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Phytoindication assessment of spatial patterns of ecological regimes in urban parks as a basis for ecologically relevant management

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Urban parks are increasingly recognised as key components of green infrastructure that provide multiple ecosystem services. However, their management is still rarely guided by ecologically grounded indicators. The present study evaluated the potential of phytoindication approaches to diagnose ecological regimes within a single urban park, with the aim of supporting spatially differentiated management decisions. The research was conducted in Ivan Starov Square (Dnipro, Ukraine; 11.2 ha), where the herb layer was surveyed in 150 plots arranged on a quasi-regular grid. Phytoindication scales have been demonstrated to be a highly informative tool for quantifying major ecological regimes within the park, including soil moisture and its variability, aeration, acidity, nutrient and salinity levels, thermal and cryoclimatic conditions, continentality, light regimes, and degree of synanthropization. The indicator-based assessment demonstrated a clear separation between relatively natural, moderately used fragments and intensively managed and heavily disturbed lawns, playgrounds, and informal paths. Plots located in peripheral and less accessible zones exhibited higher environmental heterogeneity, lower hemeroby, more balanced life-form spectra, and greater contributions of competitive and stress-tolerant strategies. In contrast, central and highly visited zones demonstrated increased nutrient and disturbance scores, dominance of therophytes and ruderal strategies, and reduced species diversity. These patterns underscore the notion that indicator values derived from the herb layer integrate cumulative effects of management and environmental stress, as opposed to merely reflecting short-term fluctuations. For the majority of diversity metrics, phytoindication variables and disturbance indices, statistically significant positive spatial autocorrelation and a considerable proportion of spatially structured variance were detected. Variogram analysis revealed clear ranges of spatial dependence on the order of dozens to hundreds of metres, corresponding to the functional zones of the park. Furthermore, the spatial dependence level (SDL) reached up to several dozen per cent for many indicators. The results obtained demonstrate that the distribution of phytoindication values is far from random; rather, it reflects coherent spatial gradients of environmental conditions and management regimes. These gradients can be visualised by kriging maps and linked directly to concrete landscape elements. A significant practical outcome of this study is that the entire analytical framework is based on standard vegetation surveys and existing indicator scales, obviating the necessity for expensive equipment, continuous logging, or complex laboratory measurements. Phytoindication is therefore a low-cost, methodologically simple and reproducible tool for diagnosing ecological regimes in urban parks. Concurrently, the documented spatial dependence of these scales signifies that they can be interpreted not only as local descriptors of plant communities but also as spatially explicit ecological benchmarks that integrate long-term effects of management and environmental filtering. The results of the study provide quantitative evidence that phytoindication scales are suitable as operational guides for ecologically oriented management of urban parks. These measures enable managers to identify zones exhibiting high naturalness and conservation value, which is imperative. Furthermore, the detection of hotspots of degradation, ruderalisation and excessive disturbance is crucial. The optimisation of mowing and recreation regimes is also essential, as is the planning of targeted nature-based solutions that enhance biodiversity and ecosystem services. The approach proposed here is readily transferable to other urban parks and green spaces, as indicator systems such as those developed by Didukh and Ellenberg are widely available for different regions. The integration of such indicator-based, spatially explicit diagnostics into routine park management would facilitate the transition from predominantly aesthetic and technical criteria towards adaptive, ecologically informed governance of urban green spaces.

Keywords: species richness; hemeroby; naturalness; succession; urban park; recultivation; ecosystem comparison.

Introduction

The ecological functions of urban parks are now considered within the framework of the ecosystem services concept, which emphasises that even highly urbanised areas remain dependent on processes occurring in the city's green infrastructure (Sarı & Bayraktar, 2023). Urban parks, as concentrated pockets of vegetation in dense built-up areas, provide a wide range of regulating, supporting, cultural and, in part, provisioning services. Classic works on urban ecology have demonstrated that parks and other green elements within the city filter the air from dust and gaseous pollutants, reduce noise levels, accumulate carbon in biomass, regulate the microclimate, and mitigate the urban heat island effect (Mexia et al., 2018). Later generalisations within the urban ecosystem services approach confirmed that trees and ground vegetation cover in parks play a key role in capturing particulate matter, binding ozone and nitrogen oxides, infiltrating rainwater, retaining surface runoff and replenishing groundwater (Tkachuk et al., 2024), as well as buffering extreme temperatures and wind loads (Cotler et al., 2024). Shading conditions, humidity, and tree canopy structure create a specific microclimate that can differ significantly from the surrounding buildings, providing a "climatic refuge" for residents during hot periods and reducing the risks associated with climate change (Ge et al., 2024). Equally important is the supporting function of urban parks as elements of the ecological network (Wang & Chang, 2023). They serve as habitats for a diverse array of flora and fauna, including numerous species of birds, pollinating insects, small mammals, and invertebrates, thereby forming "islands of biodiversity" within the urban matrix (Miguez et al., 2025). Thanks to the structural diversity of plantings, micro-relief, and moisture regimes, parks provide a wide range of niches, increasing the overall functional diversity of urban ecosystems (Myalkovsky et al., 2023). Studies show that parks, urban forests, and gardens are key components of green infrastructure that support dispersal flows, species migration, and the connectivity of urban and suburban ecosystems (Martens et al., 2022). This role is vital in the context of environmental fragmentation: even relatively small parks, when combined with other green elements, contribute to the conservation of regional biodiversity and serve as refuges for species sensitive to urbanisation stress (Kabisch & Egerer, 2025).

The cultural and regulatory services of urban parks are closely linked to the well-being and health of the population (Stępniewska, 2021). Urban studies and medical and epidemiological reviews indicate that access to green spaces and regular visits to parks are associated with lower stress levels, improved mental health, a reduced risk of cardiovascular and metabolic diseases, and increased overall physical activity among the population (Bai et al., 2024). Parks serve as venues for recreation, informal education, social interaction, and the formation of a "sense of place," promoting social cohesion and environmental awareness among city dwellers (Bai et al., 2024). In this context, urban green spaces are viewed as nature-based solutions that integrate environmental and socio-economic goals, including mitigating the effects of climate change, adapting to extreme events, and reducing ecological injustice in terms of access to a high-quality natural environment (Jabbar et al., 2022).

A separate area of research concerns how the spatial characteristics of parks and their management regimes affect the range and intensity of ecosystem services (Kunakh et al., 2022). Recent studies have demonstrated that the structural diversity of green spaces, the presence of natural elements (e.g. meadows, undergrowth, water bodies), restrictions on excessive mechanical intervention (e.g. frequent mowing, soil compaction) and the integration of parks into a wider network of green infrastructure significantly increase their contribution to climate regulation, hydrological, biotic and cultural services (Qiu et al., 2021). At the same time, monotonous, intensively exploited lawn surfaces, characteristic of the traditional "aesthetics of a well-groomed park," have a limited capacity to support biodiversity, functional stability, and the ecological resilience of urban systems (Liu et al., 2024). In this regard, modern approaches to urban park planning and management are increasingly focused on multifunctionality and nature-oriented solutions, where ecological functions and services are considered not as a by-product, but as a central goal of design and management (Simončič et al., 2024).

The biological diversity of urban parks is considered a key indicator of the ecological quality of urban areas and the ability of cities to support viable populations of species (Keinath et al., 2025). Green spaces form a mosaic of tree, shrub, and grass communities, often including aquatic and semi-aquatic habitats, creating a wide range of niches for plants, invertebrates, birds, and small mammals (Borysiak et al., 2025). It is parks, together with other elements of green infrastructure, that act as "islands" and "stepping stones" of biodiversity in the urban matrix, ensuring the preservation of local populations and functional groups and maintaining ecological connectivity between urban and suburban ecosystems (Dondina et al., 2025). The urban environment exerts powerful and complex pressures on park biota (Chien, 2025). Urbanisation is accompanied by land use transformation, fragmentation of green spaces, soil compaction, air and water pollution, urban heat islands, and intense flows of people and transport, which alter both the physical conditions of species' existence and disturbance regimes (Douglas, 2014). These factors typically reduce the richness of native flora and fauna, promoting the spread of cosmopolitan, ruderal, and invasive species that are better adapted to unstable, eutrophic, and often disturbed environments. Generalisations across different taxonomic groups show that the impact of urbanisation on species composition is ambiguous: at the local level, species richness may even increase due to the mass introduction of introduced species, but this increase is accompanied by the loss of native taxa and biotic homogenisation, i.e. the levelling of species composition between different areas of the city (Zimmerer et al., 2021). Within urbanisation gradients, the highest proportion of rare and specialised species is found in semi-natural and peripheral areas. In contrast, the city centre is characterised by the dominance of a small set of stress- and disturbance-resistant species with similar functional traits (Hayes et al., 2023). The nature of urban park management plays an important role: intensive and spatially homogeneous maintenance (frequent low mowing, removal of undergrowth and dead wood, use of fertilisers and pesticides) leads to a simplification of structural diversity, a reduction in the number of microhabitats and a predominance of ruderal species, while more extensive regimes with elements of nature-oriented management (mosaic mowing, undergrowth preservation, creation of meadow areas, minimisation of soil disturbance) are associated with higher levels of taxonomic and functional diversity (Castelli et al., 2021). The interaction of two opposing trends shapes the biological diversity of urban parks. On the one hand, fragmentation, pollution, heat stress, invasions, and intensive use reduce the diversity of native species, leading to the homogenization of urban flora and fauna (Horvat et al., 2024). On the other hand, parks that are integrated into green infrastructure and managed according to the principles of adaptive, nature-oriented management are capable of maintaining high levels of biodiversity, serving as reserves for local species while providing ecosystem services to city residents (Threlfall et al., 2017).

The biological diversity of urban parks is fundamental to their ability to perform ecosystem services, as it is the diversity of species, life forms, and functional strategies that ensures the completeness and stability of ecological processes (Zari, 2018). The broader the variety of plant and animal communities, the more effectively the park delivers regulatory services – such as air purification, dust and pollutant filtering, water retention and infiltration, soil stabilisation, moderation of microclimatic extremes, and reduction of the 'urban heat island' effect (Stępniewska, 2021). Diverse in structure and species composition, plantings create a complex vertical and horizontal mosaic that enhances solar energy capture, biomass production, carbon sequestration, humus formation, and nutrient cycling (Eldridge et al., 2024). The functional diversity of flora and fauna also determines the ability of parks to support pollination networks, predation, organic matter decomposition, and pest biocontrol, i.e., the so-called supporting services on which long-term ecological stability depends (Perfectti et al., 2009). At the same time, biodiversity shapes cultural and recreational services (Wang et al., 2022). A rich species composition, seasonal changes, and the presence of rare or symbolic species enhance the park's aesthetic value, stimulate environmental education, promote psychological and emotional well-being, and foster ecological awareness (Langlois et al., 2021). Decreased diversity, on the contrary, leads to a simplification of community structure, loss of functional groups, and a reduction in the reserve of resilience, making a park more vulnerable to disturbances, climate extremes, and invasive species. At the same time, the range and intensity of ecosystem services are significantly reduced (Thompson et al., 2022). Maintaining and restoring biodiversity in urban parks should be viewed not as an additional task, but as a fundamental prerequisite for providing regulatory, supporting, cultural, and, in part, provisioning services to the urban population (Chinga et al., 2024).

