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SOIL INVERTEBRATES IN SEMI-COKE HEAPS OF ESTONIAN OIL SHALE INDUSTRY

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Abstract. *Semi-coke is classified as an environmentally harmful residue of oil shale industry due to its toxic components: several organic and inorganic compounds – oil products, asphaltenes, phenols, PAHs, sulphuric compounds. The aim of the present work was to compare the abundances and species compositions of soil invertebrate assemblages (Collembola, Lumbricidae, Araneae, Myriapoda, Coleoptera) in the artificial substrate from vegetated and bare residue sites of semi-coke heaps of Estonian oil shale industry. Invertebrate communities in semi-coke heaps were studied at three heights of each heap slope; all sampling points in the heaps were divided into four groups based on plant cover. The authors concluded that the communities of micro- and macroarthropods and earthworms in oil-shale processing waste heaps were formed under certain conditions – a high pH and extremely low moisture. The presence of several invertebrate groups (springtails, earthworms, epigeic predators, etc.) and soil communities can be used for monitoring the success in restoration.*

Keywords: *semi-coke, oil shale industry waste, revegetation, springtails, earthworms, spiders, myriapoda, beetles.*

1. Introduction

The history of Estonian oil shale industry, an important branch of the country's economy, runs back to 1918. 15.86 million tons of oil shale had been mined by 2012 [1]. The peak of mining, 31.3 million tons, was in 1980. At present oil shale is used for electricity generation in power plants, shale oil production and in small amounts also for cement production. Since the 1960s, Estonia has been the major oil shale producer and consumer in the

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world. Up to 1960, the main oil shale users were Kohtla-Järve and Kiviõli shale oil plants, and the railway. Fine oil shale was employed as a fuel at local power stations. Later large oil shale-fuelled power stations were launched in Narva – the Balti Thermal Power Station in 1966 and the Eesti Thermal Power Station in 1973. This altered the structure of oil shale consumption: about 80% of mined oil shale was used for producing energy. Now the situation is changing again and shale oil is assuming an ever-increasing importance, having good prospects especially in the fuel and chemical products markets [2].

The total oil resource in the Estonian deposit amounts to 985.7 million tons [3]. Presently shale oil is mainly used for producing fuel oil, and small amounts go to the production of calcined petroleum coke and road asphalt. Also phenols, resins, glues, impregnators, tanning agents, mastic, and other products are produced. The composition of crude shale oil is distinguished by a high content of oxygen compounds in addition to aliphatic and aromatic hydrocarbons. Unfortunately, large amounts of organic matter get lost with harmful semi-coke which is generated by oil shale combustion and piled (Fig. 1).

Oil shale semi-coke is classified in Estonian and European Union waste lists as hazardous waste since it contains toxic tarry and bituminous substances. Its chemical composition strongly resembles that of raw oil shale. Semi-coke contains high amounts (mg/kg) of Ca (about 250,000), Mg (9800–12,000), Fe (25,000–27,000), Al (12,000–16,000), K (7300–8800)

Fig. 1. Kohtla-Järve semi-coke hills containing 53,639,000 tons of hazardous waste on the territory of 0.93 sq km. Photo by A. Käärd.

and Na (990–1100), and in lower amounts Mn (190–230), Pb (39–45), As (about 10), Ba (44–54), Cr (16–18), Cu (7–10), Zn (12–13), Ni (16–17), Mo (3.9–45), Se (up to 9) and other elements [4].

The artificial landforms have a shape of eccentric cones, are dark grey or black in colour and of specific smell [5]. When deposited, the "fresh" semi-coke is highly toxic, but the toxicity decreases over time. Liquid wastes (leachates) from the depository area are characterized by a high concentration of oil products, phenols, cresols, dimethylphenols and resorcinols [6]. The liquid pollution from the semi-coke dump area has deteriorated the surface water as well as underlying aquifers during a long period. At present, the semi-coke heaps are partly covered with vegetation.

Up to now the research on Estonian industrial habitats has focused mainly on plant succession. The knowledge of invertebrates in the soil of industrially contaminated areas is important for improving the application of recultivation technologies on the reclaimed land, as well as for bioindication. The soils of mined areas and waste spoils have been studied quite well, but no data have yet been published on the invertebrate fauna of oil-shale thermal processing waste heaps. The vegetation of mine waste heaps can fulfil the objectives of their stabilization, pollution control, and visual improvement [7]. The formation of soil with its typical biota is crucial for the restoration of former mining areas and remediation of waste heaps, nevertheless, little attention has been paid to the processes of belowground development. The knowledge of invertebrate recolonization in wastes and post-mining lands is considered essential to meet the objectives of establishing self-sustaining ecosystems [8].

A number of studies have dealt with the rehabilitation of mine sites on the basis of single invertebrate groups, for example ants [9, 10] and beetles [11]. Belowground diversity is essential for the aboveground ecosystem functioning. Soil invertebrates are responsible for a number of tasks such as facilitating aeration, draining the soil, decomposing litter, pollinating, and dispersing seed as well as providing food for vertebrate predators; some authors have published data on invertebrates in industrial spoils [12]. Soil fauna, an important part of soil environments, is involved in organic matter decomposition, partial regulation of microbial activities, nutrient cyclization and crumbly soil structure formation.

