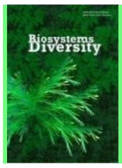

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Tree stand structure drives hemeroby and naturalness, jointly shaping the functional diversity of the herb layer in urban parks

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Urban parks play a vital role in providing essential ecosystem services, including the maintenance of biodiversity and the enhancement of urban well-being. We analysed how variations in tree stand structure influence microclimate, hemeroby, naturalness, and the functional diversity of the herbaceous layer in two parks in Dnipro, Ukraine. Denser and more diverse tree stands with a higher leaf area index created cooler and moister understory conditions with reduced light, whereas open and homogeneous stands produced hotter, drier, and more brightly lit patches. Tree stand structure drove microclimatic contrasts that underpinned the hemeroby–naturalness gradients of the herb layer: Shaded, humid interiors supported communities dominated by native perennial species of higher naturalness, while exposed, warm, and dry sites beneath open canopies were occupied by ruderal and adventive species indicative of high hemeroby. In this framework, hemeroby reflects the degree of anthropogenic transformation of the herb layer, whereas naturalness captures the retained memory of its near-natural state. Hemeroby and naturalness were found to jointly shape the functional diversity of the herb layer: Disturbed sites favoured short-lived, light-demanding species with high dispersal potential, elevated leaf nitrogen content, and persistent seed banks, whereas more natural sites were characterised by taller perennials with more conservative leaf traits. Using Structural Equation Modelling, we demonstrate that these effects can be described by four main gradients linking stand density/thinning, stand diversity, and cooling versus heating potential to herb layer functional richness, evenness, and divergence. Our results show that tree stands do not merely “matter” in a general sense but actively engineer the microclimate, degree of anthropogenic transformation, and functional composition of the herbaceous layer. This understanding provides a biologically grounded basis for park management that utilises stand structure to enhance biodiversity and stabilise ecosystem services in urban green spaces.

Keywords: hemeroby; naturalness; urban green space; functional traits; structural equation modelling.

Introduction

Urban parks provide numerous ecosystem services that enhance the environment and quality of life in urban areas (Molozhon et al., 2023a). They hold significant aesthetic and cultural value and contribute to the conservation of biodiversity (Myalkovsky et al., 2023). Parks assist in alleviating the urban heat island effect, decreasing stormwater runoff, absorbing pollutants like gases and dust, and can also capture heavy metals (Nowak & Crane, 2002). One of the critical ecological functions of parks is the removal of greenhouse gases, mainly through the ability of trees to absorb carbon dioxide (Lemanowicz et al., 2020). The influence of tree stands on other ecosystem elements, including microclimatic conditions, soil composition, and herbaceous cover, is crucial for the overall functioning of park stands (Komlyk et al., 2024). Urban parks provide a variety of ecosystem services, including the purification of water and air, the reduction of wind and noise, carbon sequestration, microclimate regulation, habitat provision for wildlife, recreational opportunities and the establishment of conditions that promote the social and psychological well-being of city residents (Mexia et al., 2018). The quantity and quality of these ecosystem services depend on the structure of the park's plantings. A diverse array of tree-planting strategies can be employed to optimize specific ecosystem services, such as air purification and mitigating urban heat island effects (Bodnaruk et al., 2017). However, these strategies must also consider how a park's stand structure influences the functioning of other park components, which can either facilitate or hinder the intended outcomes of park design.

The forest canopy significantly influences the environment by determining light availability, resource allocation, microclimate variability, and biotic interactions (Lenk et al., 2024). These interactions, in turn, shape the functional diversity of herbaceous plants (Zheng et al., 2022). The tree canopy in urban parks, comprising natural wooded areas and tree plantations, significantly influences environmental regimes (Kunakh et al., 2021). The density and species composition of the tree canopy in urban parks significantly affect illumination levels (Öztürk & Ağırtaş, 2021). A dense tree cover creates favorable conditions for herbaceous species that are adapted to shady environments (Nieto-Lugilde et al., 2015), while a sparse tree cover fosters an environment that supports light-loving species, thereby enhancing plant community diversity (Ren et al., 2022; Kunakh et al., 2023). The accumulation of leaves and other organic residues beneath the canopy forms a litter layer that significantly influences the composition and productivity of herbaceous plants (Rawlik et al., 2018). Nutrient-rich tree litter promotes the growth of herbaceous species with high ecological demands for soil fertility (González et al., 2022), while dense tree litter layers can inhibit the germination of less competitive species (Zhang et al., 2022). Competition for resources between trees and herbaceous plants can restrict access to water and minerals for less resilient species (Nambiar & Sands, 1993), thereby altering the functional diversity of the herbaceous cover (Reczyńska et al., 2022). The microclimatic effects of the tree canopy regulate temperature and humidity (Meili et al., 2021), creating favourable conditions for moisture-loving and temperature-sensitive herbaceous species (Verheyen et al., 2024). In urban parks with a more diverse tree composition, a mosaic of conditions is established that supports the growth of herbaceous species with varying ecological adaptations (Dylewski et al., 2023). The predominance of homogeneous plantations or species with allelopathic effects can limit the functional diversity of herbaceous vegetation (Xu et al., 2023). It is crucial to recognize the significant anthropogenic pressures that parks face, as reflected in the concepts of hemeroby and naturalness. Anthropogenic factors, such as recreational pressure and changes in the physical state and chemical composition of the soil and climate, interact with the influence of the tree canopy to affect the functional diversity of the herbaceous cover. The term 'hemeroby' is employed to indicate the degree of anthropogenic transformation of the ecosystem, whereas 'naturalness' is used to indicate the level of departure from the most natural state of the ecosystem (Fehrenbach et al., 2015). Further research is needed to elucidate the impact of hemeroby and naturalness on the ecosystem functions of urban parks (Tkachuk et al., 2024). Urban parks have the capacity to resist hemeroby, and their naturalness is a source of enhanced beneficial ecosystem services.

The diversity of herbaceous communities within parks plays a crucial role in ensuring the efficiency and sustainability of ecosystem functions (Paudel & States, 2023), and holds significant aesthetic value in urban settings (Ignatieva & Hedblom, 2018). The varied perennial herbaceous communities found in urban environments can contribute to biodiversity conservation, water resource preservation, and the protection of culturally significant flora (Norton et al., 2019). The presence and biodiversity of herbaceous cover in urban parks create opportunities for physical activity and recreation, which, in turn, provide health benefits that positively affect the immune function of visitors (Lai et al., 2019). Parks and green spaces should be designed to provide adequate leisure facilities, as well as opportunities for physical activity. This can be accomplished by ensuring that sufficient herbaceous cover is available for individuals who enjoy passive leisure activities. The aesthetic quality of urban parks is enhanced by the presence of trees arranged in strips or groups, rather than by the uniform coverage of grass (Aboufazeli et al., 2024). Limitations in solar radiation due to variations in tree density can diminish the recreational and aesthetic functions of park plantations and hinder the development of herbaceous cover (Dąbrowski, 2013). Further investigations are necessary to assess the relationships between tree stands and herbaceous cover in parks, with the aim of understanding the role of these elements in providing ecosystem services.

The formation of tree stands in city parks results from a combination of factors (Wang & Zhang, 2022; Molozhon et al., 2023b). Park plantations can be established based on the remnants of the natural forest vegetation that previously existed at the site (Shanahan et al., 2015). Trees in parks may be planted by humans, utilizing both native flora and non-native tree species for this purpose (Nielsen et al., 2014). The existing tree stand can be influenced by park management and reconstruction efforts (Molozhon et al., 2023a). The propagation and spread of both native and non-native trees can occur spontaneously within a park as a result of biological processes (Padayachee et al., 2017). These processes contribute to a complex mosaic in the structure of the park's tree stand, which can be quantified. A key factor in the variability of park plantations is the alteration in stand density. Tree stand density is an essential marker for understanding the structure of natural forests and urban parks alike (Burkhart, 2013). The results indicate that stand density variability is associated with changes in stand diversity and crown openness. Alterations in stand density influence the distribution of environmental factors such as light, temperature, and humidity of soil and air (Moreno & Cubera, 2008). The modification of environmental conditions caused by trees significantly influences both the growth dynamics of woody plants (Martín-Benito et al., 2010), and the comfort levels experienced by visitors in urban parks (Talal et al., 2021). The density and diversity of tree stands influence the physical and chemical properties of the soil (Forrester et al., 2013), the carbon content and primary productivity of ecosystems (Cai et al., 2016), and the phytomass of herbaceous cover (Li et al., 2022; Tutova et al., 2025). The density of a stand plays a crucial role in determining the amount of space available for plant growth within the community (Farooq et al., 2021) and the natural resources accessible to individual trees (Lochhead & Comeau, 2012). Elevated stand density also intensifies competition for space and resources among individual trees, thereby inhibiting overall stand growth (Mäkinen & Hein, 2006).

The herbaceous cover observed in urban parks can be categorized into two main types: natural and adventive (Bayón et al., 2021). The proportions of these categories indicate the extent to which the plant communities deviate from their natural state. The presence of non-native plant species in urban parks results from the availability of unoccupied niches, as well as the relatively favourable soil and water conditions that support plant survival. Non-native plants can be found in various elements of urban parks, including lawns, flower beds, tree plantations, and hedges (Li et al., 2019; Tkachuk et al., 2024). The proliferation of non-native species in urban parks is a natural phenomenon that occurs without the need for additional financial or labour resources. However, the ecological benefits of these plants should not be overlooked. They play crucial roles in mitigating urban heat, sequestering carbon, preventing erosion, retaining stormwater, and regulating noise levels (Robinson & Lundholm, 2012). Furthermore, weeds provide a habitat for wildlife (Ilie & Cosmulescu, 2023). The phenomenon of global climate change has led to a significant expansion of summer weather patterns, which has, in turn, facilitated the spread of non-native plant species in urban parks. This proliferation of non-native plants may also contribute to the enhancement of ecosystem services in a warming climate (Tredici, 2010). Biological traits influence the distribution of spontaneous plants within urban tree plantations (Omar et al., 2018). The functional diversity of parks is responsive to the landscape matrix (Czortek & Pielech, 2020).

