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Structure of Plant Communities in the Early Succession Stages on Anthropogenic Sandy Outcrops of the Forest Tundra and Northern Taiga of Western Siberia

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Abstract—The results of a study of the taxonomic, ecological, and phytocenotic structure of plant communities formed in the early stages of overgrowth of the anthropogenic sandy outcrops within the forest-tundra zone and northern taiga forest subzone of Western Siberia are presented. In the early stages of vegetative-cover restoration, there are from 2 to 11 species growing into sparse communities of the classes *Loiseleurio-Vaccinietea*, *Artemisietea vulgaris*, and *Koelerio-Corynephoretea*. The participation of some meso-xerophytic forest-tundra, meadow-margin, and weed herbaceous plant and dwarf shrubs species, mostly with ruderal and stress-tolerant eco-phytocenotic strategies, as well as with secondary strategies—violent-ruderal and ruderal–stress-tolerant—in the secondary succession on the sandy outcrops have been shown. The primary succession begins at the bottom and slopes of the pit ditches, as well on the surface of the sand dunes, and proceeds at an accelerated scenario. Hygro-, meso- and xerophilous species, predominantly oligo-mesotrophic rhizome and densely firm-bunch grasses and shrubs of the native flora, as well as ground lichens, participate in the early stages of succession.

Keywords: oversanding, sandy outcrop, succession, overgrowing, north-taiga subzone, forest-tundra zone, Western Siberia

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INTRODUCTION

Currently, one of the most acute environmental problems in the northern regions of Western Siberia is the process of oversanding, accompanied by a radical restructuring of primary ecosystems and their further complete destruction. This process is associated with the intensive economic development of the natural resources of the northern territories and, mostly, by the development of sand quarries, the construction of a variety of engineering constructers, and mining works (Moskalenko, 1991; Sizov, 2015). The scale of this phenomenon is so great that the sandy outcrops are clearly visible on satellite images. Extremely unfavorable conditions for representatives of local biota are created within the oversand areas. Nevertheless, over time such outcrops undergo overgrowth, the speed and direction of which depend on a number of factors. The early stage of succession is the most important in this process; it contributes to the consolidation of sand and the subsequent restoration of native vegetation. There are only few publications that cover the problems of anthropogenic sand outcrops overgrowing in the Arctic and Subarctic regions of Western Siberia (Shilova, 1977; Druzhinina and Myalo, 1990; Moskalenko, 1991, 2012; Sumina, 1996, 2012; Telyatnikov and Pristyazhnyuk, 1995; Pristyazhnyuk, 1997; Ishbirdin et al., 1999; Koronatova and Milyaeva, 2011; Ektova and Ermokhina, 2012; Lobotrosova and Sizov, 2016; Sizov and Lobotrosova, 2016) and in the European part of Russia (Lavrinenko et al., 1996; Kulyugina, 2000, 2001, 2004, 2008; Kostina, 2012); however, not all works on Western Siberia show bioecological features of the developed vegetation cover. Meanwhile, the problem of man-made disturbances of vegetation cover and its subsequent restoration in the regions of the permafrost zone will only be exacerbated in the future, which is connected with large-scale plans for the further development of the northern regions of Siberia, mining, and laying of linear engineering structures. This, in turn, causes the correct solutions in the implementation of remediation. The purpose of our research was to study the composition and the structure of plant communities that initiate succession on sandy outcrops of anthropogenic origin in the areas

