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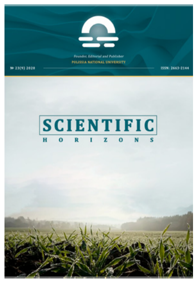

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Ecomorphic Structure Transformation of Soil Macrofauna Amid Recreational Impact

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Abstract. The level of reacreation load on the components of urban green areas is increasing, so identifying the effective management tools in these ecosystems is becoming crucial for ensuring the maintenance of soil biota habitats. The purpose of this study is to reveal a pattern of structuring community of soil macrofauna under a recreational impact based on an ecomorphic approach. The article assesses the level of recreational transformation of the soil macrofauna of public green spaces in the city of Melitopol on the territory of Novooleksandrivskyi Park. For research purposes, a testing site was allocated in an area with a high level of recreational load, with samples taken within this site. To collect soil macrofauna and assess soil properties at each point of the testing site, soil and zoological tests were carried out and the following soil indicators were measured: temperature, electrical conductivity, humidity and soil penetration resistance, litter depth and grass stand height. The community ordination was performed using two approaches: OMI and RLQ analysis. The study found that the ecological niches of soil macrofauna in recreational conditions are spatially structured. The main factors for structuring the ecological niche of soil macrofauna within the study area are soil penetration resistance in the range of the entire measured layer, soil moisture, and distance to trees. As for the number of species, the basis of the coenomorphic structure of soil macrofauna are silvants (45.5%) and pratants (24.2%). As for the species abundance, the basis of the coenomorphic structure of macrofauna comprises pratants (64.5%), slightly less stepants (19.1%) and silvants (16.1%), and sporadic occurrence of paludants (0.2%). Such coenomorphic structure can be considered as ecologically labile. Zoophages, hemiaerophobes, and megatrophs are tolerant to a high level of recreational load. The area corresponding to the highest level of recreational load is vacant. This indicates factual absence of soil macrofauna species that could exist amid intense recreational exposure

Keywords: ecomorphes, soil, ecological niche, soil invertebrates, recreational pressure

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INTRODUCTION

Public green spaces constitute a key component of urban ecosystems and provide important ecosystem services [1; 2]. Urban parkland provides the following ecosystem services: environmental regulation, resource supply, increased biological diversity, and aesthetic improvement [3-5]. The transformation of forest cover and the replacement of natural vegetation with buildings, roads, exotic vegetation, and other urban infrastructure is one of the greatest threats to global biodiversity [6; 7]. Biota in parks supports biodiversity, accumulates carbon, and improves microclimatic conditions [8; 9]. A vegetation cover and soil organisms in parklands provide the carbon sequestration, accumulating it as biomass [10]. As more and more land is allocated for urban development, identification of effective wildlife management tools in urban forests is becoming crucial for ensuring normal habitats for animal populations [11].

The forest parklands are subject to a complex impact, the sources of which are both anthropogenic pressure inherent in the urban environment in general, which is manifested in elevated air temperature, high concentrations of carbon dioxide, nitrogen compounds, and ozone in the atmosphere [12], as well as recreational load associated with visiting parks by the population for recreation [13]. Urban forests and parks, in addition to their recreational and aesthetic functions, provide carbon binding and oxygen production [14]. Another essential and rather elusive function of urban green spaces is to ensure biotic diversity. This is because considerable recreational pressure combined with the adverse impact of various anthropogenic factors negatively affects the possibility of forming habitats necessary to maintain biodiversity at a high level [15]. In this aspect, soil invertebrates are of particular importance. Since the protective ability of the soil allows preserving the conditions for the existence of groups of soil fauna, the latter consequently has a high level of abundance and diversity [16]. Notably, soil fauna is a vital component that performs many functions inherent in woodlands in an urban environment. In particular, soil animals are essential participants in the process of humification. It is the humification that is the basis of the mechanism of carbon binding to the state of persistent organic compounds that form a pool of organic matter in the soil [17]. In turn, the processes of mineralisation, which are activated by soil animals, create conditions for providing plants with nutrients, which is a factor of soil fertility [18]. As a result, soil animals regulate the intensity of primary production, which determines the performance of ecosystem services by public green spaces. Soil animals are a factor of pedogenesis, and therefore they affect the intensity of decomposition of toxic substances, deposition, and immobilisation of heavy metals and radionuclides within the urban environment [19]. In addition, the involvement of animals in the pedogenesis determines the hydrological properties of the soil, which affects the water regime of soils and the intensity of erosion [20; 21].

The diversity of soil macrofauna functions can be represented and quantified using an ecomorphic approach. Many scientists consider ecomorphes as basic components of the structural organisation of ecosystems [22-26]. The affiliation of an animal species with a particular ecomorph indicates a certain aspect of its adaptation to environmental conditions. O.L. Belgard identified trophotope, climatope, and hygrotope as the main limiting factors. Therefore, ecomorphes are divided into climamorphes (limiting factor – climatic conditions); heliomorphes (limiting factor – illumination), trophomorphes (most dependent on soil feeding modes); hygromorphes (least sensitive to the water regime of the ecosystem). Based on adaptations to the predominant phytocenosis, silvants (forest species), stepants (steppe species), pratants (meadow species), paludants (marsh species), and ruderants (weed species) are distinguished [27]. At the grouping level, a set of representatives of various ecomorphes forms an ecomorphic grouping structure, which indicates the adaptation of the grouping in general to the manifestation of a certain ecological regime (humidity or trophic conditions), or the intensity or location of a particular ecological process [28]. The ecomorphic approach has demonstrated its informational value both for diagnostics of natural soils [29] and technosol [30; 31]. This approach is effective for assessing the state of soil macrofauna groupings in conservation areas [32]. Therefore, an important scientific problem is the study of the possibility of applying an ecomorphic approach to assess the impact of recreation on soil biota.

The purpose of this study is to reveal a pattern of structuring communities of soil macrofauna under the recreational impact based on an ecomorphic approach.

MATERIALS AND METHODS

Model testing sites of public green spaces in the city of Melitopol

This study assesses the level of recreational transformation of the soil macrofauna of public green spaces in the city of Melitopol on the territory of Novooleksandrivskyi Park. A testing site was laid, within which samples were taken (Fig. 1). The level of recreational load was estimated using the average distance from recreational paths that are located within the testing site. Within the testing site, the average distance to the tracks is 3.1 m (standard deviation is 2.42 m). The testing site is classified as a high level of recreational load.

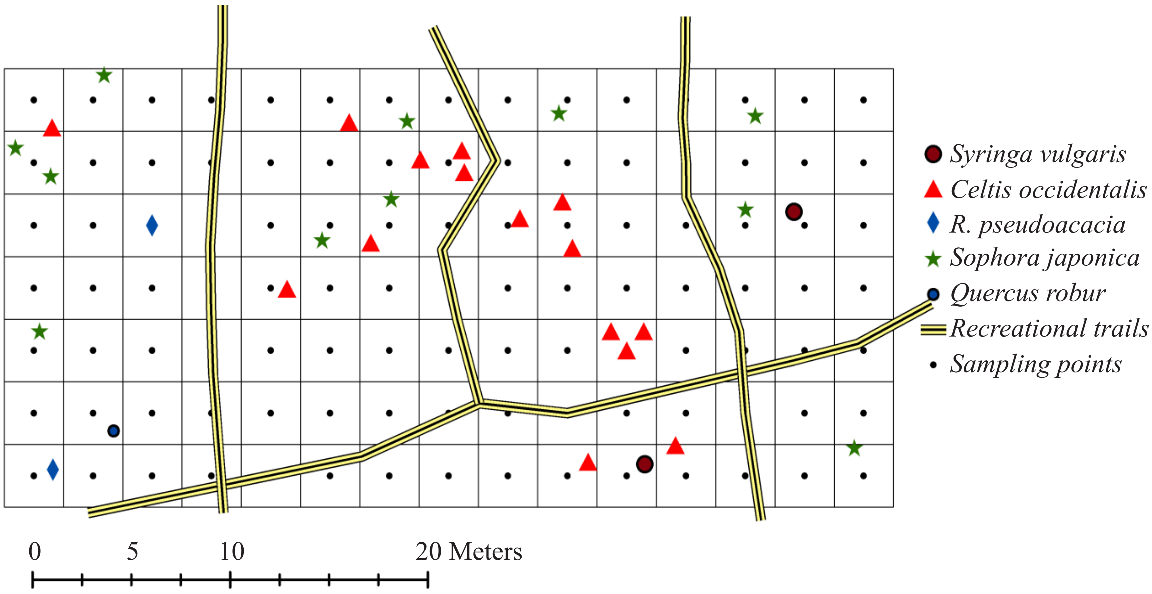

***Figure 1**. Placement of sampling points in experimental testing sites. A – testing site 1, B – testing site 2*

The testing site was a collection of 105 test points that were gathered along 7 sections placed in parallel, with 15 test points in each section. The distance between the nearest sections was 3 metres, and the distance between the nearest sampling points in the section was 3 metres. Thus, the sampling points are a regular grid with a lag of 3 meters measuring 7×15 sampling points (24×45 meters) [28]. When selecting points, the location of a point within the limits was recorded and assigned local coordinates. To collect soil macrofauna and assess soil properties at each point of the testing site, soil and zoological tests were carried out (the results are presented in *L*-tables) and the following soil indicators were measured: temperature, electrical conductivity, humidity and soil penetration resistance, litter depth and grass stand height were made (*R*-table).