The functional traits of a species are defined as morphological, physiological, or phenological features that directly or indirectly influence an organism's functional capacity, including its ability to grow, reproduce, and survive (Violle et al., 2007). The examination of the functional traits of plants revealed their capacity to adapt to diverse environmental conditions, thereby elucidating the various biological strategies employed by species for dispersal and reproduction (Asanok et al., 2013). These functional traits serve as the foundation for calculating indices of functional diversity within communities (Schleuter et al., 2010). The functional diversity of plant communities serves as an indicator of their capacity to adapt to environmental conditions and to perform essential ecosystem functions. The way of dissemination of seeds and fruits or their morpho-physiological features illustrate the influence of various environmental factors on plant reproduction and the interconnectivity between plants and animals (Galetti et al., 2013). The observed changes in leaf morphology may indicate degradation processes induced by nutrient enrichment or salinity (Wright et al., 2013). Environmental disturbance is a physical force, agent or process, of either abiotic or biotic origin, which produces a perturbation (including stress) in an ecological system relative to a specified reference state (Rykiel, 1985). Environmental disturbances lead to abiotic filtration, resulting in the formation of communities dominated by species that have adapted to these perturbations and share similar characteristics (Ding et al., 2012). The invasive nature of a plant can be assessed through various traits. Invasive species often grow more rapidly than native species. Additionally, these invasive plants frequently exhibit a larger specific leaf area, a longer flowering period, greater fecundity, and more efficient seed dispersal (Pyšek & Richardson, 2008). The functional traits of invasive plant species serve as proxies for evaluating their impacts on a range of ecosystem services (Milanović et al., 2020). Numerous metrics for measuring functional diversity have been developed, which can be categorized into three groups, each assessing a different aspect of functional diversity: functional richness, functional evenness, and functional divergence (Pakeman, 2011). Although the theoretical foundation for indicators of functional diversity is well established, there is a lack of empirical evidence regarding their actual behaviour across ecological gradients. There is limited information on changes in the indices of functional diversity of plant communities along the hemeroby–naturalness gradient. The impact of tree stands in park plantations on the functional diversity of herbaceous cover in parks remains largely unknown. Addressing these issues is crucial for gaining a deeper understanding of the dynamics of diversity and the functions of urban parks as holistic ecosystems, as well as for justifying optimal park management strategies.

The objectives of this study were to address the following questions: 1) How are microclimatic conditions within urban parks related to variations in tree stand structure, such as density, canopy openness, leaf area index, and species composition? 2) How do gradients in tree stand structure and anthropogenic pressure jointly correspond to spatial variation in the hemeroby and naturalness of the herbaceous layer in urban parks? 3) How do the functional traits and functional diversity indices of the herbaceous layer vary along gradients of hemeroby and naturalness in urban parks?

Material and methods

The study was conducted in two parks located in the city of Dnipro, Ukraine: Ivan Starov Garden Square and Studentskyi Park, each covering an area of 11.2 hectares. Ivan Starov Garden Square (48°27′ N, 35°03′ E) is situated in the historical centre of the city and has experienced a significant amount of recreational activity. By contrast, Studentskyi Park (48°25′ N, 35°02′ E) is located on the campus of Oles Honchar Dnipro National University, resulting in a considerably lower level of recreational use. The Walter–Lieth diagram (Walter & Lieth, 1960) was constructed using the climatol library on the basis of data from the Center for Environmental Data Analysis (https://data.ceda.ac.uk/). The mean annual precipitation for the period from 2018 to 2023 was 498 mm. The highest mean daily temperature recorded in August was 30.2 °C. The mean annual temperature is 11.1 °C (Fig. 1).

The vegetation cover in Ivan Starov Garden Square consists of two distinct layers: trees and herbaceous plants. The sample locations were distributed throughout the study area, and their exact coordinates were determined using GPS (Garmin eTrex, ± 5 m). At each sample site, the species composition and number of trees within a 5-meter radius were recorded, along with the number of herbaceous plants. The environmental characteristics within sampled sites were also measured. In Ivan Starov Garden Square, vegetation cover and environmental properties were measured at 150 sample sites arranged in a quasi-regular grid (Lisovets et al., 2025). The topography of Ivan Starov Garden Square is relatively flat, with elevations ranging from 115 to 128 meters. Additionally, the park management practices are relatively uniform. The sample site density in Ivan Starov Garden Square was one location per 748 m². By contrast, the geomorphological characteristics of Studentskyi Park are highly diverse, with terrain elevations ranging from 131 to 165 meters. The park has also undergone partial reconstruction (Molozhon et al., 2023a; Zhukov et al., 2023; Lisovets et al., 2024). To accommodate the observed heterogeneity, the density of the sample sites was increased. In Studentskyi Park, vegetation cover and environmental measurements were taken at 230 sample sites arranged in a quasi-regular grid, resulting in a survey density of one sample site per 501 m².

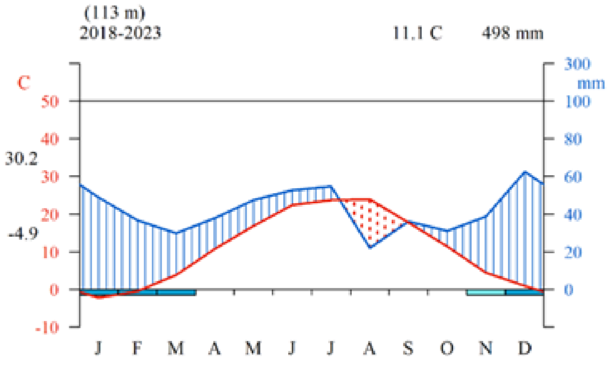

Fig. 1. Walter-Lieth diagram for the period 2018–2023. The humid period is shown in blue, the dry period is shown in red. The average rainfall in the period 2018–2023 was 498 mm per year. The highest average daily temperature recorded was 30.2°C in August, while the lowest average daily temperature was –4.9°C in January. The average annual temperature was 11.1°C

The presence of all species of vascular plants in the herbaceous layer of the 3 × 3 m *relevé* plot in the centre of each sample site was recorded during the study period, which spanned from July 7 to July 12, 2024. The projected species cover of the herbaceous plants is expressed as a percentage. Critical specimens were collected and identified using microscopy. Plant taxonomy was based on the Euro+Med Plantbase (http://ww2.bgbm.org/EuroPlusMed).

The soil moisture content was measured using an MG–44 soil moisture meter (Ukraine), with readings taken at a depth of 5–7 cm. This device has a measurement resolution of 0.1% and an associated error margin of 1%. The soil temperature within the 7–10 cm layer was assessed using a digital thermometer (TC–3M, Ukraine). The air temperature and atmospheric humidity at a height of 1.5 m were recorded with a HUATO HE–173 temperature and humidity logger (China). Illuminance at the same height was measured using an RSE–174 lux meter (Germany). The electrical conductivity of the soil was measured *in situ* with an HI 76305 sensor (Hanna Instruments, Woonsocket, RI), which operates in conjunction with a portable HI 993310 tester. This instrument is designed to evaluate the total electrical conductivity of the soil, which is defined as the combined conductivity of air, water, and soil particles. The results from this device are presented in units of soil salt concentration, expressed in grams per litter. A comparison of the HI 76305 measurements with laboratory data allowed for the estimation of the unit conversion factor, which is 1 dS/m = 155 mg/L (Pennisi & van Iersel, 2002; Yorkina et al., 2021). Within each 3 × 3 m *relevé* plot, soil and microclimatic properties were measured at five positions (one in each corner and one in the centre). For each variable, the five readings per plot were averaged and the plot-level mean value was used in the subsequent analyses. The data on the environmental properties were subjected to principal component analysis.

The crown cover of the tree stand (hereafter referred to as "the Cover") was evaluated through visual inspection, with the results expressed as a percentage. The canopy structure and gap light transmission indices were extracted from true-colour fisheye photographs using Gap Light Analyzer (GLA) software. The use of hemispherical smartphone photography allowed for a rapid assessment of the forest canopy and light regime. This method serves as a suitable alternative to traditional camera-based hemispherical photography, providing comparable results in a more efficient and cost-effective manner (Bianchi et al., 2017). The following indices were evaluated. Canopy openness, expressed as a percentage, indicates the proportion of the open sky visible beneath the forest canopy. This index is calculated exclusively from a hemispherical photograph and does not account for the influence of the surrounding topography. The Leaf Area Index (LAI) represents the effective leaf area integrated over zenith angles ranging from 0° to 60° (Stenberg et al., 1994). Direct transparency refers to the amount of direct solar radiation transmitted through the canopy, measured in moles per square meter per day (mol/m²/day). Diffuse transparency denotes the amount of diffuse solar radiation transmitted by the canopy, also measured in moles per square meter per day (mol/m²/day). Total transparency (Trans) is the sum of both direct and diffuse transparency, expressed in moles per square meter per day (mol/m²/day). Tree density (number of trees per plot) was considered a structural attribute of the stand and an indicator of management (thinning intensity), not a proxy for microclimatic conditions. Light availability, air and soil temperature, and soil moisture were measured directly and analysed as microclimatic variables.

