for exposing embedded stones through uprooting) may limit stone pile formation. Past extraction for historic construction (*e.g.*, dams, aqueducts) could also explain the deficit (KARCH, 2011; Rossier *et al.*, 2021). Similar losses have been reported in forest edges subject to canopy closure, disturbance, and mechanical clearing (Fuhrer *et al.*, 2008; Dölle *et al.*, 2022). These structures buffer temperature extremes and support thermophilic species (Dölle *et al.*, 2022).

Best-practice guidelines recommend constructing piles with internal chambers, varied entry sizes, and thermal mass to benefit multiple species (Wieselnetz, 2009). WWF (2020) stresses the biodiversity and substrate complexity value of large stones, while Völkl *et al.* (2007) show that coarse stone piles in sunny forest edges enhance edge-zone biodiversity, including for target reptiles such as Vipera berus. Restoration or reintroduction of stone piles in forest margins and canopy gaps could thus help recover microhabitat diversity and ecological resilience.

Ground-level habitat microstructures serve as essential connectors or stepping stones that aid species movement in fragmented habitats—a role especially crucial in peri-urban forests like Belgrade. Our findings mirror boreal forest studies showing that intensive management reduces mound and branch pile presence (Kilpeläinen *et al.*, 2021). Labiola guidelines highlight that even simple features such as stone piles and ant mounds support high biodiversity (Labiola, 2016, 2023). Swiss biodiversity recommendations suggest maintaining at least three ecologically functional microstructure types per 30 ares as a conservation target. Although this study did not explicitly adopt this threshold, such guidelines provide useful reference points for interpreting structural diversity in Belgrade Forest. These microstructures support nesting, foraging, shelter, and natural pest control. Ant mounds improve soil aeration and serve as keystone structures (Tschinkel, 2015). Our results align with boreal forest surveys showing low frequency of ant mounds in managed or fragmented landscapes, with most plots containing none or only a few (Punttila & Kilpeläinen, 2009). Ambach (2009) emphasized that intensive forest use and fragmentation in Austria have led to declines in mound-building Formica species, especially in lowlands where dense canopy and disturbances suppress nest persistence. Scarcity of ant mounds may reflect local absence or microclimatic and structural constraints, consistent with findings by Dewes (2006), who noted that even in diverse forests some ant species are rare or cryptic. Long-term studies in unmanaged reserves link reduced biogenic microstructures like ant mounds to habitat simplification (FVA, 2016). This supports that current mound scarcity in our study reflects habitat degradation, canopy closure, and soil disturbance. Recent research highlights Formica polyctena mounds as unique microenvironments supporting specialized fungal communities, notably Mucoromycota taxa uncommon in adjacent litter (Siedlecki *et al.*, 2024). This underscores ant mounds' role as biogenic habitat islands that maintain microclimate stability and microbial diversity, even in degraded peri-urban ecosystems. In northern systems like the Arctic tundra, sparse mound presence significantly alters local vegetation and arthropod abundance by enhancing vascular plants while suppressing mosses and lichens (Meijer, 2020). These findings support the ecological theory that wood ant mounds function as nutrient-rich microhabitats disproportionately influential relative to their size. Dead wood provides habitat for beetles, cavity-nesting birds, and fungi (Müller *et al.*, 2008; Seibold *et al.*, 2015), but in our study 58% of logs and snags were isolated and lacked key traits such as root plates or moss cover needed for functionality (Müller *et al.*, 2007; Bujoczek *et al.*, 2021). These patterns mirror Central European observations (Ambach, 2009) and highlight the need to incorporate ant mound dynamics into forest biodiversity assessments. Similarly, forest edge quality studies in Central Europe show that absence of small biogenic structures like ant mounds and dead wood clusters correlates with ecologically impoverished forest edges (Fuhrer *et al.*, 2008).

