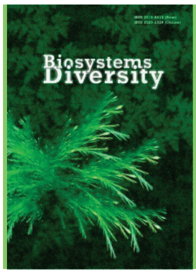

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Bioindication potentials of the grass stand and soil macrofauna for assessing the level of anthropogenic transformation of an urban park are complementary

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Changes in the environment induced by anthropogenic impact or natural stressors are subject to bioindication. Most often, the anthropogenic stressors are the main object of bioindication research. Hemeroby and naturalness are considered as indicators of the level of anthropogenic transformation of ecosystems. Hemeroby is frequently used to assess disturbances in different types of vegetation. However, this concept has rarely been used to assess the impact on animals. According to the method of indicator values, species richness of a community is a marker of bioindication potential. The article compares the patterns of response of species richness of soil macrofauna and herbaceous cover communities in a city park, taking into account gradients of environmental factors, naturalness, and hemeroby. Within the study area, test plots were located. Soil macrofauna samples were taken at 105 points in each of the test sites, and soil hardness, electrical conductivity and soil temperature, litter height, and grass cover height were also measured. A geobotanical description of the vegetation cover was made within each plot. In the survey plots, 7.6 ± 3.0 plant species were found in the herbaceous layer. In soil samples, 6.8 ± 2.9 species of macrofauna were found. With an increase in the number of plant species in the herbaceous layer, the number of soil macrofauna species showed a downward trend. An increase in the number of soil macrofauna species is accompanied by a decrease in both naturalness and hemeroby of the plant community. The naturalness index does not depend on the number of plant species, but the largest number of plant species was observed under conditions of naturalness level from 0 to 1. With an increase in hemeroby, the number of plant species increases, although this relationship also has a nonlinear component. The largest number of plant species is observed at hemeroby levels from 45 to 65. Environmental factors and indicators of hemeroby and naturalness were able to explain 27% of the variation in the number of soil macrofauna species. Humidity regime and continentality did not affect the number of species. Increased variability in moisture conditions, carbonate content, and indicators of frost and cryoclimate contributed to an increase in the number of invertebrate species. Increases in acidity, mineral salts, nitrates, and soil aeration had a negative impact on the number of soil macrofauna species. Soil properties were able to explain 21% of the variation in the number of soil macrofauna species. Environmental factors and indicators of hemeroby and naturalness were able to explain 72% of the variation in the number of herbaceous plant species. Increases in moisture, acidity, mineralization, thermocline, and cryoclimate indicators had a negative impact on the number of plant species. Biological indicators can be used to assess complex environmental factors that are difficult to measure using instrumental methods. Bioindicators are also used to assess the level of anthropogenic transformation of ecosystems. The key concepts for solving this problem are the naturalness and hemeroby of plant communities, which are used as markers of ecosystem disturbance in general. Vegetation cover as a source of bioindication information can provide a biased assessment of the level of anthropogenic transformation due to its greater sensitivity to certain types of anthropogenic pressure. The potential of soil animals as a source of information on the level of anthropogenic transformation in the urban environment is quite significant. Species richness is a marker of the potential ability of a plant or animal community to provide reliable bioindication information. The bioindication complementarity of animal and plant communities is that the highest species richness of soil macrofauna is observed at a relatively low level of species richness of plant communities. Therefore, soil macrofauna can complement and clarify estimates of the level of anthropogenic transformation made using plant communities or can be an independent source of information for such estimates.

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

Introduction

Bioindication is derived from information obtained from the biological processes, species or communities (Puig-Gironès & Real, 2022). This technique is used to evaluate the state of the environment and changes in it over time (Chowdhury et al., 2023). Environmental changes induced by anthropogenic impact or natural stressors are subject to bioindication (Zymaroieva et al., 2021). Anthropogenic stressors are most often the focus of bioindication research (Adesakin et al., 2023). Species-specific ecological traits can be considered strong predictors of sensitivity to environmental disturbances (Zymaroieva et al., 2022). Such features can be quantitatively characterized as indicator values (Mouillot et al., 2013). Hemeroby and naturalness are understood as indicators of the level of anthropogenic transformation of ecosystems. To assess the landscape, the concept of hemeroby is regarded as the opposite of the concept of naturalness (Tian et al., 2020). Hemeroby is considered as an integrated indicator that can assess the anthropogenic transformation of ecological systems (Kowarik, 2020) and displays the combined impact of disturbances on natural complexes (Yorkina et al., 2022). The level of naturalness indicates the distance of a particular ecosystem that has been subjected to anthropogenic impact from its original natural state (Angermeier, 2000), while hemeroby is a measure of the degree of anthropogenic disturbance of the ecosystem. Among the approaches currently used to quantify the environmental impact of land use, the concept of hemeroby is the most effective in terms of the practicality of the method and the quality of the conclusions (Fehrenbach et al., 2015). The classification into hemeroby classes reflects the complexity of land use well (Fehrenbach et al., 2015). The idea of the naturalness, or cleanliness, of an ecosystem has been considered as a reference standard for assessing the impact of human activity on the landscape. Hemeroby can be clearly defined by assessing the species composition of any habitat type (Fanelli et al., 2006). Hemeroby and naturalness are calculated using the indicator value method. The accuracy of the estimates, or bioindication potential, depends on the sample size, which is quantitatively equal to the species richness of the community.

