

Collembola communities in soils affected by treated wastewater discharge: A first insight into the fauna of the European North of Russia

Сообщества коллембол (Collembola) в почвах, подверженных воздействию очищенных сточных вод: первое изучение фауны европейского Севера России

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КЛЮЧЕВЫЕ СЛОВА: ногохвостки, почвенная мезофауна, зональные, пойменные, техногенные участки, таежная, тундровая зона, европейский север России.

ABSTRACT. This study investigates the diversity and community structure of collembolans in soils forming under the influence of treated wastewater, and assesses the contribution of such habitats to the overall diversity of the European North of Russia. Faunistic research was conducted in two climatic zones: taiga and tundra. For comparison, floodplain and zonal (undisturbed) habitats were also examined. A total of 153 collembolan species were recorded in the studied ecosystems, with 122 species found in the taiga zone and 96 in the tundra zone. Importantly, certain springtail species were found exclusively at technogenic (wastewater-affected) sites, including species new to the European part of Russia. This indicates the existence of distinct faunal communities associated with the influence of treated wastewater. The analysis revealed impoverished species richness and low levels of α -diversity in floodplain and technogenic sites compared to zonal ecosystems. Population density showed different trends depending on the climatic zone: it decreased significantly at technogenic sites in the tundra, while no significant differences were found in the taiga. The obtained results open new perspectives for further research into the functional role of soil mesofauna in the processes of organic matter transformation and self-purification of anthropogenically disturbed soils. This research is crucial

for developing scientific foundations for remediation and sustainable environmental management.

РЕЗЮМЕ. Настоящее исследование посвящено изучению разнообразия и структуры населения коллембол в почвах, формирующихся в районе влияния очищенных сточных вод и вклада таких местообитаний в общее разнообразие европейского Севера России. Фаунистические исследования проводились в двух климатических зонах: таежной и тундровой. Для сравнения изучены пойменные и зональные местообитания. В рассмотренных экосистемах обнаружено 153 вида коллембол, из них в таежной зоне — 122, в тундровой — 96. Важно отметить, что определенные виды ногохвосток были обнаружены исключительно на техногенных участках, в том числе и новые для европейской части России, что указывает на наличие фаунистически обособленных сообществ, связанных с влиянием очищенных сточных вод. Проведенный анализ свидетельствует об обеднённости видового богатства и низком уровне инвентаризационного разнообразия ногохвосток в пойменных и техногенных участках по сравнению с зональными экосистемами. Численность изменяется в зависимости от климатической зоны: в тундре она снижается на техногенных участках, а в тай-

ге достоверных отличий не выявлено. Полученные результаты открывают дополнительные перспективы для дальнейших исследований функциональной роли почвенной мезофауны в процессах трансформации органического вещества и самоочищения антропогенно нарушенных почв, что имеет ключевое значение для разработки научных основ ремедиации и устойчивого природопользования.

Introduction

Intensive human economic activity is one of the primary drivers of global ecosystem changes, leading to their degradation and the decline of biodiversity [Contos *et al.*, 2021]. A significant environmental issue is the generation and release into the environment of multicomponent wastes, which include treated wastewater. As high-volume by-products of industrial and municipal activities, they constitute a complex mixture of organic and inorganic compounds, the full spectrum of which is often unknown [Selivanovskaya, 2004]. While their use as soil ameliorants or fertilizers is potentially beneficial [Selivanovskaya, 2004; Singh *et al.*, 2023], the presence of toxic components can have ambiguous effects on aquatic and soil communities [Karvelas *et al.*, 2003; Ojedokun, Bello, 2016; Yakamercan *et al.*, 2021].

Effective biological indicators are required to assess the consequences of such anthropogenic impact. Collembolans, or springtails, represent one of the most suitable groups of soil invertebrates for this purpose. They are characterized by high abundance, biomass, and ubiquitous distribution [Potapov *et al.*, 2023], possess a broad range of adaptations to various environmental conditions [Hopkin, 2007], and are highly sensitive to environmental changes, responding with shifts in community structure [Kuznetsova, 2009a; Salmon, Ponge, 2012; Taskaeva *et al.*, 2019; Taskaeva, 2021]. These attributes make them valuable bioindicators of soil condition [Martins da Silva *et al.*, 2016].

Despite this, the influence of treated wastewater on collembolan communities remains poorly understood. The limited available data suggest a negative impact on their diversity and abundance [Pour *et al.*, 2024]. Soils forming in areas of long-term wastewater discharge are of particular interest. They are typically rich in organic matter and can support the emergence of invasive species [Kolesnikova *et al.*, 2019]. Often classified as hydro-extreme soils with a pulsating water regime [Goryachkin *et al.*, 2019], they create specific conditions, potentially serving as extreme habitats for soil fauna. However, information on the fauna, diversity, and community structure of collembolans in such anthropogenic soils in northern Russia is virtually absent.