Sampling methods

Soil and zoological samples had a size of 0.25×0.25 m to the depth of the greatest occurrence of soil animals. Admittedly, this depth was 0.20-0.25 m. Reduction of the size of the soil and zoological sample was made according to the recommendations of D. Pokarzhevskyi and co-authors [33; 34]. The transition from the conventional sample size in soil zoology from 0.50×0.50 m to 0.25×0.25 m allows considerably increasing the number of samples at the same working time expenditures. The soil macrofauna is selected by manual disassembly of the soil. The animals found were recorded in a 4% formalin solution and then identified in the laboratory. In the field, soil penetration resistance was measured at a depth of up to 1 m with an interval of 0.05 m using an Eijkelkamp hand-held penetrometer [31]. To measure the electrical conductivity of the soil *in situ,* a HI 76305 sensor (Hanna Instruments, Woodsocket, R. I.) was used. This sensor works together with the HI 993310 portable device.

Statistical analysis

Group ordination was performed using two approaches: OMI analysis [36; 37] and RLQ analysis [38]. The idea of OMI ordination is to apply the concept of an ecological niche to explain the patterns of grouping organisation. In turn, the RLQ ordination allows testing the hypothesis that the ecological properties of species (in a broad understanding – the so-called *traits*) are capable of explaining the patterns that are formed in the grouping structure. The ecomorphes of plants were characterised by O.L. Belgarde [22] and V.V. Tarasov [39], the Q-table demonstrates the ecomorphes of soil animals [40]. Statistical procedures for RLQ and OMI analyses were performed using the ade4 package [41] for the R Shell [42]. The significance of RLQ is evaluated using the randtest.rlq procedure.

RESULTS AND DISCUSSION

Ecomorphic structure of soil macrofauna

Thirty-four species of soil animals were identified at the study site (Table 1). The population density of soil macrofauna is 376.53 ind./m^2. The most numerous and diverse group of saprophages of the testing site under study are earthworms, which are represented by 3 species. The share of the earthworm population from the total number of soil macrofauna is 66.78%. The largest number among earthworms has a medium-tiered soil species *Aporrectodea trapezoides*, the population density of which is 209.91 ind./m^2.

Table 1. *Species structure, ecological Indicators, and abundance of soil macrofauna*

Species	Coenomorph	Trophomorph	Topomorph	Hygromorph	Trophocoenomorph	Phoromorph	Aeromorph	Carbonatomorph	Phase	Density±st. error, ind./m^2
Aporrectodea trapezoides	Pr	SF	End	Ms	OlgTr	B4	APhil	HCarPhil	Imago	208.91±15.93
Aporrectodea rosea	St	SF	End	Ms	MsTr	B4	SAPhil	CarPhil	Imago	31.39±2.75
Dendrobaena nassonovi	St	SF	Anec	Ks	UMgTr	B4	SAPhil	CarPhil	Imago	11.89±1.65
Lumbricidae sp.	Sil	SF	End	Ms	UMgTr	B4	APhil	CarPhil	Cocoon	20.57±2.52
Enchytraeus sp. 1	Pr	SF	End	Hg	MgTr	A1	SAPhil	CarPhil	Imago	9.60±1.14
Pardosa lugubris	Sil	ZF	Ep	Ms	MsTr	A2	SAPhil	ACarPhil	Imago	0.15±0.15
Geophilus proximus	Pr	ZF	End	Ms	MgTr	A2	SAPhil	HCarPhil	Imago	0.76±0.33
Lithobius curtipes	Sil	ZF	Ep	Hg	OlgTr	A1	SAPhil	ACarPhil	Imago	0.15±0.15
Megaphyllum rossicum	Sil	SF	Ep	Ms	MsTr	A2	APhil	ACarPhil	Imago	29.71±2.86
Malthodes marginatus	Sil	ZF	Ep	Hg	MsTr	A2	SAPhil	ACarPhil	Larvae	0.15±0.15
Brachinus crepitans	Sil	ZF	Ep	Ms	MgTr	A1	APhil	HCarPhil	Imago	0.46±0.33
Calathus fuscipes	St	ZF	Ep	Ms	UMgTr	A2	APhil	HCarPhil	Imago	0.15±0.15
Harpalus affinis	Pr	ZF	Ep	Ms	UMgTr	A2	APhil	HCarPhil	Imago	4.88±1.33
Harpalus affinis	Pr	ZF	Ep	Ms	UMgTr	A2	APhil	HCarPhil	Larvae	1.68±0.53
Harpalus distinguendus	St	ZF	Ep	Ms	UMgTr	A3	APhil	HCarPhil	Imago	0.30±0.30
Ophonus azureus	Pr	ZF	Ep	Ms	MgTr	A2	APhil	CarPhil	Imago	0.15±0.15
Poecilus versicolor	Pr	ZF	Ep	Ms	MgTr	A1	SAPhil	CarPhil	Imago	0.15±0.15
Cetonia aurata	Sil	SF	End	Ms	UMgTr	B7	SAPhil	CarPhil	Larvae	0.15±0.16
Otiorhynchus raucus	Sil	FF	End	Ks	MgTr	B7	HAPhob	CarPhil	Larvae	1.98±0.64
Silpha carinata	Pal	SF	Ep	Hg	MgTr	A3	HAPhob	ACarPhil	Imago	0.30±0.22
Silpha carinata	Pal	SF	Ep	Hg	MgTr	A3	HAPhob	ACarPhil	Larvae	0.30±0.21
Philonthus decorus	Sil	ZF	Ep	Ms	OlgTr	A1	APhil	ACarPhil	Imago	0.30±0.22
Staphylinus erythropterus	Sil	ZF	Ep	Hg	MsTr	A1	SAPhil	ACarPhil	Imago	0.15±0.15
Rhizotrogus aestivus	St	FF	End	Ms	UMgTr	B7	SAPhil	CarPhil	Larvae	1.83±0.59
Chloromyia formosa	Sil	SF	Ep	Hg	MgTr	A2	SAPhob	HCarPhil	Larvae	0.15±0.15
Tabanus bromius	Pr	ZF	End	Ms	MsTr	B5	SAPhil	CarPhil	Larvae	0.30±0.21
Agrotis segetum	Sil	FF	End	Ks	MsTr	B4	SAPhil	CarPhil	Larvae	1.52±0.63
Armadillidium vulgare	Sil	SF	Ep	Ms	MgTr	A3	APhil	CarPhil	Imago	0.15±0.15
Trachelipus rathkii	Pal	SF	Ep	Hg	MgTr	A3	HAPhob	CarPhil	Imago	0.15±0.15
Chondrula tridens	St	FF	Ep	Ks	MgTr	A3	APhil	CarPhil	Imago	5.33±1.20
Helix albescens	St	FF	Ep	Ks	MgTr	A3	APhil	HCarPhil	Imago	15.24±2.12
Monacha cartusiana	Sil	FF	Ep	Ks	MgTr	A2	APhil	CarPhil	Imago	0.15±0.15
Limacus maculatus	Sil	FF	End	Ms	MgTr	B4	SAPhob	ACarPhil	Imago	0.15±0.16

***Notes**: Coenomorphes: St – stepants, Pr – pratants, Pal – paludants, Sil – silvants; Trophomorphes: SF – saprophages, FF – phytophages, ZF – zoophages; Topomorphes: End – endogeic, Ep – epigeic, Anec – burrowers; Hygromorphes: Ks – xerophiles, Ms – mesophiles, Hg – hygrophiles, Uhg – ultrahigrophiles; Trophocoenomorphes: OlgTr – oligotorophocoenomorphes, MsTr – mesotrophocoenomorphes, MgTr – megatrophocoenomorphes, UMgTr – ulramegatrophocoenomorphes; Phoromorphes: A – movement through existing soil fracturing; B – active tunnelling; 1 – body sizes smaller than soil fracturing, 2 – body sizes comparable to fracturing, 3 – body sizes larger than cavities in the subsoil or comparable to large crevices or cracks in the soil, 4 – moving with a change in body thickness, 5 – moving without a change in body thickness, 6 – digging holes with limbs, 7 – C-shaped body; Aeromorphes: APhil – aerophiles, SAPhil – subaerophiles, HAPhob – hemiaerophobes, SAPhob – subaerophobes, APhob – aerophobes; Carbonatomorphes: CarPhob – carbonatophobes, ACarPhil – acarbonatophiles, HCarPhil – hemicarbonatophiles, CarPhil – carbonatophiles, HpCarPhil – hypercarbonatophiles*