Hemeroby is often used to assess disturbances in different types of vegetation (Battisti & Fanelli, 2016). However, this framework has rarely been applied to animal impact assessment (Battisti & Fanelli, 2016). The role of animals in assessing anthropogenic impacts on ecological systems is well known. Animal species respond specifically to the disturbance of the environment due to their natural history and ecology (Sousa, 1984). The urban soil invertebrate communities are taxonomically and functionally diverse and are a robust source of information on the state of ecosystems (Rochefort et al., 2006). Multiple anthropogenic effects reduce the abundance and diversity of soil invertebrates. The direction and extent of the response of pedobiont communities may differ depending on the taxonomic group. Thus, in most invertebrate taxa, the population density decreases in response to heavy metal contamination of soil (Pey et al., 2014). However, for example, isopods can respond positively to metal contamination in urban soils (Pouyat et al., 2015). Pesticides are also well known to reduce the abundance of invertebrate communities in urban soils. However, the effects can vary considerably depending on the pesticide active ingredient, frequency of application, and frequency of use (Gan & Wickings, 2017). Other types of human activity can produce a uniformly positive impact on soil invertebrates. The increase in the density of invertebrates from different taxonomic and functional groups is known to be caused by an increase in the content of organic matter in urban soils (Joimel et al., 2017). Soil invertebrates are sensitive to soil disturbance, so they are important indicators of soil regimes (Nahmani & Lavelle, 2002) and bioindicators of soil quality in urban areas (Santorufo et al., 2012).

The diversity and abundance of soil invertebrates may decrease in the short term due to urbanization. The increase in the abundance of tolerant species may lead to changes in the structure and overall abundance of the community in the long term (Salminen et al., 2001). Communities of millipedes and terrestrial isopods were used to assess the naturalness of habitat (Tuf & Tufova, 2008). Epigean arthropod standardized sampling was used for the ecological assessment of protected areas (Borges et al., 2005). Species and functional diversity of millipedes decreases in the gradient of urbanization regime (Bogyó et al., 2015; Tóth & Hornung, 2019). Woodlice represent herpetobiont saprophages, which are important decomposers of leaf litter. The trophic level that woodlice occupy significantly constrains the possibility of recolonising habitats in the urban environment (Nagy et al., 2018). Woodlice are very sensitive to decreased density and changes in leaf litter quality due to various land use practices, including recreational loads (Souty-Grosset et al., 2005). This and other features of terrestrial isopod biology make them sensitive organisms for assessing ecosystem stability (Paoletti & Hassall, 1999). It was found that both the abundance and diversity of beetle communities demonstrate a tendency to increase from urban centres to ruderal areas (Niemelä, 1999; Niemelä et al., 2002; Niemelä & Kotze, 2009). Beetles that inhabit the forest litter and soil are also indicators of the level of anthropogenic transformation of ecosystems. The abundance of rove beetles is known to increase significantly with decreasing urbanisation (Magura et al., 2013; Simon et al., 2013). Spiders are common members of the soil macrofauna in urban areas. The richness of spider species in urban territories was found to be significantly higher than in suburban and rural areas, which is explained by an increase in the number of species in urban areas that prefer open habitats (Magura et al., 2010). The removal of rotten wood due to direct anthropogenic transformation of habitats promotes the appearance of Carabidae and Staphylinidae species adapted to life in the open environment (Deichsel, 2006). The response of different functional groups of carabids in the ruderal-urban gradient is the key to the design of practical tools and protocols for assessing the ecological impacts of human-induced landscape change (Niemelä et al., 2000). The trophic level may be a crucial factor in the response of animals to urbanisation. Urbanisation was suggested to be the least harmful for predators (Nagy et al., 2018). Communities of terrestrial molluscs are part of the soil macrofauna and exhibit high bioindication capacity (Zhukov et al., 2023).

Thus, vegetation cover is a common bioindication object for assessing hemeroby and naturalness under the influence of anthropogenic environmental transformation. Radical impacts on vegetation cover in urban environments can make this source of information unsuitable for reliable bioindication. In addition, markers of hemeroby and naturalness have a limited range of levels of anthropogenic transformation where their respective scores can be relevant. Soil is a habitat that is to some extent protected from spontaneous impacts. Soil animals are a reliable source of information for bioindication of anthropogenic transformation. According to the indicator value method, species richness of a community is a marker of bioindication potential. Therefore, the aim of the article is to compare the patterns of response of species richness of soil macrofauna and herbaceous cover communities in a city park, taking into account gradients of environmental factors, naturalness and hemeroby.

Material and methods

The study was conducted in the Botanical Garden of the Oles Honchar Dnipro National University (Dnipro, Ukraine). There were 20 polygons within the study area (Fig. 1). Soil macrofauna samples were taken at 105 points in each of the test plots, and soil penetration resistance, electrical conductivity and soil temperature, litter height, and grass cover height were also measured. A geobotanical description of the vegetation cover was made within each plot.

Fig. 1. The location of the test polygons within the city park: the dots indicate the numbering of the polygons, each of which consists of 105 survey points where soil macrofauna was extracted in 0.25 × 0.25 cm pits to the depth of animal occurrence (usually 25–30 cm); the pits were located in the centre of 2 × 2 metre squares within which herbaceous plants were recorded; the polygons are 14 × 30 metres in size (7×15 survey points); the yellow line indicates the boundaries of Yuri Gagarin Park (the traditional name of this part of the DNU Botanical Garden)

The soil penetration resistance was measured in the field using a hand-held Eijkelkamp penetrometer to a depth of 50 cm at intervals of 5 cm (at depths of 0–5, 5–10, ..., 45–50 cm) (Yakovenko & Zhukov, 2021). The HI 76305 sensor (Hanna Instruments, Woonsocket, R. I.) was used to measure the soil electrical conductivity in situ (Kunakh et al., 2022). This sensor operates in conjunction with the handheld HI 993310 (at depths of 0–5 cm in triplicate at each point) (Zhukov et al., 2022). Each polygon was a 14 × 30 m plot within which 105 2 × 2 m squares were placed. The quadrats were arranged into 7 transects, with each transect consisting of 15 contiguous quadrats. Macrofauna were collected manually from soil samples from the centre of each quadrat (Tutova et al., 2022). Samples consisted of single blocks of soil, 25 × 25 × 30 cm^3, quickly excavated. Soil macrofauna was sorted and animals were preserved in 4%

formaldehyde (Zhukov et al., 2023). Soil macrofauna was defined as a group of invertebrates found in terrestrial soil samples, which are animals visible to the naked eye (macroscopic organisms) (Warren & Zou, 2002; Lavelle et al., 2003). Geobionts (large soil invertebrates that permanently inhabit the soil) and geophiles (organisms that live in the soil only in certain phases of their life) were recorded (Gholami et al., 2016). Lists of vascular plant species were compiled for each quadrat within the site. The projective cover of each plant species was assessed visually. The projective cover of plant species was recorded at the level of soil, undergrowth (up to 2 m) in the stand (above 2 m in height). We were able to identify all the plants on the landfills to the species level.

