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# FEATURES OF FOREST COMMUNITIES AND SOILS FORMED ON AN ASH DUMP OF THE MIDDLE URALS

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## Abstract

Forest communities formed on a part of ash dumps during their existence can be taken into account when assessing forest lands. The aim of this study is to identify the features of forest communities and soils formed on a fly ash dump located in southern taiga. The structure of forest communities and physico-chemical characteristics of soils formed during spontaneous overgrowth of an ash dump of Sredneuralskaya Thermal Power Plant (TPP) were studied. Mixed forest phytocoenoses with a predominance of *Populus tremula* L. and *Betula pendula* Roth aged 45–50 years age have formed on the non recultivated area of the ash dump. They are close in composition to the zonal secondary forests, have less species richness and similar reserves of living aboveground phytomass. The soils formed on the ash dump have horizons with low thickness, in which pH has shifted towards the neutral, and organic matter and basic nutrients have accumulated. Technosol humus horizons in terms of the main biogenic element content (C, N, Ca, Mg, K, P) are close to that of the background soil or even contain them in larger quantities. The formation of forest communities and soils on the ash dump is proceeding according to the zonal type. Studying forest phytocoenosis forming on the ashes with different properties and a varied combination of natural conditions will make it possible to establish patterns in the formation of forest communities on technogenic substrates and influence their speed.

**Key words:** *Betula pendula* Roth, fly ash, natural colonization, *Populus tremula* L., southern taiga, Technosols.

## Introduction

Intensive industrial development has led to accumulation of various wastes, which, for example, ash from power plants, occupy large areas in many countries (Gajic et al 2019, Khokhlov and Melnikov 2019, Marinina et al. 2021). On some ash dumps several decades old (subjected to recultivation or left for natural colonisation), forest communities were formed, the state of which must be taken into account in the overall assessment of forest lands, including in accordance with the challenges of the time in terms of carbon sequestration.

Due to the fact that the features of plant communities formed on technogenic substrate are influenced by the physico-chemical features of a particular object and the climate of ash dump location (Jusaitis and Pillman 1997, Makhnev et al. 2002, Pandey and Bajpai 2016), available data on them are diverse. Since the properties of ash depend on the characteristics of the burnt coal, technological factors, as well as the natural and climatic conditions of its storage (Pasynkova 1974, Maiti 2013, Shaheen et al. 2014), information on forest communities formed on the surface of ash dumps with different properties and varied combination of natural conditions is of high scientific and practical importance.

During the formation of forest communities on ash dumps, the properties of technogenic substrate are changed by the processes of soil formation. A number of publications are devoted to issues touching the characteristics of individual tree species and young soils of ash dumps where they grow (Kostic et al. 2012; Mitrovic et al. 2012; Uzarowicz et al. 2017, 2018a,b; Pietrzykowski et al. 2018). At the same time, only planted woody species and soils formed on the recultivated ash dump surface are studied, which certainly affects the speed and, possibly, the direction of community and soil formation, while forest communities and soils formed on a technogenic substrate without human assistance are rarely investigated (Nekrasova et al. 2020). Not enough attention is paid to comprehensive studies of forest phytocoenoses and soils formed under their influence on ash substrate, mutually dependent on each other. Forest communities of ash dumps in the southern taiga of the Middle Urals have been also actively studied in relation to the characteristics of individual plant species (Filimonova et al. 2017, Kalashnikova et al. 2021, Maleva et al. 2021), while the system 'forest community – young soil' in which a biological (small) cycle occurs remains poorly understood.

The purpose of this study is to identify the features of forest communities and soils formed during 50 years on non recultivated fly ash derived from Ekibastuz brown coal in southern taiga conditions.

## Materials and Methods

The work was done on an ash dump after Ekibastuz brown coal burning by Sredneuralskaya Thermal Power Plant (SUTPP) in Sverdlovsk region in the Middle Urals (57°00' N and 60°28' E). The ash dump is located on the eastern shore of Lake Isetskoe. The relief of the area is hilly: the prevailing heights vary from 250 to 300 m a.s.l. The territory under study is located in the Middle Urals southern taiga, its climate is moderately cold (the average annual temperature is 2.2 °C, the sum of the temperatures more than 10 °C is equal to 1600 °C), and over-humidified (the annual precipitation is near 600 mm, the hydrothermal coefficient is about 1.5) (National atlas … 2008, CLIMATE-DATA.ORG 2021). Indigenous vegetation is represented by southern taiga pine forests, pine-spruce forests as well as by secondary birch and mixed birch-pine forests (Shakirov 2011).