In the context of escalating urbanisation and the mounting demand for ecosystem services, the perception of urban parks is evolving. These green spaces are no longer regarded as mere aesthetic embellishments, but rather as complex ecosystems that necessitate management in accordance with environmentally sound principles (Aly & Dimitrijevic, 2022). Traditional management focuses primarily on visual neatness, safety, and technological convenience (such as mowing frequency, sanitary felling, and path placement), which often leads to simplification of vegetation structure, ruderalization, and loss of naturalness (Battisti et al., 2023). Under such conditions, it becomes imperative to shift from purely aesthetic or technical criteria to indicators that reflect the actual state of the ecosystem, its stability, and ability to provide regulatory and supporting services (Kabisch et al., 2021). It is advisable to propose ecological indicators of plant communities as such benchmarks – phytoindication assessments of environmental factors, indices of naturalness and hemeroby (Ponomarenko et al., 2024), Raunkiaer's life form spectra, Grime's strategies, disturbance indicators, and other integral characteristics that synthesise information about soil, microclimatic, and anthropogenic conditions (Tutova et al., 2025b). It is plant communities, as a relatively "inert" component of urban ecosystems, that accumulate the effects of long-term exposure to moisture, trophic, shading, and disturbance regimes (Zelenova et al., 2024). Their indicator properties allow us to identify hidden gradients and degradation trends that are not visible from short-term technical monitoring. The use of such indicators as target or threshold values in park management enables the justification of zoning, mowing regimes, restoration of semi-natural communities, control of invasive species, and planning of nature-based solutions based on quantitative criteria rather than intuitive ideas. In this sense, ecological indicators of plant communities become a key tool for adaptive management: they simultaneously describe the current state, set the desired "ecological profile" of the park, and allow tracking the effectiveness of management decisions over time (Tutova et al., 2025a). Ecologically relevant benchmarks for urban park management should reveal spatially regular dynamics within the park, reflecting gradients in environmental conditions, vegetation cover structure, and recreational load zoning (Russo et al., 2025). Only if phytoindication indicators and related ecological indices form reproducible spatial patterns can they serve as a reliable basis for planning differentiated management decisions (e.g., designation of enhanced protection zones, visitor regulation, targeted greening, etc.). Suppose the spatial distribution of these indicators does not differ significantly from a random distribution. In that case, it is advisable to consider them primarily as a tool for comparative assessment of the condition of different parks or urban areas in general, rather than as a practical tool for internal spatial management of a specific park.

The study aims to determine whether phytoindication indicators of ecological regimes and functional strategies of plants (according to Grime) form spatially regular patterns within an urban park, and to assess the extent to which these indicators can serve as ecologically relevant benchmarks for spatially differentiated management and assessment of park ecosystem services as opposed to a random alternative for their distribution.

Material and methods

The study was conducted in Ivan Starov Park (Dnipro, Ukraine), which covers an area of 11.2 hectares. Ivan Starov Park is located in the historic centre of the city and is subject to significant recreational use. The vegetation cover of Ivan Starov Park consisted of two layers: trees and herbaceous plants. Thirty-three tree species were identified in the park's tree stand, among which (in descending order of abundance) *Robinia pseudoacacia*, *Ulmus pumila*, *Acer platanoides*, *Tilia platyphyllos*, *Styphnolobium japonicum*, *Aesculus hippocastanum* and *Fraxinus pennsylvanica* predominated. The canopy closure of the tree stand was 0.61±0.25. Sampling sites were distributed throughout the study area, and their exact locations were determined using a Garmin eTrex GPS device (accuracy ± 5 m). On Ivan Starov Square, vegetation cover was recorded and ecological properties were measured at 150 locations in a quasi-regular grid. Ivan Starov Park is situated in a relatively flat area with an elevation ranging from 115 to 128 m. In addition, park management measures are relatively uniform. The survey density in Ivan Starov Square was one location per 748 m^2.

The presence of all vascular plant species in the herbaceous layer on 3 × 3 m study plots was recorded during the study period, which spanned from July 7 to 12, 2024. The predicted species composition of plants is given in percentages. In the context of this study, the term "species" is generally used to refer to infra-taxa. Critical samples were collected and identified using microscopy. Plant taxonomy was based on the Euro+Med Plantbase database (http://ww2.bgbm.org/EuroPlusMed). Ecological regimes were assessed based on the description of vegetation cover using the phytocommunity scales developed by Didukh (2011). Phytocommunity scales include edaphic and climatic scales. Edaphic phytoindication scales include soil water regime (Hd), moisture variability (fH), soil aeration (Ae), soil acidity (Rc), total salt regime (Sl), soil carbonate content (Ca) and soil nitrogen content (Nt). Climatic scales include thermal climate parameters (thermal regime, Tm), humidity (Om), cryoclimate (Cr) and continentality (Kn). In addition, there is a light scale (Lc), which is recognised as a microclimatic scale. The phytoindication assessment of environmental factors was carried out using the Buzuk ideal indicator method(Buzuk, 2017).

To represent ecological factors, Ellenberg's ecological indicators for Europe were used, namely: light availability, temperature, soil moisture, soil reaction, and nutrient availability (Dengler et al., 2023). Continentality was assessed using Ellenberg's original scales (Ellenberg, 1974; Ellenberg et al., 1991). The Frank and Klotz scales (Frank & Klotz, 1990) were used to assess hemeroby (Lisovets et al., 2025). The original scales were converted by calculating the average of the minimum and maximum values for each species, which were then converted to a 100-point scale. To characterise the hemeroby of each sample, a weighted average of hemeroby scores was used, taking into account the predicted vegetation cover (Yorkina et al., 2022). The types of social behaviour of plants are based on the role of plant species in communities. They reflect how plants are related to their habitats, as well as the informativeness and naturalness of these relationships. The properties of the types present in a community can be used to determine the richness of ecological information within the community, its stability and naturalness, the degree of niche occupancy, the community's ability to regenerate, and the degree of disturbance, transformation, or deviation from its natural state (Borhidi, 1995). Life forms, according to Raunkiaer, are categorised into logophytes and diaspophytes, as described by Tarasov (Tarasov, 2012). Information on the significance of disturbance indicators that determine the optimum along gradients of natural and anthropogenic disturbances was used as indicators of the intensity of vegetation cover disturbances, the intensity of disturbances in the grass cover, the frequency of disturbances in the community as a whole and in the grass cover, the frequency of mowing and grazing load(Midolo et al., 2023). Grime's strategies were used to identify the ecological filters that plant communities exhibit as a result of the combination of resources and disturbances (Pierce et al., 2017).

Results

The diversity and indicators of the ecological structure of plant communities demonstrated spatial dependence in their variation, as indicated by statistically significant Moran's I coefficients (Table 1). A linear trend and spatial autocorrelation represented the spatial aspect of variability. The linear trend explained between 2% and 22% of the variability in the indicators. The level of spatial dependence (SDL), which is determined by spatial autocorrelation, explained 6–66% of the variability, i.e., this proportion of residual variability is due to spatial autocorrelation after removing the linear trend. Within a single location, the number of species varied from 6 to 17. The most species-rich communities were concentrated in the north and east of the park (Fig. 1). The plant communities in the south-east of the park were the poorest in terms of species richness. The Shannon diversity index ranged from 0.77 to 3.45. According to this indicator, the park's territory is clearly divided into two parts: the eastern part, which has higher diversity, and the western part, which has lower diversity.

The projective cover of hemicryptophytes in the community ranged from 5.66 to 98.51%. The largest projective cover of species in this ecological group was found in the north-west of the park, and the smallest in the south of the study area. The projective cover of therophytes in the community ranged from 1.49 to 94.34%. The largest projective cover of species of this ecological group was found in the south of the studied territory, and the smallest was in the south-west. Hemicryptophytes and therophytes are ecological antagonists, as evidenced by the negative correlation coefficient between the projective cover of these environmental groups ($r = –0.98$, $P < 0.001$). Geophytes are not permanent members of the plant community and were found in only 39% of locations. The projective cover of geophytes reached 28.57%. The largest projective cover of this ecological group was observed in the southern part of the park, and it was also sporadically present in other areas.

The projective cover of anemophilous species ranged from 30 to 96%. The highest projective cover of this ecological group was observed primarily in the western part of the park. In contrast, the lowest was observed in the east and south (Fig. 2). The projective cover of entomophilous species ranged from 4% to 70%. This indicator was highest in the east and south of the park and lowest in the west. Species with autogamous pollination syndrome were found in 51% of locations and accounted for 30% of the projective cover. The highest projective cover of this ecological group was found in the north-west and east of the park. Species with mixed pollination syndrome were found in 91% of locations and reached 38% projective cover. The highest projective cover was observed in the north of the study area for this ecological group. The projective cover of ballistochorous species varied from 47 to 100%. The largest projective cover of this environmental group was observed in the south-west of the territory. Barochorous species were found in 37% of locations, and their projective cover reached 43%. The largest projective cover of barochorous species was observed in the north of the park. Epizoochorous species were found in 25% of locations and accounted for 14% of the projective cover. The largest projective cover was established for the south-west of the park.