Assessment of the level of hemeroby and naturalness of the ecosystem within the polygons was carried out based on the description of the vegetation cover. The Goncharenko scale was used as a scale of plant hemeroby (Goncharenko, 2017), which is an adaptation of the European scale (Frank & Klotz, 1990) to the realities of the Ukrainian flora. Naturalness is assessed according to the Borhidi scale (Borhidi, 1995). The assessment of hemeroby was carried out as a weighted average value of the hemeroby of plant species in the community:

$$HV = \sum_{i=1}^{N} p_i * hv_{i,}$$

where HV is the hemerobicity score of the plant community (values are in the range of 0–100); p_i is the projective cover of the i-th species; hv_i is the value of the hemeroby index for the i-th species.

Didukh phytoindicator scales include edaphic and climatic ones (Didukh, 2011). The edaphic phytoindicator scales include soil water regime (Hd), water regime variability (fH), soil aeration (Ae), soil acidity (Rc), total salt regime (Sl), soil carbonate (Ca) and soil nitrogen (Nt). The climate scales include thermal climate (Tm), humidity (Om), cryoclimate (Cr) and continental climate (Kn). In addition to them, there is a light scale (Lc), which is characterised as a microclimate scale. Phytoindicative assessment of environmental factors was performed using the Buzuk ideal index method (Buzuk, 2017). The descriptive statistics and principal component analysis (Zymaroieva et al., 2019) were calculated using Statistica 10.0 (Statsoft Inc., USA).

Results

There were 7.6 ± 3.0 species of plants in the herbaceous layer of the plots, and this indicator ranged from 3 to 17 species. There were 6.8 ± 2.9 species of macrofauna in the soil samples, and this indicator ranged from 3 to 18 species. The number of species of soil macrofauna tended to decrease with the increase in the number of plant species in the herbaceous layer (Fig. 1). It should be noted that, in addition to this linear trend, the relationship also has a bell-shaped character. The number of invertebrate species reaches its maximum at 6–8 plant species per plot. When the number of plant species deviates from this number, either upwards or downwards, the number of species decreases. The relationship between the number of soil macrofauna species and the number of plant species is asymmetric, so the decrease in the number of invertebrates when the number of plant species deviates to the lower side of the optimum is faster than when the number of plants deviates to the higher side. The regression dependencies of the impact of environmental factors, naturalness, hemerobia and soil properties on the number of animal and plant species indicate a specific nature of the sensitivity of species richness of animal and plant communities to environmental factors.

The naturalness score was 0.08 ± 1.38 and ranged from –2.2 to 3.87. The lowest naturalness of plant communities was observed in the thalweg of the ravine, in the south-east and south-west of the park (Fig. 2). The highest naturalness of plant communities was typical for the central and northern parts of the park. The hemeroby score was 46.2 ± 25.5 and ranged from 25.7 to 88.2. The lowest hemeroby was in the central part of the park and in the south-eastern part of the park. The highest hemeroby was in the area of anthropogenic soils and in the area of contact between the park and the road border.

The increase in the number of soil macrofauna species is followed by a decrease in both the naturalness and hemeroby of the plant community (Fig. 3). In addition to the linear trend, a non-linear bell-shaped curve can be identified in the dependence. The largest number of soil macrofauna species is observed at the naturalness level from 0 to –1, and at the hemeroby level from 35 to 45. The naturalness index does not depend on the number of plant species, but the largest number of plant species was observed under conditions of naturalness from 0 to 1. The number of plant species increases with increasing hemeroby, although this relationship also has a nonlinear component. The largest number of plant species was observed at hemeroby levels from 45 to 65.

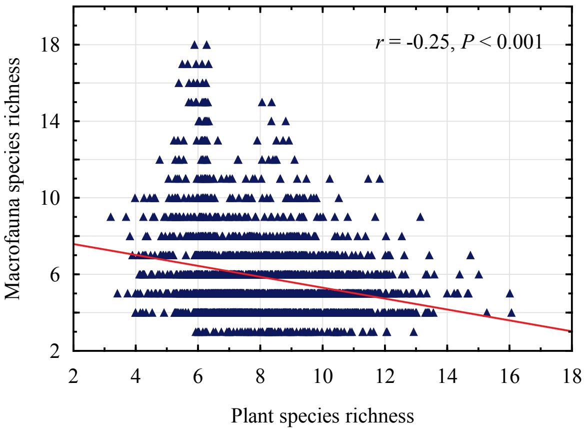

Fig. 2. Correlation of species richness of plant communities and soil macrofauna: the abscissa is the number of species of herbaceous plants in a 2 × 2 metre plot; the ordinate is the number of soil macrofauna species found in the centre of the corresponding plant plot in a 0.25 × 0.25 metre soil pit