The fly ash dump occupies 1.04 km$^2$. Part of it was left for natural revegetation after the end of dumping in 1968.

The objects of our investigation carried in 2019 were forest communities formed on non recultivated part of Sredneuralskaya TPP ash dump in the process of natural colonisation. Complex geobotanical and soil studies were carried out on three identified typical forest sites. Two undisturbed background forest sites were used as control.

The area of geobotanical description

was 250–300 $m^2$ in each site. Species composition, crown density, as well as height and trunk diameter (at 1.3 m) were taken into account during describing the tree layer. Beside, all individuals of each species were counted and young growth and self-sown ones were recorded. The projective cover, height and composition of shrub layer, herb-shrub layer, and moss-lichen cover were determined.

Fifty of Raunkier's plots (S = 0.25 $m^2$) were laid at each site to characterise the herb-shrub layer. Floristic lists with an assessment of each species abundance were made using Drude scale, the dominant species were identified based on the assessment of projective cover and phytomass stocks (Lavrenko et al. 1964).

Soil sections and their morphological descriptions were done in each site of ash dump and control areas. Sampling was done every 5–10 cm, taking into account the horizon boundaries. pH was determined in a supernatant of soil and water in a ratio of 1:2.5 (ANION 4100, Russia), particle size distribution – by the pipette method (Kachinsky 1958), total organic carbon (TOC) – by wet combustion in a mixture of potassium dichromate and sulphuric acid (Tjurin method), total N – by Kjeldahl method with termination on a spectrophotometer UNICO 2100 (United Product & Instruments, Dayton, NJ, USA). Available phosphorus ($P_2O_5$) was detected by ammonium molybdate method using UV spectrophotometer (UV-probe 1650), available potassium ($K_2O$) – in the same extract by flame photometer PFA-378 (Russia), and exchangeable $Ca^{2+}$ and $Mg^{2+}$ – complexometrically, using Trilon B (Arinushkina 1970, Vorob'eva 2006).

Statistical processing was carried out using Mann-Whitney criterion (Quinn and Keough 2002).

## Results

### Characteristics of ash dump forest communities

In the forest sites of SUTPP ash dump flora species richness is represented by 55 species of vascular plants. The forest stand is dominated by *Populus tremula* L. and *Betula pendula* Roth., less often are *B. pubescens* Ehrh. and *Pinus sylvestris* L. The young growth is represented by the same species as the previous layer, their height is up to 2 m high. The shrub layer is formed by 11 species of shrubs 1.5–2 m high. It is sparse, with average projective crown coverage of 30–35 %. *Chamaecytisus ruthenicus* (Fisch.ex Woloszcz.) Klaskova, *Sorbus aucuparia* L., *Viburnum opulus* L., *Padus avium* Mill. predominate, *Caragana arborescens* Lam., *Rosa acicularis* Lindl. and *Frangula alnus* Mill. predominate.

The herb-shrub layer in all studied forest sites on ash is sparse, the following herbaceous plants predominate: *Equisetum pratense* L., *Vicia sylvatica* L., *Lathyrus pratensis* L., *Agrostis tenuis* Sibth., *Festuca rubra* L. and *Fragaria vesca* L. Moss-lichen cover is poorly expressed. *Amblystegium serpens* (Hedw.) Bruch et al., *Ceratodon purpureus* (Hedw.) Brid., *Leskea polycarpa* Hedw., *Myrinia pulvinata* (Wahlenb.) Schimp, *Sciuro-hypnum starkei* (Brid.), Ignatov et Huttunen and *Sanionia uncinata* (Hedw.) Loeskem are found mainly on woody remains and tree trunks with a small coverage. *Brachythecium salebrosum* (F. Weber et D. Mohr) Bruch et al., *Climacium dendroides* (Hedw.) F. Weber et D. Mohr, *Leptobryum pyriforme* (Hedw.) Wilson, *Pleurozium schreberi* (Brid.) Mitt., *Pohlia nutans* (Hedw.) Lindb., *Pylaisia* *polyantha* (Hedw.) Bruch et al. are common on the substrate; *Bryum violaceum* Crundw. et Nyholm is rare. A brief description of the sites is given in Table 1.