Table 1

Summary statistics, spatial autocorrelation (Moran's I), and variogram parameters (nugget, sill, range, SDL) for indicators of diversity and ecological structure of plant communities

Indicator	Variable	Mean ± SE	Min	Max	Moran *I*	Moran P	R^2 linear	Nugget	Sill	Range	SDL
Diversity	Species richness	9.79 ± 0.19	6.0	17.0	0.31	< 0.001	0.05	2.95	5.48	125.84	46.14
	Shannon	2.30 ± 0.05	0.77	3.45	0.35	< 0.001	0.21	0.14	0.25	60.12	42.57
Raunkiaer life form	HKr	62.56 ± 1.94	5.6	98.51	0.36	< 0.001	0.22	314.45	457.96	163.82	31.34
	T	34.22 ± 1.88	1.49	94.34	0.34	< 0.001	0.20	285.45	414.39	93.61	31.12
	G	2.34 ± 0.41	0.00	28.57	0.24	< 0.001	0.07	9.28	22.02	65.22	57.85
Pollenochores	Anph	70.60 ± 1.14	30.00	95.59	0.14	0.002	0.04	93.88	190.21	35.06	50.65
	Ent	29.40 ± 1.14	4.41	70.0	0.14	< 0.001	0.04	135.47	190.21	30.56	28.78
Diasporochores	Ach	3.07 ± 0.40	0.00	30.0	0.29	< 0.001	0.13	15.54	23.53	121.35	33.96
	Anch	8.09 ± 0.57	0.00	38.10	0.14	< 0.001	0.09	38.98	100.51	237.96	61.21
	Bal	86.06 ± 0.87	46.58	100.00	0.26	< 0.001	0.19	81.90	338.92	400.82	75.83
	Bar	1.89 ± 0.42	0.00	42.47	0.19	< 0.001	0.05	23.22	24.69	609.79	5.95
	EpZ	0.87 ± 0.18	0.00	14.29	0.30	< 0.001	0.02	3.60	10.14	276.39	64.52

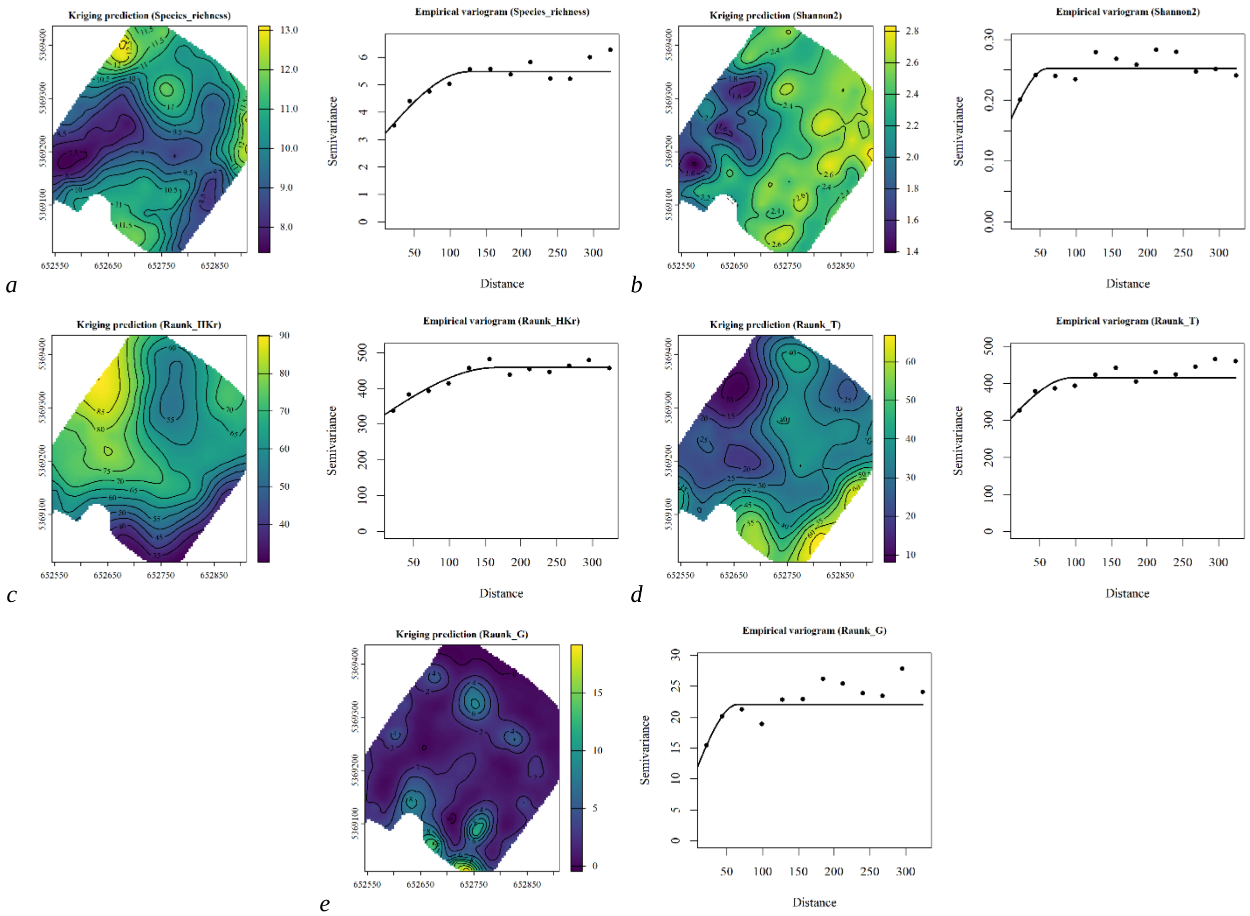

Fig. 1. Results of ordinary kriging (left panels) and empirical variograms with approximated models (right panels) for selected indicators of diversity and ecological structure of plant communities. Each pair of panels corresponds to a separate indicator: kriging maps reflect the spatial distribution of indicators within the study area, while variograms characterise the scale and strength of spatial dependence (nugget, sill and range parameters): *a* – species richness indicates the number of species in the sample area; *b* – Shannon represents the Shannon diversity index (H′); *c* – HKr suggests the proportion of hemicryptophytes in the Raunkiaer life form spectrum (%); *d* – T represents the proportion of therophytes (%); *e* – G represents the proportion of geophytes (%)

According to Didukh's phytoindication assessments of ecological factors, a distinct spatial gradient of environmental conditions has formed within the park. Soil moisture and its variability varied widely, with moisture indicators showing a predominance of mesophytic and moderately moist conditions, accompanied by localised areas of increased moisture, spatially coinciding with lower micro-relief elements. In contrast, the moisture irregularity indicator suggests the presence of regions with contrasting water regimes, where periods of excess and deficiency of moisture alternate. Such areas tend to be located on the periphery of the park and in areas with disturbed turf.

The values of acidity, carbonate and nitrogen content indicate a predominance of slightly acidic to neutral conditions and an average trophic status; however, the spatial field structure clearly shows local "cores" of increased fertility, probably associated with the accumulation of organic residues and local fertilisation points. The salinity indicator has generally low values, and spatial models do not reveal large areas with elevated salt content, confirming the absence of pronounced salinisation processes in the studied territory. All these indicators are characterised by statistically significant positive spatial autocorrelation (Moran's I within 0.3–0.6, P < 0.001) and a high proportion of spatially structured dispersion (SDL reaches more than half of the total variability), which is reflected in variograms and kriging maps (Fig. 3).

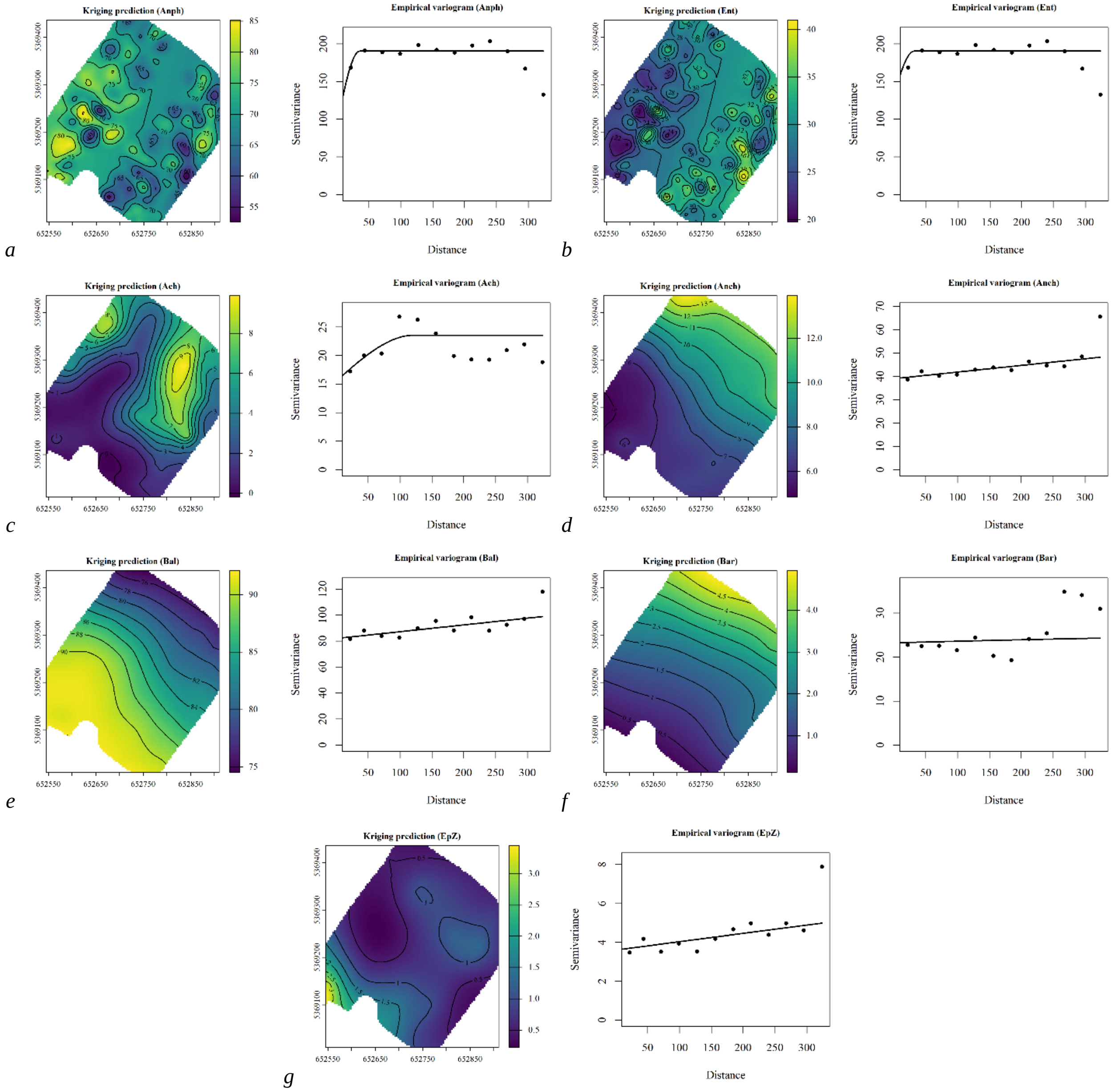

Fig. 2. Results of ordinary kriging (left panels) and empirical variograms with approximated models (right panels) for indicators of pollination syndromes and dispersal of diaspores in plant communities: each pair of panels corresponds to a separate indicator; kriging maps reflect the spatial distribution of indicators within the study area, while variograms characterise the scale and strength of spatial dependence (nugget, sill and range parameters): *a* – Anph represents the proportion of anemophilous (wind-pollinated) species (%); *b* – Ent represents the proportion of entomophilous (insect-pollinated) species (%); *c* – Ach represents the proportion of species with autogamous pollination syndrome (%); *d* – Anch represents the proportion of species with other/mixed pollination syndromes (%); *e* – Bal represents the proportion of ballistochorous (ballistic dispersal of diaspores) species (%); *f* – Bar represents the proportion of barochorous (gravitational dispersal) species (%); *g* – EpZo represents the proportion of epizoochorous species (dispersal of diaspores on the surface of animal bodies, %)