The phytoindication method allowed us to estimate the quantitative values of environmental factors (Table 1). The productive moisture content within the park ranged from 57.7 to 151.4 mm. The lowest moisture content was observed in the soil in the north-west of the park and in the east. The thalweg of the gully and the slope of the northern exposure form the conditions under which the soil moisture reserve is the highest. The variability of moisture conditions ranged from 0.13 to 0.30. This indicator was strongly correlated with the indicator of soil moisture regime ($r = -0.48$, $P < 0.001$), so the spatial pattern of moisture regime variability well repeated the pattern of moisture regime variability. The most stable moisture regime was observed in the central part of the park and in its west. Plant communities are best adapted to soil acidity in the range from 5.97 to 6.91. The lowest soil acidity was observed in the south-west of the park. In other parts of the park, combinations of loci with high and moderate soil acidity were observed. The salt content in the soil solution varied from 14.17 to 58.68 µg/L. The variation in salt content followed the relief features well, so in the upland area, the salt content in the soil was lower, and in the gully, this indicator was higher. Areas with higher salt content were also observed along the park boundary in the area close to the road. The content of carbonates in the soil varied from 0.27 to 2.52%. The highest carbonate content was in the central and south-western parts of the park. The nitrogen content in the soil varied from 2.77 to 4.63 g/kg. The spatial pattern of this indicator had a complex structure. Areas with a high nitrogen content were surrounded by areas with a lower value, which resulted in a patchy pattern. The lowest nitrogen content was found for artificial soils in the thalweg of the gully. The highest nitrogen content was in the soils in the west of the gully. The aeration rate ranged from 23.4% to 68.8%, which created contrasting conditions for animals and plants. The most aerated soils were in the north and east of the park.

The least aerated soils were in the west of the park. The radiation balance ranged from 1.56 to 2.51 gJ/(m^2 year). The peripheral areas of the park had the highest radiation balance, while the central and northern parts, which are in contact with the rest of the Botanical Park, had the lowest radiation balance. The humidity of the climate varied from –2.79 to 1.11 mm. The predominance of evaporation over precipitation was observed in the majority of the park. Areas with a predominance of precipitation over evaporation were limited in space and located in the centre, east, southeast and southwest of the park. The continentality was highest in the thalweg of the gully. The lowest temperatures in the coolest month of the year are usually associated with areas where there is no tree cover or the density of the tree stand was low. A similar spatial pattern was characteristic of the light regime. Naturally, the light regime indicators were higher in open areas. The principal component analysis allowed us to extract five principal components with eigenvalues greater than one. These components together were able to explain 72.8% of the variation in the feature space. Principal component 1 was able to explain 25.5% of the variation in the trait space and indicated opposite variability in soil water content and soil moisture variability regime. Higher moisture content is associated with lower aeration, higher soil nitrogen content and lower light. Higher moisture levels are accompanied by a greater naturalness of plant communities and their lower hemeroby. Thus, principal component 1 can be meaningfully interpreted as a soil moisture regime. Analysis of the spatial variability of the principal component 1 scores indicates that the highest soil moisture was in the central and southwestern parts of the park, and the lowest in the northwestern and eastern parts of the park.

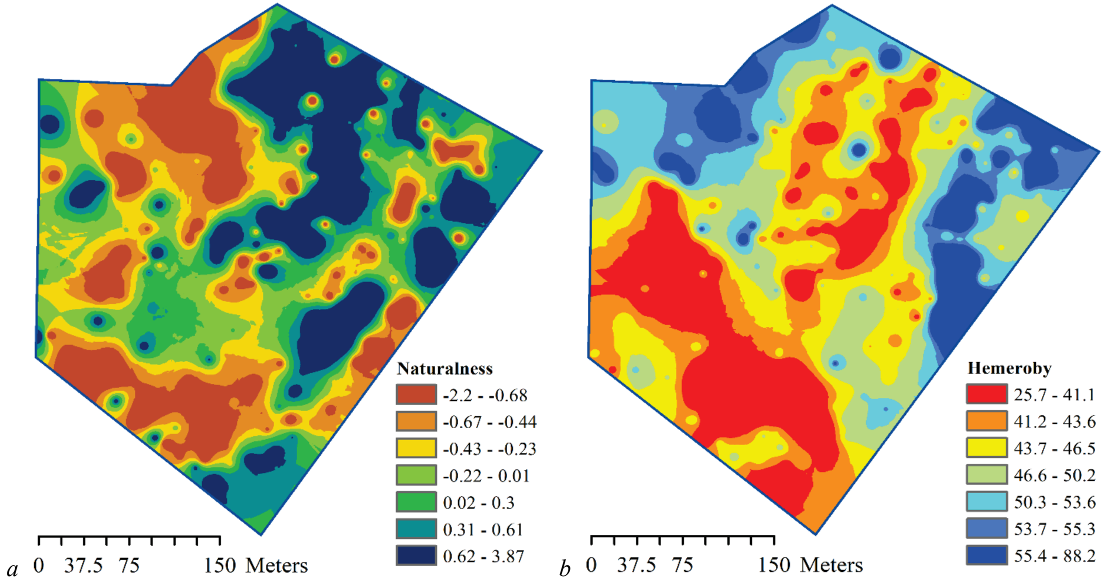

Fig. 3. Spatial variation of naturalness (*a*) and hemeroby (*b*) within the park