In each 3 × 3 m plot, herb-layer height (canopy height of the dominant grasses and forbs) was measured at five positions (one in each corner and one in the centre), and the mean of these five measurements was used in the analyses. The following morphological parameters were considered functional properties of plants: leaf area (mm²), leaf area per leaf dry mass (mm²/mg), leaf dry mass per leaf fresh mass (mg/g), leaf nitrogen (N) content per leaf dry mass (mg/g), plant height (cm), seed mass (g), and phenological parameters, including the beginning of the flowering period (month), end of flowering (month), time of seed dispersal (month), and seed bank duration (years) (Kattge et al., 2011). Dispersal distance classes were taken from Lososová et al. (2023). Ellenberg-type ecological indicator values were employed to estimate the environmental requirements of plant species, specifically in terms of moisture (W), soil pH (R), temperature (T), light (L), and continentality (K) (Dengler et al., 2023). Ecological indicators offer numerous advantages, as they facilitate a comprehensive assessment of environmental conditions, integrate environmental parameters over extended periods, circumvent costly and time-consuming instrumental measurements, and reflect anthropogenic impacts. Similar to abiotic environmental factors, naturalness and degradation can be viewed as a continuum ranging from artificial (i.e., degraded) to 'natural' conditions. Species exhibit varying responses to anthropogenic degradation; some plants are typically found in predominantly natural or near-natural environments, while others can tolerate, benefit from, or even require anthropogenic influences. This variability allows for the assessment of a site's naturalness or degradation based on its species composition. To this end, two types of indicator value systems have been developed: naturalness and hemeroby. Hemeroby measures the extent of ecosystem transformation due to anthropogenic pressure, while naturalness indicates the degree to which an ecosystem approximates the ideal least disturbed state (Erdős et al., 2022). The projected cover of herbaceous plant species was used as a factor in the calculation of the hemeroby assessment:

$$Hem = \frac{\sum_{i=1}^{n} H\text{–score}_i \times Pr_i}{\sum_{i=1}^{n} Pr_i},$$

where H–score$_i$ is the hemeroby indicator score of the i-th species, and Pr$_i$ is the projective cover of the i-th species in the *relevé*. Plant hemeroby scores are provided according to Frank and Klotz (1990) with adaptations for regional conditions by Goncharenko (2017). The naturalness values of the plant species are based on those of Borhidi (1995) with our adaptations reflecting the conservation status of the species and the potential for the spread of adventitious species in the region. The Borhidi category of naturalness can be evaluated based on social behaviour types and their corresponding naturalness values. The social behaviour types are derived from the competitor, stress tolerator, and ruderal (C–S–R) strategic model proposed by Grime (1974). The following social behaviour types (SBT) were utilised: competitors (C, naturalness value +5); stress tolerators of narrow ecology, specialists (S, naturalness value +6); and stress tolerators of broad ecology, generalists (G, naturalness value +4). Ruderals (R) encompass the following categories: natural pioneers (NP, naturalness value +3), disturbance-tolerant plants of natural habitats (DT, naturalness value +2), native weed species (W, naturalness value +1), introduced alien species (I, naturalness value –1), adventitious species (A, naturalness value –1), ruderal competitors (RC, naturalness value –2), alien competitors, and aggressive invaders (AC, naturalness value –3). The projected cover of herbaceous plant species was used as a weight in the calculation of the naturalness assessment:

$$Nat = \frac{\sum_{i=1}^{n} Nat\text{–score}_i \times Pr_i}{\sum_{i=1}^{n} Pr_i},$$

where Nat–score$_i$ is the SBT scores of the i-th species, and Pr$_i$ is the projective cover of the i-th species in the *relevé*.

Plant life-form are classified according to Raunkiaer (1937). Pollenochores are groups of plants characterised by their method of pollination; for spore-producing plants, this distinction is based on the type of gamete transfer. Diasporochores, also known as ecobiochores, are groups of plants that exhibit varying mechanisms for the dispersal of their diasporas (Zhukov et al., 2023). Pollenochores and diasporochores are defined according to Tarasov (Tarasov, 2012). The Shannon index (tree diversity) was calculated to assess the diversity of the tree stands.

The calculation of distances between pairs of species on the basis of functional traits for species collected in communities was conducted via the mFD package (Magneville et al., 2022). Trait-based distances between species were computed with the funct.dist() function of the mFD package using Gower distance, combining continuous traits (e.g. leaf area, seed mass) with categorical traits (Raunkiaer life-form, dispersal type, pollination strategy) specified in a trait-descriptor table; all traits were standardised and equally weighted. This study considered the following species and functional diversity indices: species richness (Sp_richn), Gini-Simpson (GSimpson), functional richness (FRic), functional evenness (FEve), functional divergence (FDiv), functional originality (FOri), functional specialization (FSpe), functional identity (FIde), functional dispersion (FDis), Rao's quadratic entropy (FunRao), functional redundancy (FunRedundancy), functional mean pairwise distance (Fmpd), and functional mean nearest neighbour distance (Fnnd). Species richness (Sp_richn) is the number of species present in a community (Magurran, 2021). The Gini-Simpson (GSimpson) index is a measure of species diversity. GSimpson, FunRao, and FunRedundancy were calculated using the rao.diversity function from the SYNCSA package (Debastiani & Pillar, 2012). The response of the functional diversity indices to the gradient of environmental factors was elucidated using a quadratic model, which is suitable for describing a 'hump-backed' relationship. Additionally, a linear model and a model with one intercept were considered; however, neither of these were statistically significant. The optimal model was identified by utilizing a set of indices and employing the compare_performance function from the performance package (Lüdecke et al., 2021).

A non-metric multidimensional scaling (NMDS) analysis was conducted to evaluate tree species composition. We used NMDS as a flexible, distance-based ordination to summarise patterns in tree species composition among plots, because it makes no assumptions about linear relationships and is well suited for multivariate community data. This ordination method was implemented using the vegan package (Oksanen et al., 2018). Various data transformations were tested, including untransformed, log-transformed, square root (sqrt)-transformed, column total-normalised, column maximum-normalised, frequency-transformed, normalised, range-transformed, Hellinger-transformed, chi-square-transformed, Wisconsin-transformed, and arcsine-transformed data. Additionally, we evaluated several distance metrics: Euclidean, Manhattan, Gower, Bray-Curtis, Kulczynski, Morisita, Horn–Morisita, Cao, Jaccard, Mountford, Raup-Crick, Canberra, Chao, Mahalanobis, Binomial, and Clark distances. We then used the rankindex function of the vegan package as a diagnostic tool to check that the resulting dissimilarity matrices retained an interpretable relationship with key stand- and microclimate-related variables, which act as environmental descriptors for the herb layer. The purpose of this procedure was to ensure that the chosen combination of transformation and distance measure produced an ecologically interpretable ordination. The Gower distance combined with arcsine data transformation produced the best results and was subsequently used for the NMDS procedure. The NMDS spatial variability model was developed in ArcGIS 10.2.

The impacts of urban park trees on the environment and herbaceous cover under anthropogenic pressure are complex. While not all factors and processes involved in these interactions can be measured directly, they are crucial for understanding the structure and dynamics of urban ecosystems. Structural Equation Modelling enables testing hypotheses regarding the causal relationships between factors and their effects, as well as to evaluate latent factors that cannot be directly measured but are significant. Latent variables are theoretical, unobserved constructs that are inferred from multiple observed variables. They represent underlying concepts that cannot be measured directly but capture the essential properties of a phenomenon or process. Structural Equation Modelling (SEM) uses the relationships between latent variables and their observed indicators to estimate and test complex causal and correlational links among these underlying constructs. The set of observed indicators allowed us to extract a series of latent factors, which were interpreted as heating potential, cooling potential, stand density/thinning, and diversity/uniformity of the stand's species composition. Heating potential denotes the relative capacity of a given surface–vegetation configuration to increase near-surface air and ground temperature for a given amount of incoming radiation. It is determined by the physical properties of the ground surface and the structure of the vegetation cover (e.g. albedo, canopy openness, surface roughness, and evapotranspiration), which together control how absorbed energy is partitioned into sensible heat (Stewart & Oke, 2012). The cooling potential of an urban park refers to its ability to reduce temperatures within a city, primarily by creating a cooler microclimate known as a park cool island (Toparlar et al., 2018). In this study, stand density/thinning is defined as the spatio-temporal variation in the number of trees per unit area resulting from management interventions (e.g. felling, sanitary cutting, creation of infrastructure) and/or natural processes (e.g. mortality, regeneration) within the park. Diversity/uniformity of the stand's species composition refers to spatio-temporal changes in tree-species diversity, including both increases in species richness and evenness and, conversely, decreases leading to a more uniform (monodominant) species composition, driven by management interventions or natural dynamics within the park.

The method of partial least squares was employed for Structural Equation Modelling (Hair et al., 2021). The calculations were conducted using the seminr package. To evaluate the fit and explanatory power of the SEM, we followed the procedure proposed by Hair et al. (Hair et al., 2021). First, the statistical significance of the structural paths was assessed by non-parametric bootstrapping (999 resamples, two-tailed tests, α = 0.05); path coefficients were considered significant when the absolute value of the bootstrap t-statistic exceeded 1.96. Second, the model's explanatory power was examined using the coefficients of determination (R^2) of the endogenous constructs. Following the guidelines of Hair et al. (Hair et al., 2021), R^2 values of 0.75, 0.50, and 0.25 were interpreted as indicating substantial, moderate, and weak explanatory power, respectively.

Results

The tree stands in the park plantations comprised 47 species or subspecies of woody plants. The distribution of the number of trees per plot followed a Poisson distribution ($\lambda = 2.4$, $\chi^2 = 2.7$, P = 0.74). The tree stand density in Studentskyi Park was significantly greater than that in Ivan Starov Garden Square (Mann–Whitney test, P < 0.001) (Table 1), which was mainly driven by the very high density of trees in the central part of Studentskyi Park.

