FORESTRY IDEAS, 2022, vol. 28, No 1 (63): 112–125

FOREST PHYTOCOENOSES FORMATION ON SERPENTINE DUMPS OF ASBESTOS DEPOSIT, MIDDLE URALS, RUSSIA

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Received: 28 December 2021 Accepted: 01 April 2022

Abstract

The mineral deposits' development is accompanied by significant disturbances of soil and vegetation in large areas. The study of initial stages of disturbed lands natural overgrowing makes it possible to assess patterns of vegetation formation. Forest phytocoenoses formation on serpentine substrates in the Middle Urals, Russia (taiga zone, subzone of southern taiga) was studied in this work. The research was carried out at four dumps of Anatol'sko-Shilovsky asbestos deposit. It was found that forest communities with the dominance of *Pinus sylvestris* L. are formed on dump sites with the predominance of overburden rocks. The herb-shrub layer of these phytocoenoses was dominated by *Calamagrostis arundinacea* (L.) Roth. The slopes of dumps and areas with compacted soil are overgrown with sparse undersized forest vegetation dominated by *P. sylvestris* and *Betula pendula* Roth. In herb-shrub layer of these areas, the most common were relict species *Dendranthema zawadskii* (Herbich) Tzvel. and rare for the Urals species, *Epipactis atrorubens* (Hoffm.) Besser (orchid) and *Thymus talijevii* Klok. & Des.-Shost. The geobotanical and soil investigations have shown that all studied parameters (such as humidity, pH value, Mg:Ca ratio) influenced the formation of forest phytocoenoses. In general, the formation of forest vegetation on serpentine dumps is a very long process and it depends on specific climatic and soil conditions.

Key words: asbestos mining, forest communities, orchids, *Pinus sylvestris,* relict and endemic species, ultrabasic rocks.

Introduction

Keeping and restoration of biological diversity and rational usage of natural resources are fundamental to sustainable development of regions. Primarily it is due to the global anthropogenic transformation of natural ecosystems, accompanied by the radical biocoenotic rearrangements, the change in succession processes, and a number of other negative consequences (Bolshakov and Chibrik 2007).

The Middle Urals (Russia) is the industrial developed territory, where intensive mining and processing of minerals is carried out, and as a result, there are significant areas of lands disturbed by industry (Chibrik et al. 2018, Filimonova et al. 2020). Deposits of chromium, platinum, sulphide copper-nickel and silicate nickel, iron ores and ores of rare metals, mica, asbestos, diamonds, gemstones and other minerals, confined to the outcrops of ultrabasic rocks, are widespread (Rakov and Chibrik 2009). During production of mining products, a significant amount of unused mineral mass is removed to the surface and stored in dumps. Waste rock dumps are often 3–5 times larger in area than opencast mine workings themselves (Mormil et al. 2002).

The extraction of minerals leads to catastrophic changes in ecosystems and is accompanied by the destruction of lithological base, soil and vegetation cover. The dumps formed as a result of the transfer of rocks produce various ecological conditions that have a great influence on the species composition, abundance, and distribution of plants (Chibrik and Yelkin 1991, Manakov et al. 2011).

The weathering of ultrabasic rocks is very slow. The resulting serpentine soils are stony and contain a minimum amount of silty and clay particles, characterised by high contents of iron, magnesium, nickel, chromium and cobalt, which are toxic to most plants and bacterial communities and low ones in calcium, potassium, sodium and aluminium (Alexander et al. 2007, Brković et al. 2015, Kierczak et al. 2016). The serpentines contain little nitrogen, phosphorus and differ significantly from other soil types in chemical composition; the pH values vary from acidic to alkaline (Brady et al. 2005, Kazakou et al. 2008, Galey et al. 2017). The restoration of vegetation in such areas is extremely slow. Flora formed in serpentine areas is usually characterised by low species diversity and a sparse vegetation cover contributing to erosion and increase in soil temperature (Kruckeberg 2002). The combination of physical, chemical and biotic components that affecting the growth and development of plants on serpentine soils is called 'serpentine syndrome' (Jenny 1980).

All these environmental factors together with a small amount of moisture and a low level of nutrients create extremely unfavourable conditions for plant growth. In this regard very peculiar plant communities are formed on serpentines (Kruckeberg 2002, Branco and Ree 2010, Cano et al. 2014). The volume of this specificity depends on climate, age of the forest community, and chemical composition of rocks (Brooks 1987, Krämer 2010). Serpentine communities are known to botanists for accumulations of rare and narrowly endemic species, distribution of which is largely or entirely limited by serpentine areas (Alexander et al. 2007).

The aim of this work was to study forest phytocoenoses formation on serpentine substrates in the Middle Urals (taiga zone, subzone of the southern taiga). Study of flora and vegetation formation, as well as the growth and development of plants on serpentine rocks is very important to understand the ecology and evolution of plant adaptation to unfavourable conditions.