The aim of the present study was to conduct the first investigation of the fauna, taxonomic diversity, and community structure of collembolans in soils subjected to the impact of treated municipal and industrial wastewater in the taiga and tundra zones of the European North of Russia. We assessed the contribution of these technogenic habitats to the regional diversity of collembolans. In accordance with Thienemann's ecological rule [Thienemann, 1939],

we hypothesized that under conditions deviating from the optimum, caused by wastewater discharge, collembolan communities would be characterized by reduced taxonomic diversity and the dominance of one or two species.

Material and methods

Study sites

The study was conducted in two climatic zones of European North: (1) taiga (60°N, Komi Republic, Russia) with the mean annual air temperature of 0.5 °C and annual precipitation of 620 mm [Lopatin *et al.*, 2006]; (2) tundra (67°N, Komi Republic, Russia) with the mean annual air temperature of –6 °C and annual precipitation of 550 mm [Mazhitova, 2008]. In each climate zone, we selected nine sites, three of which are located in the area of wastewater influence, three in river floodplains and three in zonal ecosystems. A total of 18 sites (Table 1). In the taiga zone, technogenic plots, which are subaqueous formations (sediments), are located in the zone of influence of an artificial gravity canal organized by AO “Syktyvkarskyi LPK” for the discharge of treated wastewater. Due to the warm municipal sewage that is discharged into the stream, in winter it does not freeze. In tundra zone technogenic plots represented by organic remains, created from a mixture of discarded poultry factory food stores, city hospital, and railway depot [Getsen, 2011], are located along Vodny stream. The considered technogenic areas are identical to natural floodplain soils, which are in the mode of constant influence of river waters, which we selected for comparison. Floodplain biotopes in both climatic zones are represented by sedge-forb and cereal-forb meadows. To assess the general diversity of collembola, we considered spruce, pine forests, as well as shrub and dwarf shrub tundra in the corresponding climatic zone as zonal biotopes.

Sampling, extraction and species identification

Sampling was done in July and August in different years 2003–2025. Five soil cores (5 x 5 x 10 cm depth) were collected from each plot using standard method [Potapov *et al.*, 2022]. The soil cores were packed into polythene bags for transport to the laboratory. Extraction of Collembola was performed in the laboratory using Berlese funnels at approximately 25 °C into 96% ethanol for 7–10 days until the soil was completely dry. Collembola were separated from other soil animals and sorted into species under a stereomicroscope (Olympus SZ61-TR) based on morphological characters. All individuals from each sample were inspected using an Olympus CX 43 microscope. Collembola were identified to species using relevant keys [Fjellberg, 1998, 2007; Bretfeld, 1999; Potapov, 2001; Thibaud *et al.*, 2004; Kaprus *et al.*, 2016; Kaprus, Pašnik, 2017; Pašnik, Weiner, 2017; Weiner, Fiera, 2020].

Statistical analysis

Three independent plots were surveyed for each habitat type in each natural zone. Soil samples collected within an individual plot were treated as pseudoreplicates and pooled to form a composite sample, which served as one true replicate for the plot. Thus, each of the 18 investigated plots (3 plots × 3 habitat types × 2 natural zones) provided one independent replicate for subsequent statistical analysis. Soil samples collected within the three plots were considered pseudoreplicates and were therefore pooled to form one true replicate [Kozlov, 2003]. Inventory, or α -diversity, was assessed by calculating species richness (S) and the Shannon index (H'). Species richness was understood as the mean number of species per sample. Differentiating, or β -diversity, was characterized by

Table 1. Description of studied sites.
Таблица 1. Описание исследованных участков