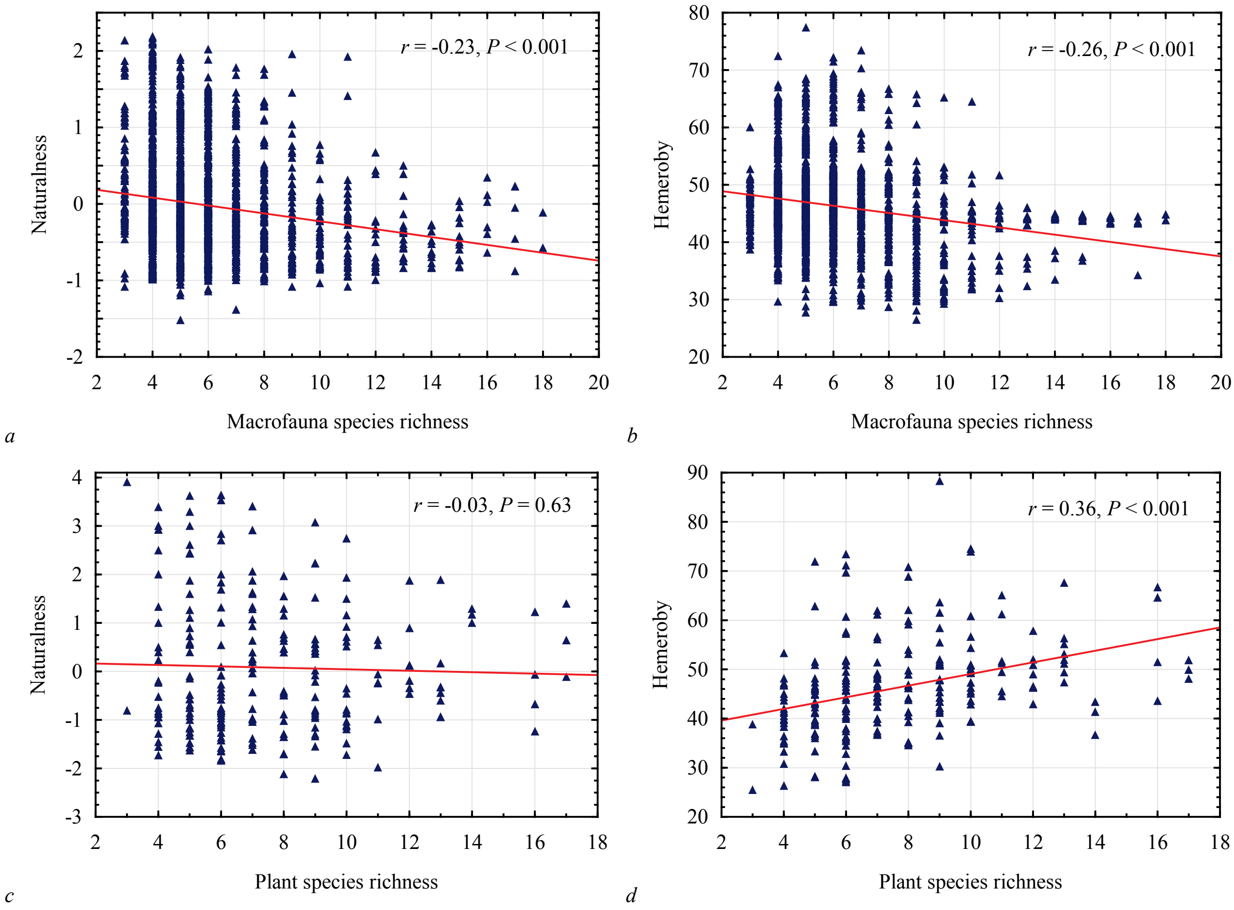

Fig. 4. The dependence of naturalness and hemeroby on the number of plant species: *a* is the dependence of naturalness on the number of soil macrofauna species ($Y = 0.28–0.05X$, $R^2 = 0.05$), *b* is the dependence of hemeroby on the number of soil macrofauna species ($Y = 50.1–0.63X$, $R^2 = 0.07$), *c* is the dependence of naturalness on the number of plant species in the herbaceous layer ($Y = 0.19–0.015X$, $R^2 = 0.001$), *d* is the dependence of heterobiosity on the number of plant species in the herbaceous layer ($Y = 37.2+1.18X$, $R^2 = 0.13$)

Table 1
The descriptive statistics of ecological factors, hemeroby, naturalness and number of herbaceous plant species (N = 230) and principal component analysis of variability of these indicators (correlation coefficients are statistically significant for $P < 0.05$)

Ecological factor	Mean ± standard deviation	Range		Range				
		minimum	minimum	PC1, $\lambda = 3.8$	PC2, $\lambda = 2.5$	PC3, $\lambda = 1.9$	PC4, $\lambda = 1.5$	PC5, $\lambda = 1.3$
Productive moisture content in the one-metre soil layer, mm (Hd)	96.70 ± 12.89	57.66	151.39	0.82	–	–	–	0.16
Variability of the moisture regime ω (fH)	0.20 ± 0.03	0.13	0.30	–0.71	–	–	–0.34	–0.16
Soil acidity, pH (Rc)	6.64 ± 0.17	5.97	6.91	–0.21	–0.57	0.54	–	–0.28
Salt regime, salt content in soil solution, µg/l (Sl)	25.73 ± 8.33	14.17	58.68	–	0.73	–0.52	–	–
Carbonate content in the soil, % (Ca)	0.89 ± 0.42	0.27	2.52	–0.62	–	–	0.41	–
Nitrogen content in the soil, g/kg (Nt)	4.08 ± 0.30	2.77	4.63	0.56	–0.23	–	–	0.62
Aeration regime, aeration porosity, % (Ae)	50.14 ± 8.83	23.40	68.83	–0.48	–0.28	–0.39	–0.24	–
Radiation balance, gJ/(m^2 year) (Tm)	2.01 ± 0.20	1.56	2.51	–	0.68	–0.20	–0.41	–0.22
Climate humidity, difference between precipitation and evaporation, mm (Om)	–0.50 ± 0.66	–2.79	1.11	0.51	–0.36	–0.44	0.29	–
Continentality according to Ivanov (Kn)	116.38 ± 26.33	55.23	179.09	–	0.55	0.67	–	0.23
Mean temperature of the coldest month, °C (Cr)	0.93 ± 3.84	–12.98	11.11	–	–0.44	–0.50	–0.41	–
Lighting mode (Lc)	7.47 ± 0.93	4.51	8.94	–0.68	–	–0.37	0.36	0.29
Naturalness	0.08 ± 1.38	–2.21	3.91	0.32	–0.31	–0.15	0.47	–0.65
Hemeroby	46.20 ± 9.80	25.52	88.30	–0.68	–0.50	–	–	–