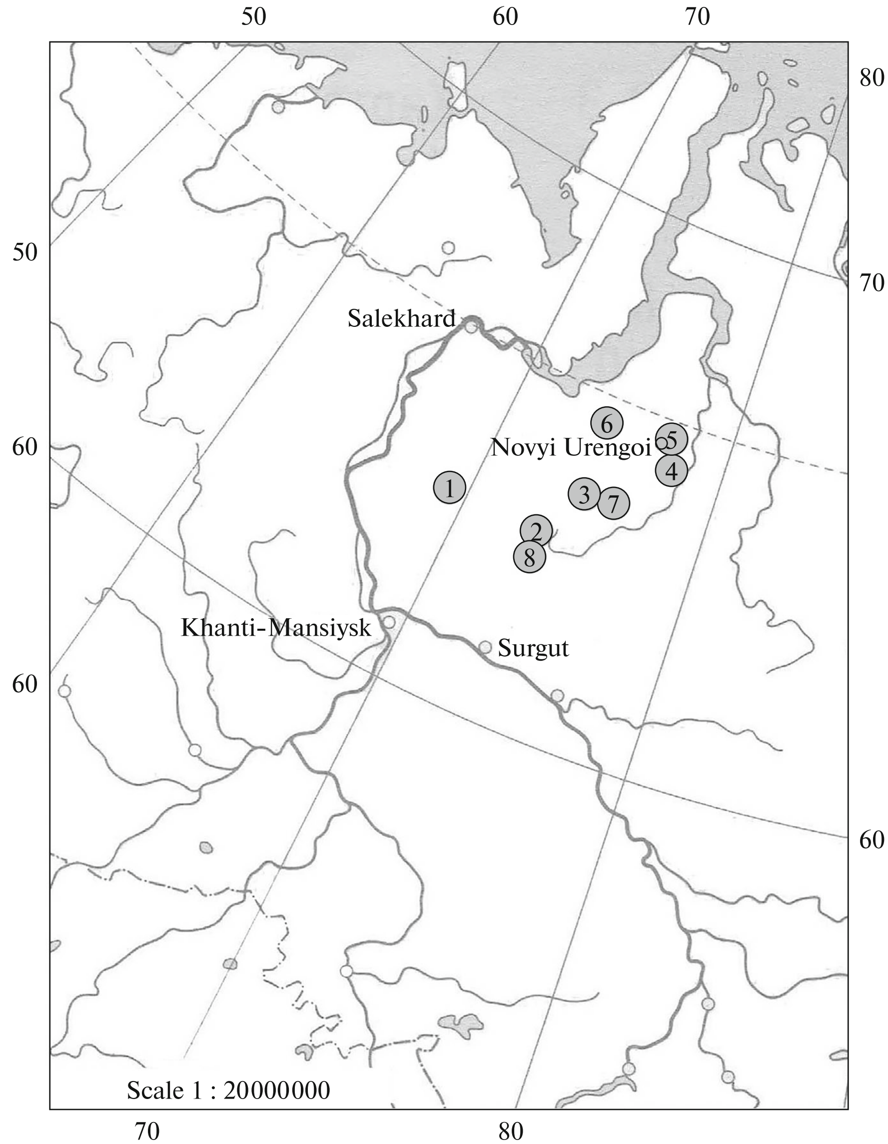

Fig. 1. Location of the studied sand outcrops. The studied sites are marked with numbers (see explanation in text).

of the Western Siberian forest tundra and the subzone of the northern taiga.

MATERIALS AND METHODS

We consider objects of various genesis such as deflation basins, bulge, and aeolian sands caused by the anthropogenic transformation of natural ecosystems and the subsequent effect of wind under the umbrella of sandy outcrops (Kulyugina, 2000, 2004). In order to find out the location and estimate the area of sandy outcrops in the northern regions of Western Siberia, previously actual space images were studied. Their visualization was carried out using Sas.Planet and Google Earth Pro software. The field part of the research was carried out in July–August 2016 in the Beloyarskii and Surgutskii districts of Khanty-Mansiysk Autonomous Okrug—Ugra—(KhMAO) and in Purovskii and Nadymskii districts of the Yamalo-Nenets Autonomous Okrug (YaNAO) (Fig. 1) in the following sites:

(1) Beloyarskii district, KhMAO (63°0′23″ N, 66°32′28″ E), July 24, 2016;

(2) Purovskii district, YaNAO (63°32′22″ N, 74°36′29″ E), July 27, 2016;

(3) Purovskii district, YaNAO (64°17′30″ N, 75°50′6″ E), July 28, 2016;

(4) Purovskii district, YaNAO (65°41′54″ N, 78°1′7″ E), July 29, 2016;

(5) Purovskii district, YaNAO (66°0′0″ N, 77°17′32″ E), July 29, 2016;

(6) Nadymskii district, YaNAO (65°47′37″ N, 74°19′6″ E), July 30, 2016;

(7) Purovskii district, YaNAO (64°17′47″ N, 75°56′10″ E), July 31, 2016;

(8) Surgutskii district, KhMAO (63°1′44″ N, 74°25′47″ E), August 01, 2016.

Two of the studied sites (5 and 6) were located near the southern boundary of the forest-tundra zone; the remaining sites were located within the north-taiga subzone (*Zapadnaya Sibir'*, 1963).

To study the structure of plant communities in various areas of sandy outcrops, stripes of trial plots were laid along transects. The transects in turn were laid from the sites with the most closed and least disturbed vegetation cover to areas with an absence of vegetation cover due to oversanding. The transects, if possible, were laid in similar moistening conditions. Along the transects, trial plots with an area of 1 m^2 were laid. The number of trial plots along the transects varied from 5 to 10, depending on the extent of the transect and the nature of the change in vegetation along them. Thirteen transect and 58 plots were laid. The abundance of all the higher plants species was estimated according to the Braun–Blanquet scale at the plots (Aleksandrova, 1969). The items of the plant cover were measured according to the following scale: *r*, single species; +, <1%; *1*, 1–5%; *2*, 6–25%; *3*, 26–50%; *4*, 51–75%; and *5*, 76–100%.

The laboratory part of the research consisted of determining the plants and processing geobotanical descriptions. The names of the vascular plants species are given according to the bulletin of S.K. Cherepanov (1995), mosses according to the list of mosses of Eastern Europe and Northern Asia (Ignatov et al., 2006), and lichens according to the bulletin of G.P. Urbanavichyus (2010). The geobotanical descriptions were processed using Microsoft Excel 2013 software in accordance with the classification methods of Brown–Blanquet (Aleksandrova, 1969; Mirkin, Naumova, 2012). The plant samples were stored in the herbarium of the Tobolsk Complex Scientific Station, Ural Branch, Russian Academy of Sciences (Tobolsk).