Despite their macroclimatic content, the climatic phytoindication indices, as shown by Didukh, demonstrated sensitivity to microclimatic conditions within the park. Assessments of the aeration regime reflect the micro-mosaic of soil air permeability: the most aerated areas are associated with elevated, better-drained fragments and regions of intense trampling, while lower values are recorded in depressions and under dense tree stands. Thermal and climatic humidity regimes show gradients consistent with exposure and shading: warmer and more "continental" conditions are characteristic of open, well-sunlit parts of the park, while cooler and more humid microclimatic conditions are associated with shaded areas under the canopy of trees and near water bodies. Cryoclimate and light regime indicators confirm this picture: areas with the highest light index values are concentrated on the periphery of the park and in its open central parts, while lower values correspond to the inner, shaded parts of the plantings (Fig. 4). The variograms of these indices are characterised by a rapid plateau at distances of about 100–150 m, indicating the scale of spatial structures related to micro-relief, tree stand configuration and buildings.

Phytoindication assessments using the Ellenberg scales generally agree with the results obtained using the Didukh scales, but emphasise certain aspects of ecological gradients (Table 2). The light indicator clearly divides the territory into more illuminated peripheral lawns and shaded inner areas, which correlates with the spatial distribution of tree species and the density of their crowns. The temperature and continental indices reflect subtle differences in microclimate between open and sheltered areas. In contrast, the humidity index confirms the presence of moisture gradients from mesophytic to meso-hydrophytic conditions. The soil reaction indicator suggests the predominance of slightly alkaline or near-neutral conditions, with local areas of more acidic soils under deciduous tree stands, where litter accumulation is prevalent. The indicators of nutrient content and salinity according to Ellenberg indicate generally eutrophic conditions with separate fragments of elevated trophic status, which are probably associated with local sources of nitrogen and other nutrients (Fig. 5). For most of Ellenberg's scales, significant spatial autocorrelation and high SDL values were also recorded, confirming the structured nature of ecological gradients even within a relatively small urban green area.

Table 2
Summary statistics, spatial autocorrelation (Moran’s I), and variogram parameters (nugget, sill, range, SDL) for phytoindication and hemeroby variables (N = 150)

Indicator system	Variable	Mean ± SE	Min	Max	Moran *I*	Moran P	R^2 linear	Nugget	Sill	Range	SDL
Didukh	Hd	72.39 ± 0.68	51.44	91.85	0.39	< 0.001	0.16	35.29	59.13	95.76	40.33
	fH	0.28 ± 0.00	0.21	0.35	0.48	< 0.001	0.26	0.00	0.00	130.37	57.99
	Rc	6.76 ± 0.01	6.47	7.10	0.51	< 0.001	0.32	0.01	0.01	85.65	44.57
	Sl	29.61 ± 0.44	14.84	44.72	0.29	< 0.001	0.19	19.69	24.45	98.40	19.44
	Ca	2.20 ± 0.05	0.76	4.13	0.30	< 0.001	0.08	0.23	0.38	199.63	40.19
	Nt	2.94 ± 0.04	1.57	3.91	0.16	< 0.001	0.02	0.13	0.20	114.62	35.32
	Ae	60.80 ± 0.50	44.30	77.93	0.22	< 0.001	0.03	27.59	38.30	146.71	27.96
	Tm	2.11 ± 0.01	1.79	2.56	0.28	< 0.001	0.01	0.01	0.02	65.98	58.28
	Om	–1.06 ± 0.04	–2.42	0.06	0.40	< 0.001	0.18	0.07	0.21	83.35	65.87
	Kn	86.21 ± 1.07	58.77	123.87	0.05	0.13	0.01	117.43	172.63	25.22	31.97
	Cr	–0.62 ± 0.38	–13.01	9.17	0.50	< 0.001	0.34	7.03	14.52	94.63	51.61
	Lc	87.62 ± 0.34	70.53	92.93	0.37	< 0.001	0.16	6.90	16.95	116.07	59.28
Ellenberg	Light_Regime	7.67 ± 0.02	6.73	8.23	0.40	< 0.001	0.23	0.02	0.06	66.57	60.84
	Temperatures	4.71 ± 0.02	4.32	5.28	0.41	< 0.001	0.14	0.02	0.05	69.63	59.85
	Continentality	8.25 ± 0.15	4.69	11.26	0.59	< 0.001	0.45	1.14	1.86	184.70	38.47
	Humidity	3.87 ± 0.02	3.41	4.23	0.51	< 0.001	0.27	0.02	0.03	215.43	41.62
	Acidity	6.39 ± 0.01	6.17	6.72	0.45	< 0.001	0.09	0.01	0.01	163.03	43.13
	Nutrients	5.96 ± 0.04	4.56	6.60	0.28	< 0.001	0.18	0.14	0.19	84.28	27.44
	Salinity	1.63 ± 0.01	1.33	2.11	0.41	< 0.001	0.30	0.02	0.02	185.61	26.77
Naturalness/ Hemeroby	Naturalness	–2.12 ± 0.10	–5.89	0.25	0.29	< 0.001	0.03	0.69	1.47	59.23	52.90
	Hemeroby	78.12 ± 0.55	54.84	94.47	0.37	< 0.001	0.13	14.56	38.05	56.38	61.75
Disturbance	Severity	0.65 ± 0.00	0.55	0.77	0.33	< 0.001	0.14	0.00	0.00	94.37	39.34
	Severity in the herb layer	0.61	0.47	0.74	0.34	< 0.001	0.10	0.00	0.00	66.13	52.22
	Frequency	1.41 ± 0.01	1.0	1.72	0.60	< 0.001	0.41	0.01	0.02	155.74	40.06
	Frequency in the herb layer	1.96 ± 0.01	1.76	2.14	0.62	< 0.001	0.44	0.00	0.01	173.93	45.47
	Mowing frequency	0.83 ± 0.01	0.54	1.31	0.38	< 0.001	0.31	0.01	0.02	2,092.97	16.92
	Grazing pressure	0.30 ± 0.01	0.21	0.44	0.52	< 0.001	0.40	0.00	0.00	303.23	34.55
	Soil disturbance	0.73 ± 0.02	0.30	1.59	0.30	< 0.001	0.09	0.03	0.07	52.68	56.20
Grime	Competitor (C)	24.93 ± 0.37	14.93	40.61	0.17	< 0.001	0.08	11.95	19.71	66.99	39.38
	Stress-tolerant (S)	14.30 ± 0.54	2.84	32.81	0.38	< 0.001	0.31	24.53	31.04	172.18	20.95
	Ruderal (R)	60.77 ± 0.67	41.2	75.97	0.28	< 0.001	0.19	41.81	55.04	137.25	24.05

The proportions of species with different ecological strategies according to Grime indicate that the park's vegetation cover is generally ruderal in nature. On average, competitors (C) account for approximately 25% of the projected cover, ranging from 14.9% to 40.6%. Stress-tolerant species (S) account for an average of 14.3% of the cover, but are characterised by the broadest range of values (from 2.8% to 32.8%). In contrast, ruderal species (R) dominate, accounting for an average of over 60% of coverage, with a range of 41.2% to 76.0%. All three components of Grime's triangle exhibit statistically significant positive spatial autocorrelation (Moran's I = 0.17–0.38; P < 0.001), indicating the presence of clearly defined areas with a predominance of a specific type of strategy. According to variogram data, approximately 20–40% of the dispersion of these indicators is attributed to spatially dependence level (SDL), with characteristic scales of spatial structures ranging from 70 to 170 m, which corresponds to the size of individual functional zones within the park. Kriging maps indicate that areas with a high proportion of the naturalness and hemeroby indices reflect the degree of anthropogenic transformation of different parts of the park. Spatial models demonstrate the presence of areas with elevated naturalness values within the most stable fragments of tree and shrub plantings, where species characteristic of semi-natural forest and meadow communities have been preserved. At the same time, hemeroby values are reduced here, indicating a relatively weak direct human influence. The opposite situation is observed on open lawns, along the main alleys and on the periphery of the park, where ruderal and synanthropic species dominate. These areas are characterised by high values of hemeroby and reduced naturalness (Fig. 6). This spatially mosaic structure indicates that within a single park, there are both areas with a regime close to semi-natural ecosystems and areas with almost complete replacement of natural phytocomplexes by urbanised vegetation.

Disturbance indicators confirm the critical role of recreational load and maintenance measures in shaping modern vegetation. The degree of disturbance at the community level and within the herbaceous layer varies widely: maximum values are characteristic of areas with intensive use, such as playgrounds, walking paths, and open lawns, while minimum values are characteristic of inaccessible or rarely visited places. The frequency of disturbances shows a similar pattern, indicating the regularity of mechanical impact on the vegetation cover in most open areas of the park. The models for mowing frequency reflect the dominance of this type of management: the most frequently mowed areas form long strips along paths and on central lawns. In contrast, in peripheral regions, the mowing frequency is reduced. For the grazing indicator, local "hot spots" were recorded, located mainly on the outskirts and near informal footpaths, indicating an episodic but spatially structured impact of this type of disturbance (Fig. 7).

The proportions of species with different ecological strategies, according to Grime, indicate that the park's vegetation cover as a whole has a distinctly ruderal character. On average, competitors (C) account for approximately 25% of the projected coverage, ranging from 14.9% to 40.6%. Stress-tolerant species (S) make up on average

14.3% of the cover, but show the widest range of variation (from 2.8% to 32.8%), whereas ruderals (R) dominate, contributing on average more than 60% of the cover and ranging from 41.2% to 76.0%. All three components of Grime's triangle exhibit statistically significant positive spatial autocorrelation (Moran's I = 0.17–0.38; $P < 0.001$), which indicates the presence of clearly delineated areas with a predominance of a given strategy type. According to variogram analysis, about 20–40% of the variance in these metrics is attributable to spatially structured variability (SDL), and the characteristic spatial scales of the structures fall within 70–170 m, which corresponds to the size of individual functional zones of the park.