Climatic zone	Site	Coordination	Ecosystem type	Dominant species	Years
Taiga	Z1	N 61.2014 E 50.2090	Pine forest	<i>Pinus sylvestris</i>	2018, 2023–2025
	Z2	N 61.2156 E 50.4727	Spruce forest	<i>Picea obovata</i>	2019, 2023–2025
	Z3		Spruce forest	<i>Picea obovata</i>	2019, 2023–2025
	P1	N 61.1400 E 50.3230	Floodplain meadow	<i>Poa pratensis</i> <i>Equisetum palustre</i> <i>Filipendula ulmaria</i>	2003–2005, 2025
	P2	N 61.4061 E 50.6063	Floodplain meadow	<i>Poa pratensis</i> <i>Achillea millefolium</i> <i>Agrostis gigantea</i>	2003–2005, 2025
	P3	N 61.9230 E 50.2077	Floodplain meadow	<i>Poa pratensis</i> <i>Equisetum palustre</i> <i>Filipendula ulmaria</i>	2003–2005, 2025
	ISK1	N 61.9561 E 50.4815	Technogenic substrate formed by wastewater	<i>Lycopus europaeus</i> <i>Typha latifolia</i> <i>Poa palustris</i> <i>Agrostis capillaris</i>	2018–2020, 2025
	ISK2	N 61.9558 E 50.4813	Technogenic substrate formed by wastewater	<i>Lycopus europaeus</i> <i>Agrostis capillaris</i> <i>Bidens cernua</i>	2018–2020, 2025
	ISK3	N 61.9458 E 50.4835	Technogenic substrate formed by wastewater	<i>Lycopus europaeus</i> <i>Agrostis capillaris</i> <i>Bidens cernua</i>	2018–2020, 2025
Tundra	LDT	N 67.5322 E 64.1239	Large dwarf shrub-moss tundra	<i>Betula nana</i> <i>Salix lanata</i> <i>Salix phylicifolia</i> <i>Salix glauca</i>	2015–2017, 2025
	SDT	N 67.4306 E 63.8394	Small dwarf shrub-moss tundra	<i>Betula nana</i> <i>Salix lanata</i> <i>Salix phylicifolia</i>	2015–2017, 2025
	ST	N 67.4356 E 63.8289	Shrub lichen-moss tundra	<i>Vaccinium uliginosum</i> <i>Arctous alpina</i> <i>Vaccinium vitis-idaea</i>	2015–2017, 2025
	P4	N 67.5350 E 64.0336	Floodplain meadow	<i>Bromopus inermis</i> <i>Veronica longifolia</i> <i>Pachipleurum alpinum</i> <i>Angelica archanlelica</i>	2016–2017, 2025
	P5	N 67.5300 E 64.0336	Floodplain meadow	<i>Alopecurus pratensis</i> <i>Aconitum</i> <i>Chamaenerion angustifolium</i>	2025
	P6	N 67.5294 E 64.0339	Floodplain meadow	<i>Angelica archanlelica</i> <i>Alopecurus pratensis</i>	2025
	SI1	N 67.5086 E 64.0706	Technogenic substrate formed by wastewater	<i>Taraxacum officinale</i> <i>Deschampsia cespitosa</i> <i>Agrostis</i> <i>gigantea</i>	2017–2019, 2025
	SI2	N 67.5100 E 64.0519	Technogenic substrate formed by wastewater	<i>Deschampsia cespitosa</i> <i>Achillea millefolium</i> , <i>Taraxacum officinale</i>	2017–2019, 2025
	SI3	N 67.5089 E 64.0728	Technogenic substrate formed by wastewater	<i>Achillea millefolium</i> , <i>Deschampsia cespitosa</i> <i>Taraxacum officinale</i>	2025

pairwise comparison of soil invertebrate species composition in natural communities, with the results graphically represented as a dendrogram. The Bray-Curtis index for qualitative data was used as a similarity measure. To assess the effect of phytocoenosis type on abundance and taxonomic richness, the nonparametric Kruskal–Wallis test was used, followed by Dunn's test for pairwise group comparisons with Bonferroni correction. Ordination of springtail communities from zonal, floodplain, and technogenic sites located in the taiga and tun-

dra zones was performed using non-metric multidimensional scaling (NMDS) based on the Bray-Curtis index calculated from species relative abundance. The significance of differences in springtail community structure between biogeocoenosis types was tested using permutational multivariate analysis of variance (PERMANOVA; 999 permutations). Dominance classes were defined based on the Engelmann scale [Engelmann, 1978]. Statistical analysis was performed using the PAST and R software.

Results

Fauna

A total of approximately 98,000 individual collembolans, belonging to 153 species, were collected and identified. A total of 122 species (56 genera, 17 families) were recorded in the taiga zone, compared to 96 species (39 genera, 13 families) in the tundra zone. In the study sites of the taiga zone, 122 species belonging to 56 genera and 17 families were recorded, while in the tundra zone, 96 species from 39 genera and 13 families were recorded [Taskaeva, 2025; Taskaeva, Konakova, 2025]. The most species-rich family was traditionally Isotomidae, accounting for 23 to 35% of species in the taiga zone and 22 to 40% in the tundra zone (Table 2). This “isotomoid” faunal type is characteristic of almost all boreal faunas of the Palaearctic [Kaprus, 2010]. This is followed by two families: Onychiuridae (18 species in both climatic zones) and Neanuridae (15 and 13 species, respectively). The five largest families are rounded out by Hypogastruridae (11 and 5 species, respectively) and, surprisingly, Tullbergiidae (9 and 5 species, respectively). The latter achieves its greatest diversity precisely in soils forming in the area influenced by treated wastewater (Table 2). The set of genera represented by the highest number of species is also typical for the Subarctic: *Folsomia*, *Desoria*, *Protaphorura* (Table 2). Exceptions are the genera *Sminthurinus* and *Mesaphorura*, whose diversities in the taiga zone include five and seven species, respectively. In the tundra zone, they are represented by two and

four species. Structural peculiarities also include the low species richness of the genera *Anurida*, *Hypogastrura*, and *Ceratophysella* (1–4 species in each climatic zone), which is difficult to explain.