RESULTS AND DISCUSSION

Studies have shown that the investigated sand outcrops have anthropogenic origins, some of which are represented by anthropogenically transformed bulges of aeolian relief elements of natural origin. Among the first, two groups of objects can be marked: (1) existing and developed sand quarries and (2) outcrops where the vegetation cover has been disturbed due to the movement of vehicles and the construction of elements of industrial infrastructure (unpaved roads, oil and gas pipelines, power lines, and production sites). After a decrease or cessation of direct anthropogenic impact on these objects, the vegetation restoration process begins there, and by its origin it can be both primary and secondary succession. Primary (ecogenetic) succession begins in areas where vegetation and soil have been completely destroyed during economic activities. Such conditions are created, for example, at the bottom and the slopes of pit ditches and on the surface of sand dunes of significant thickness. Due to the relatively small areas of such sites, primary succession proceeds by the accelerated scenario; the species composition of its early stages is determined mainly by anemochore and zoochoric representatives of the surrounding indigenous and derived ecosystems. The secondary (regenerative) succession develops in places of sand bulges, under which soil and viable plant derivatives are preserved. A relatively small number of plants and ground lichens participate in the primary and secondary types of overgrowth of sand outcrops; their seeds, fruits, spores, and vegetative parts are provided by nearby ecosystems, and this phytocoenotically brings together seral communities developing at different sites both with the destroyed and preserved soil cover.

The succession forms of the early stages of overgrowth of sandy outcrops with completely destroyed soil and vegetation cover shows the diversity of germing plant communities, which are rather difficult to classify. The difficulties of classification, together with the small number of species and the weak closeness of the pioneer communities, also include a strong variation in the species composition, assembly and abundance of dominants, the presence of different ecological groups of plants, widespread geographical distribution, species habitat versatility, etc. (Sumina, 2012). Such open pioneer cenoses can exist for a long time as chronic seral communities with permanent or occasional disturbances of habitats. However, they can also develop rather quickly in the following stages of succession during ecotope stabilization (Ishbirdin et al., 1988). The investigated parts of sandy outcrops, despite their localization in different natural zones, show a certain similarity in the types of overgrowth associated primarily with the properties of the substrate. Some differences in the composition of developing plant communities are determined by the local topography of the overgrowing sites and soil moistening.

Forest-Tundra Zone

The area of the investigated sand outcrops located in the forest-tundra zone (sites 5 and 6). Before the beginning of the anthropogenic transformation of the landscape, it was covered with rare dry pine forests with the domination of representatives of the family Ericaceae and the ground lichens in the second storey. They indicate the environmental conditions with insufficient moisture of the substrate. The overgrowth of sandy outcrops in the studied quarries has small differences at different sites, depending on soil moisture. The habitats can be divided into two groups: normal and wet (*a*) and dry (*b*) ecotopes.

Fig. 2. Early stage of succession, sand fixing by *Juncus trifidus* L. Photo by V.I. Kapitonov.

Normal and wet habitats. The most stable and favorable conditions for vegetation restoration are formed on the bottom of quarries with sufficient (sometimes excessive) moisture. The overgrowth of such sites begins with the appearance of meso- and hygrophilous oligo-mesotrophic perennial species with a predominantly violent-ruderal strategy. One of the most active participants in this process is *Juncus trifidus* L., whose dense sods effectively trap sand particles and contribute to their fixation (Fig. 2). On moister and damper areas *Carex acuta* L. dominates. These two species in different variants of the initial stage of succession may be accompanied by several other species with very low abundance values. These species include *Eriophorum vaginatum* L., *Salix triandra* L., and *Pinus sylvestris* L., as well as leafy moss *Polytrichum juniperinum* Hedw. (Table 1, descriptions 1–4).

The next stage of the vegetation development at the bottom of sand quarries is an increase in the abundance of cotton grass and the appearance and spread of a number of hydrophilous species: *Eriophorum angustifolium* Honck. and *Calamagrostis canescens* (Weber) Roth. An increase in the occurrence and abundance of *Eriophorum angustifolium* (=*E. polystachion* L., nom. ambig.) in anthropogenically disturbed environments of the West Siberian northern taiga was also noted by Moskalenko (2012). On moistened sandy outcrops, the behavior of this species corresponds to the intermediate violet–ruderal type of the ecological–phytocoenotic strategy, since the plants, growing rapidly under relatively favorable conditions in the absence of competition, retain their positions for a long time, but quickly give in with the next external adverse effect.

The communities formed at the bottom of sand quarries under normal or sometimes excessive moistening conditions within the forest-tundra zone (Table 1, descriptions 1–4). They have similarities with the communities described in Pechora tundra by Kulyugina (2008). She also showed that similar plant groups should be classified as association *Arctostaphylo alpini-Empetretum hermaphroditi* (Zinserling 1935) Koroleva 1994, which belongs to the alliance *Phyllodoco-Vaccinion myrtilli* Nordhagen 1936, the order *Rhododendro-Vaccinietalia* Br.-Bl. in Br.-Bl. et Jenny 1926 of the class *Loiseleurio-Vaccinietea* Eggler ex Schubert 1960. The synonymy and detailed characteristics of the syntaxa were also presented (Kulyugina, 2008). This order includes arctoalpine erica-subshrub and shrub moss–lichen communities on oligotrophic acid substrates common in Eurasia and North America (Mirkin and Naumova, 2012). Diagnostic species of the class and the order are *Arctous alpina* (L.) Niedenzu, *Empetrum nigrum* L., *Cladonia stellaris* (Opiz) Pouzar et Vězda, *Vaccinium vitis-idea* L., *V. uliginosum* L., and *Flavocetraria nivalis* (L.) Kärnefelt et A Thell. Within the mentioned association, Kulyugina identified variant *Jun-*

cus trifidus; we refer to this variant the communities described by us with the participation of this species.