4.5 Restoration priorities and conservation ımplications

Micro-pools were notably deficient in the study area, with only six recorded and none retaining visible water beyond early spring, indicating a clear hydrological imbalance. This pattern aligns with unsustainable habitat conditions reported elsewhere in Europe, often linked to historic overexploitation and altered hydrological regimes (Ammer, 1991; Jedicke, 1995; Möller, 1994). In contrast, forest conservation models from Germany and Switzerland emphasize the preservation and restoration of microstructures as essential components of forest ecosystem health (SVS, 2006; Müri, 2012; König & Chevillat, 2017). Increasingly, structural diversity is recognized as equally important as species richness for maintaining resilient forest ecosystems (Malcolm & Hunter, 1999).

The discrepancy between our findings and international benchmarks highlights an urgent need for standardized criteria addressing microstructure presence and quality within Turkish forestry practices. As Kırca (2009) emphasized, ongoing urbanization and infrastructure development have fragmented the Belgrade Forest, exacerbating habitat simplification. Restoration efforts should prioritize enhancing structural diversity by reintroducing dead wood, creating and maintaining wet micro-sites, and increasing microhabitat complexity. Importantly, these features must be distributed in functional networks to support species movement and ecosystem processes. König and Chevillat (2017) recommend spatial arrangements such as 20-30 meter spacing of species-specific microhabitats (*e.g.*, stone piles for reptiles and moist logs for amphibians) to maximize ecological benefits.

Our data revealed that 65% of plots contained one or fewer functional microstructures per 100 m^2, falling short of connectivity and habitat heterogeneity standards essential for biodiversity conservation. Protecting forest extent alone is insufficient; maintaining and restoring internal structural complexity is critical. Microstructures, despite being cost-effective restoration targets, hold disproportionately high ecological value. Yet, in Belgrade Forest, most microhabitat features are degraded; only mounds achieved a "Moderate" quality rating. The near-complete absence of quality dead wood and persistent micro-pools calls for immediate, scientifically informed restoration interventions.

This degradation is particularly alarming in a forest with significant historical and ecological value. Similar declines in habitat complexity have been documented along the edges of Belgrade Forest (Tüfekçioğlu, 2013), with Çolak *et al*. (2022) emphasizing forest edges as vital biodiversity corridors that require targeted rehabilitation. Studies on altitudinal variation in edge habitats (Özdemir Kurt, 2019; Yoran-Susuz, 2019) further support the ecological importance of structurally rich edges.

European studies demonstrate that even limited additions of microstructures per hectare can sustain rare and specialized species (Riedel *et al.*, 2022). Moreover, Dross and Dunger (2023) stress the critical role of dead wood for saproxylic and soil fauna—groups notably underrepresented in our findings. Indeed, 87.5% of plots scored below 2.0 (on a 5-point scale) for saproxylic habitat availability, indicating severe resource deficits. Integrating microstructure restoration into forest management planning is essential to safeguard the ecological integrity and biodiversity of ancient forests such as Belgrade.

The current structural impoverishment in Belgrade Forest underscores the urgent need for proactive restoration and habitat enhancement measures centered on ground-level habitat microstructures. Despite moderate diversity indices at the plot level, our systematic inventory revealed a stark scarcity and uneven distribution of key microstructural elements (particularly coarse dead wood, perennial micro-pools, and branch piles) highlighting the long-term ecological simplification driven by past forestry practices, urban encroachment, and hydrological disruption (Ammer & Utschick, 1990; Kırca *et al.*, 2013; Tüfekçioğlu, 2013).

These findings align with broader European recommendations advocating for a two- to threefold increase in ground-level habitat structures across forested landscapes (Verein biodivers, 2022). In particular, the near-complete absence of perennially wet microsites and stone piles eliminates critical refugia that contribute to microclimatic buffering, species dispersal, and ecological stability (Dueser & Shugart, 1978; Merkblatt für ökologisch wertvolle Steinhaufen, 2017; Rossier *et al.*, 2021; Joshi *et al.*, 2023).