Principal component 2 was able to explain 16.8% of the variation in the traits. This principal component was most sensitive to soil salt content. An increase in salt content is accompanied by a decrease in soil acidity, nitrogen content and aeration. Higher salt content is observed in areas with better radiation balance and greater continentality. Principal component 2 indicates a unidirectional change in the naturalness and hemeroby indicators. Thus, principal component 2 can be meaningfully interpreted as a soil mineralisation regime. Analysis of the spatial variability of the principal component 2 scores indicates that the highest soil mineralisation was in the thalweg of the gully, and the lowest in the eastern part of the park. Principal component 3 was able to explain 12.1% of the variability in the feature space. It is the most sensitive to the indicator of continentality of the plant community. The analysis of spatial variability of the principal component 3 scores indicates that the greatest continentality of conditions was characteristic of the central part of the park. Principal component 4 was able to explain 9.8% of the variability of the traits and mainly reflects the variability of carbonate content in the soil. The analysis of spatial variability of the principal component 4 scores indicates that the highest carbonate content was observed in the soils in the thalweg of the gully and in the southeastern part of the park. Principal component 5 was able to explain 8.4% of the variability in the traits and mainly reflects the variability in the naturalness of the plant community. Higher nitrogen content negatively affects this aspect of naturalness.

Soil penetration resistance naturally increases with depth (Table 2). The electrical conductivity of the soil ranged from 0.10 to 3.24 dS/m. The litter thickness ranged from 1.00 to 9.67 cm, and the height of the grass stand was up to 75 cm. The temperature of the upper soil layer varied from 15.2 to 25.6 °C. The principal component analysis of the soil properties allowed us to extract three principal components with eigenvalues greater than one. Together, the first three principal components were able to explain 75.0% of the variation in the feature space. Principal component 1 was able to explain 52.7% of the variability in the feature space and indicated a consistent pattern of variability in soil penetration resistance across the entire soil profile. This aspect of soil penetration resistance variability was independent of variability in soil electrical conductivity and litter height. Soil penetration resistance was higher in plots with lower stand height and higher soil temperature. Thus, principal component 1 can be meaningfully interpreted as variability in soil penetration resistance. The analysis of the spatial distribution of the principal component 1 scores indicates that the highest soil penetration resistance was characteristic of soils of anthropogenic origin in the south-west of the park and in the active recreation area in the west of the park. Principal component 2 was able to explain 13.1% of the variability in the feature space. It indicated opposite dynamics of hardness at the depth of 0–20 cm on the one hand and 25–50 cm on the other. The increase in hardness in the upper layer was accompanied by a decrease in the electrical conductivity of the soil. The principal component 2 can be interpreted as the variability of soil penetration resistance in the upper layer, which is induced by moisture redistribution. The highest values of this principal component were observed in the southern part of the park, and the lowest in the central part and northwest of the park. Principal component 3 was found to explain 9.2% of the variability. It indicates the opposite dynamics of soil penetration resistance at depths of 0–5 cm on the one hand and 10–25 cm on the other. The component is most sensitive to variability in litter depth. An increase in litter depth is accompanied by a decrease in temperature and an increase in soil electrical conductivity. This principal component can be meaningfully interpreted as the sensitivity of soil properties to the impact of recreation. According to this interpretation, the sensitivity of recreation (negative scores) was highest in the central part of the park and in the north-east.

Table 2
Descriptive statistics of soil properties and grass height (N = 2100)

Property		Mean ± standard deviation	Range		Principal components		
			minimum	maximum	PC1, $\lambda = 3.8$	PC2, $\lambda = 2.5$	PC3, $\lambda = 1.9$
Penetration resistance, MPa at depth, cm	0–5	0.45 ± 0.11	0.18	0.79	0.61	0.55	–0.17
	5–10	0.51 ± 0.11	0.20	0.85	0.68	0.61	–
	10–15	0.55 ± 0.12	0.22	0.90	0.79	0.43	0.11
	15–20	0.57 ± 0.13	0.22	0.98	0.87	0.19	0.10
	20–25	0.59 ± 0.14	0.22	1.10	0.90	–	0.12
	25–30	0.60 ± 0.15	0.25	1.02	0.92	–0.13	–
	30–35	0.62 ± 0.18	0.20	1.11	0.87	–0.11	–
	35–40	0.63 ± 0.15	0.27	1.02	0.91	–0.30	–
	40–45	0.64 ± 0.15	0.30	1.03	0.89	–0.32	–
	45–50	0.66 ± 0.15	0.33	1.05	0.89	–0.30	–
Soil electrical conductivity, dS/m		0.59 ± 0.35	0.10	3.24	–	–0.68	0.43
Litter depth, cm		2.04 ± 0.92	1.00	9.67	–	0.19	0.87
Height of grass stand, cm		30.03 ± 14.42	0.00	75.00	–0.28	0.33	–
Soil temperature, °C		18.95 ± 1.70	15.20	25.60	0.50	–	–0.60

Environmental factors and indicators of hemeroby and naturalness were able to explain 27% of the variation in the number of soil macrofauna species (Table 3). Moisture regime and continentality did not affect the number of species. Increased variability in moisture conditions, carbonate content, and indicators of frost and cryoclimate contributed to an increase in the number of invertebrate species. Increases in acidity, mineral salts, nitrates and soil aeration had a negative impact on the number of soil macrofauna species. Increases in illumination, hemeroby and naturalness also negatively affected the number of species in soil macrofauna communities. Environmental factors and indicators of hemeroby and naturalness were able to explain 72% of the variation in the number of herbaceous plant species. Increases in moisture, acidity, mineralisation, thermocline and cryoclimate indicators had a negative impact on the number of plant species. In turn, increased variability in moisture, carbonate and nitrogen content, aeration regime, continentality and light had a positive effect on the number of plant species. With increasing hemeroby and decreasing naturalness, the number of plant species decreases.