The other two representatives of earthworms are *Aporrectodea rosea* and *Dendrobaena nassonovi*. The distribution density of earthworm cocoons is 20.57 ind./m^2. The structure of earthworm hygromorphes is dominated by xerophiles and mesophiles. Among the representatives of earthworms, there are pratants and stepants. Consequently, the structure of the earthworm grouping in the study area is numerous and diverse both in terms of taxonomy and ecology. The trophic group of saprophages also includes endogeic enchitreids (9.60 ind./m^2), epigeal millipedes *Megaphyllum rossicum* (29.71 ind./m^2), larvae and imagos *Silpha carinata* (0.30 ind./m^2), larvae Chloromyia formosa (0.15 ind./m^2) and woodlice *Trachelipus rathkii* (0.15 ind./m^2) and Armadillidium vulgare (0.15 ind./m^2).

Representatives of predatory lip legged millipedes are in themselves the soil centipede *Geophilus proximus* (0.76 ind./m^2 for its movement, it uses a system of soil burrows and cracks and an epigeal stone centipede *Lithobius curtipes* (0.15 ind./m^2). Representatives of predators are imagos of ground beetles (*Brachinus crepitans, Calathus fuscipes, Harpalus distinguendus, Harpalus affinis, Ophonus azureus, Poecilus versicolor*), an adult of short-winged beetles (*Staphylinus erythropterus* and *Philonthus decorus*), larvae *Harpalus affinis, Malthodes marginatus, Tabanus bromius* and spiders. The group of phytophages is diverse and is represented by larvae turnip moth (*Agrotis segetum*), lamellar beetles (*Rhizotrogus aestivus*), broad-nosed weevil (*Otiorhynchus raucus*) and shellfish (*Limacus maculatus, Chondrula tridens, Helix albescens, Monacha cartusiana*).

The basis of the coenomorphic structure of soil macrofauna in terms of the number of species is silvants (45.5%) and pratants (24.2%) (Fig. 2). The number of stepants (21.2%) and paludants (9.1%) is slightly less. As for the species abundance, the situation is somewhat different – the basis of the coenomorphic structure of macrofauna comprises pratants (64.5%), slightly less stepants (19.1%) and silvants (16.1%), and sporadic occurrence of paludants (0.2%).

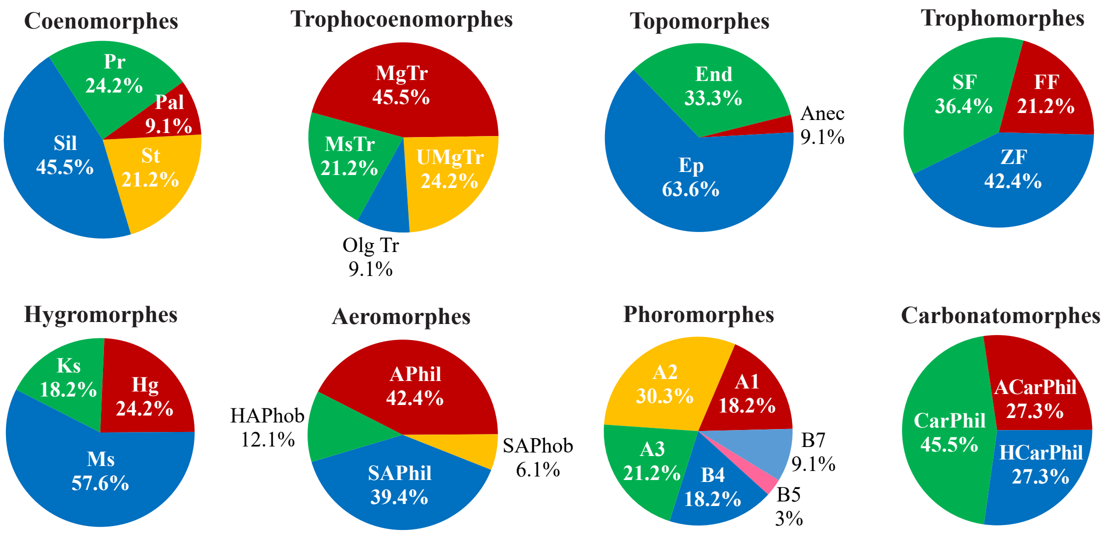

Figure 2. *Ecological structure of soil macrofauna (% by number of species)*

Notes*: Coenomorphes: St – stepants, Pr – pratants, Pal – paludants, Sil – silvants; Hygromorphes: Ks – xerophiles, Ms – mesophiles, Hg – hygrophiles, Uhg – ultrahigrophiles; Trophocoenomorphes: MsTr – mesotrophocoenomorphes; MgTr – megatrophocoenomorphes; UMgTr – Ultramegatrophocoenomorphes; Aeromorphes: APhil – aerophiles; SAPhil – Subaerophiles; HAPhob – hemiaerophobes; Carbonatomorphes: CarPhob – Carbonatophobes; ACarPhil – acarbonatophiles; HemiCarPhil – hemicarbonatophiles; CarPhil – carbonatophiles, HiperCarPhil – Hypercarbarbonatophiles; Topomorphes: End – endogeic. Ep – epigeic, Anec – burrowers; Phoromorphes: a –movement through existing soil fracturing; B – active laying of passages; 1 – body sizes smaller than soil fracturing, 2 – body sizes comparable to fracturing, 3 – body sizes larger than cavities in the subsoil or comparable to large crevices or cracks in the soil, 4 – moving with a change in body thickness, 5 – moving without a change in body thickness, 6 – digging holes with limbs, 7 – C-shaped body; Trophomorphes: SF – saprophages; F – phytophages; ZF – zoophages*

The environmental conditions determine the potential for settlement of a biotope, which is reflected in the features of the ecomorphic structure of populations, which, in turn, determines the ecological groups that will prevail in a particular ecosystem. Consequently, this ecosystem is developed in a predominantly meadow-forest environment, and the conditions in the middle of this ecosystem are steppe-meadow. The forest coenomorphes, represented by a considerable variety of species, is inferior in number compared to other coenomorphes. Marsh species are represented by a certain number, but in terms of abundance, these coenomorphes practically disappear from the grouping. Among hygromorphes, mesophiles predominate in terms of the number of species (57.6%), slightly less so – hygrophiles (24.2%) and xerophiles (18.2%). As for the species abundance, the hygromorphic structure is considerably dominated by mesophiles (86.4%), slightly less by xerophiles (10.4%) and hygrophiles (3.22%). Thus, the general conditions in which the population of the studied biotope is developed are mesophilic. The specific features of particular conditions lie in a shift towards greater mesophytisation due to a decrease in the proportion of both xerophilic and hygrophilic species. Thus, this grouping is stenotopically mesophilic. The structure of Trophocoenomorphes is dominated by megatrophocoenomorphes (45.5%) and ultramegatrophocoenomorphes (24.2%) in terms of the number of species. The proportion of megatrophocoenomorphes (21.2%) and oligotrophocoenomorphes (9.1%) is slightly lower. As for the species abundance, the positions of these ecomorphes change places: representatives of oligotrophocoenomorphes become the leader (59.6%), they are considerably superior to mesotrophocoenomorphes (18.3%). The proportion of other Trophocoenomorphes is much smaller. This suggests that the ecosystem is formed in an ultramega-megatrophic edaphotope in terms of trophic level, but certain factors of the ecosystem cause a change in its trophic level to an oligotrophic one.