Depending on diet (saprophagous, phytophagous or predative), soil invertebrates are closely linked to each other as well as to microorganisms, plants and soil. Disturbances caused by pollutants in the soil result in both qualitative and quantitative changes in fauna, which affect soil functioning. Some of the soil fauna groups can act as bioindicators [13–15]. Soil organisms are of crucial importance in primary succession, the unassisted processes of natural decolonisation deliver functional, fully developed ecosystems in spoil heaps [16]. However, no information is available on the invertebrate primary succession in the wastes of oil shale industry including alkaline semi-coke residues or in the residues mix of limestone and oil shale.

The aim of the present study was to compare the abundances and species compositions of invertebrate assemblages (*Collembola, Lumbricidae, Araneae, Myriapoda, Coleoptera*) in the artificial substrate from vegetated and bare residue sites of waste heaps. We hypothesized that fresh semi-coke is toxic for most soil organisms and only invertebrate species tolerant to extreme soil conditions are able to disperse in the older parts of heaps having a decreased toxicity.

2. Material and methods

2.1. Study area

The authors investigated two types of waste heaps in the Estonian oil shale basin: Kiviõli new, Kiviõli old and Kohtla-Järve semi-coke hills, and Kukruse hill made up of limestone shivers and oil shale pebbles (Table 1). Soil microbial community, meso- and macrofauna were sampled in two heaps that have been closed by now (columns 2 and 3, Table 1), and in one older heap, which was closed in the middle of the 1970s (column 4, Table 1). To compare the habitats in semi-coke heaps with those in the other types of oil shale industry waste, one sampling area was located in the residues dump consisting mainly of limestone material with residual oil shale. The share of oil shale and semi-coke in the older dumps was higher, and some of those dumps have ignited spontaneously. We sampled soil, epigeic invertebrates, microarthropods and earthworms in the heap (column 5, Table 1), which was closed for waste disposal in 1967. The heap was overgrown with dense grass and trees. Since closure there has occurred spontaneous ignition of substrate in the heap, recurring from time to time even today.

Invertebrate communities in semi-coke heaps were studied at three heights of each heap slope: at a relative height of approx 60 m (ca 30 m in Kukruse hill), at the foot of the hill and in-between, the same design was used in case of the residues mix heap. The determination of an exact age of

Table 1. Characteristics and substrate parameters of studied waste heaps

Parameter \ Heap number and name	1 Kiviõli new	2 Kohtla-Järve	3 Kiviõli old	4 Kukruse
Substrate	Semi-coke	Semi-coke	Semi-coke	Residues mix of limestone and oil shale
Location	59°21’39’’ 26°55’44’’	59°23’16’’ 27°13’33’’	59°21’51’’ 26°57’15’’	59°23’38’’ 27°20’26’’
Years of deposition	1951–1990s	1930s–2009	1927–1975	1916–1967
Relative height of hill, m [5]	116	110	96	43
Substrate dry matter, %	93.0 ± 3.9	79.5 ± 0.8	94.9 ± 3.6	97.7 ± 0.2
Substrate pH	8.0 ± 0.1	7.9 ± 0.1	7.9 ± 0.2	7.6 ± 0.1
Substrate organic matter, %	7.6 ± 0.9	9.6 ± 0.8	6.8 ± 1.2	4.7 ± 0.6
Substrate total N, %	0.15 ± 0.07	0.10 ± 0.03	0.19 ± 0.05	0.17 ± 0.00

waste layer in each sampling point was impossible, therefore all sampling points in the semi-coke heap were divided into four groups based on plant cover: I – patchily vegetated semi-coke heap surface; II – patchily vegetated semi-coke heap surface with sparse bushes; III – dense sward; IV – older waste heap with dense turf. Soil and microbial community as well as springtails and earthworms characteristics were studied in June 2010, epigeic invertebrates in June and July 2010. The two sampling periods differed in weather conditions. In June, the mean air temperature was 13.9 °C and precipitation 79.9 mm, in July, the respective values were 22.3 °C and 6.0 mm.

2.2. Methods

For the characterization of habitats for the same period the soil and epigeic invertebrates were sampled, the following soil characteristics were measured: pH (5 study points per height, Multi 340i WTW, Germany), total nitrogen content by Kjeldahl, organic content (composite sample, muffle furnace at 360 °C) and volumetric water content (10 study points per height, Fieldscout TDR300, Spectrum Technologies Inc.).

Soil microbial respiration rates (basal respiration) were measured using manometric respirometers (Oxitop®, WTW), which allow determination of sample oxygen consumption. 100 g of soil was incubated in a closed vessel at 25 °C in darkness in a thermostated incubator for 4 days. The principle of operation was based on the measurement of pressure difference in the closed vessel system. During respiration, the CO_2 produced was bound to an absorber (soda lime pellets), and microbial oxygen consumption resulted in the pressure drop. The quantity of oxygen consumption per gram of dry soil was calculated based on the recommended procedure [17]. Substrate Induced Respiration (SIR) was also determined with the help of the Oxitop® manometric system. 50 grams of field moist soil was amended with glycose (0.5 g per 100 g soil) and incubated in a closed vessel at 22 °C in the dark for 24 hours. After the incubation the microbial biomass C was calculated.

Springtails and mites were collected with a soil corer (Ø 5 cm) from the upper soil layer (0–10 cm), six samples from each sampling point. The individuals were extracted from soil by Tullgren's funnel system [18]. All extracted individuals were counted and springtails were identified on species level. The abundance was calculated on 1 m^2 of soil surface.

Earthworms were collected in three 50 × 50 cm soil plots using a 15% mustard powder solution [19] as the handsorting method was too complicated because of the inappropriate substrate texture. The earthworms were identified on species level and the composition of the community was calculated by ecological group (epigeic, endogeic and anecic [20]).