Material and Methods

Studies were carried out in 2018–2020 on the dumps of Anatol'sko-Shilovsky asbestos deposit located within Tagilo-Nevyansk hyperbasite area on the eastern slope of the Middle Urals, 132 km north of Yekaterinburg, 2.5 km from Novoasbest village, Sverdlovsk Region, Russia (Fig. 1).

The relief of province is ridge-valley, dissected, altitude ranges from 298 to 325 m a.s.l. The climate of region is sharply continental. The average annual air temperature is +1.0 °C, the average

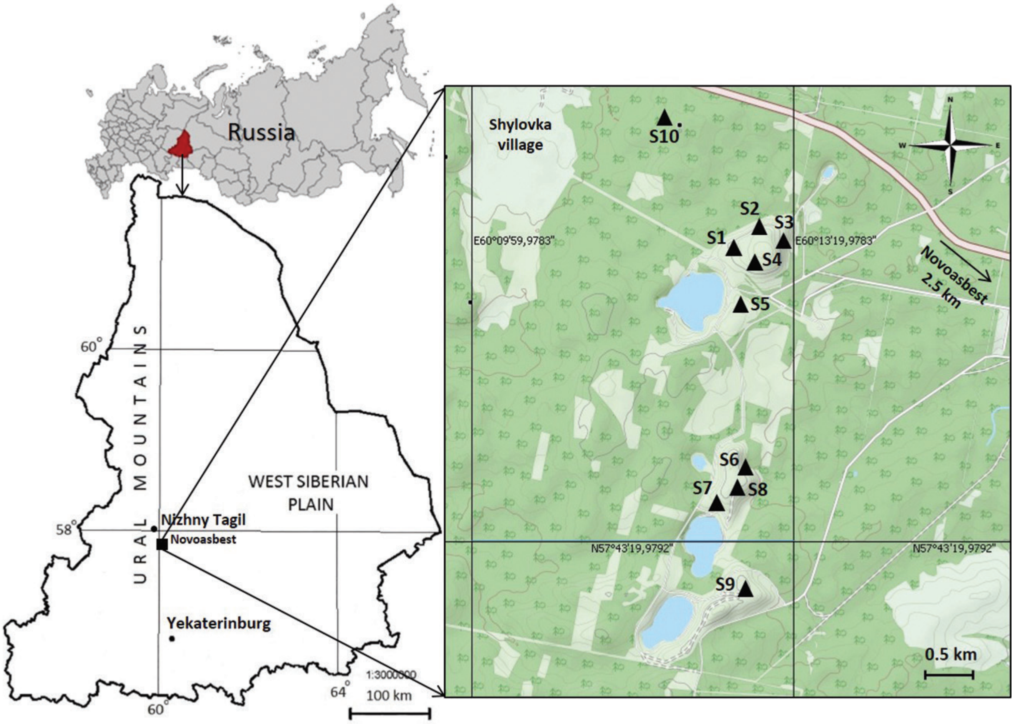

Fig. 1. Schematic map of Sverdlovsk Region with the study sites (S1–S10).

July temperature is +17.2 °C, the average January temperature is -16.0 °C (according to weather station in Nizhny Tagil) (Shakirov 2011). Minimum temperature was recorded in December (-39 °C), maximum in July (+35 °C). The average annual rainfall is 628 mm. The snow cover lasts from the second half of November to the beginning of April; its average thickness is 0.7 m. The depth of soil freezing is 0.8–1.7 m. The prevailing direction of winds in summer is west and south-west, in winter – west and north-west (Shakirov 2011).

At the Anatol'sko-Shilovsky deposit, a fibrous variety of serpentines (rezhikite-asbestos) belonging to the group of amphibole asbestos was mined as a mineral. The average asbestos content in rocks was about 4–5 % (Yanin 2013).

The development of fields was carried out by open pit mining from 1952 to 1992. As a result, the enterprise formed large 2–5-tier dumps of overburden, dumped by vehicles: Shilovsky (S1–S4), Anatol'sky (S6–S8), and Yuzhny (S9) with a total mass of 228.9 million tons. In addition, the dump-open pit complex includes a waste dump of crushing factory (S5). The dumps are mainly composed by rocks and only about 10 % of volume is loose material (harzburgites, serpentines and clay). As a control (S10), the pine forest community growing on the slope of Golaya Mount located between Shilovka and Novoasbest villages (about 2.0–2.5 km from Anatol'sko-Shilovsky asbestos deposit) was studied (Fig. 1, Table 1).

Table 1. General characteristics of studied sites.