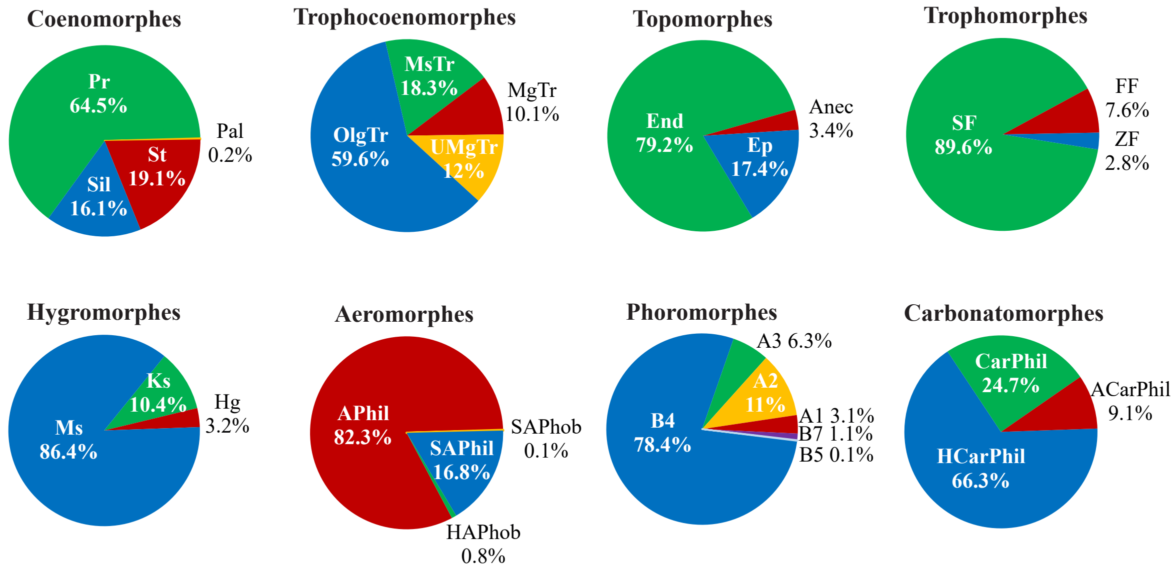

***Figure 3**. Ecological structure of soil macrofauna (% by species abundance)*

***Notes**: Coenomorphes: St – stepants, Pr – pratants, Pal – paludants, Sil – silvants; Hygromorphes: Ks – xerophiles, Ms – mesophiles, Hg – hygrophiles, Uhg – ultrahigrophiles; Trophocoenomorphes: MsTr – mesotrophocoenomorphes; MgTr – megatrophocoenomorphes; UMgTr – Ultramegatrophocoenomorphes; Aeromorphes: APhil – aerophiles; SAPhil – Subaerophiles; HAPhob – hemiaerophobes; Carbonatomorphes: CarPhob – Carbonatophobes; ACarPhil – acarbonatophiles; HemiCarPhil – hemicarbonatophiles; CarPhil – carbonatophiles, HiperCarPhil – Hypercarbarbonatophiles; Topomorphes: End – endogeic. Ep – epigeic, Anec – burrowers; Phoromorphes: a – movement through existing soil fracturing; B – active laying of passages; 1 – body sizes smaller than soil fracturing, 2 – body sizes comparable to fracturing, 3 – body sizes larger than cavities in the subsoil or comparable to large crevices or cracks in the soil, 4 – moving with a change in body thickness, 5 – moving without a change in body thickness, 6 – digging holes with limbs, 7 – C-shaped body; Trophomorphes: SF – saprophages; F – phytophages; ZF – zoophages*

The predominant number of Aeromorphes in terms of the number of species are aerophiles (42.4%) and subaerophiles (39.4%). As for species abundance, the share of aerophiles is considerably increasing (82.3%). Thus, the animal population of the soil of the ecosystem under study is described by a high need for a sufficient level of soil aeration. Among Topomorphes, epigeal forms predominate (63.3%). The share of endogeic species is almost twice as low (33.3%). Burrowers make up 3%. As for abundance, endogeic species significantly predominate (79.2%). This indicates favourable conditions for the existence of pedobionts in the soil, and on the other hand – considerable pressure on the subsoil block in recreational conditions in public green spaces. In terms of the number, Phoromorphes are represented by a wide range of species, which are generally represented equally. In terms of abundance, Phoromorphes are considerably dominated by species capable of laying soil passages with changes in body shape (78.4%).

The representation of Trophomorphes concerning the number of species is quite equalised. Zoophages make up 42.4% of the number of species, saprophages – 36.4%, phytophages – 21.2%. Saprophages significantly predominate in abundance (89.6%). Zoophages account for 7.6% and phytophages – for 2.8%. Among Carbonatomorphes, carbonatophiles predominate in terms of the number of species (45.5%). Acarbonatophiles and hemicarbonatophiles are presented in equal proportions (27.3%). The abundance of species is dominated by hemicarbonatophiles (66.3%). Acarbonatophiles make up 9.1% and carbonatophiles make up 24.7%.

Soil determinants of the spatial structure of ecomorphes of soil macrofauna

The soil indicators are used as determinants of the ecological space of macrofauna communities (Table 2). The soil penetration resistance within the test site under study increases along with depth. Thus, the upper layer of soil has an average hardness of 1.41±0.049 MPa, and the lower layer has an average hardness of 3.75±0.059 MPa.

***Table 2**. Soil indicators that determine the ecological space of macrofauna and their correlations with axes obtained during OMI and RLQ analyses (statistically significant for $p<0.05$)*

Environment variable	Average ± st. deviation	Percentile		CV, %	OMI-Axis 1	OMI-Axis 2	RLQ-Axis 1	RLQ-Axis 2
		2.5%	97.5%					
Soil penetration resistance at depth, MPa								
0-5 cm	1.41±0.049	0.60	2.50	35.87	−0.15	−0.11	−0.12	0.14
5-10 cm	1.86±0.052	0.90	2.90	28.52	−0.23	−0.11	−0.26	0.05
10-15 cm	2.23±0.064	1.00	3.50	29.51	−0.24	−0.05	−0.16	−0.01
15-20 cm	2.55±0.079	1.20	4.30	31.69	−0.21	−0.04	−0.09	−0.06
20-25 cm	2.56±0.052	1.70	3.67	20.90	−0.21	−0.03	−0.27	0.04
25-30 cm	2.59±0.060	1.65	4.30	23.70	−0.27	0.01	−0.27	−0.18
30-35 cm	2.70±0.059	1.60	4.00	22.36	−0.26	−0.02	−0.32	−0.16
35-40 cm	2.80±0.059	1.70	4.00	21.57	−0.27	0.00	−0.35	−0.05
40-45 cm	2.91±0.058	1.90	4.10	20.48	−0.26	−0.02	−0.23	−0.14
45-50 cm	3.05±0.061	2.00	4.40	20.55	−0.26	−0.01	−0.25	0.13
50-55 cm	3.28±0.067	2.25	4.53	21.01	−0.28	0.01	−0.21	0.12
55-60 cm	3.39±0.069	2.20	4.50	20.71	−0.29	−0.01	−0.18	0.21
60-65 cm	3.50±0.065	2.30	4.80	19.05	−0.27	0.00	−0.19	0.05
65-70 cm	3.54±0.067	2.30	5.00	19.40	−0.27	0.02	−0.21	0.07
70-75 cm	3.54±0.067	2.30	4.80	19.33	−0.22	0.02	−0.11	−0.02
75-80 cm	3.62±0.065	2.30	5.00	18.45	−0.26	0.04	−0.13	−0.12
80-85 cm	3.70±0.072	2.00	5.15	19.96	−0.26	0.03	−0.15	−0.13
85-90 cm	3.69±0.082	2.30	5.30	22.85	−0.26	0.04	−0.11	−0.13
90-95 cm	3.75±0.058	2.60	5.00	15.95	−0.24	0.01	−0.23	−0.30
95-100 cm	3.75±0.059	2.60	5.00	16.12	−0.24	0.01	−0.23	−0.30
Physical properties of the soil								
Electrical conductivity, dS/m	0.11±0.004	0.04	0.19	38.10	0.02	−0.13	0.14	0.41
Humidity, %	22.8±0.33	16.00	29.01	14.67	0.08	−0.09	0.15	0.48
Distances to walking paths and trees								
Distance to recreation tracks, m	3.08±0.236	0.00	9.07	78.58	0.01	0.12	0.13	−0.14
Distance to trees, m	3.16±0.190	0.68	8.19	61.66	0.16	−0.16	−0.10	0.41

The upper layer of soil is described by a rapid increase in the soil penetration resistance, which stops at a depth of 20-25 cm. Within the test site under study, the average soil penetration resistance values starting from soil layers of 10-15 cm are, with varying probability, higher than those critical for the growth of plant root systems (3-3.5 MPa) [43]. This confirms the fact that spatial variability in soil penetration resistance has a considerable structuring effect on the formation of grass cover and the organisation of soil animal populations. The coefficient of variation in soil penetration resistance tends to decrease with increasing depth, but local highs interrupt this monotonous trend. The coefficient of hardness variation has a local maximum in the soil layers of 20-25 cm and 90-95 cm and is 31.69% and 22.84%, respectively. The minimum variability of soil penetration resistance, which is 15.95-16.12%, falls at a depth of 90-100 cm.