Five species, recorded exclusively in the area influenced by treated wastewater in the taiga zone, were new to the European North of Russia. *Folsomia candida* — a ruderal species recorded in small numbers on technogenic substrates with elevated soil temperature; *Mackenziella psocoides* and *Thalassaphorura halophila* were found as single specimens; as well as *Megalothorax willemi*, previously recorded in Central Europe, Canada, and South America (gbif.org); and *Protaphorura pannonica* — in Fennoscandia [Fjellberg, 1998].

Diversity and abundance

Collembolan communities in zonal ecosystems of the taiga and tundra zones comprised 35–60 species (109 species in total). Assessing the overall composition and structure of springtail communities in floodplain and technogenic sites reveals their high diversity (86 and 87 species, respectively). This diversity is primarily driven by the high values recorded for these site types within the taiga zone (Table 3). However, the species richness of collembolans was significantly lower in floodplain and technogenic sites across both climatic zones. (Table 3).

Density, in contrast, exhibited different trends depending on the climatic zone. While in the tundra zone, abundance decreased significantly by 2.5–3 times in floodplain

Table 2. The number of species of the richest families and genera of springtails and their ratio (%) in studied sites.
Таблица 2. Число видов, родов коллембол наиболее многочисленных семейств и их доля (%) на исследованных участках.

Family, genus	Zta (n = 135)	Fta (n = 135)	Tta (n = 135)	Ztu (n = 135)	Ftu (n = 44)	Ttu (n = 44)
Isotomidae	18 (23.4)	18 (25.4)	25 (34.7)	29 (40.8)	10 (22.2)	17 (39.5)
<i>Desoria</i>	4 (5.2)	3 (4.2)	7 (9.7)	9 (12.7)	2 (4.4)	4 (9.3)
<i>Folsomia</i>	6 (7.8)	6 (8.5)	7 (9.7)	9 (12.7)	5 (11.1)	6 (14.0)
Onychiuridae	12 (15.6)	9 (12.7)	8 (11.1)	10 (14.1)	12 (26.7)	8 (18.6)
<i>Protaphorura</i>	6 (7.8)	5 (7.0)	5 (6.9)	6 (8.5)	9 (20.0)	6 (14.0)
Neanuridae	10 (13.0)	10 (14.1)	5 (6.9)	10 (14.1)	8 (17.8)	4 (9.3)
Hypogastruridae	7 (9.1)	8 (11.3)	4 (5.6)	5 (7.0)	1 (2.2)	2 (4.7)
Tullbergiidae	5 (6.5)	3 (4.2)	6 (8.3)	1 (1.4)	3 (6.7)	4 (9.3)
Katiannidae	5 (6.5)	3 (4.2)	2 (2.8)	1 (1.4)	1 (2.2)	2 (4.7)
Остальные	25 (26.0)	23 (28.2)	28 (30.6)	16 (21.1)	13 (22.2)	10 (14.0)

Notes: n means the number of samples. Numbers show the number of species and their relative abundance (in % in brackets). Ecosystems: Z — zonal, F — floodplain, T — technogenic. Climatic zones: ta — taiga, tu — tundra.

Table 3. Species richness, diversity index and density of Collembola in studied sites.
Таблица 3. Видовое богатство, индекс разнообразия и численность коллембол на исследованных участках.

Parameters	Taiga zone			Tundra zone			F
	Zonal	Floodplain	Technogenic	Zonal	Floodplain	Technogenic	
Total species number	77 (42-60)	71 (36-53)	72 (44-56)	71 (35-53)	45 (12-43)	44 (15-36)	
Species richness, S	11.1 ± 0.4 ^a	8.5 ± 0.3 ^b	8.3 ± 0.3 ^b	12.0 ± 0.3 ^a	7.6 ± 0.4 ^b	6.6 ± 0.5 ^b	28.43***
Shannon diversity, H	1.63 ± 0.03 ^a	1.37 ± 0.04 ^b	1.21 ± 0.04 ^b	1.75 ± 0.02 ^a	1.47 ± 0.06 ^b	1.25 ± 0.08 ^b	33.34***
Density, thous. ind./m ²	45.7 ± 3.0 ^a	51.6 ± 4.7 ^a	80.0 ± 12.6 ^a	87.7 ± 6.3 ^b	28.1 ± 4.6 ^c	33.3 ± 4.7 ^a	10.50***

Notes: different letters indicate significance differences between researched sites based on the Tukey HSD test (p-level of significance: *** = < 0.001). The minimum and maximum values of species number per site are given in brackets.

and technogenic sites, no statistically significant differences were found in the taiga zone. Nevertheless, an increase in density was noted from zonal ecosystems to technogenic ones (Table 3).