Table 1
Parameters of the tree stands of the park plantations

Tree stand parameter	Park		Total (N = 380)	Test	*P*-value
	Ivan Starov Garden Square (N = 150)	Studentskyi Park (N = 230)			
Tree number per sample plot	2.0 ± 1.2	2.7 ± 1.6	2.4 ± 1.5	Mann-Whitney	< 0.001
Tree stand Shannon diversity	0.9 ± 0.6	0.9 ± 0.6	0.9 ± 0.6	Student's *t*-test	0.68
Cover, %	51.7 ± 19.9	51.5 ± 26.0	51.6 ± 23.7	Student's *t*-test	0.93
Canopy openness, %	57.0 ± 17.4	27.5 ± 13.4	39.1 ± 20.9	Student's *t*-test	< 0.001
Leaf Area Index (LAI)	0.9 ± 0.6	2.1 ± 0.8	1.6 ± 0.9	Student's *t*-test	< 0.001
Transparency (direct)	5.1 ± 3.9	4.4 ± 2.9	4.7 ± 3.3	Student's *t*-test	0.044
Transparency (diffuse)	5.4 ± 3.7	4.1 ± 2.4	4.6 ± 3.0	Student's *t*-test	< 0.001
Transparency (total)	10.5 ± 7.3	8.5 ± 4.9	9.3 ± 6.1	Student's *t*-test	0.002

The Shannon tree diversity index was 0.9 ± 0.6, and this index did not differ between the parks (t = 0.41, P = 0.68). Visually assessed canopy cover was not significantly different between the parks (t = 0.08, P = 0.93). However, the canopy openness and transparency scores were greater for the stand in Ivan Starov Garden Square than for the stand in Studentskyi Park. The leaf area index (LAI) was greater for the stand in Studentskyi Park than for the stand in Ivan Starov Garden Square.

The dependence of stress statistic derived after NMDS on the number of dimensions indicated that a four-dimensional solution was sufficient for a qualitative representation of the tree community space in a low-dimensional space (Stress = 0.13, Non-metric fit: $R^2 = 0.97$, Linear fit: $R^2 = 0.81$). Fitting the stand parameters to the extracted dimensions enabled a meaningful interpretation of these dimensions. Dimension 1 indicated the variability of the stand structure, which was associated with the variable number of trees in the survey plot, the diversity of the stand, and the transparency of the stand canopy (Fig. 2). Among the trees, *Acer platanoides* and *Robinia pseudoacacia* were indicators of high stand density, diversity, and low canopy transparency. The indicators of the contrasting conditions included *Acer pseudoplatanus*, *Acer negundo*, *Ailanthus altissima*, *Aesculus hippocastanum* and several other tree species. The parks exhibited similar patterns of spatial variability in dimension 1.

Negative values for dimension 1 were observed in the central areas of the parks, whereas the peripheral regions displayed positive values for this dimension. The LAI was most sensitive to dimension 2, with *Acer platanoides* serving as the key indicator among the tree species. The spatial patterns suggested the presence of comparable structures in the tree canopy of the parks, resulting from the formative influence of *A. platanoides*, which contributed to the increase in LAI values. The LAI served as an indicator for dimension 3, which exhibited an increase in LAI due to the proliferation of *Acer negundo* and *Gleditsia triacanthos* and a decrease in *A. platanoides* and *Ulmus pumila*. In both parks, elevated values of dimension 3 were predominantly found in the peripheral areas. Dimension 4 indicated a trend of increasing stand diversity coupled with greater canopy openness, set against a backdrop of a decreasing LAI. The primary marker for this dimension was *Acer platanoides*. This dimension also showed a similar spatial pattern in both parks.

The principal component analysis of the variability in environmental and herbaceous cover properties revealed two principal components with eigenvalues greater than one (Table 2). Principal components 1 and 2 can be meaningfully interpreted as the gradients of hemeroby and naturalness, respectively. An increase in hemeroby was correlated with higher light intensity, soil and air temperatures, a decrease in atmospheric humidity, and a reduction in soil moisture and electrical conductivity. Furthermore, an increase in hemeroby was linked to greater functional diversity within plant communities and a decrease in the height of the herbaceous cover. Conversely, a decline in the naturalness of the herbaceous community was associated with increased light intensity, species richness, height, and projective cover of the herbaceous layer.

The dimensions derived from the results of multidimensional scaling of the stand structure were correlated with the environmental properties and herbaceous cover. The positive values of NMDS 1 indicated conditions characterized by elevated soil and air temperatures, as well as increased levels of illumination (Table 2). Furthermore, the positive values of NMDS 1 suggested a greater degree of hemeroby and less natural conditions, which were associated with greater projective cover of herbaceous plants. Conversely, an increase in the naturalness of ecosystems was associated with higher levels of soil and air humidity. The correlation structure for NMDS 2 closely resembled that of NMDS 1, with the notable exception of the lack of a statistically significant correlation between NMDS 2 and the projective cover of herbaceous vegetation and naturalness. At the same time, NMDS 3 was also responsive to hemeroby and naturalness, with its distinctive feature being its sensitivity to soil electrical conductivity and grass height. In addition, NMDS 4 illustrated the variability of projective cover and light in relation to the stand.

The variability of plant traits in the herbaceous layer was characterised by five functional axes (Table 3). The first five functional axes explained 76.7% of the total variation in the functional trait space. Functional axis 1 indicated consistent changes in plant properties related to their hemeroby and naturalness. Hemeroby plants exhibited elevated leaf nitrogen content, delayed onset and termination of the flowering period, increased dispersal potential, and heightened light requirements.

The plants with higher values for axis 1 were typically therophytes, whereas those with lower values were predominantly synzoochores (Fig. 2). Additionally, functional axis 2 was associated with hemeroby and the naturalness of plants, highlighting the significant dispersal potential of hemeroby species and their relatively smaller seed sizes. The plants with higher values on functional axis 2 were typically hemicryptophytes, anemophilous plants, and ballistochores, whereas those with lower values were generally seedlings of phanerophyte or nanophanerophyte species. The results for functional axis 3 indicated that species with a greater degree of hemeroby exhibited a lower specific leaf area and a greater dry weight of leaves relative to their wet weight. Positive values on functional axis 1 corresponded to hemicryptophytes and entomophilous plants, whereas lower values were associated with seedlings of phanerophytes and synzoochores. The findings demonstrated that functional axes 4 and 5 were independent of hemeroby or naturalness. Functional axis 4 allowed for the differentiation of species on the basis of their sensitivity to nutrient content. Species exhibiting greater sensitivity to nutrient levels were also found to be sensitive to the soil moisture content, displaying greater height and larger leaf areas in terms of dry weight. Meanwhile, plants that were less sensitive to the soil nutrient content presented greater dry weights of leaves than wet weights and presented a greater tendency toward thermophily and a more continental habitat.

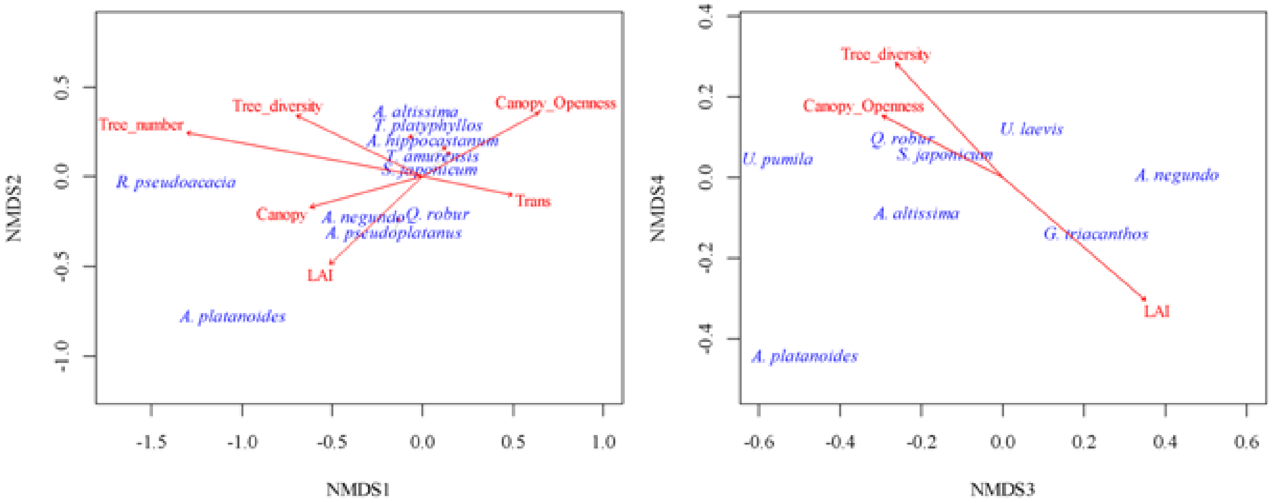

Fig. 2. The locations of the tree species in the space of dimensions derived from non-metric multidimensional scaling, which were adjusted to reflect the changes characterizing the conditions of the park stand: Tree species exhibiting a distance greater than 0.15 from the origin are depicted; LAI represents the Leaf Area Index, Trans represents the transparency of the tree canopy, Tree_number represents the number of trees per recording plot, Tree_diversity represents the Shannon diversity index of the tree community per the recording plot, Canopy represents the closeness of the park canopy, determined via the visual method, and Canopy_Openness represents the openness of the park canopy, determined via the fisheye method; parameters of the tree stands were fitted post hoc to the NMDS configuration using the envfit function; only parameters showing a significant correlation with the ordination axes ($P < 0.05$) are displayed; The full set of parameters is presented in Table 2

Table 2

Correlations among the soil, air, and herbaceous cover properties, as well as the dimensions, were derived from the results of non-metric multidimensional scaling of the park tree stands (only statistics that achieved significance at $P < 0.05$ are included)