The average electrical conductivity of the soil is 0.11±0.004 dS/m and has a variation coefficient of 38.10%. The maximum value of this indicator is approximately 0.19 dS/m, which does not exceed the lower threshold of electrolyte concentrations (1.5-2.0 dS/m), which negatively affect vegetation [44]. The low level of electrical conductivity of the soil suggests a low trophic level of the soil of the ecosystem under study. Electrical conductivity is statistically significantly correlated with soil penetration resistance at different depths. The correlation is positive with soil penetration resistance at a depth of 0-5 cm (r=0.25, p<0.01). The correlation is negative with hardness at depths from 55-60 cm to 90-95 cm (statistically significant correlation coefficients are within -0.20 – -0.31). Soil moisture is 22.8±0.33%, and in 95% of cases is with 16.00%-29.01%. Humidity and electrical conductivity are positively correlated with each other (r=0.52, p<0.01). In turn, the correlation between soil moisture and soil penetration resistance is negative (statistically significant correlation coefficients are within -0.21--0.36). The distance to recreational paths averages 3.08±0.236 and in 95% of cases varies between 0.00-9.07 m. The distance to tree trunks, regardless of the species, averages 3.16±0.19 and in 95% of cases varies between 0.68-8.19 m.

Spatial ordination of soil macrofauna groups

The simultaneous measurement of soil indicators and features of the structure of groups of organisms allowed assessing the distribution of the ecological space of the ecosystem between the ecological niches of soil macrofauna (Table 3). The analysis determined the total inertia at the level of 1.47. As a result of OMI analysis, two axes were obtained, the one of which describes 86.72%, and the other – 7.03% of inertia. Thus, 93.75% of inertia is described by the first two axes, which proves that the space created by these axes is sufficient to describe the differentiation of ecological niches of macrofauna in the test site under study. The average value of the grouping marginality is OMI=25.07 with the significance level R=0.01, which reflects the essential role of the investigated variables in structuring soil macrofauna groups.

Of the 33 species for which OMI analysis was performed, for 18 species, marginality differs statistically significantly from the random alternative (Table 3). Thus, the typical edaphic conditions of the test site do not coincide with the centroid of the ecological niche of a considerable part of macrofauna species. The marginality of a niche determines the degree of difference between the optimum conditions for the existence of a species and the factual conditions of a particular place of existence. Niche tolerance is the opposite of specialisation: the higher the tolerance, the lower the specialisation. Residual tolerance is an indicator of the role of random and neutral factors, as well as measurement errors.

***Table 3**. Assessment of the marginality of soil macrofauna species*

Macrofauna species	Inertia	OMI	Tol	Rtol	*p-level*
Aporrectodea rosea	24.25	1.90	44.50	53.50	0.05
Aporrectodea trapezoides	26.26	3.30	54.00	42.70	0.01
Dendrobaena nassonovi	20.51	1.60	19.90	78.60	0.53
Lumbricidae (cocoon)	22.66	2.80	41.50	55.70	0.15
Enchytraeus sp.	28.36	4.80	52.10	43.10	0.03
Pardosa lugubris	9.20	100.00	0.00	0.00	0.94
Geophilus proximus	20.55	15.70	26.40	57.90	0.15
Lithobius curtipes	32.04	13.20	56.10	30.70	0.10
Megaphyllum rossicum	24.49	1.10	34.40	64.50	0.31
Malthodes marginatus	23.27	5.80	5.50	88.70	0.99
Brachinus sclopeta	12.37	38.10	13.00	48.80	0.91
Calathus fuscipes	25.62	12.60	22.70	64.70	0.66
Harpalus affinis	40.26	22.20	37.70	40.10	0.01
Harpalus affinis (larvae)	22.04	4.40	29.40	66.20	0.69
Harpalus distinguendus	24.05	21.50	29.50	49.00	0.31
Ophonus azureus	24.74	100.00	0.00	0.00	0.38
Poecilus versicolor	16.85	7.90	12.70	79.40	0.95
Cetonia aurata	16.43	37.00	15.50	47.50	0.86
Otiorhynchus raucus	26.09	4.10	12.10	83.80	0.33

Table 3, Continued

Macrofauna species	Inertia	OMI	Tol	Rtol	*p-level*
Silpha carinata	34.77	28.30	42.20	29.50	0.05
Silpha carinata (larvae)	27.50	25.20	35.50	39.30	0.05
Philonthus decorus	22.01	29.90	18.00	52.10	0.69
Staphylinus erythrocephalus	8.56	100.00	0.00	0.00	0.98
Rhizotrogus aestivus	25.28	5.60	43.70	50.70	0.63
Chloromyia formosa	35.43	14.50	53.90	31.60	0.09
Tabanus bromius	20.12	58.30	3.70	38.00	0.05
Agrotis segetum	25.80	15.70	42.10	42.20	0.01
Armadillidium vulgare	29.84	6.30	4.20	89.50	0.68
Trachelipus rathkii	40.98	48.60	25.00	26.40	0.01
Chondrula tridens	23.40	9.20	35.50	55.20	0.02
Helix albescens	27.51	10.80	47.50	41.70	0.01
Monacha cartusiana	18.60	27.20	17.10	55.70	0.05
Limacus maculatus	47.41	77.50	1.40	21.00	0.01
OMI	25.07	–	–	–	0.01

***Notes**: OMI-index of the average distance (marginality) for each species; Tol – tolerance, Rtol – residual tolerance; index data are presented in % of the total variability; R – Monte Carlo level after 999 iterations*

Species such as *Staphylinus erythrocephalus* and *Pardosa lugubris* have a high marginality. This means that the typical ecological conditions of the test site are considerably different from the optimum for these species. These types are subsoil. A significant transformation of the subsoil block under the influence of recreation drastically transforms the ecological environment of these species.

The most tolerant species are as follows: *Aporrectodea rosea, Helix albescens, Enchytraeus sp., Chloromyia formosa, Aporrectodea trapezoides, Lithobius curtipes*. In fact, this list indicates a complex of species that is typical of a given ecosystem and occupies the corresponding territory in general as one that best meets the ecological standard of the species. On the contrary, highly specialised species, the existence of which is possible only in limited areas within the territory, are *Malthodes marginatus* and *Poecilus versicolor*.

The residual tolerance is high for a number of species (for *Armadillidium vulgare* – 89.5%, for *Malthodes marginatus* – 88.7%, for *Otiorhynchus raucus* – 83.8%), which indicates that the structuring of the grouping of soil macrofauna factors is greatly influenced by factors of a neutral nature, including those that are not considered in this study. Correlation analysis of soil properties and OMI axes demonstrated that the main factors for structuring the ecological niche of soil macrofauna within the study area are soil penetration resistance in the range of the entire measured layer, soil moisture, and distance to trees (Axis 1) (Table 2). Soil penetration resistance in the surface layers (0-5 and 5-10 cm), electrical conductivity, humidity, and distance from recreational paths (Axis 2) also play an essential role. Axis 1 can be interpreted as a natural variation in the environment properties, which leads to structuring of the grouping. Axis 2 can be interpreted as variability in the grouping structure, which is caused by the influence of recreation. OMI axes define gradients of the medium along which the views are ordered (Fig. 4). On one side, the extreme positions along the OMI-Axis 1 are occupied by *Monacha cartusiana, Pardosa lugubris, Tabanus bromius, Limacus maculatus,* and on the other – by *Trachelipus rathkii, Ophonus azureus, Silpha carinata, Harpalus affinis*. Along the OMI-Axis 2, the extreme positions are occupied by *Rhizotrogus aestivus, Malthodes marginatus, Pardosa lugubris, Ophonus azureus,* on one side, and *Harpalus affinis, Tabanus bromius, Armadillidium vulgare, Chondrula tridens* – on the other. Notably, the vast majority of species are subsoil, but at this stage of analysis it is extremely difficult to put forward a hypothesis that would explain the observed ordination of species in the grouping.