The cluster analysis of community similarity revealed a clear spatial and disturbance-related pattern (Fig. 1). The most isolated position was occupied by the technogenic sites of the tundra zone (Ttu), forming a distinct cluster at the lowest similarity level. In contrast, all three habitat types from the taiga zone were grouped into a single, unified cluster. Similarly, the natural habitats of the tundra zone formed another distinct cluster. This structure indicates that for collembolan communities, the macroclimatic factor is primary, overriding the influence of local habitat type within the taiga. However, in the more extreme tundra environment, anthropogenic disturbance creates a unique and strongly divergent faunal assemblage.

Structure

The composition of mass species and their relative abundance is presented in Table 4. The set of dominant species in the surveyed springtail communities is quite broad. The widely distributed species *Folsomia quadrioculata* is almost ubiquitous and predominant, though it occurs in low densities at technogenic sites. A typical dominant in forest biocoenoses is *Isotomiella minor*, while in tundra biocoenoses it is *Tetracanthella wahlgreni*, as previously noted in the literature [Kuznetsova, 2005; Taskaeva *et al.*, 2019]. In floodplain sites of the tundra zone, *Desoria violacea* and *Parisotoma notabilis* reach high abundance levels. High relative abundance at technogenic sites in the taiga zone is exhibited by *Xenyllodes armatus* and *P. notabilis*, and in the tundra zone by *Sphaeridia pumilis* and *Ceratophysella denticulata*.

The analysis based on multidimensional scaling revealed the distinctiveness of the collembolan communities in the studied ecosystems (Fig. 2), which is confirmed by PERMANOVA results ($F = 32.33$; $p < 0.001$). Thus, collembolan communities in zonal and floodplain ecosystems differ more in the abundance of species common to the area rather than in the presence of specific forms. However, at technogenic sites, species characteristic of early successional stages appear — *Proisotoma minuta*, *Folsomia fimetaria*, and a number of others — and even the invasive species *Desoria trispinata*. Fifteen species not found in zonal or floodplain biotopes were recorded exclusively at these sites (Table 5).

Discussion

The conducted research has for the first time enabled the characterization of the collembolan fauna in technogenic sites forming under the influence of treated wastewater in the taiga and tundra zones of the European North of Russia. The overall taxonomic list, comprising 153 species, confirms the high biological diversity of the region and corresponds to the general “isotomoid” type of boreal and hypoarctic Palaearctic faunas, dominated by the family Isotomidae with the leading roles of the genera *Folsomia*, *Desoria*, and *Protaphorura* [Kuznetsova, 2005; Kaprus,

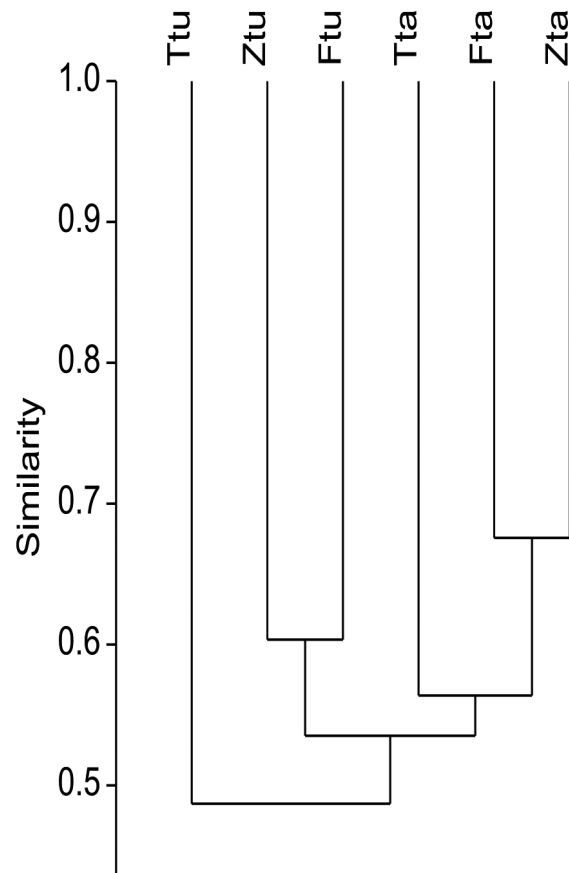


Fig. 1. Similarities of the faunas of collembolans in zonal, floodplain and technogenic sites. Designations of the sites and climatic zones are given in Table 2.

Рис. 1. Сходство фауны коллембол зональных, пойменных и техногенных участков. Обозначения участков и климатических зон приведены в таблице 2.

2010; Babenko *et al.*, 2017]. The highest springtail diversity recorded in the taiga (122 species) compared to the tundra (96 species) within this study does not align with their global distribution pattern [Potapov *et al.*, 2023] or known regional species lists (e.g., 229 species for tundra and 175 for taiga) [Kuznetsova, 2005; Babenko *et al.*, 2017; Taskaeva, 2024]. This discrepancy is likely explained by the historically more comprehensive inventory of diverse tundra biotopes, including specific coastal, ornithogenic substrates, etc.