**Table 1. Characteristics of plant communities.**

| Characteristic | SUTPP ash dump | | | Control | |
|---|---|---|---|---|---|
| | Site 1 | Site 2 | Site 3 | Site 1 | Site 2 |
| Forest stand | | | | | |
| Crown density | 0.50 | 0.55–0.60 | 0.4–0.45 | 0.55-0.65 | 0.40-0.60 |
| Average height of trees, m | 17.5 | 18.0 | 18.5 | 19.0 | 23.0 |
| Average diameter, cm | 16.3 | 16.5 | 17.7 | 25.0 | 30.0 |
| Age, years | 45–50 | 45–50 | 45–50 | 80–100 | 100 |
| Young growth and self-sown tree species | | | | | |
| Young growth height, m | 1.5 | 1.2 | 1.8 | 0.1–3.8 | 0.1–6.2 |
| Total number per hectare | 8400 | 10000 | 1600 | 2100 | 1360 |
| Shrub layer | | | | | |
| Projective cover, % | 35 | 15 | 35–40 | 20 | 25-30 |
| Average height, m | 1.8 | 1.2 | 1.5 | 0.6–3.5 | 0.8–4.2 |
| Ground layer | | | | | |
| Herb–shrub layer cover, % | 80–90 | 80–85 | 75–80 | 80–85 | 80–95 |
| Herb–shrub layer height, cm | 22–40 | 15–35 | 35–40 | 45–55 | 50–70 |
| Moss–lichen layer cover, % | 5 | 5 | 10 | 305 | 35 |
| Number of species per 0.25 $m^2$, (min–max) | 8.9 (6–15) | 9.5 (7–15) | 8.8 (6–13) | 9.6 (4–19) | 14.1 (6–19) |
| Floristic abundance on the accounting area | 42 | 36 | 31 | 51 | 66 |

## Characteristics of ash and ash dump soils

Young soils have been formed on SUTPP ash dump for 50 years under the forest communities with the following horizons: O – litter with a thickness of about 0.5 cm; A – 2.5 cm thickness, grew, weakly textured, crumbling-pulverescent; AC – 7 cm thickness brownish-grew, weakly textured, lamellate-pulverescent; and C – from the depth of 10 cm opened to a depth of 40 cm, a loose structureless ash substrate serving as a soil-forming rock. They can be classified as Technosols (World Reference … 2014).

Alumosilicates predominate in the bulk composition of SUTPP ash on which Technosols were formed, while the rest of the oxides account for only 8–11 % (Table 2). As the results show, in the smallest amounts, not exceeding 1 %, the ash contains oxides of calcium, magnesium, potassium, sodium and phosphorus.

Analysis of the particle size distribution in Technosols mineral part (Fig. 1) showed dominating >0.01 mm (62–83 %) mainly due to the silt 0.01–0.05 mm in most samples, the sand particles with the diameter 0.25–1.00 mm had the smallest values not exceeding 4 %. Clay particles (important as main source of plant nutrition) were found in low amounts (4–6 %) in C horizons, their value increased up to 8–10 % in AC horizon. The accumulation maximum of particles <0.001 mm in the profile was in A horizon (14–20 %).