Epigeic invertebrate fauna was sampled using pitfall traps (a plastic cup with a diameter of 7 cm and height of 12 cm), one third filled with 20% NaCl solution, and placed in the soil for 7 days. In all sampling points, 10 traps were placed in one row at a distance of 3 m from each other. All individuals in traps were counted and identified on species (spiders, beetles, myriapods), or family (all other groups) level [21–23]. The predators/ herbivores ratio of carabid species was calculated using the characterisation of species by [24].

Data analysis was performed using Microsoft Excel (mean values and standard deviation) and STATISTICA 8.0 (nonparametric methods: Spearman's correlation, Kruskall-Wallis one-way analysis of variance and the Mann-Whitney U-test). Canonical Correspondence Analysis (CCA) was used to analyse the data on invertebrate communities with regard to environmental variables by using the CANOCO 4.52 programme [25]; the forward selection method with the Monte Carlo test (999 permutations) available in the CANOCO software was used.

3. Results

The main characteristics of the studied waste heaps and the substrate are presented in Table 1. The moisture of substrate was similar (2.3–7%) in all heaps except heap 2 (20.5%). Substrate pH was 7.9–8 in the semi-coke heaps and lower (7.6) in the residues mix heap. Substrate organic content was higher in the younger heap 2. Total N% did not differ in different heaps. The basal respiration of microbial community in the semi-coke heap varied but did not differ between heaps statistically; basal respiration in the residues mix heap was similar. Microbial biomass was the highest in the residues mix heap and somewhat lower in the semi-coke heap.

Analysis showed that there were no statistical differences in the mean values of substrate parameters, such as moisture, organic content and pH, between habitats I–IV (Table 2). The content of total nitrogen was lower in habitat I, the difference was not statistically significant. The basal respiration of microbial community was lower in habitats I and IV and higher in habitats II and III ($P < 0.05$). Microbial biomass was slightly higher in habitat III.

The values of parameters did not correlate between the habitats except the substrate moisture content correlated positively with organic content ($R = 0.678$, $P < 0.05$). The parameters of microbial community also did not correlate between the habitats except the total nitrogen content in substrate correlated with microbial biomass ($R = 0.866$, $p < 0.05$).

The abundance of soil mesofauna – springtails and mites, and the number of springtail species were the highest in semi-coke sampling areas where there was a dense plant cover (Table 2). The mesofauna abundance was also high in the mixed residues heap. Altogether 27 species of springtails were found but of all specimens, only ten species accounted for more than 1%. 56% of all specimens in traps consisted of *Parisotoma notabilis* (Schäffer 1896), 13.6% of *Folsomia candida* Willem 1902, and 8.2% of species *Willemia anophthalma* Börner 1901. Of all invertebrate communities specimens of *Neelus murinus* Folsom 1896 accounted for 5.5%, *Protaphorura armata* (Tullberg 1869) 4.2%, *Folsomia quadrioculata* (Tullberg 1871)

Table 2. Substrate characteristics and invertebrates abundances of habitats in the heaps of semi-coke and residues mix

Parameter or taxon	Semi-coke, habitat I	Semi-coke, habitat II	Semi-coke, habitat III	Semi-coke, habitat IV	Residues mix
Moisture, %	33.35 ± 5.55	29.6 ± 1	37.5 ± 8.4	18.1 ± 1.8	2.3 ± 0.2
pH	7.7 ± 0.4	8.1 ± 0.1	8 ± 0.2	8 ± 0.2	7.6 ± 0.1
Organic matter, %	8.9 ± 0.4	8.7 ± 2.5	8.4 ± 0.9	6.9 ± 1.2	4.7 ± 0.6
Total nitrogen, %	0.07 ± 0.01	0.12 ± 0.04	0.19 ± 0.09	0.19 ± 0.05	0.17 ± 0.01
Basal respiration, mg O_2/kg DM*h	1.968 ± 0.358	4.263 ± 2.553	4.604 ± 0.124	3.176 ± 0.713	2.942 ± 0.471
SIR, mg biomass C/g DM	0.264 ± 0.135	0.482 ± 0.097	0.693 ± 0.228	0.51 ± 0.141	0.740 ± 0.070
Epigeic fauna, ind per trap:					
Aranei,	4.9 ± 1	3.4 ± 1.3	5 ± 0.9	7.1 ± 1.9	4.6 ± 0.2
incl Gnaphosidae	0	0.1 ± 0.01	0.9 ± 0.2	0.1 ± 0.03	0.3 ± 0.1
incl Linyphiidae	0.1 ± 0.01	0.4 ± 0.15	0.4 ± 0.2	1.3 ± 0.1	1 ± 0.8
incl Lycosidae	4.4 ± 0.7	2.7 ± 0.9	3.3 ± 0.8	6.9 ± 1.1	2.5 ± 0.6
Opiliones	0.8 ± 0.5	1.8 ± 1.8	0.6 ± 0.4	3 ± 1.1	5.6 ± 1.1
Coleoptera,	6.5 ± 0.7	5.5 ± 0.9	28 ± 22	26.9 ± 5	17.4 ± 6
incl Carabidae	2.6 ± 0.9	2.3 ± 0.8	1.6 ± 0.8	6.4 ± 1	5.1 ± 2
incl Staphylinidae	0.7 ± 0.1	1.3 ± 0.1	12.8 ± 11	8.7 ± 1.9	8 ± 6
Formicidae	86.9 ± 2	25.5 ± 22.3	135 ± 82	35.3 ± 13.4	618 ± 223
Diptera	1.6 ± 0.4	0.7 ± 0.1	2.2 ± 0.4	6 ± 2.2	11.6 ± 7
Chilopoda	0.6 ± 0.2	0.2 ± 0.1	0.1 ± 0.01	0.2 ± 0.1	0.4 ± 0.2
Diplopoda	0.1 ± 0.01	0.1 ± 0.01	4.3 ± 2	0.7 ± 0.3	1.7 ± 0.9
Isopoda	4.3 ± 3.3	0.4 ± 0.01	10 ± 9	2.4 ± 0.1	23.7 ± 15
Soil fauna:					
Lumbricidae, ind m^{-2}	2.5 ± 2	73.7 ± 11.6	46 ± 5.5	21 ± 10	63 ± 18
incl epigeic, %	67 ± 60	28 ± 6	40 ± 4.5	65 ± 3.5	23 ± 9
incl endogeic, %	0	70 ± 8	37 ± 19	35 ± 3.4	67 ± 8
incl anecic, %	33 ± 31	2 ± 0.2	23 ± 3.5	0	10 ± 4.4
Collembola, 1000 ind m^{-2}	4.18 ± 0.7	2.91 ± 1.67	16.52 ± 9.11	27.17 ± 9.75	20.93 ± 5.45
Acari, 1000 ind m^{-2}	8.43 ± 3.23	6.48 ± 0.08	11.87 ± 2.0	7.25 ± 0,80	10.69 ± 0.60