An interesting result of the study is the establishment of the uniqueness of the collembolan fauna at technogenic sites. Twenty-two species (14.4% of the total list) were found exclusively in soils influenced by treated wastewater. Notably, most of these are not typical synanthropic species or indicators of heavy pollution. Their presence, including five species new to the European North-East of Russia (*Folsomia candida*, *Mackenziella psocoides*, *Thalassaphorura halophila*, *Megalothorax willemi*, *Protaphorura pannonica*), indicates the formation of specific edaphic

Table 4. Abundance (%) of mass species of Collembola in studied sites.
Таблица 4. Относительное обилие (%) массовых видов коллембол на исследованных участках.

Species	Zta	Fta	Tta	Ztu	Ftu	Ttu
<i>Ceratophysella denticulata</i>	+	5.1	+	+	–	16.9
<i>Desoria hiemalis</i>	6.4	+	+	+	–	–
<i>Desoria neglecta</i>	–	–	+	+	–	7.5
<i>Desoria violacea</i>	+	+	+	+	13.6	+
<i>Folsomia fimetarioides</i>	–	6.2	+	–	–	–
<i>Folsomia quadrioculata</i>	13.4	47.7	3.9	22.5	22.5	+
<i>Isotomiella minor</i>	36.3	7.7	+	4.7	7.0	4.0
<i>Mesaphorura krausbaueri</i>	+	–	6.1	–	+	+
<i>Mesaphorura macrochaeta</i>	+	+	5.4	+	4.1	+
<i>Pachytoma miserabilis</i>	–	–	–	5.4	–	–
<i>Parisotoma notabilis</i>	10.1	+	16.1	4.9	13.6	8.6
<i>Protaphorura bicampata</i>	+	+	+	+	4.6	+
<i>Protaphorura boedvarssoni</i>	+	5.7	+	+	8.2	+
<i>Protaphorura subarctica</i>	+	+	–	7.5	+	–
<i>Schoettella ununguiculata</i>	–	7.3	–	–	–	–
<i>Sminthurinus aureus</i>	+	+	+	+	7.9	6.4
<i>Sphaeridia pumilis</i>	+	+	+	+	4.0	32.4
<i>Tetracanthella wahlgreni</i>	–	–	–	14.9	–	+
<i>Willemia anophthalma</i>	+	+	+	6.6	–	+
<i>Xenyllodes armatus</i>	+	+	27.9	+	–	–

Notes: «+» means, that species is present, but does not reach the level of subdominant (3.9 %),

«–» means, that species is absent; dominants are highlighted in gray. Ecosystem and climate zone designations are shown in Table 2.

and microclimatic conditions (e.g., altered moisture and temperature regimes, chemical composition). These sites may act as refugia or dispersal channels, highlighting the significance of anthropogenic ecosystems for maintaining regional diversity. The particularly notable increase in the role of the family Tullbergiidae specifically at technogenic sites may indicate its tolerance to conditions created by wastewater discharge. Of special interest is the finding of *Folsomia candida* — a cosmopolitan ruderal species often used in laboratory tests but rarely encountered in natural communities in the north [Fountain, Hopkin, 2005]. Its presence, along with other species (*Folsomia fimetaria*, *Proisotoma minuta*), signals the anthropogenic transformation of the soil environment. Similar results regarding faunal specificity under the influence of treated wastewater have been obtained for zooplankton and zoobenthos [Baturina *et al.*, 2021; Kononova, 2021]. Furthermore, new species of copepods for the European North have been discovered in such aquatic ecosystems [Fefilova *et al.*]. The number of hygrophilic species confined to floodplains is even lower. Most likely, these ecosystems are inhabited by species relatively tolerant and ecologically plastic to riparian conditions. In such biotopes, species with different ecological strategies withstand unfavorable hydrological conditions due to the high spatial heterogeneity of floodplains, which ensures the long-term stability of the communities as a whole [Kuznetsova, 2009b; Taskaeva *et al.*, 2021]. Zonal ecosystems exhibit the greatest degree of specificity, with 28 species found that were not recorded in other biocoenoses. On one hand, this is explained by their better study and the presence of hypoarctic species in the tundra, and on the other, it confirms their high natural specificity and vulnerability.

Despite the overall high diversity of collembolans in floodplain and technogenic habitats (86 and 87 species, respectively), the statistically significant reduction in species richness at these sites reflects their stressful nature, where specific conditions (flooding, temperature, soil physico-chemical parameters) act as ecological filters [Kuznetsova, 2009b; Taskaeva, 2009, 2021]. At the same time, the response of collembolan communities to disturbance shows pronounced zonal specificity: in the tundra, a sharp decrease in abundance (by 2.5–3 times) is observed, indicating the high vulnerability of hypoarctic communities, which is confirmed by literature data [Coulson *et al.*, 2015; Taskaeva *et al.*, 2019], whereas in the taiga, a trend towards its increase is noted, pointing to their greater plasticity and the possibility of compensatory restructuring.