Study area	Coordinates	Dump area, ha	Dump height, m	Sites	Code
Shilovsky dump	57°44′57″ N 60°12′35″ E	40	up to 50	Cultivated forest community	S1
				Forest community on the flat top	S2
				Emerging forest on the flat top	S3
				Emerging forest on the lower tier	S4
Stone cutter dump	57°44′34″ N 60°12′32″ E	7	5–8	Area with sparse undersized vegetation	S5
Anatol'sky dump	57°43′34″ N 60°12′30″ E	35	30–40	Forest community (30–40 years old)	S6
				Forest community (20–30 years old)	S7
				Emerging forest at the edge and along the road	S8
Yuzhny dump	57°43′04″ N 60°12′45″ E	35	up to 40	Sparse forest undersized vegetation	S9
Control site	57°46′05″ N 60°12′27″ E	-	-	Natural forest community on the slope of Golaya Mount	S10

The quarry-dump complex is surrounded by pine herbaceous and pine herbaceous bilberry forests dominated by *Pinus sylvestris* L. with the admixture of *Larix sibirica* Ledeb. and *Betula pendula* Roth. *Juniperus communis* L. and *Tilia cordata* Mill. were found undergrowth. The soils in this territory are sod-medium-podzolic, thin, heavily crushed, formed on ultrabasic rocks.

The study of phytocoenosis formed on the dumps was carried out according to generally accepted geobotanical methods: floristic richness as number of species in a community, abundance of each species according to Drude (Nekrasova et al. 2020), and similarity of floristic composition were determined. The qualitative similarity was assessed using Sørensen–Chekanovsky coefficient, calculated on the basis of pairwise comparison of the floristic lists in the studied sites by the presence of common species (Smith and Smith 2012). To quantify the species biodiversity, Shannon–Wiener diversity index was calculated and on its basis, Pielou evenness index, an indicator of community equitability, was estimated as it was described earlier (Filimonova et al. 2020). At each site at least 3 plots (S = 100 m^2) and at each plots at least 15 of Raunkier sites (S = 0.25 m^2) were laid; tree crown density, total projective cover (TPC) of vegetation by tiers were determined, and recalculation and measurement of tree species were carried out.

Soil samples for research were taken at each site from depth of 20 cm. The main physicochemical characteristics (presented in Table 3) were determined by the conventional methods of Russian pedology (Arinushkina 1970, Vorobyova 2006). The particle size distribution was determined by the pipette method; the total organic carbon (TOC) was measured by Tyurin's method; soil pH was analysed potentiometrically in the water solution (1:2.5 *w/v*). Exchangeable Ca^{2+} and Mg^{2+} were detected by the titration method (Nekrasova et al. 2020). The hygroscopic moisture content of soil was determined by air drying method (Maiti 2013).

For comparative studies, *P. sylvestris* trees of the same age (20–25-year-old) were selected both in the natural forest community (control) and on the dumps of the Anatol'sko-Shilovsky asbestos deposit.

The statistical interpretation of the results was made by using the standard software package StatSoft STATISTICA 12.0 and Microsoft Excel 2013. The cluster analysis was performed using the following parameters: distance measure – Euclidean distance; the union rule is a single link. The initial data were the estimates of the abundance of species according to Drude, translated into expert estimates of the abundance (Chibrik and Yelkin 1991). Data shown in Table 3 are the means ± standard errors (n = 3). The correlation analysis was performed using Pearson's r-test at $p < 0.05$ (n = 10).

Results and Discussion

The study of the Anatol'sko-Shilovsky serpentine dumps showed the uneven formation of vegetation. This is probably due to variegated ecological conditions of technogenic habitats such as the composition and properties of rocks, the degree of rockiness and the compaction of surface, the exposure and steepness of slopes, the forms of meso- and micro-relief (Rakov and Chibrik 2009, Filimonova et al. 2020).

Site 1 was located on the southeastern side of Shilovsky dump loose overburden. In 1974 seedlings of *P. sylvestris* and *L. sibirica* were planted in this site. By 2018, a forest community with tree crown density of 0.7 was formed at the planting site. The average height of *P. sylvestris* was 9.3 ±1.0 m; the trunk diameter at 1.3 m was 7.5 ±0.6 cm; the average height of *L. sibirica* was 15.8 ±2.6 m; the trunk diameter at 1.3 m was 13.8 ±1.7 cm. In herb-shrub layer cover, TPC with vegetation varied from 0 to 20 % (Table 2). Species composition was dominated by *Calamagrostis arundinacea* (L.) Roth, *C. epigeios* (L.) Roth, with a high abundance of *Festuca pratensis* Huds., *Seseli libanotis* (L.) W.D.J. Koch, *Hieracium umbellatum* L., *Solidago virgaurea* L., *Poa pratensis* L., *Orthilia secunda* (L.) House, *Fragaria vesca* L., *Achillea millefolium* L.