**Table 2. Bulk composition of SUTPP ash in % to air-dry sample.**

| Variants | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $K_2O$ | $Na_2O$ | $TiO_2$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 44.3 | 47.1 | 4.3 | 0.9 | 0.6 | 0.5 | 0.4 | 1.6 | 0.4 |
| 2 | 52.0 | 39.7 | 4.4 | 0.8 | 0.6 | 0.5 | 0.4 | 1.3 | 0.3 |
| 3 | 48.0 | 44.0 | 4.4 | 0.5 | 0.3 | 0.7 | 0.2 | 1.4 | 0.5 |
| 4 | 56.0 | 36.5 | 4.2 | 0.6 | 0.3 | 0.6 | 0.2 | 1.3 | 0.4 |
| 5 | 44.8 | 44.0 | 7.2 | 0.6 | 0.4 | 0.6 | 0.2 | 1.5 | 0.6 |
| 6 | 50.3 | 41.6 | 4.4 | 0.5 | 0.4 | 0.8 | 0.2 | 1.5 | 0.4 |
| x | 49.2 | 42.2 | 4.8 | 0.7 | 0.4 | 0.6 | 0.3 | 1.4 | 0.4 |
| SD | 4.5 | 3.7 | 1.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

Legend: x – average; SD – standard deviation.

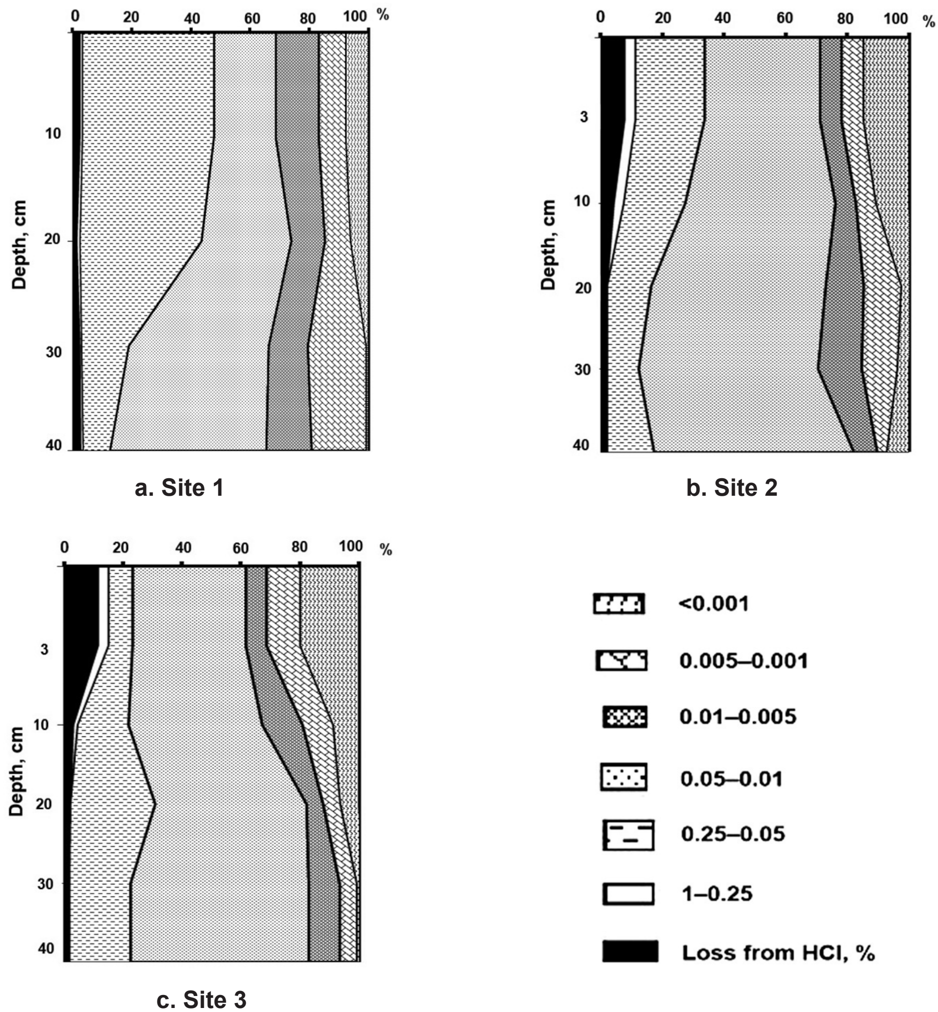


**Fig. 1. Texture of Technosols.**

The texture of the horizons of Technosols and ash substrate is mainly silt loam and silt in a few cases.