Cluster and ordination analyses statistically confirmed a profound qualitative difference between technogenic and natural ecosystems (Figs 1, 2). Technogenic sites formed a distinct cluster, inhabited by disturbance indicator species (*F. candida*, *F. fimetaria*, *Proisotoma* spp.) and successional forms characteristic of early soil recovery stages [Fountain, Hopkin, 2005], including the invasive species *Desoria trispinata* [Potapov, 2001]. At the same time, zonal and floodplain habitats grouped into one cluster with subsequent separation according to the climatic principle, demonstrating the priority of natural zonality in structuring natural communities and the preservation of a common structural core of collembolans in floodplains, despite periodic hydrological stress [Kuznetsova, 2005; Taskaeva, 2009; Taskaeva *et al.*, 2019]. This is also supported by the data obtained on the dominance structure.

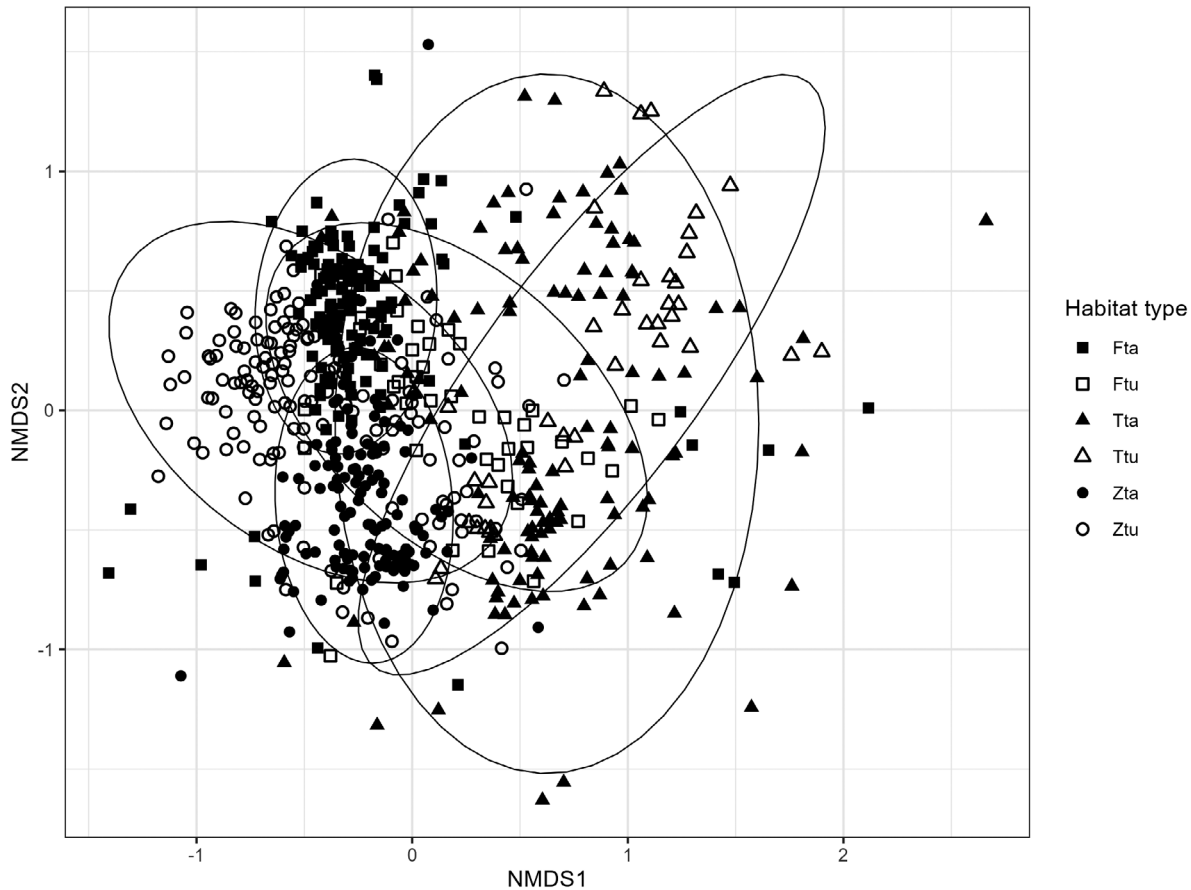


Fig. 2. Ordination (NMDS) of collembola communities of zonal, floodplain and technogenic sites based on the relative abundance of species. Designations of the sites and climatic zones are given in Table 2.

Рис. 2. Ординация (NMDS) сообществ коллембол зональных, пойменных и техногенных участков на основе относительной численности видов. Обозначения участков и климатических зон приведены в таблице 2.