Site 2 was located on the flat top of Shilovsky dump in the area of loose soil dumping. The forest phytocoenosis with the dominance of *P. sylvestris* was formed there; the age of trees was between 20 and 30 years. Their height reached 7–8 m, the diameter of trunks was 12–16 cm. Tree crown density was 0.6–0.7 (Table 2). Forest species found singularly were *Populus laurifolia* Ledeb., *P. suaveolens* Fisch., *Salix caprea* L. The herb-shrub layer was sparse, and TPC varied from 10 to 40 %. Shrubs included *Vaccinium vitis-idaea* L. and *V. myrtillus* L. Herbaceous species were presented by *C. epigeios*, *C. arundinacea*, *F. vesca*, *Rubus saxatilis* L., *Dendranthema zawadskii* (Herbich) Tzvel.

Site 3 was located on the top of Shilovsky dump covered with stony compacted soil. This site was overgrown with undergrowth *P. sylvestris*, *B. pendula*, *Populus tremula* L., *P. balsamifera* L., *P. laurifolia*, *P. suaveolens*, *Salix bebbiana* Sarg., *S. caprea*, *S. myrsinifolia* Salisb., *S. pentandra* L., *S. phylicifolia* L., *S. rosmarinifolia* L. and *S. viminalis* L. The height of the trees and shrubs did not exceed 2.0 m. Herbaceous vegetation was fragmentary and sparse, and TPC varied from 0 to 10 %. The most common herbaceous species were *D. zawadskii*, *Epipactis atro-*

rubens (Hoffm.) Besser, *C. epigeios*, *Rumex thyrsiflorus* Fingerh.; other species were rare.

Site 4 was an open area located on berm of the first tier (on the south side of Shilovsky dump). On the flat surface, rolled by road transport, there was a sparse undergrowth of *B. pendula*, *P. sylvestris*, *P. tremula*, as well as species of *Populus* and *Salix* genera. There was no dense forest stand. In herb-shrub layer (TPC 0–15 %), *D. zawadskii*, *E. atrorubens*, *Thymus talijevii* Klok. & Des.-Shost., *S. virgaurea*, *C. epigeios* prevailed; *O. secunda*, *Antennaria dioica* (L.) Gaertn., *F. vesca* were rare (Table 2).

Site 5 was located on a crushing factory waste heap. The dump is being overgrown with the forest species undergrowth: *P. sylvestris* and *B. pendula* were 0.3–0.7 m high; *P. tremula* was found occasionally. Some individuals of *P. sylvestris* were 20–25 years old. Herb-shrub cover was very sparse (TPC was 0–5 %) and was represented by single individuals of *Dianthus versicolor* Fisch. ex Link, *R. thyrsiflorus*, *D. zawadskii*, *E. atrorubens*, *Festuca rubra* L.

Site 6 was a forest phytocoenosis formed on the second tier of Anatol'sky dump on the eastern side. The tree layer was dominated by *P. sylvestris*, the age of trees was from 10 to 35 years, tree crown density was 0.5–0.6. The average density of *P. sylvestris* was 10 individuals per 100 m^2, height varied from 4 to 9 m. *Sorbus aucuparia* L. and *Chamaecytisus ruthenicus* (Fisch. ex Wołoszcz.) Klásková were found in undergrowth. *C. arundinacea* dominated in herb-shrub layer (TPC was 0–20 %);

Table 2. Geobotanical characteristics and biodiversity of phytocoenoses in studied sites.

Code	Phytocoenotic characteristics				Biodiversity of studied populations			
	Community age, years	Tree crown density	Herb-shrub layer cover, %	Moss-lichen layer cover, %	Species richness, total number of vascular plants	Species diversity, number of species per 0.25 m^2/min–max	Shannon-Wiener index	Pielou evenness index
S1	43–45	0.7	0–20	15–35	39	4.1/1–6	2.17	0.90
S2	25–30	0.6–0.7	10–40	1–5	46	5.2/3–8	2.56	0.92
S3	25–27	-	0–10	-	48	3.8/0–8	2.58	0.85
S4	25–27	-	0–15	1–2	39	2.4/0–7	2.48	0.80
S5	20–25	-	0–5	1–5	11	2.1/1–3	1.98	0.86
S6	30–35	0.5–0.6	0–20	60–80	32	6.9/5–9	2.80	0.94
S7	25–30	0.5–0.6	40–50	35–45	51	4.6/1–8	2.96	0.88
S8	25–27	-	15–30	1–5	38	5.9/1–10	2.68	0.89
S9	25–27	-	0–3	-	22	1.9/0–5	1.60	0.69
S10	60–80	0.5–0.6	40–80	20–65	76	8.6/4–14	3.21	0.84

S. libanotis, *Th. talijevii*, *Sanguisorba officinalis* L. were found in groups, shrubs included *V. myrtillus* and *V. vitis-idaea*.