Variable	Factor loadings		Dimensions, derived from the results of non-metric multidimensional scaling			
	PC1, $\lambda = 4.9$	PC2, $\lambda = 1.8$	NMDS 1	NMDS 2	NMDS 3	NMDS 4
Soil temperature (log-transformed)	0.88	–	0.35	0.24	–0.27	–
Soil moisture (log-transformed)	–0.82	–	–0.20	–0.12	0.29	–
Soil electric conductivity	–0.56	–	–	–	0.15	–
Lighing (log-transformed)	0.67	0.36	0.42	0.25	–0.19	0.10
Air temperature	0.91	–	0.31	0.26	–0.34	–
Air humidity	–0.90	–	–0.34	–0.26	0.33	–
Grass height	–0.46	0.66	–	–	0.23	–
Herbaceous cover	–	0.80	0.24	–	–	0.16
Hemeroby	0.84	–	0.27	0.21	–0.38	–
Naturalness	–	–0.40	–0.15	–	0.11	–
Herb species richness	0.30	0.56	0.36	–	–	0.27
PC1	–	–	0.36	0.22	–0.35	–
PC2	–	–	0.49	–	–	0.46

Table 3

Relationships among all traits and all axes of the functional space (for continuous traits a linear model was computed, and the Pearson r was returned; for other types of traits, a Kruskal-Wallis test was computed, and the Kruskal-Wallis eta2 statistics were returned; only those statistically significant at $P < 0.05$ are presented)

Trait	Test	Functional axes				
		PC1	PC2	PC3	PC4	PC5
Leaf area	linear model	–0.32	–0.58	–	–	–
Leaf area per leaf dry mass	linear model	–	–	0.49	–0.29	–0.40
Leaf dry mass per leaf fresh mass	linear model	–0.58	–	–0.34	–	–
Leaf nitrogen (N) content per leaf dry mass	linear model	0.47	–0.21	0.28	–0.49	–
Plant height	linear model	–	–	–	–0.65	0.44
Beginning of flowering period	linear model	0.35	–	–	–	0.65
End of flowering	linear model	0.59	0.35	0.30	–	–
Time of seed dispersal	linear model	0.25	–	–	–	0.28
Seed mass	linear model	–0.31	–0.51	–	–	–
Dispersal distance class	linear model	0.58	–0.57	–0.18	–	–
Seedbank duration	linear model	0.76	0.23	–	–	–
Light regime	linear model	0.65	0.44	–	–	0.20
Temperatures	linear model	–	–0.41	–0.39	0.34	–

Trait	Test	Functional axes				
		PC1	PC2	PC3	PC4	PC5
Continentality of climate	linear model	0.30	0.36	–	0.22	–
Humidity	linear model	–0.41	–0.23	–	–0.63	–
Acidity	linear model	–	–	–	–	–
Nutrients availability	linear model	–	–0.21	0.28	–0.73	–
Naturalness	linear model	–0.76	–0.19	0.20	–	–
Hemeroby	linear model	0.84	0.21	–0.24	–	–
Raunkiaer’s life-form	Kruskal-Wallis	0.44	0.45	0.29	–	0.41
Pollenochor	Kruskal-Wallis	–	0.15	0.57	0.12	–
Diasporochor	Kruskal-Wallis	0.06	0.63	0.20	0.11	0.07

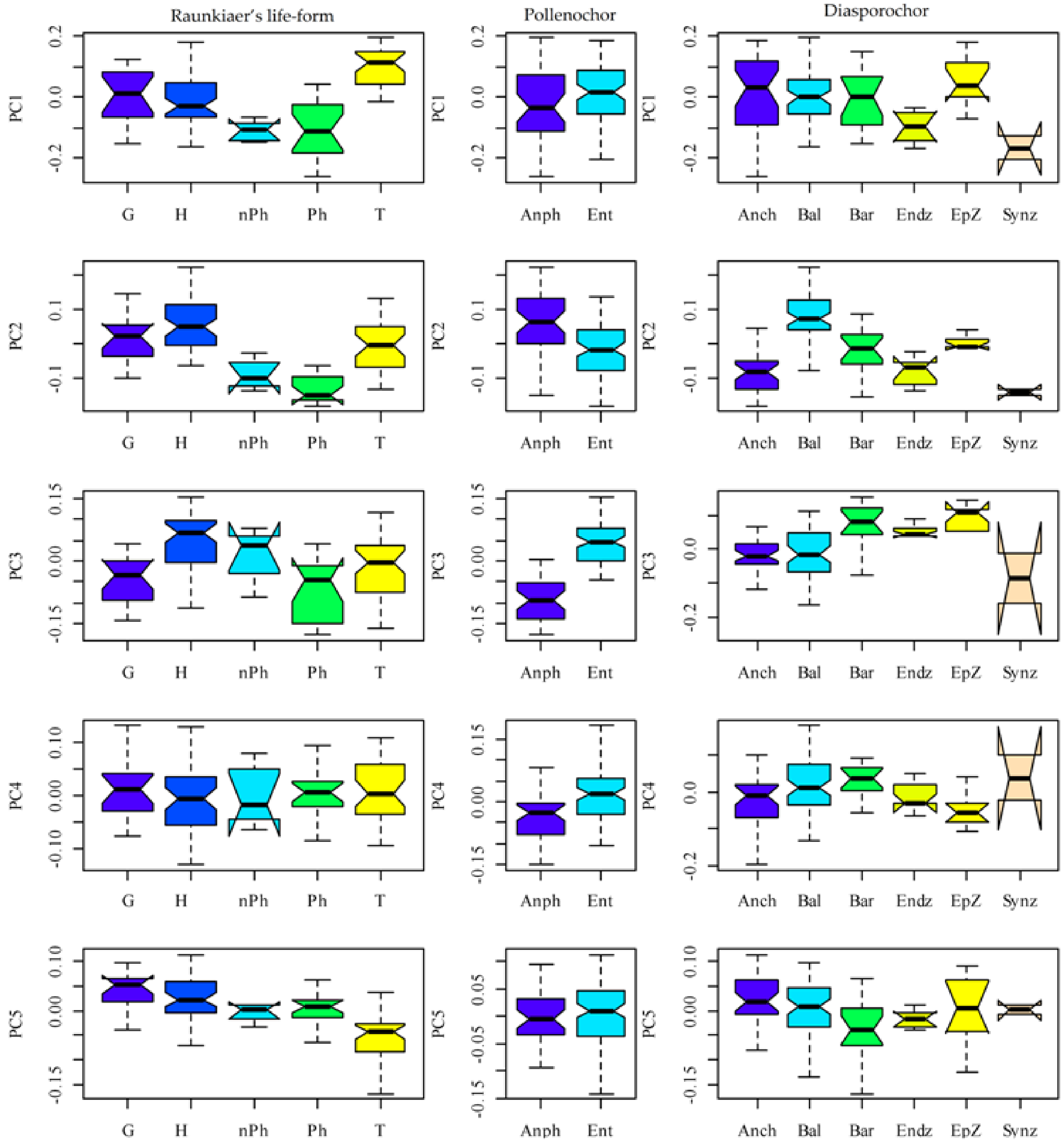

Fig. 3. Boxplots illustrating the variability of plant traits along ordination axes PC1–PC5 depending on Raunkiaer’s life-forms, pollenochors and diaspochores: Raunkiaer’s life-form: G is a geophyte, H is a hemicryptophyte, nPh is a nanophanerophyte, Ph is a phanerophyte, and T is a therophyte; pollenochor: Amb is an anemophilous plant, and Ent is an entomophilous plant; diaspochor: AnCh is an anemochor, Bal is a ballistochor, Bar is a barochor, Endz is an endozoochor, Epz is an epizoochor, and Synz is a synzoochor

A higher value on functional axis 4 was indicative of ballistochores. Dimension 5 distinguished plants based on their flowering date. The plants that began flowering later were taller, had a greater affinity for light, and had smaller leaf areas in terms of dry weight. Higher values on functional axis 5 were indicative of geophytes and hemicryptophytes, whereas lower values were associated with therophytes. The functional diversity indices exhibited distinct patterns of response along the gradients of hemeroby and naturalness (Figs. 4 and 5).