Kriging maps indicate that areas with a higher proportion of competitors tend to be associated with relatively stable communities characterised by a dense turf layer and moderate use intensity, where perennial grasses and tall forbs with well-developed vegetative regeneration prevail. Stress-tolerant species form mosaic patches related to more extreme environmental conditions, such as drier, nutrient-poor, or heavily shaded microsites, as well as local zones with compacted soil. The most spatially extensive patterns are characteristic of the ruderal strategy: areas with a high share of R coincide with zones of intense recreational pressure, along paths and on open lawns, where recurrent turf disturbance, trampling and mowing select for fast-growing annual and perennial species with high seed production. Thus, the C–S–R balance reflects the relationship between stabilised, relatively little disturbed vegetation fragments and spatially dominant ruderal assemblages shaped by recurrent disturbance, whereas stress-tolerant species are localised in specific microhabitats with elevated ecological stress.

Discussion

In this study, we considered a wide range of ecological indicators of urban park vegetation cover. We assessed their spatial organisation at both the level of large-scale spatial trends and the level of local spatial autocorrelation. The identification of statistically significant spatial patterns for most of the analysed indicators indicates that their distribution is not random but reflects structured gradients of environmental conditions and land use regimes. This confirms our initial assumption that such ecological indicators can be used as ecologically relevant benchmarks for spatially differentiated management of urban parks, and not only as a tool for general comparative assessment of their condition (Tkachuk et al., 2024). The results obtained indicate that both diversity indicators and parameters of the ecological structure of plant communities demonstrate a clearly expressed spatial organisation. Significant Moran I values and high SDL values for most indicators confirm that variation within the park is determined not only by random fluctuations, but also by spatially correlated processes that manifest themselves on a scale of dozens to hundreds of metres. This is consistent with the idea that spatially structured gradients of the environment and anthropogenic load play a key role in urban green spaces (Paudel & States, 2023).

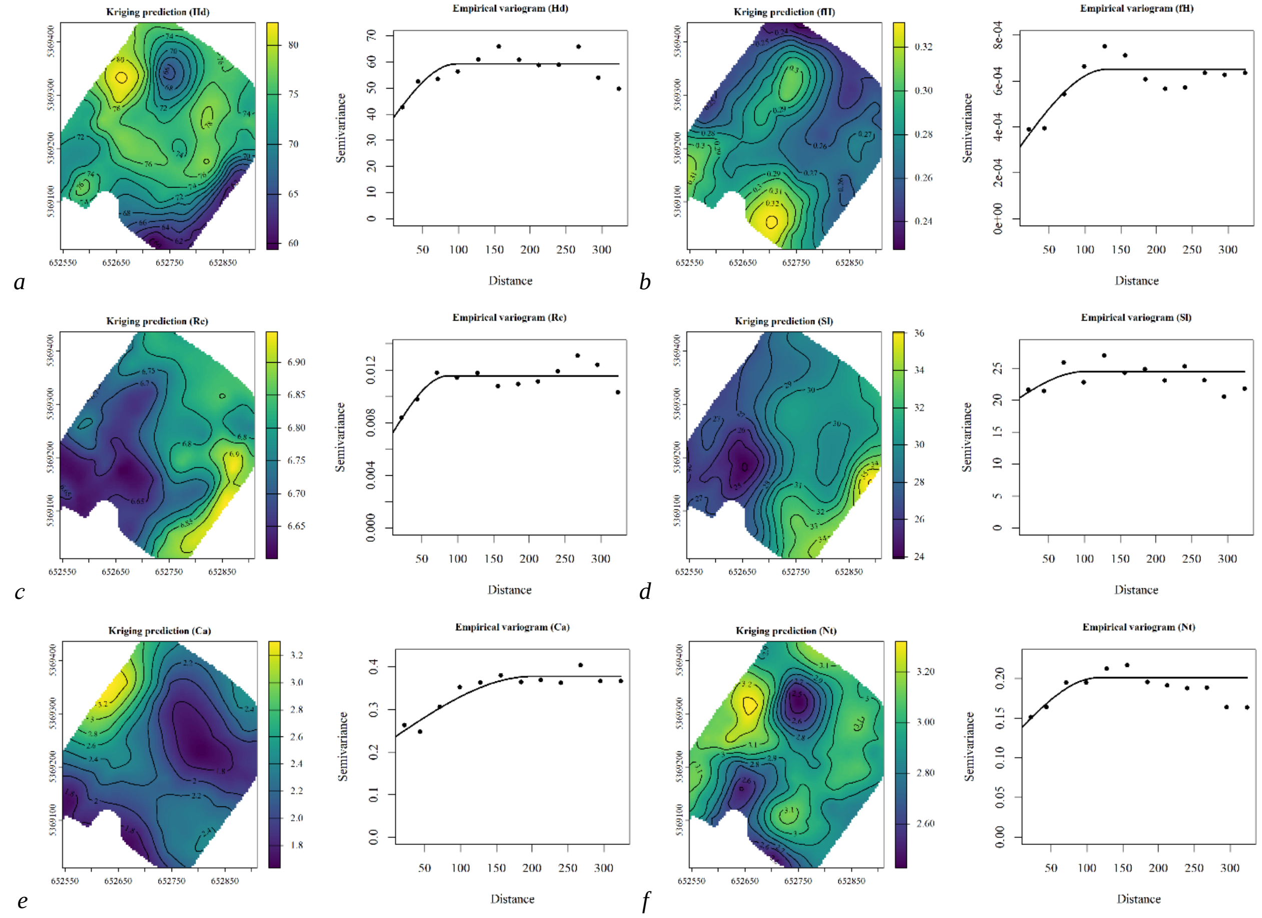

Fig. 3. Spatial models of variation and empirical variograms of phytoindication assessments of environmental factors according to Didukh: *a* – H is a score of the moisture regime, quantitatively expressed as the content of productive moisture in the one-metre soil layer (mm); *b* – fH is a score of the variability of the moisture regime, quantitatively expressed as the ω-coefficient of irregularity of moisture; *c* – Rc is the acidity score, quantitatively expressed as the negative logarithm of the concentration of hydrogen ions in the soil solution (pH); *d* – Sl is the score of the soil salinity regime, quantitatively expressed as the salt content in the soil solution (μg/L); *e* – Ca is a score for carbonate content, quantitatively expressed as the carbonate content (in terms of calcium and magnesium oxides); *f* – Nt is a score for the soil trophic regime, quantitatively expressed as the nitrogen content in the soil (g/kg)

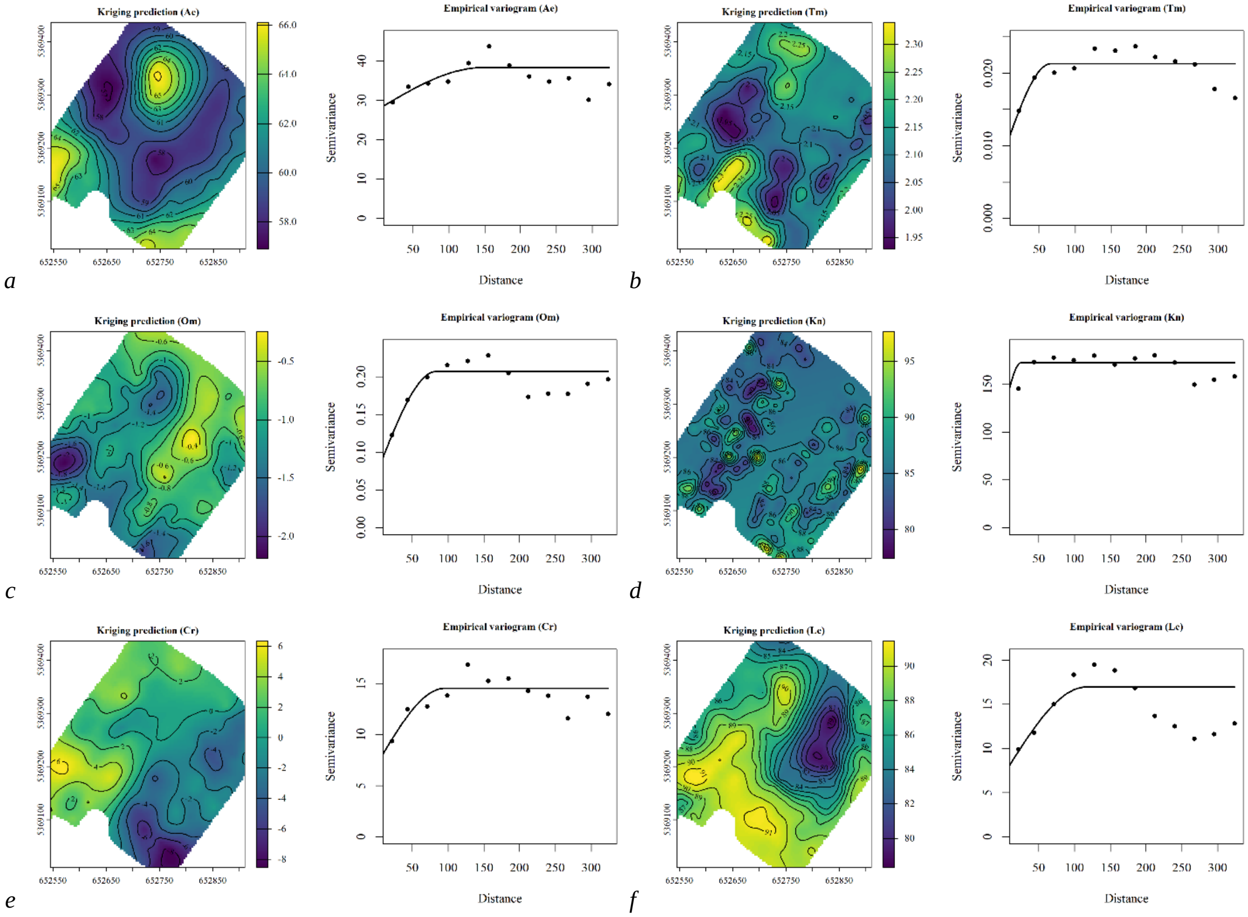

Fig. 4. Spatial models of variation and empirical variograms of phytoindication assessments of environmental factors according to Didukh: *a* – Ae is the score of the aeration regime, quantitatively expressed as the air-filled porosity percentage (% of the total volume of the pore space in the soil); *b* – Tm is the thermal regime score, quantitatively expressed as the radiation balance (gJ/(m^2 year)); *c* – Om is the climate humidity score, quantitatively expressed as the difference between the average annual precipitation per day and evaporation from the open water surface over the same period (mm); *d* – Kn is the score of the continentality regime, quantitatively expressed as the Ivanov continentality scale; *e* – Cr is a score for the cryoclimate, quantitatively expressed as the average temperature of the coldest month of the year (°C); *f* – Lc is a score of the light regime, quantitatively expressed as the percentage of the maximum possible solar radiation

The number of species and the Shannon index are among the most informative indicators for assessing the state of plant communities in urban parks (Chetvertak et al., 2025), as they integrate both species diversity and the degree of evenness of species participation within the community (Xu et al., 2025). Our results show that the number of species and the Shannon index of park vegetation are characterised by pronounced spatial heterogeneity. The most remarkable species richness is concentrated in the north and east of the park, while the poorest communities are found in the south-east. For the Shannon index, there is a clear division of the territory into the eastern, more diverse part and the western part, where diversity is reduced. This division can be interpreted as a manifestation of the edge effect: peripheral areas that are in contact with other types of cover (street plantings, areas adjacent to buildings, undeveloped fragments) form a kind of ecotone where species from several phytocomplexes coexist.