Site 7 was located on the southwestern side of Anatol'sky dump. The forest phytocoenosis with the dominance of *P. sylvestris* was formed there; the age of trees was between 25 and 30 years, tree crown density was 0.5–0.6 (the height was from 6 to 8 m). *Trifolium lupinaster* L. predominated in herb-shrub layer (TPC was 10–30 %); there were only single individuals of *C. arundinacea*, *C. epigeios*, *S. virgaurea*, *H. umbellatum*, *D. zawadskii*.

Site 8 was located on a tier 2 berm of Anatol'sky dump. Here at the edge of forest phytocoenosis in an open area with a compacted substrate undergrowth included *P. sylvestris* and *B. pendula* and species of *Populus* genus (*P. balsamifera*, *P. laurifolia*, *P. suaveolens*, *P. tremula*), and *Salix* genus (*S. bebbiana*, *Salix cinerea* L., *S. phylicifolia*). *D. zawadskii*, *Th. talijevii* dominated in sparse herbaceous layer (TPC 15–25 %). High abundance had *Festuca rubra*, *F. pratensis*, *E. atrorubens*, *H. umbellatum*, *T. lupinaster*, *A. millefolium*, *F. vesca*, *Lathyrus pratensis* L.

Site 9 was located on the upper tier of Yuzhny dump. Plateau-like top and slopes of dump were overgrown, mainly with low-growing forest vegetation; there was no closeness of tree layer. Dominant tree species were *P. sylvestris*, *Betula pubescens* Ehrh., *B. pendula;* undergrowth and seedlings were presented by *P. balsamifera*, *P. laurifolia*, *P. suaveolens*, *P. tremula*, *S. phylicifolia*, *S. myrsinifolia*, *S. caprea*, *S. pentandra*. TPC of herb-shrub layer was 1–3 %. Herbaceous species: *E. atrorubens*, *C. epigeios*, *F. rubra*, *Poa trivialis* L., and *Puccinellia hauptiana* (V.I. Krecz.) Kitag. were rare.

Control forest area (site 10) was dominated by *P. sylvestris*. The average age of trees was between 60 and 80 years, height of stand averaged 20 m, the diameter of trees at 1.3 m varied from 15 to 35 cm, tree crown density was 0.5–0.6 (Table 2). Besides, *L. sibirica*, *B. pendula*, *Picea obovata* Ledeb. were rarely found in stand; single individuals of *J. communis*, *Rosa acicularis* Lindl., *S. aucuparia*, *Ch. ruthenicus* grew in undergrowth. In it *P. sylvestris* and rare groups of *B. pendula* grew in height from 0.4 to 2.5 m. In herb-shrub layer (TPC 40–80 %), shrubs were represented by such species as *V. myrtillus* and *V. vitis-idaea*, *Linnaea borealis* L., *O. secunda*, *Pyrola media* Sw. and others; the herbaceous species were dominated by *C. arundinacea*, *Brachypodium pinnatum* (L.) Beauv., *Geranium sylvaticum* L., *R. saxatilis*, *F. vesca*, *Potentilla erecta* (L.) Raeusch. Orchids, such as *E. atrorubens*, *Platanthera bifolia* (L.) Rich., and *Goodyera repens* (L.) R.Br., were rarely found in herb-shrub layer on mountain side. *D. zawadskii* and *Th. talijevii* grew on rocky areas with a thin grassy cover.

The indicators of the species richness of studied plant communities are presented in Table 2. Plant communities formed on serpentine dumps (S1–S9) were characterised by lower values of **α-**diversity indicators (species richness and diversity, Shannon-Wiener index) and a sparser vegetation cover compared to control forest phytocoenosis (S10). With the increase in the age of plant communities, the increase in **α**-diversity was observed. Pielou evenness index varied from 0.69 to 0.94 on studied sites, which indicates an uneven distribution of plants. The plant communities formed on dumps and in control forest phytocoenosis had a low Chekanovsky-Sørensen similarity coefficient (0.38).

Previously, agrochemical analysis showed that the substrate of Anatol'sko

-Shilovsky deposit was characterised by a low content of alkaline hydrolysable nitrogen, an average content of available phosphorus and potassium, and at the same time, increased concentrations of total and available nickel, chromium, cobalt and iron compared to another type of substrate formed on granites (Filimonova et al. 2020).

The analysis of the substrates of studied sites revealed their substantial variations (Table 3). The pH of substrate varied from slightly acidic (6.44–6.79) under forest phytocoenoses to alkaline (7.75–8.11) in open stony areas dominated by sparse undersized forest vegetation. In areas with a higher content of clay particles moisture content was significantly (2.1–3.5 times) higher than in areas with a predominance of sand fraction. The studies have shown that the forest phytocoenoses on dumps were formed in the areas with admixture of loose overburden. Clay had a higher water-holding capacity than sand and gravel. Ca^{2+} content in dump samples varied from 3.6 to 5.4 mmol per 100 g of substrate. Soil from forest phytocoenoses contained more TOC and Mg^{2+}, in comparison with stony areas under sparse undersized vegetation. The ratio of Mg:Ca varied from one to six (2.9 on average) in all studied sites.