2.7%, *Desoria violacea* (Tullberg 1876) 2.4%, *Metaphorura affinis* (Börner 1903) 1.5%, *Stenaphorurella denisi* (Bagnall 1935) 1.2% and *Willowsia buski* (Lubbock 1870) 1.1%. The specimens of all other 17 species made up less than 1% of the total amount of springtails. The abundance of springtails was related with total nitrogen content in the substrate, all other factors were not related with parameters of springtails communities. The abundance of dominant species *Parisotoma notabilis* and also numerous *Neelus murinus* were positively related ($R = 0.594$ and 0.746, respectively; $p < 0.05$) to microbial biomass (by SIR). In habitats I and II (sparse plant cover) the abundance of springtails was low.

Altogether ten species of earthworms were collected in the studied semi-coke heaps. Eight species were found in the mining waste dump where the abundance of the community was the highest. The abundance and diversity of the community were the lowest in the old semi-coke heap. Two semi-coke heaps investigated (heaps 1 and 2, Table 1), which were in use yet recently, differed in soil moisture, microbial parameters and abundance of earthworm community, but the communities in the two heaps were similar in ecological structure. The community abundance and diversity increased from the highest to lowest sampling areas depending on waste layer age and development of vegetation. The most abundant species *Aporrectodea caliginosa* (Savigny 1826) formed one third to half of the community in recently used semi-coke heaps, less than one third in the old semi-coke heap and was missing in the waste dump. *A. rosea* (Savigny 1826) and *Lumbricus rubellus* Hoffmeister 1843 were abundant in sampling areas with plant cover (habitats III and IV). Anecic species *A. longa* (Ude 1885) and *L. terrestris* Linnaeus 1758 were present in all sampling areas except the old semi-coke heap, epigeic *Dendrobaena octaedra* (Savigny 1826) was sampled in all studied heaps. We also found single individuals of *Allolobophora chlorotica* (Savigny 1826) and *Dendrodrilus rubidus* (Savigny 1826) in the semi-coke heap. Species *Octolasion cyaneum* (Savigny 1826) was present in semi-coke as a single individual and constituted 10% of individuals in the oil-shale mining waste dump.

In total, specimens of seven classes of epigeic invertebrates were identified (Table 2). The diversity and relative abundance (number of individuals per trap) varied between different groups of invertebrates.

Spiders of 12 families, altogether 45 species in June and 47 species in July, were collected. The total abundance of spiders was slightly higher in traps in June and in habitats with dense sward (III and IV). The most numerous families (Gnaphosidae, Linyphiidae, Lycosidae) were more abundant also in habitats III and IV. The most abundant species in June were *Pardosa fulvipes* (Collett 1875), *Xerolycosa nemoralis* (Westring 1861) and *Trochosa ruricola* (De Geer 1778), in July, *Xerolycosa nemoralis*, *Pardosa prativaga* L. Koch 1870 and *P. lugubris* (Walckenaer 1802) (Lycosidae) predominated. The abundance of order Opiliones was higher in July, in the older semi-coke heap but the highest in the residues mix heap.

The density of beetles (Coleoptera) was lower in June and significantly higher in July when the air temperature was higher and precipitation lower. In June the most numerous families were Carabidae (25 species) and Staphylinidae (41 species), all other beetles were present with 20 species. In July we sampled 34 species of Carabidae, 41 species of Staphylinidae and 16 species of other beetle families. The most numerous species were *Poecilus versicolor* (Sturm 1824), *Pterostichus melanarius* (Illiger 1798), *Calathus melanocephalus* (Linne 1758), *C. fuscipes* (Goese 1777) (Carabidae), *Euplectus signatus* (Reichenbach 1816), *Drusilla canaliculata* (Fabricius 1787) (Staphylinidae), *Otiorrhynchus scaber* Stephens JF 1831, *Brachysomus echinatus* (Bonsdorff 1785) (Curculionidae). The relative abundance of Coleoptera was the highest in the habitats with dense plant cover (III and IV), the number of carabids and rove beetles per trap was also the highest in these habitats. The number of Formicidae in traps was very high (up to 430) in the mixed residues heap; also Diptera and Isopoda were the most abundant there. The number of myriapods was low in waste heaps. Class Chilopoda was more abundant in habitat I, in all studied heaps seven species were found, with *Lithobius forficatus* Linnaeus 1758 and *L. curtipes* C. L. Koch 1847 being the most numerous. The abundance of class Diplopoda was higher in the habitats with dense plant cover. During two sampling periods four species of Polydesmidae (*Polydesmus denticulatus* C. L. Koch 1847 was the most abundant species) and six species of Julidae (the most abundant species *Ommatoiulus sabulosus* (Linnaeus 1758)) were found in traps.