Communities of the *Juncus trifidus* variant develop on flattened sites or sloping slopes of the outcrops on a well-sorted sandy substrate with noticeable wind operation. The share of sand in soil samples varies from 90 to 95%, clay is 1%, dust particles are 4–9%, and the medium reaction is neutral to slightly alkaline (pH 7.9) (Tokareva and Utkina, 2016). The communities represent floristically highly depleted derivatives of the variant described by Kulyugina. They, as a rule, are single-storey, rarely double-storey, and the storey of ground lichens is completely absent. The unique feature of the communities is the absence of diagnostic class species, which could be explained by their initial stage. The growth of 3 to 5 species was registered in the described communities. The total number of species was eight; the total plant cover ranges from 3–10% in normal humidifying conditions to 50% in wet habitats. Communities developing in more humid areas include species of the class *Phragmito-Magno-Caricetea* Klika in Klika et Novak 1941 (the order *Magno-Caricetalia* Pignatti 1953, the alliance *Magno-Caricion elatae* Koch 1926), sometimes with a high abundance; however, their share did not exceed 20–25% of the floristic composition of communities. In addition, the community includes species of the class *Bidentetea tripartitae* Tx. et al. ex von Rochow 1951, which indicates the disturbance of ecotopes and their sufficient moisture. There are also species of the classes *Oxycocco-Sphagnetea* Br.-Bl. et Tx. ex Westhoff et al. 1946 and *Salicetea purpureae* Moor 1958 in small amounts. Further development of the discussed communities, given that the moisture content of the substrate remains sufficient, will go towards the increase of the plant cover of the grass and shrub storey and the formation of secondary birch forests (Moskalenko, 1991).

Dry habitats. On drier parts of quarries, overgrowth is also mainly initiated by perennial rhizome or firm–bunch grasses, to which tap-rooted grasses (*Trifolium montanum* L. and *Vicia cracca* L.) are added. In regards to the moisture content of the substrate, mesophytes predominate (*Agrostis clavata* Trin., *Bromopsis inermis* (Leyss.) Holub, and *Chamaenerion angustifolium* (L.) Scop., Etc.). Mesoxerophytes (*Trifolium montanum* and *Calamagrostis epigeios* (L.) Roth) also participate in the overgrowth.

On the slopes of sand quarries and the upper parts of the sides of pit ditches, communities adapted to more arid conditions, as well as to mobile substrates, are formed (Table 1, descriptions 5–8). The dominant species on such sites were *Calamagrostis epigeios* and *Festuca polesica* Zapal, and among their partial bushes there are rare individuals of mosses, ground lichens, and *Arctous alpina* (L.) Niedenzu. Subsequently, the plant cover and species richness increase due to the appearance of several more species of bushy lichens and the spread of *Arctous alpina*.

Developing in the high and dry parts of pit ditches, the sparse cenoses of *Festuca polesica* were attributed to the basal community *Festuca polesica* (*Loiseleurio-Vaccinietea / Koelerio-Corynephoretea*). The described communities are a pioneer stage of succession on poorly developed sandy acidic soils. Plant cover varies widely from 4 to 50%, the number of species in the descriptions is 5–11, and the total species number is 16. *Arctous alpina* and *Empetrum nigrum* L. are abundant; leafy mosses *Polytrichum piliferum* Hedw. and *P. juniperinum* Hedw., as well as *Hieracium pseudoarctophilum* Schljakov, are less abundant but often present in communities. The communities have three or two storeys; the storey of the ground lichens is developed.

The intermediate position in the relief between var. *Juncus trifidus* and community *Festuca polesica* (*Loiseleurio-Vaccinietea / Koelerio-Corynephoretea*) is occupied by the nonrating community *Calamagrostis epigeios-Bromopsis inermis* (*Artemisietea vulgaris*), a floristically and structurally depleted variant of the *Calamagrostis epigeios* (*Artemisietea vulgaris*) community, described in the frames of the alliance *Convolvulo arvensis-Elytrigion repentis* Görs 1966 of the order *Agropyretalia repentis* Oberd. et al. 1967 (Golovanov and Abramova, 2012). The face of these communities is determined by the dominance of *Calamagrostis epigeios*, which, together with other ruderal species, forms almost closed tangled vegetation. Ecologically, communities are confined to the slopes of railroads and roads, abandoned gardens, and other disturbed habitats that do not undergo frequent anthropogenic influence and are characterized by increased insolation (Golovanov and Abramova, 2012). The described pioneer cenoses (Table 1, descriptions 9 and 10) had a plant cover of no more than 20%, a double-storey structure, and were located on the dry sandy substratum on the lower parts of the slopes and the sloped sites of quarries. One constantly acting negative factor in the habitats of communities is the wind that constricts the succession. It also brings other ruderal and meadow–marge species to the forming communities (*Trifolium montanum*, *Vicia cracca*, *Matricaria perforata* Mérat, and *Chamaenerion angustifolium* (L.) Scop., Etc.), whose diasporas are kept by *C. epigeios* partial bushes. The total number of species in the descriptions was ten.

Similar communities with long-rhizome grasses were described on the drift sands of Transbaikal (associations *Leymetum crassinervii* and *Leymetum littoralis* of the class *Brometea korotkyi* Hilbig et Koroljuk 2000) (Dulepova and Korolyuk, 2015). Despite the different species composition and dominance of species of the genus *Leymus* (*L. racemosus* (Lam.) Tzvelev subsp. *crassinervius* (Kar. Et Kir.) Tzvelev and *L. littoralis* (Griseb.) Peschkova), the communities described in the Republic of Buryatia are structurally and ecologically similar to the cenoses formed on the drift sands of the north of Western Siberia.