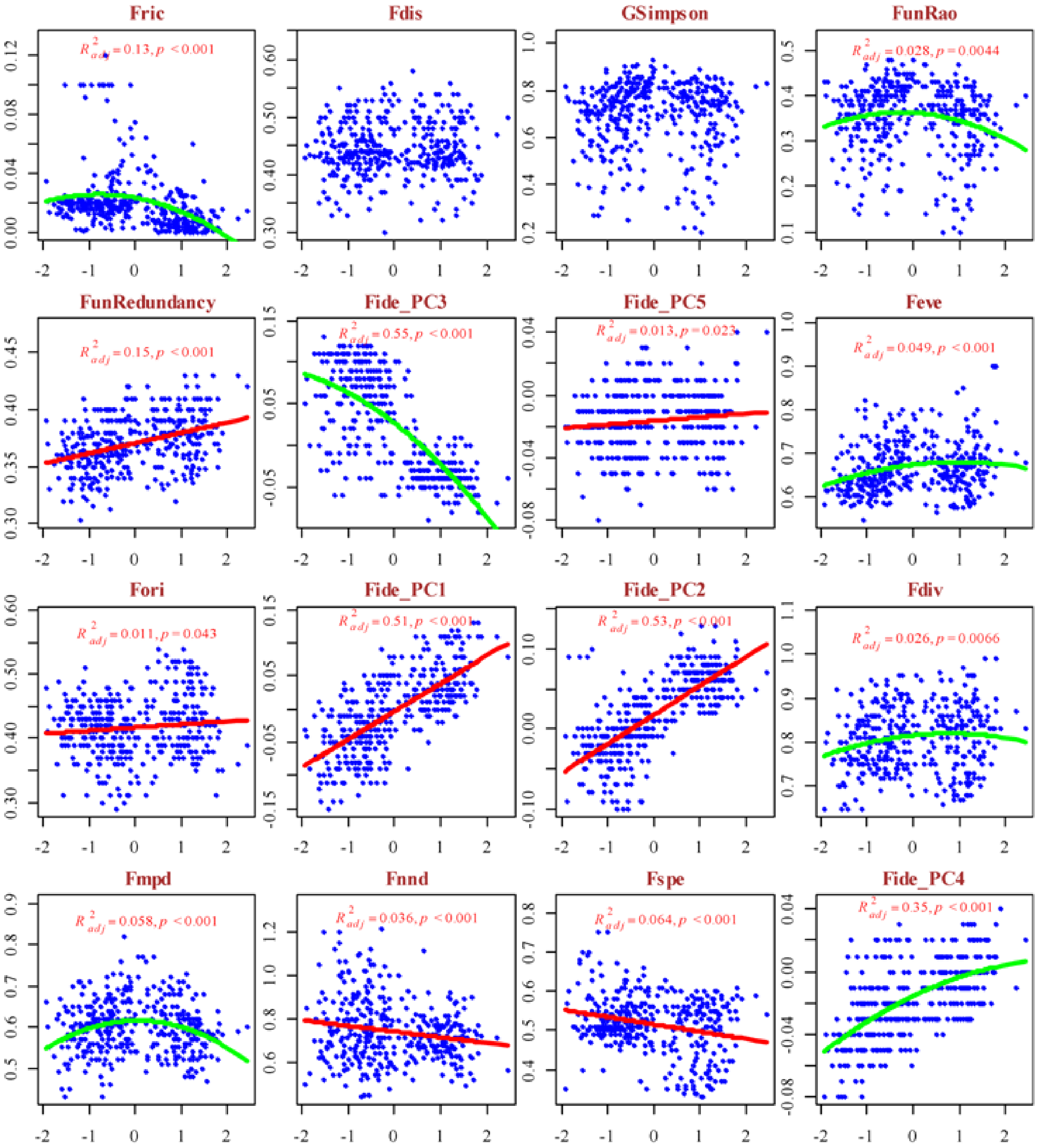

Fig. 4. The response of functional diversity indices along the gradient of the hemeroby factor (PC1) is illustrated in the scatter plot, where blue dots represent the functional diversity indices across the PC1 gradient: The green line denotes the polynomial approximation of the relationship when it is identified as the optimal model, whereas the red line similarly indicates the linear approximation for the best model; in cases where the optimal model is a constant, no line is presented; the adjusted R-squared (R_{adj}^2) reflects the proportion of variation in the functional diversity index that is accounted for by the respective model; the P-value is derived from the results of the Likelihood-Ratio Test (LRT), which compares the best model with a model that includes only a constant; the abscissa represents the PC1 scores, and the ordinate indicates the values of the functional diversity indices for the grass layer in urban parks: Fmpd is the functional mean pairwise distance, Fnnd is functional mean nearest neighbour distance, FEve is the functional evenness, FRic is the functional richness, FDiv is the functional divergence, FOri is the functional originality, FSpe is the functional specialization, Fide_PC1, … PC5 are the Functional identity indeces, GSimpson is the Gini-Simpson, FunRao is the Rao quadratic entropy, FunRedundancy is the functional redundancy

An increase in hemeroby was associated with a linear increase in FunRedundancy, Fide_PC1, Fide_PC2, Fide_PC5, and Fori, whereas Fnnd and Fspe showed a linear decrease. The responses of Fric, FunRao, Fide_PC3, Fide_PC4, Feve, and Fdiv to the hemeroby gradient were characterised by a 'hump-backed' pattern. By contrast, the responses of Fdis and GSimpson to the hemeroby gradient were irregular. The functional diversity indices Fdis, Fdiv, Fmpd, and Fnnd displayed a linear response pattern along the naturalness gradient, whereas the other indices exhibited a 'hump-backed' response. Notably, the explanatory power of the respective response models along the naturalness gradient is relatively low. The indices of functional diversity underwent cluster analysis, resulting in the identification of three clusters, which can be conditionally designated as follows (Fig. S4): functional richness (Fric, Fdis, GSimpson, FunRao, FunRedundancy, Fide_PC3, Fide_PC5), functional evenness (Feve, Fori, Fide_PC1, Fide_PC2), and functional divergence (Fdiv, Fmpd, Fnnd, Fspe, Fide_PC4). These clusters are considered latent variables in the subsequent analysis.

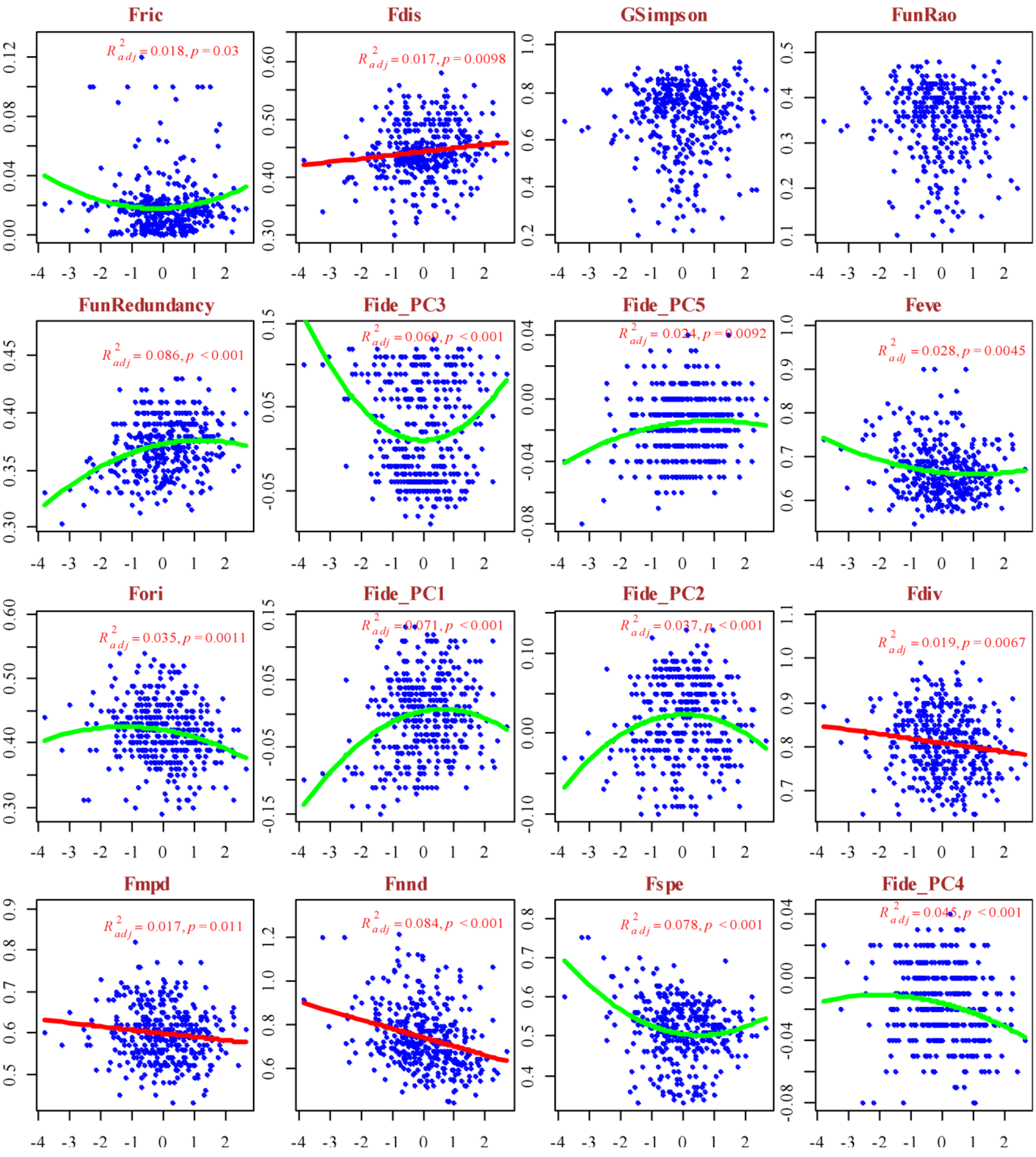

Fig. 5. The response of functional diversity indices along the gradient of the naturalness factor (PC2) is illustrated in the scatter plot, where blue dots represent the functional diversity indices across the PC1 gradient: The green line denotes the polynomial approximation of the relationship when it is identified as the optimal model, whereas the red line similarly indicates the linear approximation for the best model; in cases where the optimal model is a constant, no line is presented; the adjusted R-squared (R_{adj}^2) reflects the proportion of variation in the functional diversity index that is accounted for by the respective model; the P-value is derived from the results of the Likelihood-Ratio Test (LRT), which compares the best model with a model that includes only a constant; the abscissa represents the PC1 scores, and the ordinate indicates the values of the functional diversity indices for the grass layer in urban parks: Fmpd is the functional mean pairwise distance, Fnnd is functional mean nearest neighbour distance, FEve is the functional evenness, FRic is the functional richness, FDiv is the functional divergence, FOri is the functional originality, FSpe is the functional specialization, Fide_PC1, … PC5 are the Functional identity indeces, GSimpson is the Gini-Simpson, FunRao is the Rao quadratic entropy, FunRedundancy is the functional redundancy

The results obtained in the previous stage of the study allowed for the proposal of the following structural model (Fig. 5). Bootstrap resampling was then used to evaluate the robustness of the structural relationships, and the path coefficients were shown to be statistically significant. We evaluated the model's explanatory power by analysing the R^2 values of the endogenous constructs. The R^2 values indicate that the model explains 75.2% of the variance in distance to naturalness, 61.1% in disturbance, 78.0% in functional evenness, 54.3% in functional richness and 49.7% in functional divergence. The explanatory power of the model can be regarded as substantial for distance to naturalness and functional evenness, and moderate for disturbance, functional richness and functional divergence. The structural features of the stand that influence the effects on the environment and herbaceous vegetation cover were represented through four latent variables: heating potential, cooling potential, density/thinning of the stand, and diversity/uniformity of the stand's species composition. Moreover, NMDS1, ..., NMDS4, stand crown properties, stand density, and diversity indicators were considered as indicators of the latent variables, whereas NMDS3 and canopy openness were identified as statistically significant indicators of heating potential. At the same time, NMDS3, canopy, and LAI were statistically significant indicators of cooling potential, while NMDS1, Trans, and tree number were statistically significant indicators of thinning potential. In addition, NMDS4 and tree diversity were statistically significant indicators of stand uniformity.