Given the ecological importance of these microstructures, their restoration should be prioritized in forest management plans, particularly in peri-urban forests facing ongoing anthropogenic pressures. Enhancing habitat heterogeneity through targeted microstructure reintegration promises to support biodiversity resilience, improve connectivity, and maintain ecosystem functions critical to the long-term health of Belgrade Forest.

Microstructures like pit-and-mound topography, ant mounds, coarse woody debris, and moist depressions are key to forest ecosystem functions such as nutrient cycling, soil formation, and habitat provision (Basile *et al*., 2020; Gibb *et al.*, 2021; Seibold *et al.*, 2015; Tschinkel, 2015). Statistical analyses confirmed notable structural heterogeneity and fragmentation (Punttila & Kilpeläinen, 2009; Dölle *et al.*, 2022).

This study fills a gap by focusing on ground-level microstructures, distinct from tree-related microhabitats (TreMs), which have been studied more extensively (Müller *et al.*, 2008; Larrieu *et al.*, 2018). Building on Ibáñez and Schupp (2002), we quantitatively assessed the spatial diversity of these features, highlighting their ecological importance, especially in urban and peri-urban forests.

Microstructures are low-cost, adaptable, and compatible with routine forestry practices (Dross & Dunger, 2023; Riedel *et al.*, 2022). Measures like dead wood retention and root plate preservation, successfully implemented in Germany, provide clear ecological benefits (Landesforst MV, 2021; SVS, 2006). Additionally, their visibility and accessibility make them valuable for public education and conservation outreach (Verein biodivers, 2022).

To institutionalize these benefits, microstructures should be formally integrated into national forest policies. A Turkish ground-level microstructure guideline, adapted from successful Central European models, would fill a major policy gap. Key recommendations include:

1. Deliberate retention and design of coarse dead wood and branch piles (Seibold *et al.*, 2015),
2. Preservation and creation of pit-and-mound microtopography (Barker Plotkin *et al.*, 2017),
3. Construction of stone piles in forest edges and canopy openings (Rossier *et al.*, 2021; Merkblatt für ökologisch wertvolle Steinhaufen, 2017),
4. Protection and enhancement of wet micro-sites (Liang *et al.*, 2023).

The ecological degradation in Belgrade Forest must be viewed within its historical context. Once protected under Roman, Byzantine, and Ottoman water laws (including the 1733 firman of Sultan Mahmud I) it served as a vital hydrological sanctuary for centuries (Kırca *et al.*, 2013). The shift to mid-20th-century "clean forestry" marked a break from this legacy. Restoring ground-level habitat features is thus both an ecological and cultural responsibility.

Current threats such as recreation, branch removal, and off-road vehicles continue to reduce the already limited microstructure diversity (Kırca, 2009; Kırca *et al.*, 2013). Management practices prioritizing cleanliness and aesthetics have often led to the loss of ecologically valuable structures.

Structural patterns in Belgrade Forest likely reflect broader trends in other managed and peri-urban Turkish forests. Expanding microstructure inventories across regions is essential (Müller & Bütler, 2010; Kilpeläinen *et al.*, 2021). Restoration priorities focus on protecting existing dead wood, re-establishing perennial micro-pools, and creating branch piles, mounds, and depressions—low-cost actions with high ecological benefits.

Globally, forest management should increasingly integrate structural microhabitats into conservation and restoration, especially in historically managed and peri-urban forests. Future research should monitor restored microstructures' functionality and incorporate microhabitat mapping into biodiversity planning.

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Data availability

No datasets were generated or analysed during the current study.

Declaration

The authors declare no competing interests.

Competing interests

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Authors' contributions

S.Y. conducted the fieldwork and prepared the initial draft of the manuscript. S.Y. and A.H.Ç. wrote the main manuscript text. A.H.Ç. reviewed and revised the manuscript for intellectual content. All authors approved the final version of the manuscript.

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