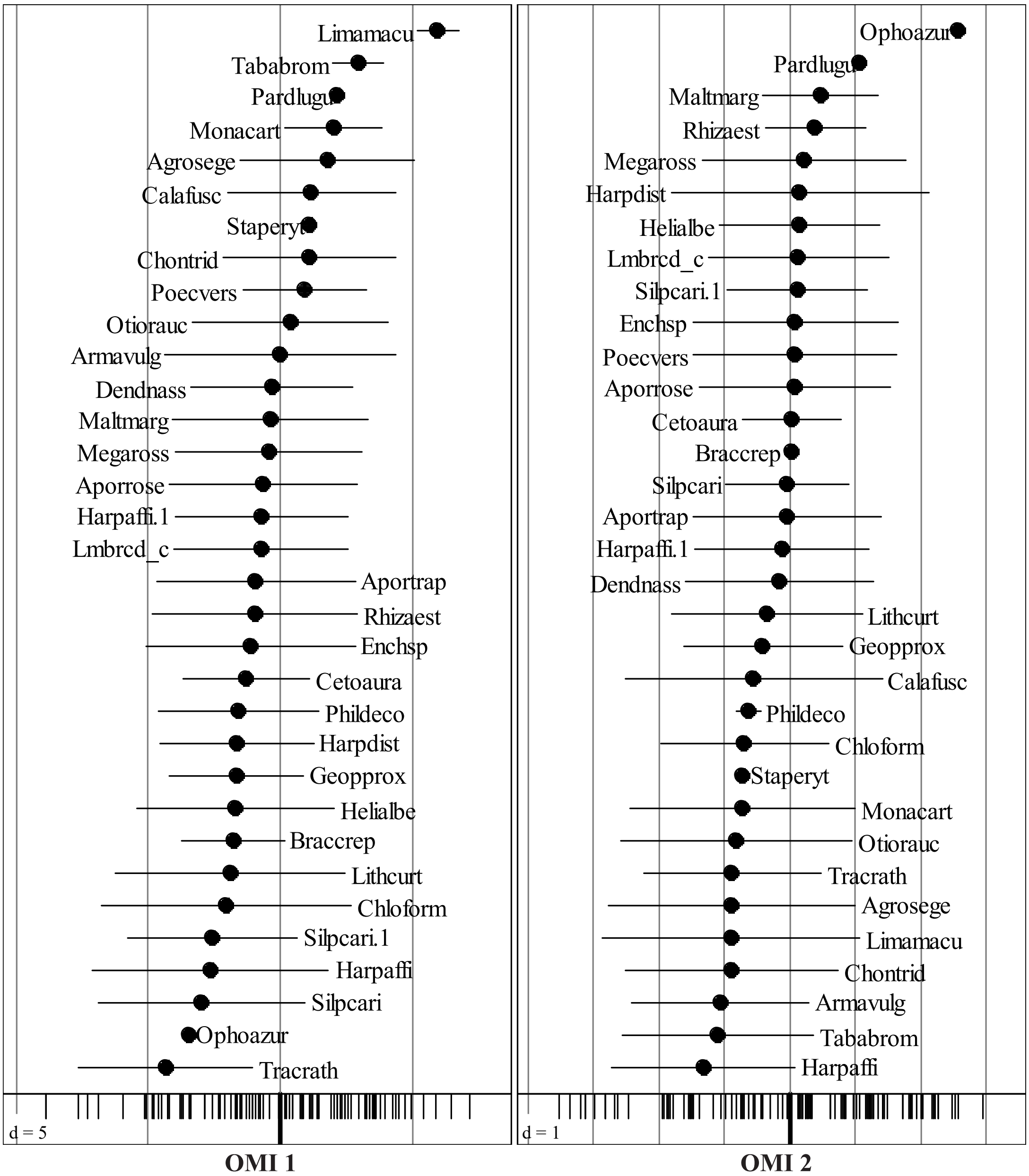

Figure 4*. Projections of ecological niches of soil macrofauna species on the OMI 1 and OMI 2 axes: the lower half – negative values of the axes, the upper half – positive values of the axes*

Notes*: Aporrose – Aporrectodea rosea; Aportrap – Aporrectodea trapezoides; Dendnass – Dendrobaena nassonovi; Lmbrcd_c – Lumbricidae (cocoon); Enchsp – Enchytraeus sp.; Pardlugu – Pardosa lugubris; Geopprox – Geophilus proximus; Lithcurt – Lithobius curtipes; Megaross – Megaphyllum rossicum; Maltmarg – Malthodes marginatus; Bracsclo – Brachinus sclopeta; Calafusc – Calathus fuscipes; Harpaffi – Harpalus affinis; Harpaffi.1 – Harpalus affinis (larvae); Harpdist – Harpalus distinguendus; Ophoazur – Ophonus azureus; Poecvers – Poecilus versicolor; Cetoaura – Cetonia aurata; Otiorauc – Otiorhynchus raucus; Silpcari – Silpha carinata; Silpcari.1 – Silpha carinata (larvae); Phildeco – Philonthus decorus; Staperyt – Staphylinus erythrocephalus; Rhizaest – Rhizotrogus aestivus; Chloform – Chloromyia formosa; Tababrom – Tabanus bromius; Agrosege – Agrotis segetum; Armavulg – Armadillidium vulgare; Tracrath – Trachelipus rathkii; Chontrid – Chondrula tridens; Helialbe – Helix albescens; Monacart – Monacha cartusiana; Limamacu – Limacus maculatus*

RLQ analysis found that 92.91% of the total variation (total inertia) describes the first two RLQ axes (84.44 and 8.47%, respectively). The randtest procedure confirmed the significance of the results of the RLQ analysis on *p*-level 0.018. The presence of a statistically significant correlation between ecomorphes of macrofauna and environmental predictors was confirmed by a multiple test of global significance of correlations based on site permutation (*p*=0.003) and based on the permutation of species (*p*=0.024). RLQ axes constitute integral indicators for assessing the correlation between environmental factors and the ecomorphic community structure. One metric space reflects the location of macrofauna species, the influence of environmental factors on them, and the value of ecomorphic indicators affecting the structuring of soil macrofauna grouping (Fig. 5). As a result of RLQ analysis, Axis 1 was identified, which explains the effect of soil penetration resistance on the structuring of macrofauna grouping at all measured depths (Table 2, Fig. 5). Axis 1 correlates negatively with soil penetration resistance, but positively with electrical conductivity and soil moisture. Axis 1 correlates positively with the distance from paths and negatively with the distance to trees. Markers of positive values of Axis 1 are xerophiles, phytophages, and carbonatophiles. Markers of negative values of Axis 1 are pratants or paludants, hypercarbonatophiles, and saprophages. This axis can be interpreted as the result of the structural influence of tree vegetation.

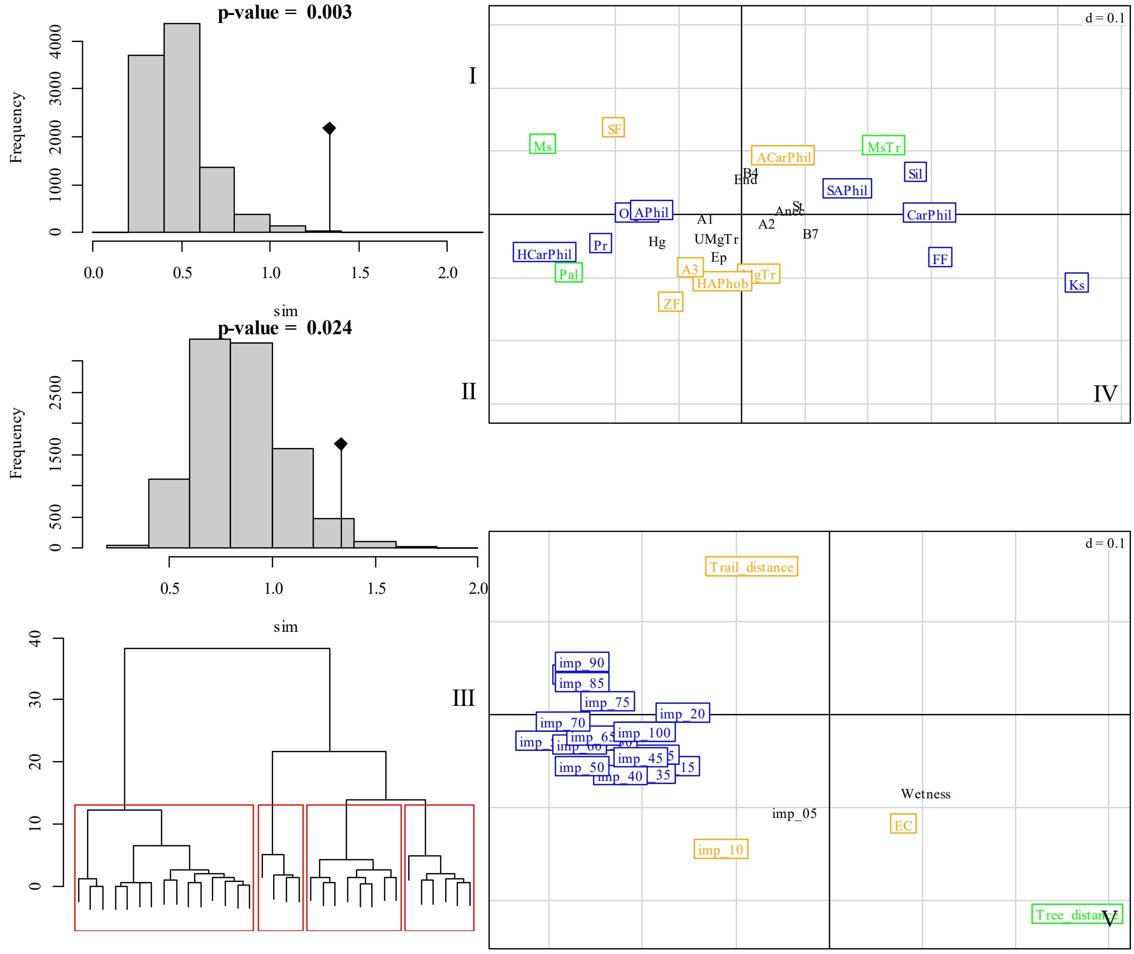

***Figure 5**. Results of RLQ analysis: I – multiple test of global significance of correlations between ecomorphes of soil macrofauna and ecological predictors based on site permutation, II – multiple test of global significance of correlations between ecomorphes of macrofauna and ecological predictors based on species permutation, III – cluster analysis of species based on values of RLQ axes, IV – placement of ecomorphes in the environment of RLQ axes (blue – statistically probable correlation with Axis 1; yellow – with Axis 2; green – with both axes), V – placement of environmental predictors in the environment of RLQ axes (blue – statistically probably correlation with Axis 1; yellow – with Axis 2; green – with both axes)*