Within these transition zones, both characteristic park species and spontaneous urban flora coexist, ensuring increased diversity. The areas with the poorest species diversity in the south-east probably correspond to areas of more intensive recreational use, levelled lawns or monodominant fragments of tree and shrub plantings. Here, the dominance of several species tolerant to trampling or mowing is accompanied by the displacement of less competitive plants, which reduces both alpha diversity and the Shannon index. Spatial trends in species composition, as recorded by variograms and kriging maps, reflect a combination of ecological gradients (humidity, shading, and soil compaction) and management gradients (mowing frequency, undergrowth removal, and recreational pressure). The spatial patterns of species richness and Shannon index we obtained are consistent with recent studies of biodiversity in urban green spaces, which show that diversity levels are sensitive to maintenance regimes and the intensity of plant care. In particular, for urban green spaces, it has been demonstrated that biodiversity indicators are significantly related to the intensity of management. Maintaining a mosaic of different maintenance regimes allows one to avoid the impoverishment of flora and preserve a higher level of diversity (Hwang et al., 2025). This is consistent with our spatial analysis results, where higher species richness and diversity are associated with areas with potentially less "severe" anthropogenic impact. At the same time, the poorest communities correspond to areas of more intensive use and cover transformation. Thus, spatially structured indicators of taxonomic diversity can be considered not only as a diagnostic tool for assessing the park's condition, but also as a practical basis for differentiating maintenance regimes and optimising management. The spatial patterns of taxonomic diversity we obtained correspond to the results of large-scale studies of urban green spaces, where diversity was assessed using Hill's numbers (species richness, effective number of species according to Shannon's index, Simpson index) and showed that it is systematically related to the size of green areas, habitat diversity, and the intensity of anthropogenic use of the territory (Leveau et al., 2022). Importantly, these relationships persist under different seasonal conditions, underscoring the enduring role of urban parks and similar green infrastructure elements in supporting biotic diversity in urban environments. In this context, the Shannon index and related diversity indices serve as sensitive integral indicators of the structure of urban biocenoses, which can be used as a basis for environmentally oriented park management.

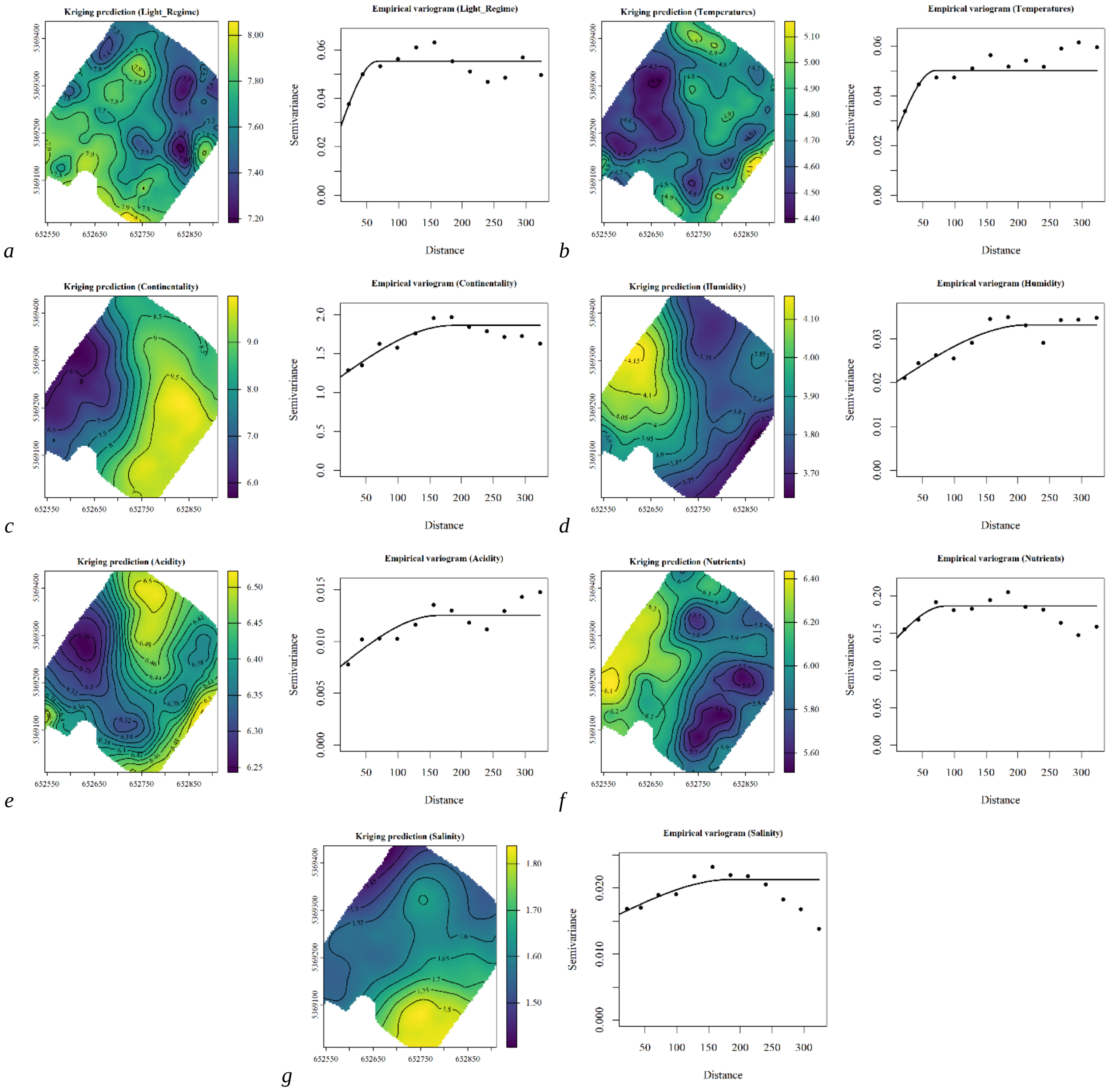

Fig. 5. Spatial models of variation and empirical variograms of phytoindication estimates of Ellenberg ecological factors: *a* – light_regime (L, 1–9) ranging from deep shade specialists (1) to species of whole light (9); *b* – temperatures (T, 1–9) ranging from species of very cold, alpine–subalpine climates (1) to species of extremely warm, Mediterranean–submediterranean climates (9); *c* – continentality (K, 1–9) ranging from strongly oceanic species (1) to strongly continental and eucontinental species (9); *d* – humidity (F, 1–12) ranging from species of extremely dry soils (1) to permanently submerged aquatic plants (12); *e* – acidity (R, 1–9) ranging from species confined to highly acidic soils (1) to species restricted to bare, calcareous soils (9); *f* – nutrients (N, 1–9) ranging from species of extremely nutrient-poor soils (1) to species of extremely nutrient-rich soils (9); *g* – salt content indicator value (S, 1–9) ranging from 0 (species absent from saline soils) through slightly to highly salt-tolerant species (1–8), up to 9 (species of extremely saline conditions where sea water evaporates and precipitates salt)

We considered Raunkier's classification of life forms not so much as a "classical botanical reference" but rather as a source of ecologically relevant information about the functional organisation of the park's vegetation cover. The distribution of biomorphs reflects where plants "invest" their renewal buds (above the ground, on their surface or in the soil profile), and thus their strategy for surviving unfavourable conditions, sensitivity to anthropogenic stress and ability to form stable communities. For urban parks, this means that the proportion of phanerophytes, hemicryptophytes, cryptophytes, and therophytes in the biomorphic spectrum is an indicator not only of climatic and edaphic conditions but also of maintenance regimes, environmental fragmentation, and recreation intensity. The predominance of perennial hemicryptophytes and cryptophytes is usually associated with an established soil profile, a more stable moisture regime and moderate intervention. At the same time, an increase in the proportion of therophytes and certain groups of phanerophytes with a short life cycle may indicate frequent disturbances, soil compaction, regular mowing, or other forms of resource limitation. Thus, Raunker's biomorph analysis complements taxonomic and phytoindication indicators, allowing the identified spatial patterns to be interpreted not only as a "diversity map" but also as a reflection of ecological regimes and management history, which can be directly relied upon when planning differentiated plant care. The structure of communities by life forms indicates that the herbaceous cover is dominated by hemicryptophytes (HKr) and therophytes (T). The extremely high range of variation in their projective cover and almost perfectly negative correlation (r ≈ –0.98) indicate that two alternative structural "regimes" are implemented within the park: some communities are represented mainly by perennial turf and rosette species, while others consist almost entirely of annual plants. This mosaic pattern corresponds to different types of anthropogenic impact. Hemicryptophytes are typical components of stabilised lawn and meadow communities of moderate anthropogenic use; they effectively withstand regular mowing but do not tolerate deep destruction of the turf. In contrast, therophytes, mainly ruderal and segetal species, dominate in areas with intensive soil disturbance, local top dressing, turf cover disturbance and increased nutrient supply. Geophytes (G) proved to be a less stable component of the flora and were found only in some locations. Their spatially fragmented structure, with maximum coverage in the south of the park, may reflect local microhabitats with preserved spring moisture conditions, elements of semi-natural undergrowth vegetation, or remnants of introduced ornamental species. The high proportion of geophytes in such areas emphasises their role as "refugia" for species sensitive to excessive trampling and summer drying. The preservation and expansion of these microhabitats will help maintain the seasonal dynamics of the flora and enhance the park's aesthetic appeal in spring.