Table 1. Communities of the early stages of the sand-outcrop overgrowth in the forest-tundra zone of Western Siberia

Associations/communities	a				b				c		Consistency		
Plant cover, %	10	3	8	50	7	4	10	50	20	8			
Number of species	4	3	5	4	7	5	6	11	2	8			
Description number	1	2	3	4	5	6	7	8	9	10	a	b	c
O.s. var. Juncus trifidus													
Juncus trifidus L.	1	+	1	+	•	•	•	•	•	•	V	•	•
Community Festuca polesica (Loiseleurio-Vaccinietea/Koelerio-Corynephoretea)													
Festuca polesica Zapał	•	•	•	•	+	+	1	+	•	•	•	V	•
Community Calamagrostis epigeios–Bromopsis inermis (Artemisietea vulgaris) and o.s. order Agropyretalia intermedio–repentis and cl. Artemisietea vulgaris													
Calamagrostis epigeios (L.) Roth	•	•	•	•	•	+	•	+	2	•	•	III	III
Bromopsis inermis (Leyss.) Holub	•	•	•	•	•	•	•	•	•	1	•	•	III
O.s. alliance Magno-Caricion elatae and order Magno-Caricetalia													
Carex acuta L.	•	•	+	3	•	•	•	•	•	•	III	•	•
O.s. order Vaccinio uliginosi–Pinetalia sylvestris and cl. Oxycocco-Sphagnetea													
Ledum palustre L.	•	•	•	•	r	•	•	•	•	•	•	II	•
Eriophorum vaginatum L.	1	•	•	•	•	•	•	•	•	•	II	•	•
Pinus sylvestris L. (p)	r	•	•	•	•	•	•	•	•	•	II	II	•
Pinus sibirica Du Tour (p)	•	•	•	•	r	•	•	•	•	•	•	II	•
O.s., cl. Loiseleurio-Vaccinietea													
Arctous alpina (L.) Niedenzu	•	•	•	•	•	•	1	3	•	•	•	III	•
Empetrum nigrum L.	•	•	•	•	1	•	•	•	•	•	•	II	•
Cladonia stellaris (Opiz) Pouzar et Vězda	•	•	•	•	•	•	•	r	•	•	•	II	•
Vaccinium vitis-idea L.	•	•	•	•	+	•	•	•	•	•	•	II	•
Vaccinium uliginosum L.	•	•	•	•	+	•	•	•	•	•	•	II	•
Flavocetraria nivalis (L.) Kärnefelt et A. Thell.	•	•	•	•	•	•	r	r	•	•	•	III	•
O.s. cl. Koelerio-Corynephoretea													
Polytrichum piliferum Hedw.	•	•	•	•	•	+	+	+	•	+	•	IV	III

Table 1. (Contd.)

Associations/communities	a				b				c		Consistency		
O.s. cl. Stellarietea mediae													
Matricaria perforata Mérat	•	•	•	•	•	•	•	•	•	r	•	•	III
O.s. cl. Bidentetea tripartitae													
Alopecurus aequalis Sobol.	r	+	r	r	•	•	•	•	•	•	V	•	•
O.s. alliance Salicion triandrae and cl. Salicetea purpureae													
Salix triandra L. (p)	•	•	•	+	•	•	•	•	+	•	•	•	III
O.s. order Galietalia veri and cl. Molinio-Arrhenatheretea													
Trifolium montanum L.	•	•	•	•	•	•	•	•	•	+	•	•	III
O.s. order Chamerio–Betuletalia nanae													
Chamaenerion angustifolium (L.) Scop.	•	•	•	•	•	•	•	•	•	r	•	•	III
Vicia cracca L.	•	•	•	•	•	•	•	•	•	r	•	•	III
Other species													
Agrostis clavata Trin.	•	•	•	•	•	•	•	•	•	+	•	•	III
Phleum alpinum L.	•	•	•	•	•	•	•	•	•	r	•	•	III
Polytrichum juniperinum Hedw.	•	•	+	•	•	+	+	+	•	•	II	IV	•
Juncus articulatus L.	•	+	+	•	•	•	•	•	•	•	III	•	•
Hieracium pseudoarctophilum Schljakov	•	•	•	•	+	r	•	+	•	•	•	IV	•
Flavocetraria cucullata (Bellardi) Kärnefelt et A. Thell.	•	•	•	•	•	•	•	r	•	•	•	II	•
Cetraria islandica (L.) Ach.	•	•	•	•	•	•	r	r	•	•	•	III	•
Alectoria ochroleuca (Hoffm.) A. Massal.	•	•	•	•	•	•	•	r	•	•	•	II	•

Location of the descriptions:

1, YaNAO, Purovskii raion, 23 km to the south from Novyi Urengoi, 66°0′0″ N, 77°17′32″ E, sand quarry, moistened bottom of the quarry, July 29, 2016; 2, YANAO, Nadymskii raion, 8 km to the southwest from the settlement of Pangody, 65°47′37″ N, 74°19′6″ E, overgrowing sand quarry, bottom of the quarry, July 30, 2016; 3, the same place, bottom of the quarry, July 30, 2016; 4, the same place, bottom of the quarry, July 30, 2016; 5, YANAO, Purovskii raion, 23 km to the southeast-east of Novyi Urengoi, 66°0′0″ N, 77°17′32″ E, sand quarry, bottom, inselberg hill, July 29, 2016; 6, YANAO, Nadymskii raion, 8 km to the southwest from the settlement of Pangody, 65°47′37″ N, 74°19′6″ E, overgrowing sand quarry, upper part of the slope of the pit ditch, July 30, 2016; 7, the same place, upper part of the slope of the pit ditch, July 30, 2016; 8, the same place, oversanding sites adjunct to the quarry, July 30, 2016; 9, YANAO, Nadymskii raion, 8 km to the southwest of the settlement of Pangody, 65°47'37" N, 74°19′6″ E, overgrowing sand quarry, low part of the slope of the pit ditch, July 30, 2016; and 10, YANAO, Purovskii raion, 23 km to the south of Novyi Urengoi, 66°0′0″ N, 77°17′32″ E, sand quarry, slight slope of the pit ditch.

Associations/communities: a, *Arctostaphylo alpini–Empetretum hermaphroditi* var. *Juncus trifidus*; b, community *Festuca polesica* (*Loiseleurio-Vaccinietea/Koelerio-Corynephoretea*); and c, community *Calamagrostis epigeios–Bromopsis inermis* (*Artemisietea vulgaris*).

Fig. 3. Crowberry knolls on the sand bulges in the northern part of Western Siberia. Photo by V.I. Kapitonov.

Thus, the vegetation of the early stages of sandy outcrops overgrowing in the forest-tundra zone is represented by a small number of floristically impoverished communities. The most hygrophilous variants develop under conditions of sufficient or excessive moistening at the bottom of quarries, and xerophilic communities are confined to the upstanding sections and sides of quarries.

Northern Taiga Subzone

In the northern taiga subzone, sand outcrops in quarries and bulges were investigated. In comparison with the lowest sites of the anthropogenic landscape that are sufficiently moistened and have favorable conditions for vegetation restoration, the deflation forms of the relief are characterized by the dryness of the substrate and a constantly acting negative factor—the wind delivery of the plants with sand. Only species with a short life cycle, mainly annuals, or perennial plants that are capable of rapid vegetative growth or using special adaptive mechanisms for dispersal (e.g., anemochory), can survive in such conditions.

The studied sand dunes moving in the wind direction completely buried the indigenous communities of the northern taiga, shrub–lichen pine forests, and alternating shrub–sphagnum bogs. On oversand surfaces, sparse communities of overgrowing initiators were formed. Their composition mainly consists of perennial herbaceous plants and shrubs.

The formation of moss and crowberry "knolls" as elements of the aeolian–phytogenic relief can be classified as the most interesting phenomena that occur in the areas of drift sands in the north of Western Siberia (Sizov, 2015). In this case, the *Empetrum nigrum* L. clumps and the leafy mosses *Polytrichum juniperinum* and *P. piliferum* are distinguished on the sandy surfaces. Their stems efficiently keep the wind-drift sand, actively growing with their apexes (Fig. 3). As a result, knolls that can fix sand form and create favorable conditions for the appearance and growth of other plant species.

The observed knolls had a slightly elongated shape, about 4–5 m in length, 3–4 m in width, and up to 0.5 m in height. Given the annual growth rate of the shoots of these mosses and crowberry, it can be assumed that knolls were formed over several years or even decades. The latter is confirmed by observations of longitudinal sections of such knolls, where alternating layers of pure sand and sand with an admixture of humus are clearly visible. This may indicate the uneven speed of sand falling over bushes in different years. Species forming such knolls are under the influence of extremely unfavorable factors, and their behavior is described by a stress-tolerant ecological–phytocenotic strategy.

Despite the low abundance of knoll-forming plants (from 1 to 3 on the Brown–Blanquet scale), their role in the vegetation restoration is very significant. Within the investigated bulges, species such as *Calamagrostis epigeios*, *Festuca polesica*, *Salix triandra*, and *Salix gmelinii* Pall. appear and spread over sands with knolls. More than that, the vegetation restoration on sand bulges can occur without the participation of crowberry and leafy mosses, which form knolls: it could occur as rush, bushgrass, and fescue types of overgrowth. These overgrown types are also typical for sandy quarries of the forest-tundra zone, which has a stochastic dependence on a number of factors: the spread of plant diasporas by wind and animals, the speed and direction of the wind, the remoteness of biocenoses, donors of diasporas, physical parameters of the substrate, etc.

As was done in the forest-tundra zone, the communities described by the properties of the ecotope can be divided into two groups: habitats with sufficient moisture of the substrate (*a*) and dry habitats (*b*).