Soil properties were able to explain 21% of the variation in the number of soil macrofauna species (Table 1). The number of soil invertebrate species was sensitive to the redistribution of soil penetration resistance along the profile. The increase in soil electrical conductivity and herbage height were markers of an increase in the number of soil macrofauna species, while litter height and soil temperature indicated a tendency to decrease species richness. Soil properties were able to explain 18% of the variation in the number of herbaceous plant species. The increase in temperature and soil penetration resistance at depths of 0–5 and 40–45 cm is a marker of an increase in species richness of the plant community. In turn, an increase in soil penetration resistance at a depth of 45–50 cm, soil electrical conductivity, litter height, and herbage height were markers of a decrease in species richness of the vegetation.

Discussion

Vegetation cover and soil fauna provide important functions for ecosystem services in urban parks (Kunakh et al., 2021). In addition to their functional significance, living components of ecosystems are an important source of information about the course of ecological processes, which is the basis for bioindication. Urban flora and vegetation are sensitive to anthropogenic disturbances (Kowarik, 1990; Hill et al., 2002). Biological indicators can be used to assess complex environmental factors that are difficult to measure using instrumental methods. Bioindication is also used to assess the level of anthropogenic transformation of ecosystems. The key concepts for solving this problem are the naturalness and hemeroby of plant communities, which are used as markers of ecosystem disturbance in general. The concept of hemeroby was formulated to reflect the transformation of ecosystems in the context of the ruderal-urban gradient from natural to fully anthropogenic habitats (Walz & Stein, 2014). The naturalness scale and the hemeroby scale differ in their sensitivity to anthropogenic transformation. It is believed that naturalness is more sensitive to changes in the ecosystem state under conditions of low anthropogenic pressure while hemeroby is more sensitive to high levels of anthropogenic transformation. It should be noted that vegetation cover as a source of bioindication information can provide a biased assessment of the level of anthropogenic transformation due to its greater sensitivity to certain types of anthropogenic pressure. For example, recreational pressure is a significant factor affecting vegetation cover, and significantly slows down the recovery of vegetation cover. Also, artificial plant care measures can significantly change vegetation cover disproportionately to the actual level of anthropogenic transformation. In this context, the role of soil animals as a source of information on the level of anthropogenic transformation can be quite significant.

Bioindication is practically an axiom that the quality and reliability of environmental factor assessments depends on the number of species on which certain conclusions are based. Due to the known dependence of the number of species on the area, it can be concluded that it is theoretically possible to select a sufficiently large area of record that will contain a sufficient number of species for a reasonable bioindication. It should be noted that anthropogenic impacts are the result of processes that are far from thermodynamic equilibrium, which also manifests itself in a significant variation in the spatial variability of anthropogenic factors. Habitat loss occurs as the intensity of urbanization increases. At the same time, the islands in the urban environment that preserve biota habitat become increasingly fragmented and smaller in size along the gradient of urban disturbance (Collins et al., 2000). In other words, the area for which bioindication assessment will be relevant is limited. Therefore, taking into account these two opposing factors leads to the realization of the importance of the specific number of species of living organisms on which bioindication is based. Our results indicate that the selected accounting plots for counting plant species (2 × 2 m) and soil animals (0.25 × 0.25 m) give comparable estimates of species richness of animal and plant communities in absolute terms. If species richness is considered as a marker of the potential ability of a community to provide bioindication information, then it can be concluded that plant and animal communities are complementary, and their bioindication potential complements each other. Under conditions of high diversity of plant communities, the species richness of soil macrofauna may be insignificant. Accordingly, the low bioindication capacity of the soil animal community is compensated by the high bioindication potential of the multispecies plant community. Herbaceous communities in areas without trees usually have a high level of plant community diversity. Such communities are usually xerophytic with a moisture deficit. This negatively affects the living conditions of soil animals, whose communities in such ecological regimes are represented by a lower species richness. The tree canopy significantly limits the access of solar energy to the herbaceous layer, which is why the species diversity of the herbage of tree plantations is often low or sometimes there is no herbage. In turn, mesophytic forest conditions are very favorable for the formation of a diverse community of soil macrofauna, which significantly increases the bioindication potential of animals for assessing the level of anthropogenic pressure. The highest species richness of soil macrofauna is observed at a relatively low level of species richness of plant communities. This is where we see the bioindication complementarity of animals and plants.

A high level of naturalness is usually found in plant communities with a relatively lower level of species richness. This indicates that, although the naturalness indicator itself is sensitive in the relevant range of anthropogenic pressure, the reliability of bioindication assessments may not be very high. A similar situation is observed for soil macrofauna communities. In communities with high naturalness, the number of soil animal species is insignificant. This indicates that other bioindication approaches other than the method of indicator values should be considered to assess the ecosystem state close to natural conditions. The number of plant species in the community increases with increasing hemeroby. This indicates an increase in the power of the indicator value method. The number of soil macrofauna species shows a general trend of decrease in the number of species with increasing hemeroby, so the most diverse animal communities are formed under conditions of low and moderate hemeroby. This indicates that the method of indicator values using soil macrofauna can compensate for the lower reliability of the plant-based approach in the range of low and medium hemeroby levels.