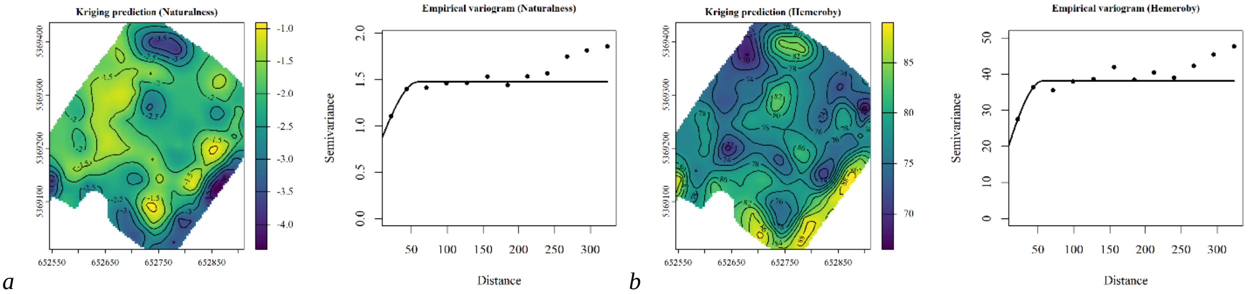

Fig. 6. Spatial models of variation and empirical variograms of naturalness and hemeroby: *a* – naturalness ranging from the least natural conditions (–4) to the most natural conditions (10); hemeroby ranging from ecosystems that have experienced minimal anthropogenic transformation (0) to those that have undergone maximal anthropogenic transformation (100)

The structure of pollination syndromes revealed a clear preference for anemophilous species (Anph), whose projective cover reaches very high values. This is typical for urban parks, where wind-pollinated trees and grasses form a significant proportion of the phytomass. The spatial pattern of Anph, with maximum values in the western part of the park, is likely due to the concentration of old tree stands and developed lawn cover dominated by Poaceae. At the same time, entomophilous species (Ent) have a lower but significant contribution, with their maximum coverage confined to the eastern and southern parts of the park, where fragments of mixed grasslands, flower beds or less intensively mowed areas have probably been preserved. This spatial complementarity of Anph and Ent indicates that the park has the potential to serve as an essential habitat for pollinators, but this function is not fully realised. The predominance of anemophilous species reflects the simplification of the vegetation cover due to lawn-type maintenance, which leads to a shortage of nectar- and pollen-bearing plants in part of the territory. To enhance the role of entomophilous species, it is advisable to: 1) create and maintain meadow-type areas with perennial herbaceous dominants; 2) reduce the frequency and height of mowing in areas that are key for pollinators, especially during mass flowering; 3) give preference to local entomophilous species when planting new plants and reconstructing flower beds; 4) limit the use of insecticides within the park and the surrounding area. Shifting the balance towards greater participation of entomophilous species will enhance the park's aesthetic value and strengthen its role as an element of green infrastructure that supports urban pollinator populations.

The structure of diasporochores demonstrates the dominance of ballistochorous species (Bal), which have high coverage and relatively evenly cover a significant part of the park. Ballistochory primarily ensures short-distance seed dispersal, contributing to the formation of compact, stable populations within a given area. This profile is characteristic of established herbaceous communities in parks, where species with localised regeneration centres predominate. The high proportion of ballistochory indicates that most communities are sufficiently self-sustainable, requiring minimal introduction of diaspores from outside. Barochorous species (Bar), which rely on gravitational dispersal, are found in a smaller proportion of locations, but their coverage is maximum in the north of the park. This probably reflects the spatial distribution of tree and shrub communities, where seeds fall near parent plants. This pattern of dispersal leads to the formation of local regeneration centres. It highlights the importance of a gentle management regime (no complete removal of leaves and fallen fruit) to avoid interrupting the natural regeneration cycle. Epizoochorous species (EpZ) are less common and have lower coverage. Still, their spatial pattern, concentrated in the southwest, may indicate the role of animal and human migration routes (walking paths, dog walking areas) in the introduction of diasporas. The presence of such species suggests the park's integration into a broader urban ecological network. It confirms that it functions as a hub for the exchange of diasporas between different urban centres. In summary, the identified structure of diasporochores indicates that the park combines communities with predominantly local seed dispersal and centres where zoogenic dispersal routes are active. Maintaining different types of dispersal strategies is crucial for the long-term sustainability of flora. Ballistochores and barochores are responsible for preserving existing populations, while epizoochorous provide the potential for colonising new microenvironments and recovering from disturbances. Thus, spatial patterns of diversity, life forms, pollination syndromes, and dispersal reflect the complex action of edge effects, environmental microgradients, and management regimes. Taking this spatial organisation into account when planning park management measures will simultaneously increase biotic diversity, community stability and ecosystem services.

Phytoindication analysis showed that even within a relatively small urban park, distinct gradients of ecological regimes have formed. The baseline consists of mesophytic, moderately humid conditions with slightly acidic to neutral soils and generally eutrophic status. Against this background, local areas of increased moisture in microdepressions stand out, as do, conversely, "dry" areas with contrasting water regimes associated with turf disturbance and soil compaction. The mosaic of light, heat and aeration regimes, reflected in the Didukh and Elenberg scales, is determined by a combination of open lawns and dense tree stands, different slope exposures, the presence of paths and buildings. In other words, the park functions as a microlandscape with a set of contrasting micro-biotopes, which in terms of size (70–170 m) correspond to individual recreational sectors and elements of the planning structure.

Such spatially structured regimes directly determine the range of ecosystem services that the park provides. Areas of increased humidity and the shaded regions under tree stands regulate the microclimate, reduce heat stress and maintain the local water balance. At the same time, eutrophic, well-aerated soils of open lawns contribute to high grass productivity and effective absorption of atmospheric precipitation, but at the expense of simplifying the species composition. Where fragments of semi-natural vegetation with increased naturalness and the participation of competitive and stress-tolerant species are preserved, the park serves as a habitat for more demanding flora and fauna, increasing regional biodiversity and self-recovery potential. In contrast, ruderalised areas with high hemeroby mainly provide "amenity services" – the possibility of free movement, playgrounds, and sports grounds, as well as visually "clean" lawns – but perform regulatory and supporting services much less effectively.

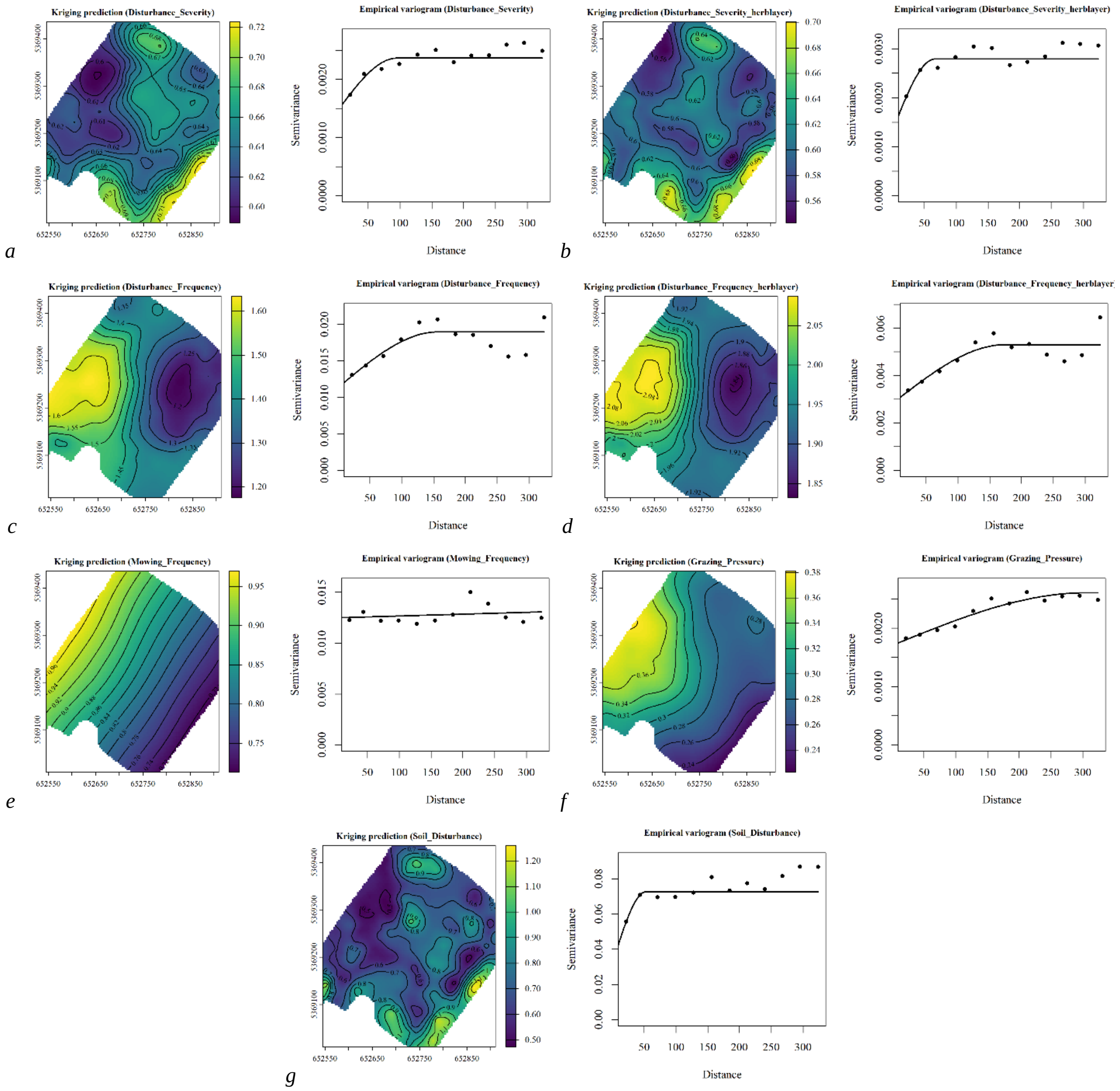

Fig. 7. Spatial models of variation and empirical variograms of disturbance indicators: *a* – Disturbance severity at the whole-community level (proportion of above-ground biomass killed by disturbance, scale 0–1); *b* – disturbance severity in the herb layer (proportion of above-ground biomass killed in the herb layer, 0–1); *c* – disturbance frequency at the whole-community level ($\log_{10}$ return interval of disturbance events (years); *d* – disturbance frequency in the herb layer ($\log_{10}$ return interval of disturbance events in the herb layer, years); *e* – mowing frequency ($\log_{10}$ return interval of mowing events, years; values of zero correspond to a 100-year return interval assigned to never-mown habitats); *f* – grazing pressure (proportion of above-ground biomass removed or killed by grazing, 0–1); *g* – soil disturbance (proportional increase in bare-ground cover due to furrowing or soil turning, 0–1)