The ash substrate serving as a soil-forming rock (horizons C1, C2 and C3) (Table 3) had acidic reaction with pH values from 4.6 to 5.3, contained relatively high amounts of TOC – 2.0–3.9 % (that may be caused by unburned coal particles), traces amounts of total N (not exceeding 0.04 %), low amounts of absorbed calcium and magnesium cations (0.5–1.3 and 0.3–1.2 mmol·100g$^{-1}$ respectively) as well as of mobile forms of potassium and phosphorus (0–3.9 and 1–5 mg·100g$^{-1}$ respectively).

**Table 3. Chemical properties of Technosols.**

| Horizon | Depth, cm | pH $_{H_2O}$ | TOC | N | $Ca^{2+}$ | $Mg^{2+}$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|
| | | | % | | mmol·100g$^{-1}$ | | mg·100g$^{-1}$ | |
| Site 1 | | | | | | | | |
| O | 0–0.5 | 6.40 | 28.55 | 1.13 | 25.0 | 20.0 | 33.1 | 9.9 |
| A | 0.5–3 | 6.70 | 9.57 | 0.47 | 17.5 | 6.3 | 18.0 | 4.6 |
| AC | 3–10 | 5.49 | 3.36 | 0.08 | 1.5 | 0.8 | 7.4 | 3.5 |
| C1 | 10–20 | 5.29 | 2.14 | 0.03 | 0.8 | 0.7 | 3.9 | 1.0 |
| C2 | 20–30 | 4.78 | 2.71 | Traces | 0.8 | 0.7 | 0.4 | 4.8 |
| C3 | 30–40 | 5.05 | 2.31 | Traces | 1.3 | 1.2 | 0 | 4.1 |
| Site 2 | | | | | | | | |
| O | 0–0.5 | 6.56 | 34.61 | 1.10 | 40.0 | 25.0 | 33.3 | 11.7 |
| A | 0.5–3 | 6.70 | 6.50 | 0.30 | 14.3 | 4.8 | 18.0 | 6.1 |
| AC | 3–10 | 5.96 | 3.62 | 0.09 | 7.0 | 1.3 | 16.6 | 1.6 |
| C1 | 10–20 | 5.37 | 2.03 | 0.03 | 1.2 | 0.3 | 2.4 | 3.2 |
| C2 | 20–30 | 5.35 | 2.72 | Traces | 0.5 | 0.8 | 0.3 | 3.1 |
| C3 | 30–40 | 5.54 | 3.93 | Traces | 0.8 | 1.0 | 0 | 4.8 |
| Site 3 | | | | | | | | |
| O | 0–0.5 | 6.55 | 34.33 | 1.18 | 50.0 | 15.0 | 31.7 | 9.5 |
| A | 0.5–3 | 5.93 | 19.44 | 0.71 | 24.5 | 14.0 | 34.2 | 10.5 |
| AC | 3–10 | 5.06 | 3.20 | 0.07 | 1.8 | 1.3 | 7.4 | 1.9 |
| C1 | 10–20 | 5.40 | 2.70 | 0.04 | 0.7 | 1.0 | 1.6 | 3.3 |
| C2 | 20–30 | 5.46 | 2.19 | 0.02 | 0.7 | 1.0 | 0.9 | 2.0 |
| C3 | 30–40 | 5.58 | 3.72 | 0.04 | 0.7 | 1.0 | 2.2 | 3.4 |

In the formed horizons of Technosols, in comparison with the corresponding horizons C1 (Table 3, Fig. 2), there was an increase of the studied elements from AC towards O horizon (the differences are significant). The maximum accumulation of TOC (29–35 %), total N (1.1–1.2 %), absorbed $Ca^{2+}$ (25–50 mmol·100g$^{-1}$) and $Mg^{2+}$ (15–25 mmol·100g$^{-1}$), mobile forms of K (32–33 mg·100g$^{-1}$) and P (10–12 mg·100g$^{-1}$) was in the litter. In the same direction, there was an increase in pH values in profile in most cases, which may be a consequence of alkaline element accumulation by plants and correspondently by upper soil horizons.

Thus, young soils of ash disposal site during 50 years had accumulated significant amounts of biogenic elements in comparison with the ash substrate.