Table 3

Regression dependence of the number of soil macrofauna and herbaceous plant species on environmental factors and indicators of naturalness and hemeroby (beta regression coefficients ± st. error, presented coefficients are statistically significant for $P < 0.05$)

Predictor	Number of macrofauna species $R_{adj}^2 = 0.27, F = 322.5, P < 0.001$	Number of plant species $R_{adj}^2 = 0.72, F = 2281.2, P < 0.001$
Hd	–	–0.35 ± 0.02
fH	0.05 ± 0.02	0.41 ± 0.01
Rc	–0.20 ± 0.03	–0.24 ± 0.02
Sl	–0.18 ± 0.02	–0.72 ± 0.01
Ca	0.14 ± 0.01	0.10 ± 0.01
Nt	–0.16 ± 0.03	0.46 ± 0.02
Ae	–0.21 ± 0.02	0.15 ± 0.01
Tm	–0.18 ± 0.02	–0.21 ± 0.01
Om	0.13 ± 0.02	–0.15 ± 0.01
Kn	–	0.17 ± 0.01
Cr	0.42 ± 0.02	–0.11 ± 0.01
Lc	–0.07 ± 0.02	0.76 ± 0.01
Naturalness	–0.44 ± 0.02	0.28 ± 0.01
Hemeroby	–0.27 ± 0.02	–0.42 ± 0.02

The number of species as a marker of the reliability of a bioindication method is influenced by various environmental factors. The pattern of sensitivity of the number of animal and plant species varies. Cryoclimate is the most significant factor affecting the number of soil macrofauna species. This factor changes mainly under the influence of relief, which correlates with the distribution of soil types. The relationship of the soil population to the relief and soil types explains the dependence of the number of species on the cryoclimate. Aeration regime is an important factor that affects the number of soil animal species. Poor aeration conditions are usually characteristic of hydromorphic soils, which are typically characterized by a high diversity of soil animals, especially litter animals. An increase in aeration often occurs in xeromorphic soils, where the conditions for animals are rather extreme and the number of species is lower. The number of species in a plant community responds positively to an increase in soil nitrogen content and a decrease in soil salinity. Soil animals are much less sensitive to these factors. In addition, the effect of nitrogen content on the species richness of animal communities is the opposite of the effect of this factor on plant communities.

Table 4
Regression dependence of the number of soil macrofauna and herbaceous plant species on soil properties (beta regression coefficients ± st.error, presented coefficients are statistically significant for $P < 0.05$)

Predictor		Number of macrofauna species $R_{adj}^2 = 0.21$, $F = 235.4$, $P < 0.001$	Number of plant species $R_{adj}^2 = 0.18$, $F = 203.6$, $P < 0.001$
Penetration resistance at depth, cm	0–5	–0.09 ± 0.01	0.18 ± 0.01
	5–10	0.04 ± 0.02	–
	10–15	–0.04 ± 0.02	–
	15–20	–	–
	20–25	–	–
	25–30	–0.09 ± 0.02	–
	30–35	0.12 ± 0.02	–
	35–40	0.06 ± 0.03	–
	40–45	–0.07 ± 0.03	0.11 ± 0.03
	45–50	0.10 ± 0.02	–0.11 ± 0.02
Electrical conductivity of the soil		0.15 ± 0.01	–0.06 ± 0.01
Litter depth		–0.03 ± 0.01	–0.07 ± 0.01
Height of the grass stand		0.17 ± 0.01	–0.17 ± 0.01
Soil temperature		–0.41 ± 0.01	0.30 ± 0.01

The impact of soil properties on species richness also differs between plants and animals. Soil invertebrates are sensitive to many human activities and soil conditions, such as physical disturbance, heavy metal pollution, pesticide contamination, timing of human impacts, and land use history (Pavao-Zuckerman & Coleman, 2007). Our results show that the soil animal community is sensitive to variability in soil penetration resistance. This is quite natural and can be explained both by the effect of hardness on soil animals and by the influence of animals on soil physical properties and penetration resistance, among other things. It is known that soil invertebrates affect the physical and chemical characteristics of urban soils (Bray & Wickings, 2019). The importance of soil penetration resistance in explaining the variability of the number of plant species in a community is much less. However, the importance of soil penetration resistance as a factor of plant habitat and as a significant environmental filter is known. The influence of the root system of plants on soil penetration resistance is also of great importance. To explain our results, we can assume that the impact of soil penetration resistance on the number of plant species is more complex, multidirectional, and multiscale. Of course, this problem requires further separate research.

Soil electrical conductivity can be considered a marker of soil moisture. The number of soil macrofauna species is higher in wetter soils, but plant communities in open areas with drier soils are more species-rich. Under the canopy of woody vegetation, the soil temperature is lower due to the reduction of solar radiation energy that reaches the soil surface. But the shade structure of park plantings creates ecosystem filters that fewer plant species can overcome. In more humid locations, the height of the grass stand is higher, which explains the positive correlation between the height of the grass stand and the number of soil macrofauna species. In turn, the height of xerophytic plant species is usually lower than that of mesophytic or hygrophytes, so there is a negative correlation between the height of the grass stand and the number of plant species.

Conclusion

Biological indicators can be used to assess complex environmental factors that are difficult to measure using instrumental methods. Bioindication is also used to assess the level of anthropogenic transformation of ecosystems. The key concepts for solving this problem are the naturalness and hemeroby of plant communities, which are used as markers of ecosystem disturbances in general. Vegetation cover as a source of bioindication information can provide a biased assessment of the level of anthropogenic transformation due to its greater sensitivity to certain types of anthropogenic pressure. The potential of soil animals as a source of information on the level of anthropogenic transformation in the urban environment is quite significant. Species richness is a marker of the potential ability of a plant or animal community to provide reliable bioindication information. The bioindication complementarity of animal and plant communities is that the highest species richness of soil macrofauna is observed at a relatively low level of species richness of plant communities. Therefore, soil macrofauna can complement and clarify estimates of the level of anthropogenic transformation made using plant communities or can be an independent source of information for such estimates.

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