Habitats with sufficient moistening conditions. These habitats are located in the lowered elements of a relief, on flat surfaces of the bottom of quarries, where favorable conditions for vegetation restoration develop. We described the communities var. *Juncus trifidus* (Kulyugina, 2008), which are also typical for similar forest-tundra habitats. The described cenoses with a low total species abundance (Table 2, descriptions 1–3) included diagnostic species of the class *Loiseleurio-Vaccinietea* Eggler ex Schubert 1960 (*Betula exilis* Sukaczev, *Empetrum nigrum* L., *Vaccinium vitis-idea* L., and *V. uliginosum* L.), which distinguishes these pioneer communities from those described in the forest-tundra zone and indicates their more advanced succession status. Plant coverage of communities was very low, 2–7%; from 3 to 9 species participate in their formation; in all, the growth of 15 species was recorded in this variant of the cenoses. From 30 to 50% of the species composition of the communities was the diagnostic types of the *Loiseleurio-Vaccinietea* class, but species of other classes were also presented: *Oxycocco-Sphagnetea* Br.-Bl. et Tx. ex Westhoff et al. 1946 (*Eriophorum vaginatum* L., *Drosera rotundifolia* L., *Ledum palustre* L., *Oxycoccus palustris* Pers., and *Pinus sylvestris* L.) and *Koelerio-Corynephoretea* Klika in Klika et Novak 1941 (*Polytrichum piliferum* Hedw.).

Dry habitats. Xeromorphic communities of the class *Koelerio-Corynephoretea* were developed on high relief elements with a pronounced deflation effect. Vegetation of this class is defined as pioneer, developing on dry, poorly developed sandy soils and outcrops of acid rocks (Mirkin and Naumova, 2012). The part of the described cenoses was attributed to the nonrating community *Festuca polesica* (*Koelerio-Corynephoretea*) (Table 2, descriptions 4–6). Its face is determined by undisturbed tangles of *Festuca polesica* with very low abundance scores (from *r* to +) and plant cover from 1 to 3%. This species is the only one among the diagnostic species of the class represented in the described cenoses. Besides this species, other species—although with low indices of abundances—were noted in the cenoses. They are affiliated with other vegetation classes: *Loiseleurio-Vaccinietea*, *Oxycocco-Sphagnetea*, and *Artemisietea vulgaris* Lohmeyer et al. ex on Rochow 1951. In total, five species were recorded in the communities, three species in each of the descriptions. Cenoses were single- or double-storey. The first storey consists of *Calamagrostis epigeios* and *F. polesica*; if there was a second storey, it included ground lichens. The communities were noted on windward parts of gentle slopes and peaks of small swells, in the habitats influenced by a constant dry sand cover up. The acidity of the sandy substrate was 5.3–5.6 pH (Tokareva and Utkina, 2016).

Another interesting type of overgrowth on substrates with insufficient moisture is associated with the development of *Hieracium pseudoarctophilum* together with *F. polesica* and several other species, including seedlings of woody plants, on blown sands (Table 2, descriptions 7, 8). The seedlings of woody plants often die in the early stages of overgrowth of sandy outcrops because of the unsuitable moistening regime and drift of the substrate. Herbaceous plants included in these communities, according to their ecological and biomorphological characteristics, refer to rhizome or dendritic perennials, which contributes to sand fixation. The adaptation of their diasporas to anemochory and zoochory increases the availability of free ecotopes colonization. These species are widespread in the northern areas of Western Siberia; they are common in the meadow–marge, coastal–meadow, and weed–field cenoses. According to the ecology–phytocenotic strategy, they belong to the ruderal type or are characterized by secondary types of strategies, violent–ruderal and ruderal–stress-tolerant.

In the described nonrating community *Festuca polesica-Hieracium pseudoarctophilum* (*Koelerio-Corynephoretea*), the dominant is *Hieracium pseudoarctophilum*, with abundance from 5 to 25% (Table 2, descriptions 7, 8). In total, 12 species were recorded. The communities were double-storey. The upper storey was formed by tall plants *Calamagrostis epigeios* and *Chamaenerion angustifolium* (L.) Scop. The lower storey is composed of *H. pseudoarctophilum*, *Festuca polesica*, *Polytrichum piliferum*, *Matricaria perforata* Mérat, and other ruderal species. The species of other classes take part in the composition of the community, albeit with a low abundance. First of all, the presence of representatives of the classes *Artemisietea vulgaris*, *Stellarietea mediae* Tx. et al. ex von Rochow 1951, *Molinio-Arrhenatheretea* Tx. 1937, and *Matricario-Poetea arcticae* Ishbirdin 2002 should be mentioned. They indicate the seral status of the community. Obviously, it is the next stage in the development of the community *Festuca polesica* (*Koelerio-Corynephoretea*). The described cenoses were confined to sites with

Table 2. Communities of the early stages of sand outcrop overgrowth in the northern forest subzone of Western Siberia

Associations/communities	a			b			c		Consistency		
Plant cover, %	2	7	2	3	1	2	25	15			
Number of species	3	9	4	3	3	3	3	11			
Description number	1	2	3	4	5	6	7	8	a	b	c
O.s. var. Juncus trifidus											
Juncus trifidus L.	+	1	+	•	•	•	•	•	V	•	•
Community Festuca polesica (Loiseleurio-Vaccinietea/Koelerio-Corynephoretea) and Festuca polesica–Hieracium pseudoarctophilum (Koelerio-Corynephoretea)											
Festuca polesica Zapał	•	•	•	+	r	+	r	1	•	V	V
Hieracium pseudoarctophilum Schljakov	+	•	•	•	•	•	2	1	II	•	V
O.s. cl. Loiseleurio-Vaccinietea											
Empetrum nigrum L.	•	r	•	•	•	•	•	•	II	•	•
Betula exilis Sukaczev	•	+	•	•	•	•	•	•	II	•	•
Vaccinium vitis-idea L.	•	•	r	•	•	•	•	•	II	•	•
Vaccinium uliginosum L.	•	r	•	•	•	•	•	•	II	•	•
Flavocetraria nivalis (L.) Kärnefelt et A. Thell.	•	•	•	+	•	•	•	•	•	II	•
O.s. cl. Koelerio-Corynephoretea											
Polytrichum piliferum Hedw.	•	•	+	•	•	•	•	1	II	•	III
O.s. order Vaccinio uliginosi–Pinetalia sylvestris and cl. Oxycocco-Sphagnetea											
Drosera rotundifolia L.	•	r	•	•	•	•	•	•	II	•	•
Oxycoccus palustris Pers.	•	r	•	•	•	•	•	•	II	•	•
Eriophorum vaginatum L.	•	+	•	•	•	•	•	•	II	•	•
Pinus sylvestris L. (p)	•	r	•	•	r	r	•	•	II	IV	•
Pinus sibirica Du Tour (p)	•	•	•	•	•	•	•	r	•	•	III