Habitat groups I–IV divided according to plant cover were also distinguished by invertebrate abundance. We analysed the substrate parameters and abundance of invertebrate groups by the CCA method (Fig. 2). The first CCA axis represents variances in pH. The second CCA axis represents the age of habitat, which is negatively correlated with moisture conditions in the substrate ($R = -0.822$, $p < 0.05$). Habitats I–III were characterised by higher moisture, habitat II by higher pH and habitat III by higher organic content in the substrate. Total nitrogen content was slightly higher in the substrate of habitat IV.

The soil biota communities in different habitats in semi-coke heaps are characterized by different parameters. Among the studied habitats those with sparse plant cover (I) are the youngest, their organic content being the highest and total N content the lowest, as are the basal respiration and SIR biomass of microbial community. The abundances of springtails, mites and earthworms are low. Spiders, whose community consists mostly of Lycosidae specimens, are more abundant.. The density of beetles is low, especially that of rove beetles. 95% of carabid individuals are predators. The number of Chilopoda specimens was the highest in habitat I. Habitat II with sparse plant cover with woody plants and of seemingly the same age was similar to habitat I in substrate condition. The leaf litter and activity of roots of woody plants make the substrate more suitable for soil organisms – the basal respiration of microbial community was significantly higher than that in habitat I, while the abundance of earthworms was the highest of all habitats. The epigeic fauna was similar to that of habitat I. The habitat with dense plant cover (turf of Graminea) (III) had somewhat lower organic and higher total N content, the microbial community parameters (basal respiration and SIR biomass) were significantly higher than in the areas with scarce plant cover (habitats I and II). Springtails and mites were also highly abundant. The abundance of earthworms was relatively high and all ecological groups were present. In traps, spiders consisting mostly of Lycosidae and Gnaphosidae specimens were numerous. The number of beetles was very high, rove beetles accounting for 46%. 72% of ground beetles were predators. In the oldest semi-coke heap,