Table 3. Physicochemical characteristics of soil in studied sites.

Code	pH_{H_2O}	Ca^{2+}, mmol/100 g of substrate	Mg^{2+}, mmol/100 g of substrate	Total organic carbon, %	Hygroscopic moisture, %	Particle diameter, %	
						1.0–0.01 mm	<0.01 mm
S1	6.44 ±0.01	4.72 ±0.22	17.30 ±1.12	4.15 ±0.17	4.69 ±0.05	45.3	54.7
S2	7.06 ±0.02	4.51 ±0.30	13.34 ±0.92	2.81 ±0.09	3.23 ±0.06	51.2	48.8
S3	8.11 ±0.06	5.14 ±0.42	6.51 ±0.35	0.46 ±0.02	2.68 ±0.02	48.6	21.4
S4	6.67 ±0.02	3.60 ±0.12	15.50 ±1.14	0.52 ±0.03	1.01 ±0.02	41.2	58.8
S5	7.75 ±0.02	4.49 ±0.25	9.54 ±0.66	0.70 ±0.04	1.99 ±0.03	77.5	22.5
S6	6.74 ±0.03	3.44 ±0.14	20.62 ±1.50	2.03 ±0.10	5.71 ±0.10	32.8	67.2
S7	6.79 ±0.02	4.10 ±0.20	12.30 ±0.82	4.16 ±0.16	3.22 ±0.06	45.5	54.5
S8	6.83 ±0.04	4.60 ±0.23	14.22 ±0.91	2.62 ±0.08	4.39 ±0.05	42.5	57.5
S9	8.06 ±0.10	5.39 ±0.26	5.50 ±0.15	0.49 ±0.02	1.56 ±0.02	81.1	18.9
S10	6.55 ±0.03	7.24 ±0.36	9.04 ±0.50	8.16 ±0.22	3.45 ±0.03	57.7	42.3

Note: data presented as the means ± standard errors (n = 3).

The dendrogram of the species composition similarity of plant communities formed on dumps of Anatol'sko-Shilovsky asbestos deposit taking into account species abundance (Euclidean distances) divided the studied sites into two groups (Fig. 2). The first group included forest phytocoenoses with the high density of forest species with a pronounced herb-shrub layer. The second group included plant communities with sparse undersized tree undergrowth with a weakly expressed herb-shrub layer.

According to the results of the cluster analysis of plant communities on the dumps of Anatol'sko-Shilovsky asbestos deposit it was revealed that granulometric composition and compaction of substrate were determining factors in serpentine rocks vegetation formation. Factor I combined areas which substrates contained the admixture of loose overburden (Ta-

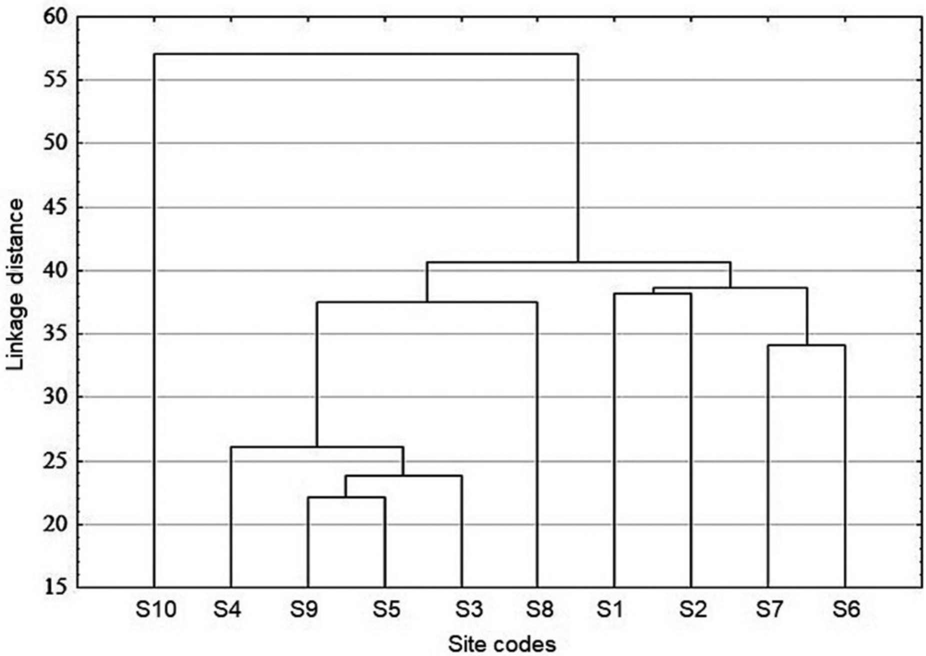

Fig. 2. Dendrogram of species composition similarity of studied plant communities, taking into account species abundance (Euclidean distances).

ble 4). In these areas the formation of vegetation proceeded according to the forest type. According to factor II the open areas of wide berms and upper tiers with strong surface rockiness and compaction of substrates with automotive technology were grouped.