Conclusions

The conducted study has for the first time provided a comprehensive characterization of the fauna and community structure of collembolans in soils forming under the influence of treated wastewater in the European North of Russia. It has demonstrated that technogenic sites represent a distinct type of anthropogenic ecosystem with a springtail species composition qualitatively different from that of natural analogues. This uniqueness is confirmed by the formation of a specific species core, which includes disturbance indicator species and taxa new to the region.

Anthropogenic disturbance leads to a profound transformation of the communities, expressed in reduced α -diversity and altered dominance structure, while simultaneously playing a potentially significant role in maintaining regional γ -diversity. At the same time, the response of collembolan communities to anthropogenic impact is mediated by the initial resilience of the regional fauna, manifesting as a pronounced depression in vulnerable tundra

ecosystems and a complex restructuring with elements of enrichment in taiga landscapes.

The obtained results will facilitate an assessment of the level of soil degradation and provide a foundation for further research into the functional role of soil mesofauna in the processes of organic matter transformation and self-purification of anthropogenically disturbed soils. This is crucial for developing the scientific basis for remediation and sustainable environmental management.

Compliance with ethical standards

CONFLICT OF INTEREST: The authors declare that they have no conflict of interest.

Ethical approval: No ethical issues were raised during our research.

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Table 5. Collembola species found exclusively in technogenic habitats during the study.
Таблица 5. Виды коллембол, обнаруженные исключительно в техногенных местообитаниях в районе исследования.

Species	Occurrence (tundra/taiga technogenic sites)	Known ecological traits and distribution [Fjellberg, 1998, 2007; Bretfeld, 1999; Potapov, 2001; Thibaud <i>et al.</i> , 2004; Schneider, D'Haese, 2013]
<i>Desoria fennica</i> (Reuter, 1895)	Taiga only	A rare species, but probably with wide distribution. Usually found in damp habitats in forests or meadows. Previously it was found in East-European tundra [Babenko <i>et al.</i> , 2017; Melekhina, Taskaeva, 2021]
<i>Desoria trispinata</i> (MacGillivray, 1896)	both	Cosmopolitan, in compost and organic debris, probably introduced. It is noticed for the first time for European North of Russia
<i>Deuterostomothus bicinctus</i> (Koch, 1840)	Taiga only	Palaeartic, in the low vegetation of deciduous forests and bushes, in sand from groundwater samples. Previously it was registered in East-European tundra [Babenko <i>et al.</i> , 2017; Melekhina, Taskaeva, 2021]
<i>Folsomia candida</i>	Taiga only	Cosmopolitan, in thick organic litter, in compost. It is a laboratory test object. It is noticed for the first time for European North of Russia
<i>Folsomia fimetaria</i> (Linnaeus, 1758)	both	Holarctic, nitrophilous and ruderal species. On the territory of European North of Russia it is found only in technogenic sites with high content of N [Kolesnikova <i>et al.</i> , 2019]
<i>Makkenziella psocoides</i> Hammer, 1953	Taiga only	Holarctic or wider. It is registered for the first time for European North of Russia
<i>Megalothorax willemi</i> Schneider et D'Haese, 2013	Taiga only	Distribution unknown, in different habitats like forest litter, moss, caves. It is found for the first time for European North of Russia
<i>Mesaphorura critica</i> Ellis, 1976	Taiga only	Palaeartic, mostly in dry lowland meadows. It is found for the first time for European North of Russia
<i>Mesaphorura jirii</i> Rusek, 1982	Taiga only	Palaeartic, forest litter, meadows, arctic tundra. Previously it was registered in East-European tundra [Babenko <i>et al.</i> , 2017]
<i>Mesaphorura pongeii</i> Rusek, 1982	Taiga only	Palaeartic, sand dunes and sea front meadows. Previously it was noticed in meadow near the Sula river [Taskaeva, 2022]
<i>Proisotoma minuta</i> (Tullberg, 1871)	both	Cosmopolitan, in compost heaps, manure, dump grounds, in decaying sewage sludge. Previously it was registered in technogenic sites of Usinsk and Vorkuta [Kolesnikova <i>et al.</i> , 2019; Melekhina, Taskaeva, 2021]
<i>Protaphorura pannonica</i> (Haybach, 1960)	Taiga only	Palaeartic, in coastal sand dunes and beach meadows, also in moist humus-rich habitats. It is found for the first time for European North of Russia
<i>Sminthurus viridis</i> (Linnaeus, 1758)	Taiga only	Cosmopolitan, usually in grassy meadow habitats. Previously it was noticed in Komi Republic (unpublished data)
<i>Thalassaphorura halophila</i> (Bagnall, 1935)	Taiga only	Palaeartic, only one individual was found.
<i>Xenylla humicola</i> (Fabricius, 1780)	Taiga only	Cosmopolitan, in humid sands of the littoral intertidal zone, beaches with organic remnants and algae. Previously it was registered in East-European tundra [Babenko <i>et al.</i> , 2017]

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