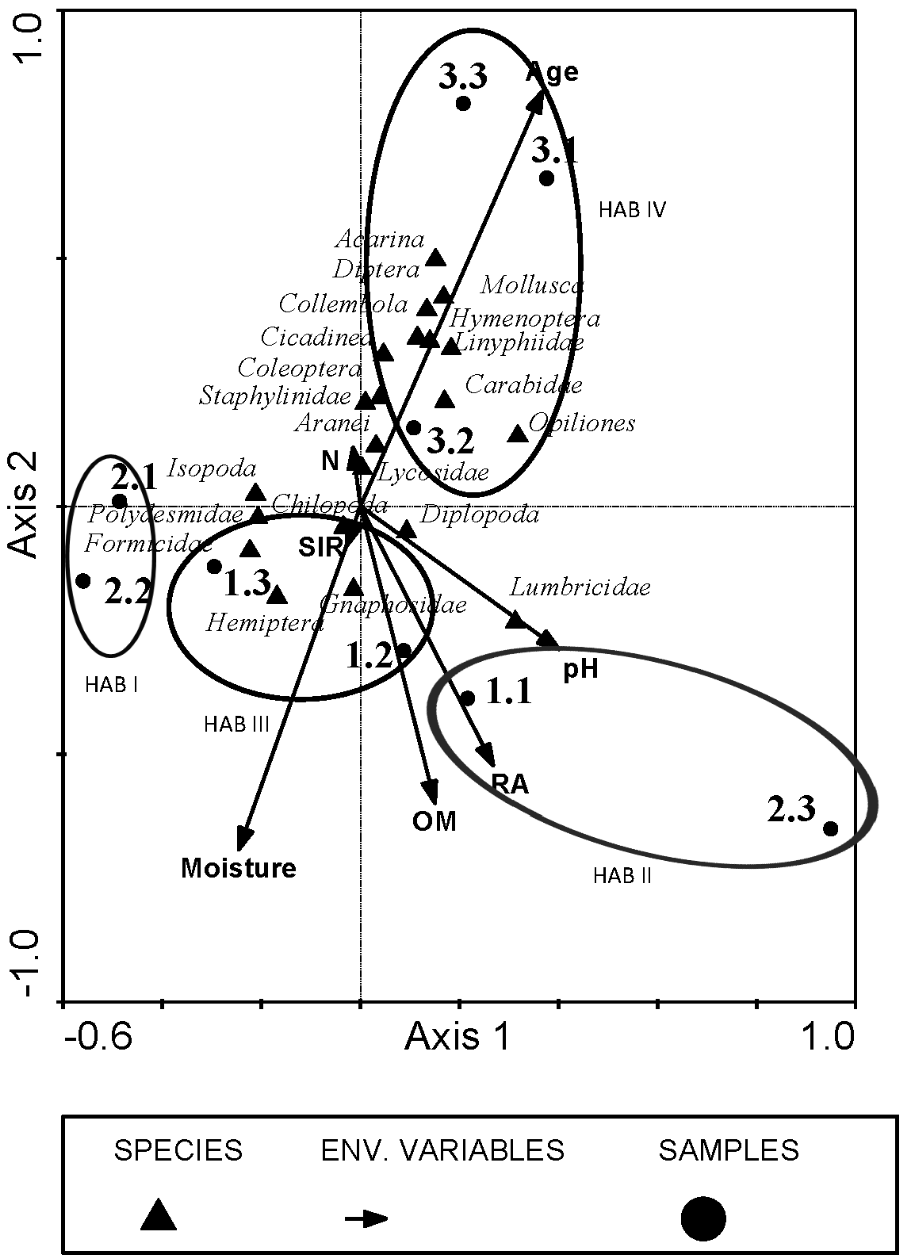

Fig. 2. Ordination triplots with environmental variables based on Canonical Correspondence Analyses (CCA) of taxonomic groups, displaying 43% of variance on axis 1 and 37% on axis 2. Abbreviations for environmental variables: pH – acidity of soil (KCl); OM – organic matter, %; moisture – volumetric water content of soil; age – period from end of exploitation of semi-coke heap in scale 1 – < 20 years, 2–38 years. Abbreviations for microbial communities parameters: RA – respiration activity SIR – microbial biomass. The sampling areas are numbered (1.1–3.3); HAB – habitat type I–IV; sum of all canonical eigenvalues 0.629.

habitat IV had the lowest organic and moisture content of the substrate. The abundance and species richness of springtails was the highest. The density of earthworms was low because of low substrate moisture. In traps the number of spiders, mostly individuals of Lycosidae, was high. The abundance of beetles was the highest, the proportion of predators in ground beetle community was similar to that of habitat III. The mixed residues heap differed from semi-coke heaps in lower moisture and organic content. The basal respiration of microbial community was low but its microbial biomass was the highest. The parameters of soil meso- and macrofauna as well as epigeic predators were similar to those of habitats with dense vegetation (III and IV). These habitats differed from those of semi-coke heaps in the high number of Formicidae, Diptera and Isopoda in pitfall traps.

4. Discussion

The heaps of oil shale mining wastes consist of pure substrate open to primary succession and constitute possible habitats for soil invertebrates. Soil micro-, meso- and macrofauna play an important role in the decomposition of wastes and formation of natural primary ecosystem. Based on earlier publications [26] and our results we conclude that soil communities appear in substrate before vegetation starts to develop. Animals, especially microarthropods, become abundant when pore- or channel-containing unconsolidated sediments transform to habitats, Collembolans are known from the early stages of primary succession [27–29]. Our results demonstrated that in soil mesofauna, mites are dominant over springtails in the substrate without dense plant cover, but springtails are more numerous in the substrate covered with a dense turf of Graminea. The prevailing springtail species *Parisotoma notabilis* and *Willemia anophthalma* are cosmopolitans and have been found as pioneer species also in other mine sites [28].

Earthworm community was not abundant but most Estonian earthworm species [30] were present, the limiting factor for earthworms seemed to be low substrate moisture. The species composition of earthworm communities was dependant on the plant cover of heaps. No earthworms were found in the higher parts of semi-coke heaps without plants or mosses. In the areas with very sparse vegetation we found only epigeic species *L. rubellus* and *D. octaedra*, which have been mentioned as the first colonizers of mine spoil heaps by numerous authors [27, 31, 32].The communities in areas with richer plant cover with young trees and bushes (mostly birches and willows) were more diverse. The old semi-coke heap differed from more recent ones in low soil moisture limiting the number of earthworms despite rich vegetation. The waste dump of limestone and oil shale residues differed from semi-coke heaps in the absence of species *A. chlorotica* and *D. rubidus,* and high abundance of *Octolasion cyaneus* which was first found in Estonia 20 years ago and is spreading in North-Estonia nowadays [33, 34]. Earthworms are considered a potential group of invertebrates to enhance the soils because of their burrowing activity, ability to mix and aggregate soil and to enhance soil porosity and water holding capacity. In addition to their key role in soil structure and chemistry, and their influence on plant communities, earthworms represent a substantial biomass capable of supporting large communities of vertebrate and invertebrate predators [11, 14, 35]. There are several studies published on the dispersal ability of earthworms [32, 36]. Earthworms invade new substrates and habitats remarkably fast, their dispersal capacity over shorter distances is effective and enables them to colonize primary substrate and change it into a better habitat. Our data confirms the distribution of earthworms to new habitats in semi-coke heaps, the leaf litter of woody vegetation contributes to the increase in earthworm density.

The most abundant groups of epigeic macrofauna were predators – spiders, beetles of families Carabidae and Staphylinidae, Chilopoda. The spider fauna of oil shale waste heaps is somewhat similar to that of other disturbed sites, such as flooded or dry meadows [37]. Bare aboveground mining areas are colonized by spiders relatively fast but are not used as sites of reproduction, which was also observed by [26, 38]. The species richness of the spider fauna of semi-coke heap habitats was rather low if compared to that of natural habitats, being between 4 and 20 species per site. We could not observe any significant relationship between age, environmental parameters or vegetation structure, which is commonly known to affect spider assemblies [39, 40] even in revegetated mining areas [26]. The weak or missing relationship between soil environmental parameters and spider community species composition was also noted by [26]; the researchers concluded that the spider abundance and species composition in disturbed habitats depended on the abundance and composition of colonizers of surrounding undisturbed habitats. The differences observed by us in the study sites can also probably be explained by this factor. Although it is well known that spiders respond to industrial pollution very rapidly [41], we could see no signs of this during the study.