The spatial structure of naturalness and hemeroby indicators clearly reflects the shortcomings of current management (Kunakh et al., 2023). The dominance of ruderal communities, high hemeroby values and low naturalness in a significant part of the park indicate a long history of intensive use: regular mowing to a low height, trampling, local top dressing and soil levelling, fragmentation of the grass cover by paths and technical facilities, and possible episodes of fertilisation (Zhukov et al., 2022). Under such conditions, selection is clearly biased towards fast-growing, nitrogen-loving, disturbance-tolerant ruderal species (Nykytiuk et al., 2025). In contrast, species that form stable competitive and stress-tolerant communities are displaced into small "refugia". High hemeroby is therefore not only a consequence of the park's location in an urban environment, but also a direct product of overly intensive and spatially homogeneous maintenance. The data obtained provide clear guidelines for management changes. Firstly, zonal differentiation of management is needed: the allocation of areas with a priority for recreation, where the current mowing regime and higher levels of hemeroby are acceptable, and regions of nature-oriented management, where the frequency and height of mowing should be reduced and the first mowing postponed until the end of mass flowering. Secondly, it is advisable to limit local fertilisation and deep soil interventions in areas of high fertility, which provoke ruderalisation, and instead promote the accumulation of organic litter in semi-natural fragments. Thirdly, targeted restoration of competitive, perennial meadow and forest edge communities is needed by sowing local competing species, forming flowering meadow strips and shrubby edges, and creating microhabitats with moderate, rather than extreme, levels of disturbance. Such measures will gradually reduce the average level of hemeroby and increase naturalness without losing recreational function.

Disturbance indicators have proven to be a key tool for assessing and planning park management. Spatial maps of disturbance intensity and frequency, as well as their differentiation between the herbaceous layer and the entire community, show where threshold levels are reached, after which the vegetation transitions to a ruderal state. This information can be used to transfer part of the recreational load, change trail trajectories, locally strengthen soil cover protection (such as fences, decking, and rest platforms), and introduce mosaic mowing patterns. Tracking disturbance indicators over time will enable the evaluation of the effectiveness of management decisions and facilitate timely adjustments to land use regimes.

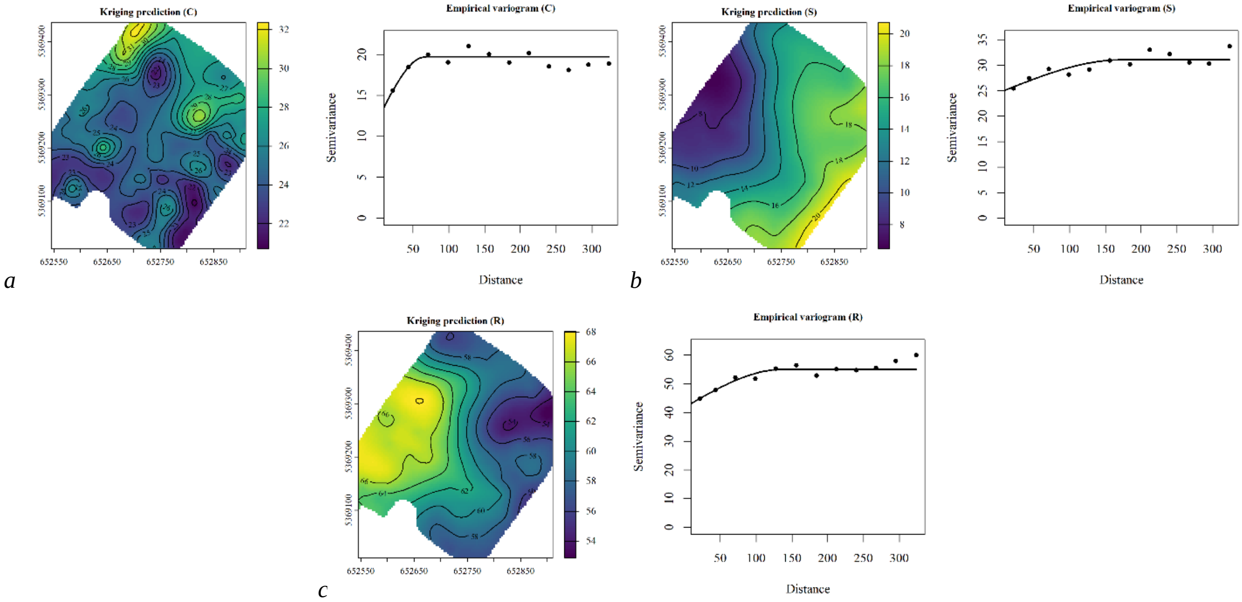

Fig. 8. Spatial models of variation and empirical variograms of Grime's ecological strategies: *a* – competitors (C, %); *b* – stress-tolerants (S, %); *c* – ruderals (R, %)

The predominance of the ruderal strategy (R) in the C–S–R structure indicates that the dominant "ecological force" in the park is not the gradients of natural factors, but rather chronic disturbance and eutrophication. The spatial correspondence of high R frequencies with areas of intense recreational use and frequent mowing confirms that management exerts selective pressure on the flora. To strengthen the role of competitive species (C), it is necessary to create stable areas with moderate but non-destructive use, ensure continuous turf cover, and mitigate extremes in both disturbance and resource scarcity. In practical terms, this means shifting some lawns towards tall grass or meadow types, using local perennial grasses and mixed grasses, reducing mowing frequency, gradually reducing excess nitrogen loading, and preserving and expanding those fragments where competitive and stress-tolerant species already dominate. In the long term, this transformation will balance the proportions of C, S and R, increase the resistance of plant communities to climatic extremes, and, at the same time, expand the range of ecosystem services that the park provides to the urban environment.

The practical significance of the study lies in its offering of a scientifically based system of ecological guidelines for the spatially differentiated management of urban parks. It has been shown that key indicators of vegetation cover (species richness, Shannon index, phytoindication assessments of ecological regimes, Raunkiaer life forms, Grime's strategies) form reproducible spatial patterns, and therefore can be used not only as "diagnostic" indicators, but also as a basis for practical decisions on zoning, regulating recreational load, choosing mowing regimes and greening schemes. The resulting maps and spatial models enable the identification of areas with varying degrees of stability and vulnerability, the distinction of priority conservation areas, the localisation of degradation hotspots, and the planning of targeted measures to restore vegetation cover. The proposed approach can be directly adapted to other urban parks and green spaces, serving as a basis for monitoring, comparing the effectiveness of different maintenance practices, and implementing environmentally-oriented solutions in urban planning.

Prospects for further research are primarily related to expanding the spatial and temporal coverage of the proposed approach. It is advisable to test the identified patterns in other urban parks with different vegetation structures, formation histories and maintenance regimes, which will allow assessment of the degree of their generalizability and help identify typical "ecological profiles" of urban green areas. An important direction is the transition from a one-time survey to long-term monitoring observations, which will allow analysis of the dynamics of ecological regimes, Grime's strategy, biomorphic spectrum, and taxonomic diversity in response to changes in management, climatic fluctuations, and new waves of urban load. The combination of ground-based phytoindication measurements with spectral remote sensing indices also appears promising, as it will allow the assessment of ecological conditions to be scaled up to the level of the entire urban green infrastructure. A separate task for future research is the development of experimental management schemes (controlled changes in mowing regimes, recreational load, planting structure) with subsequent assessment of their impact on the spatial patterns of ecological indicators, which will make it possible to move from descriptive analysis to testing causal hypotheses and formulating practical recommendations for adaptive management of urban parks.

Conclusions

The analysis showed that phytoindication scales (Didukh, Ellenberg, hemeroby, disturbance, Grime's strategies, and Raunkiaer's life forms) are a dependable tool for quantitatively evaluating ecological regimes within an urban park. They consistently mirror gradients of moisture, trophicity, aeration, microclimate, degree of naturalness, and disturbance of vegetation cover, enabling a shift from descriptive traits to formalised diagnostics of park ecosystem conditions. For most phytoindication indicators, statistically significant spatial autocorrelation. (Moran's $I > 0$, $P < 0.001$) and a high proportion of spatially structured dispersion was found, which is reflected in the parameters of variograms (SDL up to several dozen per cent). This indicates that variations in ecological regimes within the park are not random, but form reproducible spatial patterns on scales commensurate with the functional zones of the park (dozens to hundreds of metres). Thus, phytoindication scales not only record local conditions but also reflect the internal spatial structure of the ecosystem. It has been shown that spatial gradients of phytoindication assessments are consistent with land use and management regimes: areas of increased recreational pressure, frequent mowing, soil compaction and local nutrient input correspond to regions of ruderalisation, high values of disturbance and hemeroby indicators, and an increase in the proportion of therophytes and ruderal strategies. In contrast, areas with moderate intervention, a more stable moisture regime and lower visitor intensity are characterised by higher naturalness, a greater proportion of hemicryptophytes, competitive and stress-tolerant species, and increased diversity. The use of phytoindication scales is a methodologically simple and economically accessible approach based on the description of species structure and projective cover without the need for expensive instrumental monitoring. This makes them suitable for regular surveys of urban green spaces, including under conditions of limited financial and technical resources. By accumulating information about long-term environmental conditions, phytoindication indicators complement or partially replace point physical and chemical measurements. The proven spatially structured behaviour of phytoindication scales within the studied park gives grounds to consider them as ecologically relevant benchmarks for urban park management. They can be used to: (i) identify areas with increased naturalness and priority conservation regimes; (ii) identify areas with critical ruderalisation and excessive anthropogenic pressure; (iii) optimise mowing schemes, recreational zoning and targeted greening; (iv) monitor the effectiveness of implemented nature-based solutions. The results obtained indicate that phytoindication scales can and should be considered as a practical set of ecological indicators for spatially differentiated management of urban parks. Their integration into the planning and assessment system for green spaces will enable a shift from aesthetically oriented to ecologically sound management, enhancing the ability of urban parks to support biodiversity, ecosystem services and climate resilience in urban areas.

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