The changes in the environmental properties were represented by two latent variables. The indicators of hemeroby and naturalness were meaningfully interpreted as disturbance and distance to naturalness. The disturbance increased with increasing air and soil temperatures, decreasing air and soil humidity, and decreasing soil electrical conductivity. Distance to naturalness increased with increasing light availability, species richness, and grassland height. An increase in heating potential resulted in a rise in disturbance, whereas an increase in cooling potential led to a decrease in disturbance. Cooling potential reduces distance to naturalness, whereas thinning and stand uniformity contribute to a greater distance of communities from the state of naturalness.

Fig. 6. Structural Equation Modelling of the effects of tree stands on environmental transformation, disturbance levels, and functional properties of herbaceous layers in urban parks: The latent variables are depicted within hexahedra, whereas the manifest variables (indicators) are represented in quadrangles; asterisks denote the statistical significance of the factor loadings: *** indicates $P < 0.001$, ** indicates $P < 0.01$, and * indicates $P < 0.05$; Fmpd is the functional mean pairwise distance, Fnnd is the functional mean nearest neighbour distance, FEve is the functional evenness, FRic is the functional richness, FDiv is the functional divergence, FOri is the functional originality, FSpe is the functional specialization, Fide_PC1, … PC5 are the Functional identity indices, GSimpson is the Gini-Simpson diversity, FunRao is the Rao quadratic entropy, FunRedundancy is the functional redundancy

The indices Fric, FunRedundance, and Fide_PC3 were identified as statistically significant indicators of functional richness. The results indicated that Fide_PC1, Fide_PC2, and Feve were statistically significant indicators of functional evenness. Fdiv and Fide_PC4 were recognized as statistically significant indicators of functional divergence. The model demonstrated that an increase in disturbance led to a decrease in both functional richness and functional divergence, while simultaneously resulting in an increase in functional evenness. Furthermore, an increase in the distance to naturalness was associated with an increase in functional evenness and a decrease in functional richness. However, the effect of distance to naturalness on functional divergence was not statistically significant.

Discussion

Quantitative alterations in stand density are correlated with variations in the diversity of woody plant communities. The influence of stand density on the functional characteristics of vegetation cover can be elucidated based on the changes in water utilization and the effects of the stand on the distribution and infiltration of precipitation (Wang et al., 2021). These factors subsequently impact the intensity of soil erosion and the conditions of soil nutrients (Razafindrabe et al., 2010). The most diverse park plantations within the studied areas are characterised by communities that include both the native species *Acer platanoides* and the introduced species *Robinia pseudoacacia*. This phenomenon has been identified as a thinning/increasing stand density trend.

The dynamics in question have a substantial impact on the transparency of the canopy of the stand and the degree to which the stand diverges from its hypothetical natural state. Within the moderate range of LAI observed in our *Robinia*-dominated stands, higher canopy density is likely to enhance light interception and, consequently, the potential for stand-level carbon assimilation. In our study area, zones where management interventions have resulted in the thinning of tree stands (e.g., the removal of aged or diseased trees, the expansion of pedestrian pathways, and the creation of playgrounds and sports facilities) typically coincide with altered herb-layer conditions, reflecting changes in light regimes, soil disturbance, and recreational pressure (Kunakh et al., 2021). Notably, in plots with low naturalness scores of the herb layer, community dissimilarity relative to more natural stands is largely driven by the replacement of native meadow and forest species by synanthropic and often invasive, wind-pollinated taxa (e.g. *Ambrosia artemisiifolia* (Ščevková et al., 2025), *Ailanthus altissima* (Mousavi et al., 2019), *Artemisia vulgaris* (Depciuch et al., 2016), *Asclepias syriaca* (Konstantinovic et al., 2009), *Chenopodium album* (Konstantinovic et al., 2009), *Erigeron canadensis* (Hrabovský et al., 2025), *Lactuca* sp. (Paulsen & Andersen, 2016), *Sisymbrium loeselii* (Prodanović, 2017), *Portulaca oleracea* (Prodanović, 2017), *Sonchus arvensis* (Prodanović, 2017), and *Taraxacum officinale* (Hrabovský et al., 2025)), which are important sources of allergenic pollen. This pattern explains why lower naturalness tends to coincide with both higher compositional dissimilarity and a greater proportion of allergenic species. This tendency is consistent with recent findings from Central Europe, where long-term analyses of ruderal vegetation in Bratislava have documented increasing richness, cover and proportion of allergenic herbaceous species and, consequently, a rising allergenic potential of urban vegetation in response to climate warming and urbanisation (Hrabovský et al., 2025).

In our heterogeneous park, plots with a higher proportion of the native tree species *Acer platanoides* including both planted and semi-natural stands, are characterised by a higher Leaf Area Index (LAI) and a stronger local cooling effect, as confirmed by independent measurements and modelling. In the ordination space, these *Acer*-dominated plots tend to coincide with lower hemeroby and higher naturalness scores of the herb layer than *Robinia* plantations and more intensively used areas. This suggests that dense canopies of native trees create comparatively more favourable microclimatic and habitat conditions for less transformed herb-layer assemblages, without implying a fully restored 'natural' state. Beyond microclimate effects, several ecological pathways link native trees to greater naturalness in the herbaceous layer. Native tree stands in urban parks often represent remnants or structural analogues of the original semi-natural woodlands (Borghi et al., 2025; Menon et al., 2025). In the park[s] we studied, plots dominated by native trees frequently contain herbaceous species typical of regional forest and meadow communities (Kunakh et al., 2022), suggesting that these stands preserve elements of the original species pool through persistent seed banks, rhizomes, and clonal fragments. Native woody species typically support richer assemblages of local fauna (Berthon et al., 2021), such as birds (Komlyk et al., 2024; Ponomarenko et al., 2024; Villaseñor et al., 2021), small mammals (Fernández & Simonetti, 2013; Piña et al., 2019), and invertebrates (Owen, 1986), which act as dispersal agents for zoochorous native herbs. By providing suitable foraging and nesting habitats, native trees increase the likelihood that diaspores of native herbaceous species are introduced to and retained within the park. Native trees contribute litter and root exudates that sustain mycorrhizal and microbial communities co-adapted to the regional flora (Heděnec et al., 2023), thereby creating underground conditions more favourable for the establishment and persistence of native herbaceous species than those under non-native trees (Pielech et al., 2025). Taken together, these mechanisms offer a biologically plausible explanation for the observed association among a higher proportion of native trees, lower hemeroby, and higher naturalness scores of the herb layer in the park[s] we analyzed. These findings underscore the critical role of native flora in the development of parklands and align with existing research indicating that native plants fulfil multiple ecosystem functions in urban green spaces. They support urban biodiversity and provide ecosystem services more effectively than non-native plant species do, highlighting the necessity of prioritizing native species in urban horticultural practices (Tartaglia & Aronson, 2024). Park management strategies should prioritize the preservation of natural vegetation pockets, as their ecological significance is substantial in terms of optimizing environmental conditions and enhancing the aesthetic appeal of the park. When restoring or establishing park plantings, native flora should be preferred. However, it is also important to consider that introduced species possess considerable potential for the development of park plantings, particularly in areas subjected to high anthropogenic pressures, characterised by elevated levels of hemeroby and reduced naturalness. Some adventive species may exhibit a relatively high tolerance to adverse environmental conditions, thereby facilitating the establishment of park plantations that can provide substantial ecosystem services in the vicinity of pollution sources and other forms of environmental degradation. Consequently, the incorporation of resilient adventitious species is recommended for planting in areas adjacent to urban thoroughfares.

Previous research within the same urban park system has demonstrated that recreational activities and management practices significantly alter soil physical properties (Molozhon et al., 2023a), particularly by increasing soil penetration resistance (Molozhon et al., 2023b) and modifying soil aggregate structure (Umerova et al., 2022). These changes, in turn, affect the degree of hemeroby in park vegetation and the habitat conditions for soil-dwelling invertebrates (Zhukov et al., 2023). In this context, the phytoindication gradients described in our study can be interpreted as integrative responses of plant communities to a range of soil and disturbance pressures.

The openness of tree stands is a significant factor influencing the potential for surface heating within park ecosystems. The characteristics of the canopy—including overall structure, biomass distribution, and spatial arrangement of crown elements—play crucial roles in the functioning of both forests (Ivanko et al., 2025; Li et al., 2022) and park ecosystems (Hofman et al., 2016). The canopy of a forest or a park determines the intensity of light interception and influences water and gas exchange within the ground layer (Binkley et al., 2004). Different tree species present in park plantations exhibit varying aesthetic appearances and crown characteristics. The transparency of the crown impacts the functional attributes of trees and their aesthetic perception, which can be quantified using the LAI (Vogt et al., 2017). The structure of the canopy significantly influences the productivity of natural forest stands and urban parks (Kim et al., 2024; Ponomarenko et al., 2024). The crown structure of individual trees serves as a reliable indicator of their vitality, reflecting the adaptive strategies employed by trees in response to various factors, including competition for growth, environmental conditions, and climate change (Vanderwel et al., 2020). In urban parks, the configuration of tree-crown architecture, including crown size and shape, strongly influences the extent and density of shade and thereby modulates key ecosystem services, particularly local heat balance and microclimate regulation (Franceschi et al., 2022). Correlation analysis between tree species scores and indicators of surface-heating potential, including leaf area index (LAI), revealed that plots with a higher abundance of the adventive tree species *Acer negundo* and *Gleditsia triacanthos* tend to be associated with lower heating potential. This suggests that, under certain conditions, their canopies may contribute to locally reduced surface heating. Conversely, higher surface-heating potential was positively correlated with hemeroby values in our dataset. The homogeneity of the stand contributed to a decline in the naturalness of the herbaceous cover. Therefore, establishing more diverse tree stands is essential for fostering conditions that promote a more natural state of herbaceous cover.