The relative abundance of Coleoptera was influenced by weather conditions, being low in June due to lower temperature and higher precipitation, and significantly higher in traps of the second sampling in July. The presence of Coleoptera species in vegetation-free areas may be explained by their predacious nature; arriving species are not always successful colonizers, and a species becoming a resident depends on resource availability changing in parallel with succession [12]. Ground beetles (Carabidae) are among the first epigeic arthropods to colonize fresh mine spoil and Staphylinid adults can rapidly colonize isolated revegetated mine sites [42, 43]. Consequently, our results show Carabids and rove beetles to be the most abundant beetles also in semi-coke heaps, their number per trap depends on climatic conditions during the sampling period.

Fresh toxic semi-coke is obviously not a suitable substrate for soil invertebrates, however, in the course of time under aerobic conditions it changes to a more suitable habitat for colonizers. During long-term processes of changes in semi-coke, by the interaction of microbial community, plants and invertebrates, the formation of ecosystem takes place. Vegetated oil-shale processing residue hills are habitats for several invertebrate groups, including microarthropods, earthworms and epigeic arthropods. The feeding conditions and preference of habitats are reflected in the species composition and abundances of soil fauna in habitats I–IV. The knowledge of diversity, activity and abundance of soil communities is crucial to understand natural processes taking place in oil-shale processing waste heaps. The restoration of oil shale mining and processing wastes should adopt proper remediation practices to ensure the presence of a more natural soil biota community and a long-term functioning of the ecosystem.

5. Conclusions

During long-term processes of changes in semi-coke, by the interaction of microbial community, plants and invertebrates, the formation of a new ecosystem takes place. The communities of micro- and macroarthropods and earthworms in oil-shale processing waste heaps are formed under certain conditions – a high pH and extremely low moisture. The presence of several invertebrate groups (springtails, earthworms, epigeic predators, etc.) and primary succession of soil communities may indicate the ecological functioning of revegetated residue and can be used for monitoring the success in restoration. The formation of soil with its typical biota is crucial for the remediation of wastes. Species associated with these processes can be included in monitoring the efficiency of restoration.

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REFERENCES

1. Khitarishvili, T. Estonia shifts focus. Cleansing oil shale. *IEA Energy: The Journal of the International Energy Agency,* 2013, 5, 42–43.
2. Raukas, A., Siirde, A. New trends in Estonian oil shale industry. *Oil Shale*, 2012, **29**(3), 203–205.

3. Kattai, V. *Oil Shale – Source of Oil.* Eesti Geoloogiakeskus, Tallinn, 2006 (in Estonian with English summary).
4. Orupõld, K., Habicht, J., Tenno, T. Leaching behaviour of oil shale semicoke: compliance with the waste acceptance criteria for landfills. *Oil Shale*, 2008, **25**(2), 267–275.
5. Pae, T., Luud, A., Sepp, M. Artificial mountains in North-East Estonia: monumental dumps of ash and semi-coke. *Oil Shale,* 2005, **22**(3), 333–343.
6. Truu, J., Heinaru, E., Vedler, E., Juhanson, J., Viirmäe, M., Heinaru, A. Formation of microbial communities in oil shale chemical industry solid wastes during phytoremediation and bioaugmentation. In: *Bioremediation of Soils Contaminated with Aromatic Compounds*. NATO Science Series, 2007, **76**, Springer, Dordrecht, 2007, 57–66.
7. Wong, M. H. Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. *Chemosphere*, 2003, **50**(6), 775–780.
8. Gardner, J. Rehabilitating mines to meet land use objectives: bauxite mining in the jarrah forest of Western Australia. *Unasylva*, No. 207 – Rehabilitation of degraded sites, 2001, **52**(4), 3–8.
9. Majer, J. D., Brennan, K. E. C., Moir, M. L. Invertebrates and the restoration of a forest ecosystem: 30 years of research following bauxite mining in Western Australia. *Restor. Ecol.*, 2007, **15**(4), S104–S115.
10. Holec, M., Frouz, J. Ant (Hymenoptera: Formicidae) communities in reclaimed and unreclaimed brown coal mining spoil dumps in the Czech Republic. *Pedobiologia*, 2005, **49**, 345–357.
11. Topp, W., Simon, M., Kautz, G., Dworschak, U., Nicolini, F., Prückner, S. Soil fauna of a reclaimed lignite open-cast mine of the Rhineland: improvement of soil quality by surface pattern. *Ecol. Eng.*, 2001, **17**(2–3), 307–322.
12. Courtney, R., O'Neill, N., Harrington, T., Breen, J. Macro-arthropod succession in grassland growing on bauxite residue. *Ecol. Eng.,* 2010, **36**, 1666–1671.
13. Cortet, J., Gomot-De Vauflery, A., Poinsot-Balaguer, N., Gomot, L., Texier, C, Cluzeau, D. The use of invertebrate soil fauna in monitoring pollutant effects. *Eur. J. Soil Biol.*, 1999, **35**(3), 115–134.
14. Haimi, J. Decomposer animals and bioremediation of soils. *Environ. Pollut.,* 2000, **107**(2), 233–238.
15. Nei, L., Kruusma, J., Ivask, M., Kuu, A. Novel approaches to bioindication of heavy metals in soils contaminated by oil shale wastes. *Oil Shale*, 2009, **26**(3), 424–431.
16. Bradshaw, A. The use of natural processes in reclamation – advantages and difficulties. *Landscape Urban Plan.,* 2000, **51**(2–4), 89–100.
17. Platen, H., Wirtz, A. *Measurement of the Respiration Activity of Soils Using the OxiTop Control Measuring System. Basic Principles and Process Characteristic Quantities.* WTW (Wissenschaftlich-Technische Werkstätten), GmbH & Co. KG, Weilheim, Germany, 1999.
18. Coleman, D. C., Crossley, D. A., Jr, Hendrix, P. F. *Fundamentals of Soil Ecology.* Elsevier Academic Press, London, 2004.
19. Gunn, A. The use of mustard to estimate earthworm population. *Pedobiologia*, 1992, **36**(2), 65–67.
20. Bouchè, M. B. Strategies lombriciennes. In: *Soil Organisms as Components of Ecosystem* (Lohm, U., Persson, T., eds.). *Ecological Bulletin*, 1977, **25**, 122–132.