Axis 2 is sensitive to trends of opposite changes in soil penetration resistance at different depths. This refers to a tendency to increase hardness at depths of 0-5 and 55-60 cm on the one hand, which is accompanied by a decrease in hardness at depths of 25-35 and 90-100 cm, on the other hand. This axis considerably correlates with electrical conductivity and humidity, as well as distances to trees and paths. Axis 2 can be interpreted as a structuring effect of recreational load on soil macrofauna. Positive values of Axis 2, which correspond to a lower level of recreational load, are marked with saprophages and acarbonatophiles. Negative values of Axis 2, which correspond to a high level of recreational load, are marked with zoophages, hemiaerophobes, and megatrophes.

The RLQ analysis allowed classifying living organisms according to the specific features of their ecological structure and relationships with environmental factors. Cluster analysis identified four populations of species that form functional groups A, B, C, and D (Fig. 6). Functional group A has a centroid, which is close to the territories characterised by the lowest level of recreational load. This cluster includes all earthworm species, earthworm cocoons, and larvae *Cetonia aurata,* which prefer rotting wood. The opposite position within the axes is factually vacant and corresponds to the conditions of the greatest recreational load. This indicates factual absence of soil macrofauna species that could exist amid intense recreational exposure. Cluster B combines species that are moderately tolerant to recreational load. Cluster C is a group of hygrophilous species that prefer shaded parkland areas. Cluster D is a group of species that prefer more open areas where moisture deficiency is more common.

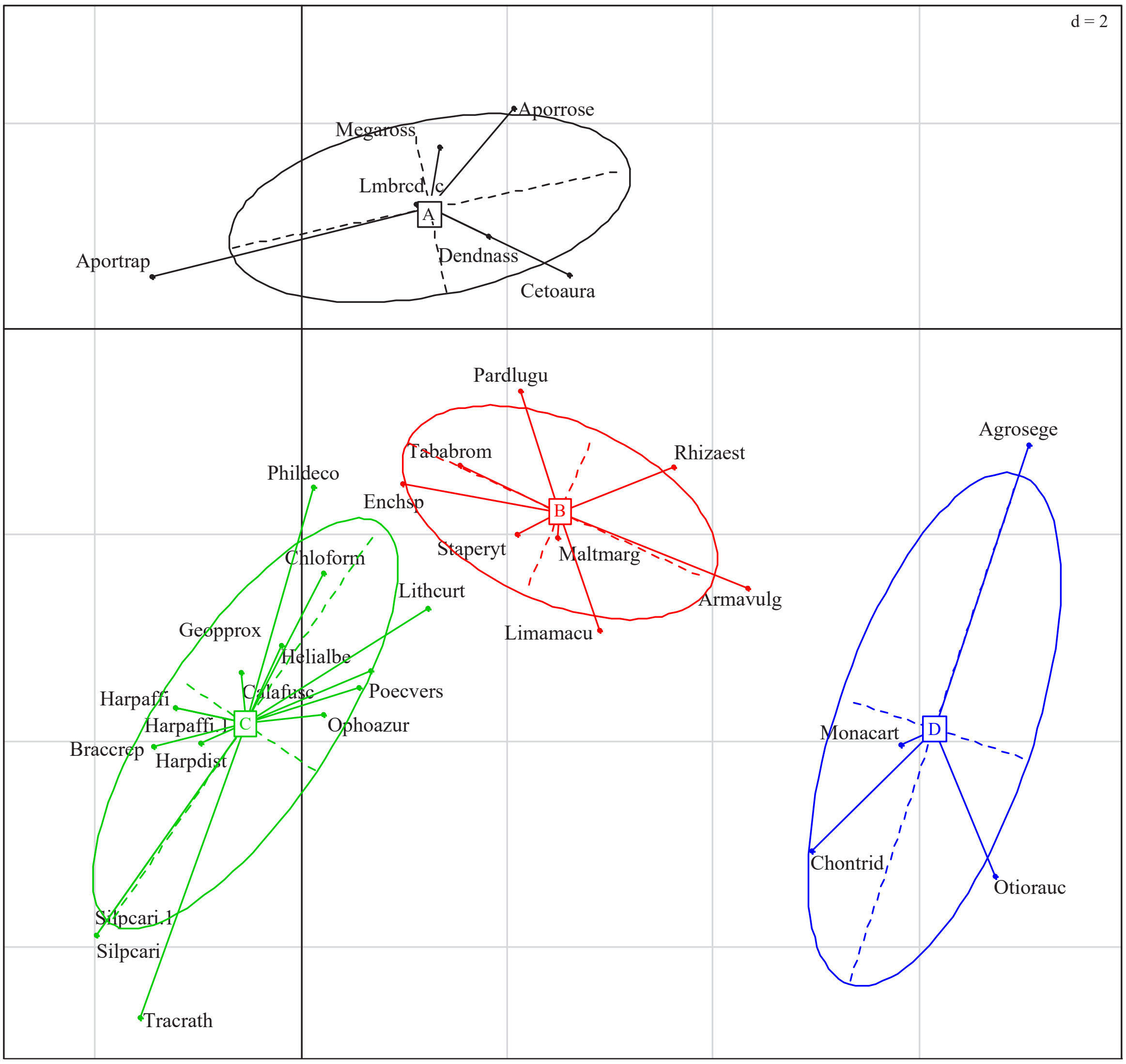

Figure 6. *Placement of functional groups (clusters) within RLQ axes: Aporrose – Aporrectodea rosea; Aportrap – Aporrectodea trapezoides; Dendnass – Dendrobaena nassonovi; Lmbrcd_c – Lumbricidae (cocoon); Enchsp – Enchytraeus sp.; Pardlugu – Pardosa lugubris; Geopprox – Geophilus proximus; Lithcurt – Lithobius curtipes; Megaross – Megaphyllum rossicum; Maltmarg – Malthodes marginatus; Bracsclo – Brachinus sclopeta; Calafusc – Calathus fuscipes; Harpaffi – Harpalus affinis; Harpaffi.1 – Harpalus affinis (larvae); Harpdist – Harpalus distinguendus; Ophoazur – Ophonus azureus; Poecvers – Poecilus versicolor; Cetoaura – Cetonia aurata; Otiorauc – Otiorhynchus raucus; Silpcari – Silpha carinata; Silpcari.1 – Silpha carinata (larvae); Phildeco – Philonthus decorus; Staperyt – Staphylinus erythrocephalus; Rhizaest – Rhizotrogus aestivus; Chloform – Chloromyia formosa; Tababrom – Tabanus bromius; Agrosege – Agrotis segetum; Armavulg – Armadillidium vulgare; Tracrath – Trachelipus rathkii; Chontrid – Chondrula tridens; Helialbe – Helix albescens; Monacart – Monacha cartusiana; Limamacu – Limacus maculatus*

The RLQ Axis 1 statistically significantly correlates with both OMI Axis 1 and RLQ Axis 2 (*r*=0.99, *p*<0.001 and *r*=0.32, *p*=0.02). The RLQ Axis 2 also statistically significantly correlates with the OMI Axis 1 (*r*=0.42, *p*<0.001) and OMI Axis 2 (*r*=0.87, *p*<0.001). Accordingly, the spatial patterns of the RLQ and OMI axes are very similar to each other (Fig. 7).