On dump sites with the admixture of loose overburden (factor I) forest phytocoenoses were formed with the predominance of *P. sylvestris*. In herb-shrub layer of forest and meadow-forest phytocoenoses such species as *C. arundinacea*, *C. epigeios*, *S. libanotis*, *R. saxatilis*, *V. vitis-idaea*, *T. lupinaster* had the highest factor loads (Table 5). In open habitats (factor II), species of the herb-shrub layer with a high abundance and occurrence had the highest factor loads. These species include a relict in the Urals *D.*

Table 4. Factor loads of studied plant communities, taking into account species abundance.

Sites	Factor loadings	
	Factor I	Factor II
S1	**0.82**	0.3
S2	**0.84**	0.24
S3	0.09	**0.81**
S4	0	**0.87**
S5	0.29	**0.75**
S6	**0.91**	0.17
S7	**0.87**	0.27
S8	0.2	**0.63**
S9	0,49	**0,55**
S10	**0.88**	-0.05
Dispersion	**0.41**	**0.29**

Note: Loadings given in bold show the highest correlations between original values and principal components scores.

Table 5. Factor loads of dominant species in studied plant communities.

Species name	Factor loadings	
	Factor I	Factor II
Pinus sylvestris L.	**9.87**	**2.71**
Betula pendula Roth	-0.54	**4.46**
Dendranthema zawadskii (Herbich) Tzvel.	-0.21	**4.33**
Epipactis atrorubens (Hoffm.) Besser	-0.71	**4.15**
Calamagrostis arundinacea (L.) Roth	**2.74**	-1.15
Thymus talijevii Klok. & Des.-Shost.	-0.49	**2.90**
Calamagrostis epigeios (L.) Roth	**1.89**	**1.2**
Seseli libanotis (L.) W.D.J.Koch	**1.67**	-0.99
Fragaria vesca L.	**1.24**	-0.61
Populus tremula L.	-0.63	**2.22**
Salix phylicifolia L.	-0.54	**1.43**
Dianthus versicolor Fisch. ex Link	-0.59	**1.58**
Rumex thyrsiflorus Fingerh.	-0.13	**1.47**

Note: Loadings given in bold show the highest correlations between original values and principal components scores.

zawadskii (Asteraceae Dumort), which in its natural habitats prefers highly illuminated and well-warmed coastal outcrops of limestone and calcareous shale, open rubble talus, as well as two rare plants included in the Red Book of Sverdlovsk region, such as *E. atrorubens* (Orchidaceae Juss.), which occurs naturally on dry stony slopes and rocky outcrops of limestone and gypsum in dry light pine and birch forests (Vakhrameeva et al. 2008), and *Th. talijevii* (Lamiaceae Lindl.), growing on scree and calcareous outcrops. Additionally, herbaceous species that prefer limestone outcrops under natural conditions (*D. versicolor*, *R. thyrsiflorus*) and some deciduous species forming tree undergrowth (*B. pendula*, *P. tremula*, *S. phylicifolia*) also had high factor loads.

Common to all sites was dominance of *P. sylvestris* (57–99 %), the most common forest-forming species in the Urals (Fig. 3). It is a species with a pioneering ecological strategy capable of quickly colonising disturbed areas characterised by strong rockiness, low fertility, and an unfavourable water regime (Smirnova et al. 2004, Treshchevskaya et al. 2017). Other woody plant species accounted for 1 to 43 %.

Morphological features of *P. sylvestris* are highly variable within range. From southern taiga and forest-steppe towards north to forest-tundra and south to steppe island forests, as well as from plain to mountains, there is a gradual decrease in absolute dimensions of trunk, crown, shoots, needles (Mamaev 1983, Galdina and Khazova 2019).

The analysis of the morphological parameters of *P. sylvestris,* carried out earlier, showed that under conditions of dumps in areas with a compacted stony substrate, the indicators of tree height, the average growth of trunk and the length of needles decreased, that indicates about xerophytic conditions (Lukina et al. 2021). A similar reaction of plants growing on serpentine substrate was described by some authors (Alexander et al. 2007, Giuliani et al. 2008).