21. Freude, H., Harde, K. W., Lohse, G. A. *Beetles of Central Europe, Band 2, Adephaga 1.* Goecke & Evers Verlag, Krefeld, 1976 (in German).
22. Heimer, S., Nentwig, W. *Spiders of Central Europe.* Blackwell Wissenschafts-Verlag, 1991 (in German).
23. Roberts, M. J. *Spiders of Britain and Northern Europe*. Harper Collins Publishers, 1995.
24. Merivee, E., Remm, H. *Key to Coleoptera*. Valgus, Tallinn, 1973 (in Estonian).
25. ter Braak, C. J. F. Canonical community ordination. Part 1: Basic theory and linear methods. *Ecoscience*, 1994, **1**(2), 127–140.
26. Mrzljak, J., Wiegleb, G. Spider colonization of former brown coal mining areas – time or structure dependent? *Landscape Urban Plan.*, 2000, **51**(2–4), 131–146.
27. Dunger, W. The return of soil fauna to coal mined areas in the German Democratic Republic. In: *Animals in Primary Succession: The Role of Fauna in Reclaimed Lands* (Majer, J. D., ed.). Cambridge University Press, 1989, 307–337.
28. Dunger, W., Schulz, H.-J., Zimdars, B., Hohberg, K. Changes in collembolan species composition in Eastern German mine sites over fifty years of primary succession. *Pedobiologia*, 2004, **48**(5–6), 503–517.
29. Dilly, O., Pfeiffer, E.-M., Irmler, U. Soil phases: the living phase. In: *Soils: Basic Concepts and Future Challenges* (Certini, G., Scalenghe, R., eds.). Cambridge University Press, Cambridge, 2006, 91–102.
30. Timm, T. *A Guide to the Estonian Annelida.* Naturalist's Handbooks 1. Estonian Academy Publishers, Tartu-Tallinn, 1999.
31. Pižl, V. Development of earthworm populations in afforested colliery spoil heaps in northern Bohemia, Czech Republic. *Pedobiologia*, 1999, **43**, 691–697.
32. Eijsackers, H. Earthworms as colonisers: Primary colonisation of contaminated land, and sediment and soil waste deposits. *Sci. Total Environ.*, 2010, **408**(8), 1759–1769.
33. Kuu, A., Ivask, M. Distribution of *Octolasion cyaneum* (Savigny, 1826) in Estonia 1993–2008. *Zool. Middle East*, 2010, **51**, Suppl. 2, 75–81.
34. Kalda, K., Ivask, M., Kuu, A., Peda, J., Kutti, S. Earthworms in waste heaps of oil-shale industry. In: *Vermicomposting and Vermiculture as basis of ecological landownership in XXI century – problems, outlooks, achievements*. Minsk, 2013, 153–158.
35. Boyer, S., Wratten, S. D. The potential of earthworms to restore ecosystem services after opencast mining – a review. *Basic Appl. Ecol.*, 2010, **11**(3), 196–203.
36. Eijsackers, H., Bruggeman, J., Harmsen, J., Kort, Th., De Schakel, A. Colonization of PAH-contaminated dredged sediment by earthworms. *Appl. Soil Ecol.*, 2009, **43**, 216–225.
37. Meriste, M. Spider fauna of coastal and floodplain meadows in Matsalu (Estonia), influence of flooding and management. In: *Books of Abstracts: 18th International Congress of Arachnology, Siedlce, Poland, 11–17.07.2010* (Zabka, M., ed.), 2010, 293–294.
38. Bröring, U., Mrzljak, J., Niedringhaus, R., Wiegleb, G. Soil zoology I: arthropod communities in open landscapes of former brown coal mining areas. *Ecol. Eng.*, 2005, **24**(1–2), 121–133.

39. Bell, J. R., Wheater, C. P., Cullen, W. R. The implications of grassland and heathland management for the conservation of spider communities: a review. *J. Zool.*, 2001, **255**(3), 277–387.
40. Dennis, P., Young, M. R, Bentley, C. The effects of varied grazing management on epigeal spiders, harvestmen and pseudoscorpions of *Nardus stricta* grassland in upland Scotland. *Agr. Ecosyst. Environ.*, 2001, **86**(1), 39–57.
41. Koponen, S., Koneva, G. G. Spiders along a pollution gradient (Araneae). In: *European Arachnology 2005* (Deltshev, C., Stoev, P., eds.), *Acta zoologica bulgarica,* 2005, Suppl. 1, 131–136.
42. Kielhorn, K., Keplin, B., Hüttl, R. Ground beetle communities on reclaimed mine spoil: effects of organic matter application and revegetation. *Plant Soil*, 1999, **213**(1–2), 117–125.
43. Good, J. A. Recolonisation by staphylinidae (Coleoptera) of old metalliferous tailings and mine soils in Ireland. *Biol. Environ.*, 1999, **99B(**1), 27–35.

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