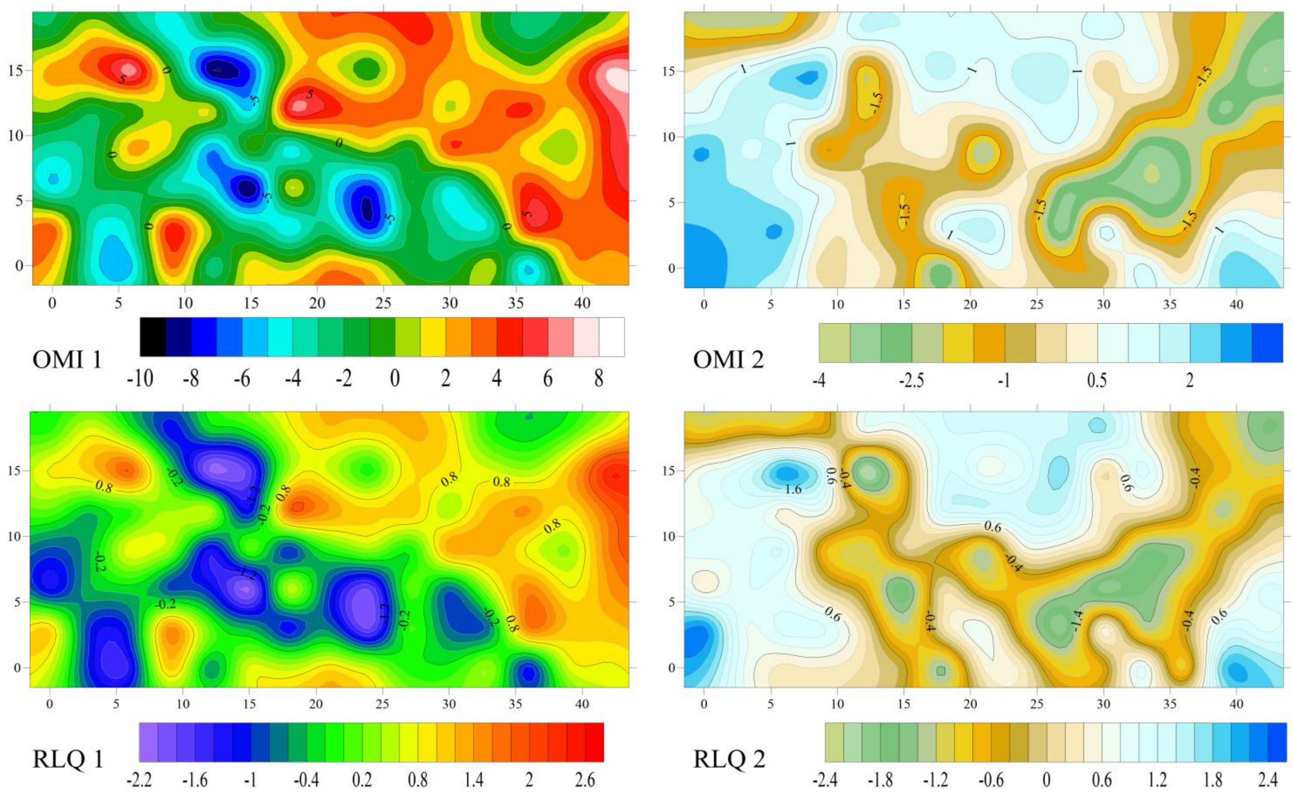

Figure 7. *Spatial variation of the OMI and RLQ axes. The abscissa and ordinate axes are local coordinates of the testing site under study*

Thus, ecomorphes reflect the adaptations of the animal population not to the ecological parameters of the environment, but to the typological indicators of the ecosystem in general. Soil is a special bioinert body, which, according to many researchers, constitutes an intermediate element between living and inanimate nature. Therefore, a topical scientific issue is the identification of the forms and degree of similarity of the characteristics of soil and living matter [45]. Genetic soil science allows considering the dynamics, structure, and functions of the soil [46; 47]. However, the manifestation of obvious changes in the composition of the soil or its functioning takes long periods of time – tens, and sometimes hundreds of years. Clearly, the soil is a full-fledged component of the ecosystem, which interacts with all its other components throughout the entire period of its existence. Plants and animals are active participants in the soil-forming process, since they are involved in the formation of humus by producing detritus [48; 49]. Thus, the metamorphism of the soil material is carried out. Being a bioinert system, the soil adapts to changes in environmental conditions in the system of soil-forming factors, which manifests itself in temporal and spatial heterogenisation, uneven structure in both horizontal and vertical profiles [50]. Since these transformations are ecological in nature, prerequisites are developing for applying an ecomorphic approach to investigating the features of soil structuring.

The obtained data indicate that the grouping of soil macrofauna of public green spaces has the features of amphicoenosis, where the steppe and meadow components are considerably represented against the background of the predominance of the forest component. Tree stands in urban parks form a common forest environment, although they do not form a stable forest monocoenosis. Recreation and other forms of anthropogenic impact do not allow a forest monocenosis or pseudomonocenosis to develop. The trophic aspect can allow deciphering the meaning in the grouping of coenotic components. The trophic structure of silvants repeats the trophic structure of the general grouping. The advantage of silvants in general grouping allows considering them as the functional basis of the complex of soil fauna of public green spaces. Phytophages predominate among steppes, which fully corresponds to the typical trophic structure of steppe zonal groups. This feature, considering the proportional representation of zoophages and saprophages, allows enables the assessment of functional stability of the structure of the group of stepants.

CONCLUSIONS

1. The ecological space of ecosystems in recreational conditions is structured between ecological niches of soil macrofauna. Marginality, tolerance, and residual tolerance quantify the position of ecological niches in the ecological space. Variability of soil properties caused by natural factors or recreation is a driver of structuring the ecological space of soil macrofauna. Soil animals are most sensitive to changes in soil penetration resistance, humidity, and electrical conductivity.

2.There is a correlation between environmental factors in public green spaces, the grouping structure of soil macrofauna, and its ecomorphic organisation. The ecomorphic aspect of the soil macrofauna grouping structure is more sensitive to recreational load than the distribution of ecological niches between species in the ecological space, which suggests that rearrangements of the ecomorphic grouping structure are a condition for the stability of its organisation.

3.The natural variability of soil conditions within the ecosystem manifests itself in changes in the ratio of xerophiles, phytophages, carbonatophiles on the one hand and pratants, paludants and hypercarbonatophiles on the other hand. Zoophages, hemiaerophobes, and megatrophs are tolerant to a high level of recreational load. The area corresponding to the highest level of recreational load is vacant. This indicates that the most transformed areas are randomly populated by representatives of different ecological groups.

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Трансформація екоморфічної структури ґрунтової макрофауни в умовах рекреаційного впливу

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Анотація. Рівень реакраційого навантаження на компоненти міських зелених зон зростає, тому визначення ефективних інструментів управління в цих екосистемах набуває вирішального значення для забезпечення підтримки місць існування популяцій тварин, зокрема ґрунтової біоти. Метою роботи є встановлення закономірності структурування угруповань ґрунтової макрофауни в умовах рекреаційного впливу на основі екоморфічного підходу. У роботі виконано оцінку рівня рекреаційної трансформації ґрунтової макрофауни зелених насаджень загального користування м. Мелітополь на території парку Новоолександрівський. У зоні з високим рівнем рекреаційного навантаження для досліджень було закладено полігон, у межах якого зроблено відбір проб. З метою збору ґрунтової макрофауни та оцінки властивостей ґрунту у кожній точці дослідженого полігону були проведені ґрунтово-зоологічні проби та здійснені вимірювання таких грунтових показників, як: температура, електропровідність, вологість та твердість ґрунту, потужність підстилки та висота травостою. Ординація угруповань проведена за допомогою двох підходів: OMI-та RLQ-аналізів. Виявлено, що екологічні ніші ґрунтової макрофауни в умовах рекреації є просторово структурованими. Основними факторами структурування екологічної ніші ґрунтової макрофауни у межах досліджуваної території є твердість ґрунту в діапазоні усього вимірюваного шару, вологість ґрунту та дистанція до дерев. Основу ценоморфічної структури ґрунтової макрофауни за кількістю видів становлять сильванти (45,5 %) та пратанти (24,2 %). За чисельністю видів основу ценоморфічної структури макрофауни становлять пратанти (64,5 %), трохи менше степантів (19,1 %) та сильвантів (16,1 %) та одинично зустрічаються палюданти (0,2 %). Таку ценоморфічну структуру можна розглядати як екологічно лабільну. До високого рівня рекреаційного навантаження толерантними є зоофаги, геміаерофоби та мегатрофи. Область, яка відповідає найбільшому рівню рекреаційного навантаження, є вакантною. Це вказує на те, що фактично не існує видів ґрунтової макрофауни, які могли б існувати за умов інтенсивного рекреаційного впливу

Ключові слова: екоморфи, ґрунт, екологічна ніша, ґрунтові безхребетні, рекреаційний тиск