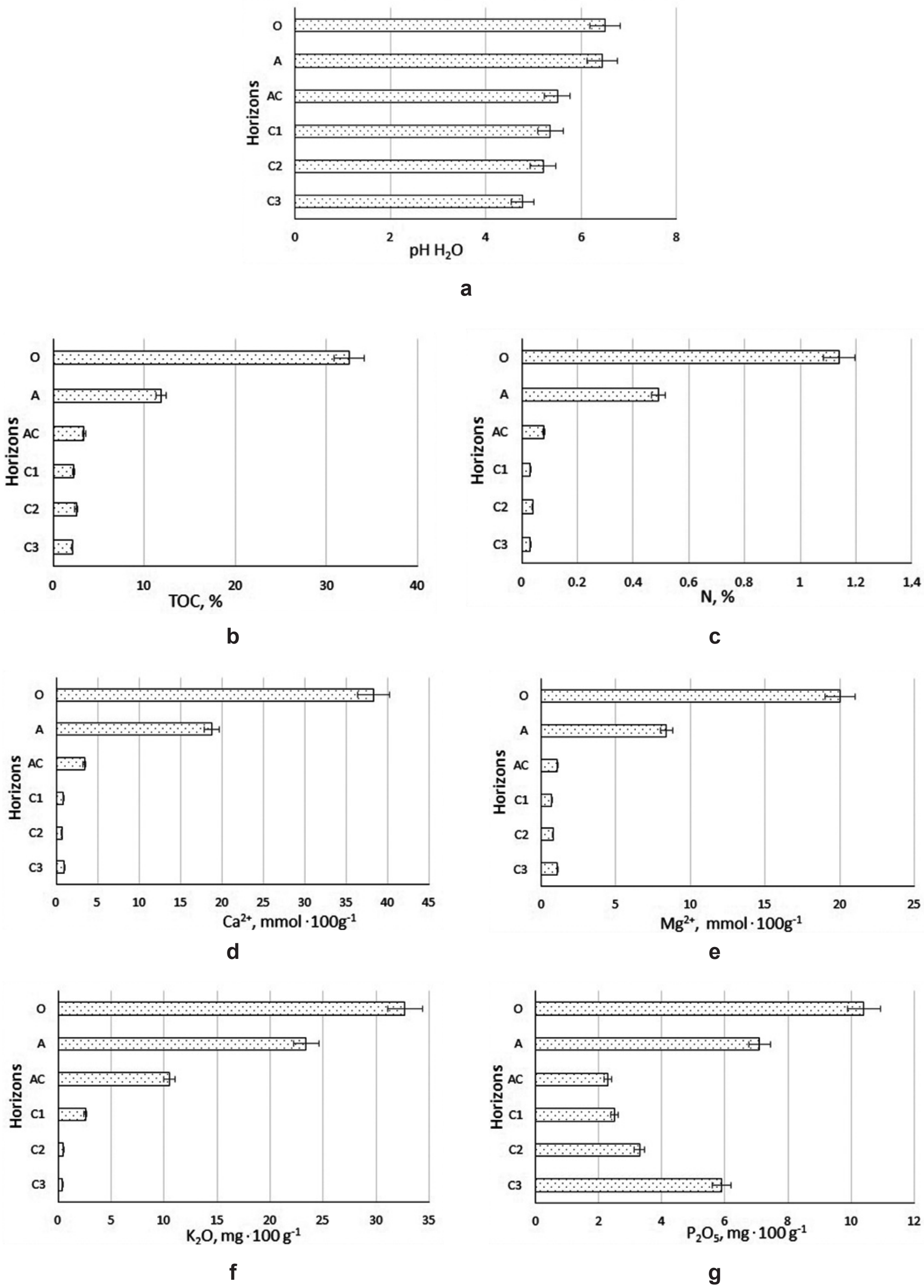


**Fig. 2. Average Technosol characteristics and standard deviation.**

## Discussion

### Features of ash dump forest communities in comparison with background ones

The forest communities formed on SUTPP ash dump have a similar species composition of the main forest-forming species, slightly differing in the share participation of individual species. All three sites are close floristically (Fig. 3). The forest communities of the ash dump differ little in crown density from the control forest, but are somewhat inferior in terms of the morphometric parameters of the stand (height and average diameter of trees). The shrub layer is poorly expressed in forest communities both on ash and in the control sites.