Hemeroby and naturalness are frequently perceived as opposing yet complementary concepts (Erdős et al., 2022). The findings suggest a disruption of symmetry between hemeroby and naturalness, indicating a certain degree of independence between these phenomena. In our case, hemeroby seems to be associated with tree stands that have a higher surface-heating potential, while higher naturalness is linked to structurally more complex, denser canopies with a greater cooling potential, which may support more natural herb-layer communities. Urban parks stand to play a crucial role in mitigating the urban heat island effect. Research indicates that an urban park's area and perimeter are positively correlated with the intensity of the park's cooling effect (Yao et al., 2022). The cooling effect is contingent not only upon the park's area but also on its structural characteristics. Tree species' composition significantly influences horizontal and vertical cooling, thereby affecting the dynamics of favourable microclimatic conditions (Chen et al., 2020). Multilayered plant communities within urban parks are particularly effective in cooling the urban environment. Tree stand density, area, tree height, and solar radiation transmittance significantly influence temperature reduction and increase relative humidity (Zhang et al., 2013; Nykytiuk et al., 2024). The LAI is a widely utilized canopy indicator representing the one-sided leaf area relative to the crown projection area of trees and shrubs (Parker, 2020). This metric facilitates the identification of numerous critical factors and processes within the urban forest ecosystem, including shading, cooling, regeneration, and the hydrological cycle (Zhang et al., 2023; Tutova et al., 2025). The LAI indicates the potential for shading and cooling effects in environments influenced by urban parks (Moser et al., 2015). Additionally, crown structure is a pivotal factor affecting the diversity of other layers within forest and park ecosystems (Onoszko et al., 2024).

Our structural equation model demonstrates that the heating potential and cooling potential of tree stands emerge as two independent latent factors that jointly influence vegetation hemeroby, whereas naturalness is controlled not only by these thermal potentials but also by both the quantitative and qualitative structure of the tree layer (stand density/thinning and species-composition diversity). This means that hemeroby and naturalness are not simply symmetric, mirror-image indicators with opposite signs, as they are often implicitly treated, but respond in a partially decoupled way to different components of stand structure and microclimate.

Hemeroby and naturalness significantly influence functional diversity indices of the herbaceous layer of park plantations, which can be more accurately understood as the relationship whereby alterations in the hemeroby and naturalness of plant communities impact their functional characteristics. The herbaceous layer of park plantations plays a crucial role in ecosystem functions and serves as a reliable indicator of environmental properties and the extent of anthropogenic disturbance (Kunakh et al., 2022). Following the commonly used framework of functional diversity, we considered three complementary components: functional richness, functional evenness, and functional divergence (Garnier et al., 2004; Schleuter et al., 2010). In our dataset, functional richness tended to be higher in communities where a substantial proportion of species combined relatively large leaf area with higher leaf dry mass, and where hemicryptophytes were more frequent, while therophytes contributed less to the total abundance. Conversely, plots with higher hemeroby and lower naturalness generally exhibited reduced functional richness and a shift towards trait syndromes typical of ruderal annuals, including higher specific leaf area in therophytes. Thus, in the context of the park[s] we studied, increased anthropogenic pressure is associated with a narrowing of the trait space occupied by the community and a replacement of trait combinations typical of long-lived, stress-tolerant herbs by those of short-lived ruderal species. This interpretation is consistent with previous studies reporting a higher proportion of therophytes in more hemerobic vegetation, while acknowledging that both therophyte proportions and hemeroby are community-level descriptors derived from the same species lists rather than fully independent measurements (Kim et al., 2002; Kunakh et al., 2024). Functional evenness describes the regularity with which the occupied trait space is filled (Schleuter et al., 2010). In our study, higher functional evenness was observed in communities where traits associated with ruderal and disturbance-tolerant strategies were more uniformly represented. These communities tended to be characterised by smaller leaf area and seed mass, lower humidity and naturalness scores, extended flowering periods, longer seed-bank persistence, and trait combinations adapted to higher light availability and more pronounced microclimatic stress. Functional evenness has been shown to be sensitive to a community's potential for productivity, reliability, and invasibility (Mason et al., 2005). In our case, an increase in functional evenness appears to reflect a homogenisation of trait composition under anthropogenic pressure, where species bearing similar disturbance-tolerant trait syndromes become more evenly dominant across the community. Rather than interpreting functional evenness as a universal indicator of hemeroby, we regard this pattern as specific to the disturbance-driven reassembly of urban park vegetation in our study system. Functional divergence reflects the extent to which species abundances are concentrated towards the extremes of the occupied trait space (Villéger et al., 2008). In our study, higher functional divergence was associated with communities containing a greater proportion of tall, nitrogen-demanding species characterised by relatively high specific leaf area and a preference for moist, fertile soils. These species occupy the edges of the trait space and tend to increase under conditions of elevated nitrogen availability and anthropogenic disturbance, consistent with findings that urban species often share ecological traits such as a preference for drier, less acidic, and more fertile environments (Hill et al., 2002). Previous research has demonstrated that hemeroby is negatively correlated with soil C:N ratios (Testi et al., 2010) and that urban environments are typically enriched in available nitrogen (Hu & Liu, 2022), which favours nitrophilous species. Our results align with the following perspective: Increasing hemeroby in the park coincides with a shift towards trait combinations typical of nitrophilous and disturbance-tolerant plants, alongside higher functional divergence. These patterns support recommendations to consider nitrogen-tolerant species in urban forest management (Xia et al., 2022), while recognising that elevated nitrogen can reduce the richness of native grasses and shrubs but leave introduced species richness unchanged, instead increasing their cover. Collectively, this contrasting response to nitrogen enrichment suggests that the proliferation of nitrogen-loving plant species under rising hemeroby is accompanied by a functional restructuring of the community, expressed as increased functional divergence.

The SEM results suggest that the functional response of the herb layer is well represented by the traditional triad of functional richness, functional evenness and functional divergence. Our key finding is that these processes are most effectively captured by functional identity indices (community-weighted mean trait values along the main functional axes), whereas the nominal indices FRic, FEve and FDiv play only a secondary role in explaining variation in community functioning. The SEM results show that hemeroby (disturbance) has a strong effect on all three components of the functional triad (functional richness, functional evenness, and functional divergence) whereas naturalness (distance to naturalness) is linked only to functional richness and functional evenness, but not to functional divergence.

The results obtained enable the formulation of practical guidelines for the management of urban parks. Open tree canopies or insufficient tree density can increase surface heating and create unfavourable microclimatic conditions. This can elevate temperatures and decrease soil moisture and humidity in recreational areas for park visitors. Dense tree canopies with a high leaf area index can provide shade and lower temperatures, contributing to a comfortable environment for visitors and enhancing the natural appearance of the herbaceous cover. This aspect is particularly significant in the context of global climate change. Using native tree species (e.g., *Acer platanoides*) helps to enhance the cooling effect, reduce hemeroby, and restore the naturalness of the herbaceous cover. Introduced species can be beneficial in areas with high levels of anthropogenic pressure, where resilience to stressful conditions is necessary. Reducing the density of plantations through thinning increases the potential for heating and promotes the growth of hemeroby, which can diminish the natural quality of the ecosystem. Multi-layered plantations with high species diversity provide a better cooling effect and improve microclimatic conditions. The cooling potential can be optimised by increasing planting density and selecting species with extensive leaf coverage. Creating zones with varying vegetation densities to balance heating and cooling potential offers opportunities to establish optimal conditions for visitors to relax in the park. The preservation and restoration of natural areas contribute to enhancing the natural quality and aesthetics of parks. These measures will ensure effective management of urban parks, thereby improving their ecosystem services and visitor comfort.

Conclusions

The influence of urban park tree canopies on their surrounding environments and herbaceous cover can be characterised through various gradients, including density/thinning, diversity/homogeneity of the stand, heating potential, and cooling potential. A notable consequence of increased hemeroby within an urban park is a rise in light levels, increases in air and soil temperatures, and reductions in electrical conductivity and soil moisture content. There has been a decrease in air humidity within the park[s]. An increase in hemeroby correlates with an increase in heating potential, whereas a decrease in hemeroby is associated with an intensification of cooling potential within the park. Conversely, the cooling potential mitigates how much the grass layer deviates from its natural state. By contrast, the uniformity and thinning of the tree contribute to an increase in this deviation. Functional diversity indices can be categorised based on their sensitivity to functional richness, evenness, and divergence. Functional identity indices aid in interpreting the variability observed in functional diversity indices concerning the functional properties of plants. Consequently, changes in functional richness depend on variations in the relative proportions of hemicryptophytes and therophytes. The functional evenness of a given ecosystem may fluctuate due to the plants' preferences for light intensity and associated traits, including leaf area, seed weight, humidity preference, level of naturalness, flowering time, seed bank duration, climate continuity, and hemeroby level. A shift in the proportion of plants requiring nitrogen compounds and soil moisture leads to a change in functional divergence. Our SEM analysis shows that hemeroby and naturalness are driven by different combinations of stand-structure and microclimatic controls: Heating and cooling potentials of tree stands act as two independent latent drivers of hemeroby, whereas naturalness additionally depends on stand density/thinning and the diversity–uniformity of stand species composition. The functional response of the herb layer can be parsimoniously described by the classical triad of functional richness, functional evenness, and functional divergence, and these components are most effectively captured by functional identity indices (community-weighted mean trait values along the main functional axes), while the nominal indices FRic, FEve and FDiv add comparatively little unique information. Hemeroby has a strong effect on all three functional components, whereas naturalness is linked only to functional richness and functional evenness, but not to functional divergence, indicating a partial decoupling in how these two indicators relate to the functional structure of herb-layer communities.

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