Pearson correlation coefficients revealed a high dependence of morphological parameters of *P. sylvestris* on properties of the substrate. So height and growth of trunk depended on content of hygroscopic moisture (r_p = 0.88, n = 10), associated with clay fraction content. In addition, these morphological parameters of *P. sylvestris* showed a high degree of dependence on acidity level of substrate (r_p = -0.89, r_p = -0.85, n = 10). In areas

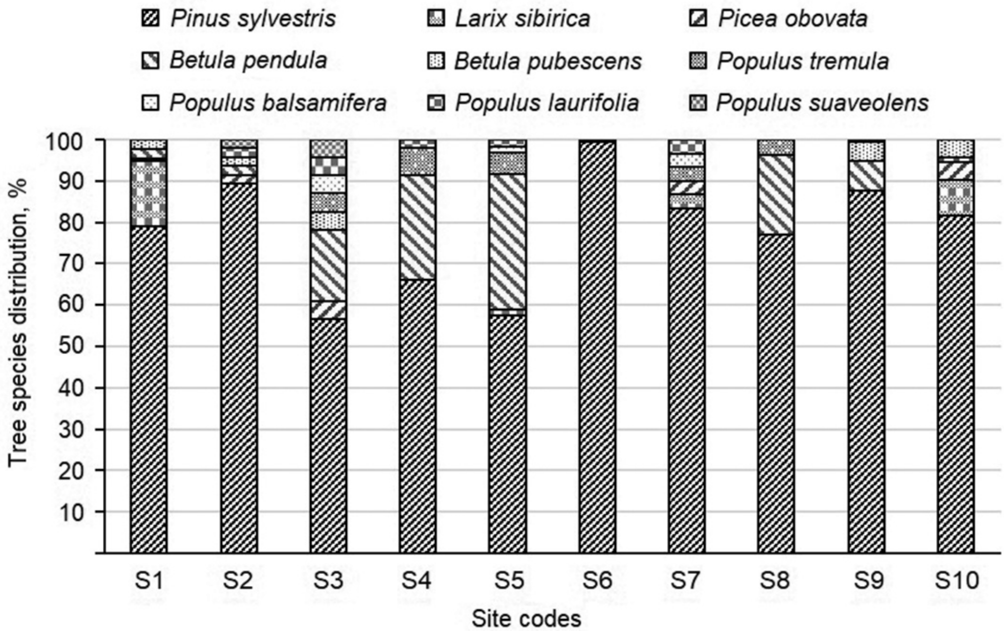

Fig. 3. Percentage distribution of tree species in studied plant communities.

with high pH values a decrease in the growth of *P. sylvestris* was observed. This is probably because of mycorrhizal fungi entering into symbiosis with *P. sylvestris* are acidophiles (Smith and Read 2008).

Our research also revealed a high degree of dependence of trunk height and growth of *P. sylvestris* on Mg content (r_p = 0.93, r_p = 0.89, n = 10). Many authors have previously noted the influence of a number of environmental factors, such as water deficiency, Mg:Ca ratio, high content of Ni and other metals, on the formation of vegetation on serpentine soils (Proctor 1999, Hughes et al. 2001, Brady et al. 2005).

Conclusions

The geobotanical survey of 20–40-year-old serpentine dumps of Anatol'sko-Shilovsky asbestos deposit showed that the intensity of their overgrowth depended on rock composition. Forest phytocoenoses dominated by *Pinus sylvestris* (79–99 %) were formed on the dump sites, composed of highly stony rocks with the admixture of loose rocks of light particle size distribution. Slopes and dump sites composed of rocks with a slight admixture of loose rocks were overgrown with sparse undersized woody vegetation with a predominance of *P. sylvestris* (57–66 %) and with a high proportion of deciduous species such as *Betula pendula*, *B. pubescens*, *Larix sibirica*, *Picea obovata*, *Populus tremula*, *P. balsamifera*, *P. laurifolia, P. suaveolenes* (34–43 %). The herbaceous vegetation on dumps was sparse; the total projective vegetation cover varied from 5 to 50 %, averaging 20 %. In the open areas of dumps under conditions of low competition, the relict species *Dendranthema zawadskii* and rare for the Urals species, *Epipactis atrorubens* (orchid) and *Thymus talijevii*, were found.

The formation of plant communities was influenced by such properties of the substrate as moisture content, pH value, Mg:Ca ratio. In particular, the high positive correlation between such morphological characteristics of *P. sylvestris* as height and growth of trunk with hygroscopic moisture and Mg content (r_p = 0.88–0.92), and a negative correlation with the pH level (r_p = 0.85–0.89) were revealed.

The process of vegetation formation on serpentine dumps is very long, depending on specific edaphic conditions. Further investigation of the self-overgrowing processes will make it possible to determine the rate of colonisation by plants on substrate of different geological ages brought to the surface, which will make it possible to develop effective methods for the biological reclamation of disturbed territories.

Acknowledgements

The reported study was partly funded by the Russian Foundation for Basic Research and the Government of the Sverdlovsk Region (Project No 20-44-660011) and a Ministry of Science and Higher Education of the Russian Federation (Project No FEUZ-2020-0057).

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