The cover of grass-shrub layer on ash dump sites is also close to the control sites, although the horizontal structure of communities on ash differs in the uneven nature of the distribution of individuals of some species (*Pyrola rotundifolia* L., *Pyrola minor* L., *Orthilia secunda* (L.) House, *Trifolium medium* L.). The phytomass reserve of living ground cover of herb-shrub layer of the forest communities of ash dump and background ones does not differ significantly (Table 4). If the maximum reserve on ash is 23.3 ±1.8 g per 0.25 m$^{-2}$, then in the control it is higher and equal to 27.4 ±1.4 g·m$^{-2}$, though the differences are not significant.

As a result of geobotanical studies on SUTPP ash dump, it was found that in the process of spontaneous vegetation mixed forest phytocoenoses formed on

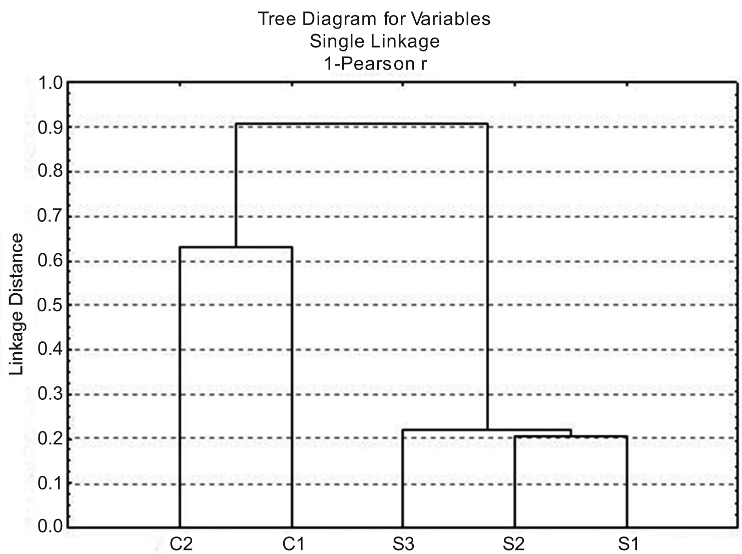


**Fig. 3. Comparison of the species composition of SUTPP ash dump forest phytocoenoses with that of background.**
Note: S1–S3 – ash dump sites; C1 and C2 – control sites.

**Table 4. Stock of living aboveground phytomass of herb-shrub layer of forest phytocoenoses.**

| Indicators | SUTPP ash dump | | | Control | |
|---|---|---|---|---|---|
| | Site 1 | Site 2 | Site 3 | Site 1 | Site 2 |
| Mass, g per 0.25 m$^2$ | 23.3 ±1.8 | 20.3 ±2.2 | 21.6 ±2.0 | 27.4 ±1.4 | 25.5 ±1.9 |
| The limits of mass variation, g per 0.25 m$^2$ | 16.1–33.6 | 10.2–33.5 | 12.4–35.2 | 21.7–33.5 | 17.9–36.1 |

non recultivated fly ash for 40–50 years, which is similar in composition to zonal secondary forests with a predominance of broad-leaved tree species. In the ash communities in comparison with the background sites, there is lower species richness, while indicators of the stock of living aboveground phytomass are similar, which indicates a relatively high degree of lower layer formation. It was shown previously that the dominant species of trees (*Betula pendula* and *Populus tremula*) on SUTPP ash dump as well as that of control sites (*Betula pubescens* and *Betula pendula*) successfully formed mycorrhiza (Betekhtina et al. 2021).

### Features of ash dump soils in comparison with background ones

Morphologically similar young soils have been formed in the upper thickness of SUTPP ash dump over 50 years with clear differentiation into litter, humus, AC and C horizons, though all horizons are of very low thickness.

An increase in the content of particles with diameter <0.001 mm in Technosols of all sites compared to the ash (Fig. 1) from which they are formed may be result of the destruction of larger size particles.

It should be noted that, as a rule, the substrate of ash dumps initially has an alkaline reaction (Pasinkova 1974, Uzarowicz et al. 2017, 2018a; Gajic et al. 2019), acidic pH values, as in SUTPP ash dump, are extremely rare. Alkalinisation in the topsoil of Technosols is probably associated with the consumption of calcium and potassium compounds by plant roots with further enrichment of the upper soil layers, which may contribute to an increase in pH values.

The storage of almost all considered elements have occurred in Technosols in comparison to the ash (Table 3 and Fig. 2). Organic carbon and nitrogen (the content of the last one was in trace amounts in ash substrate) were accumulated in Technosols during the forest community formation, while calcium and magnesium exchange cations together with potassium and phosphorus mobile forms were redistributed with the depth from the reserves in the ash.

The results obtained by us coincide with those for Technosols formed on ash after burning brown coal under cultivated woody plants in other natural and climatic conditions with respect to a decrease in pH and an increase in the content of C and N due to accumulation of organic matter (Uzarowicz et al. 2017, 2018a; Pietrzykowski et al. 2018).

Studied background soils were classified as soddy-podzolic soils (Egorov et al. 1977) or Retisols (World Reference … 2014) and characterised by the following genetic horizons O – A – E – B – BC – C.

The comparison of the limits of chemical characteristic variation of the corresponding upper horizons of Technosols and background soils (Table 5) showed the higher values of pH and the lower – of total nitrogen and exchangeable magnesium content in the litter of young soils (the differences are significant for pH and $Mg^{2+}$). The humus horizons of Technosols are close to control soils in the content of N, $Ca^{2+}$ and $Mg^{2+}$. At the same time, they differ in the higher values of total organic carbon (most likely due to the presence of unburned particles in the ash) (Pasynkova 1974), mobile forms of potassium as well as phosphorus (the differences are significant for $K_2O$ and $P_2O_5$).

**Table 5. Limits of chemical characteristic variation in the upper horizons of Technosols and background soils.**

| Horizon | $pH_{H_2O}$ | TOC | N | $Ca^{2+}$ | $Mg^{2+}$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|
| | | % | | mmol·100g$^{-1}$ | | mg·100g$^{-1}$ | |
| Technosols | | | | | | | |
| O | 6.40–6.56 | 28.55–34.61 | 1.10–1.18 | 25–50 | 15–25 | 32–33 | 10–12 |
| A | 5.93–6.70 | 6.50–19.44 | 0.30–0.71 | 14–25 | 5–14 | 18–34 | 5–11 |
| Background soils | | | | | | | |
| O | 5.73–6.02 | 22.10–33.00 | 1.18–1.36 | 23–33 | 30–45 | 29–57 | 4–12 |
| A | 5.15–6.51 | 5.83–9.35 | 0.42–0.89 | 10–23 | 8–14 | 6–13 | 0,2–0,9 |

Judging by the progressive development of forest communities on fly ash and thin topsoil litter (0.5 cm), it can be assumed that the biological cycle in the system ‘forest community – young soil’ proceeds with high intensity on SUTPP ash dump.

## Conclusion

In the process of natural revegetation of SUTPP ash dump in the Middle Urals mixed forest phytocoenoses with a predominance of broad-leaved tree species was formed over 50 years, which are similar in composition to zonal secondary forests of southern taiga with a relatively high degree of lower layer formation.

The revealed features of the composition and structure of the ash dump communities make it possible to evaluate them as a stage of progressive succession with improvement of conditions due to biotic transformation of the habitat (derivatives of the zonal type forests).

Poorly differentiated soils have been formed on SUTPP fly ash dump in the southern taiga for half a century. Technosols in comparison with the parent ash content more clay particles, have more alkaline reaction of the medium and accumulated the essential nutrients (C, N, Ca, Mg, K, P). Their humus horizons contain the main biogenic elements in equal or larger quantities to that of background soils. The soil formation is proceeding according to the zonal type in the whole.

The accumulation of data characterising forest communities and soils formed on ash dumps with a specific chemical composition of ash located in various natural and climatic conditions will eventually allow us to predict the rate of formation of forest ecosystems on a technogenic substrate and to influence this process.

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