Table 2. (Contd.)

Associations/communities	a			b			c		Consistency		
Ledum palustre L.	•	•	r	•	•	•	•	•	II	•	•
O.s. order Chamerio–Betuletalia nanae											
Chamaenerion angustifolium (L.) Scop.	•	•	•	•	•	•	•	+	•	•	III
Equisetum arvense L.	•	•	•	•	•	•	•	+	•	•	III
O.s. order Agropyretalia intermedio–repentis and cl. Artemisietea vulgaris											
Calamagrostis epigeios (L.) Roth	•	•	•	•	+	+	1	•	•	IV	III
Bromopsis inermis (Leyss.) Holub	•	•	•	•	•	•	•	r	•	•	III
O.s. cl. Stellarietea mediae											
Matricaria perforata Mérat	•	•	•	•	•	•	•	+	•	•	III
O.s. cl. Molinio-Arrhenatheretea											
Achillea millefolium L.	•	•	•	•	•	•	•	r	•	•	III
Other species											
Polytrichum juniperinum Hedw.	•	r	•	•	•	•	•	•	II	•	•
Epilobium alpinum L.	•	r	•	•	•	•	•	•	II	•	•
Dactylorhiza sp.	•	r	•	•	•	•	•	•	II	•	•
Agrostis clavata Trin.	•	•	•	•	•	•	•	r	•	•	III
Sorbus aucuparia L. (p)	•	•	•	•	•	•	•	r	•	•	III
Lichens sp.	•	•	•	+	•	•	•	•	•	II	•

Location of the descriptions: 1, YANAO, Purovskii raion, 30 km to the southwest of the settlement of Gubkinskii, 64°17′47″ N, 75°56′10″ E, sand quarry, bottom of the ditch, July 31, 2016; 2, KhMAO, Surgutskii raion, 50 km to the southwest-west of the city of Noyabrsk, 63°1′44″ N, 74°25′47″ E, industrial park, bulges on the lake shore, August 1, 2016; 3, YANAO, Purovskii raion, 27 km to the south of the city of Muravlenko, 63°32′22″ N, 74°36′29″ E, sand denudations near the Pyaku-Pur River, bulge, July 27, 2016; 4, the same place, deflation basin; 5, the same place, flattened high site; 6, YANAO, Purovskii raion, 30 km to the southwest from the settlement of Gubkinskii, 64°17′47″ N, 75°56′10″ E, sand quarry, dry bottom, July 31, 2016; 7, YANAO, Purovskii raion, 27 km to the south from the city Muravlenko, 63°32′22″ N, 74°36′29″ E, sand denudations near the Pyaku-Pur River, slight slope, July 27, 2016; and 8, YANAO, Purovskii raion, 24 km to the south-southwest of the settlement of Korotchaevo, 65°41′54″ N, 78°1′7″ E, sand denudations near the bridge over the Yamsovei River, July 29, 2016.

Associations/communities: a, *Arctostaphylo alpini–Empetretum hermaphroditi* var. *Juncus trifidus*; b, community *Festuca polesica* (*Koelerio-Corynephoretea*); and c, community *Festuca polesica–Hieracium pseudoarctophilum* (*Koelerio-Corynephoretea*).

dry sandy substrate. The reaction of the medium was neutral (pH 7.1) (Tokareva and Utkina, 2016).

The communities *Festuca polesica* (*Koelerio-Corynephoretea*) and *Festuca polesica-Hieracium pseudoarctophilum* (*Koelerio-Corynephoretea*) recorded on dry sandy outcrops develop into cenoses of anthropogenic erosiophilic vegetation of the class *Matricario-Poetea arcticae* (*Chamerio-Betuletalia nanae* (Khusainov et al., 1989) Ishbirdin 2002), widespread in arctic and northern boreal latitudes, including Western and Eastern Siberia (Cherosov et al., 2005; Sumina, 2012).

The significant difference in the species composition of the plant communities of sand outcrops in comparison with the data of other authors obtained on overgrown sand massifs within the northern taiga subzone of Western Siberia is conspicuous (Lobotrosova and Sizov, 2016; Sizov and Lobotrosova, 2016). The only common species are *Festuca ovina* L. s.l. (incl. *F. polesica*) and *Pinus sylvestris*, indicated by those authors on dry plots. The presence of representatives of the family Fabaceae (*Trifolium montanum* L. and *Vicia cracca* L.) in the seral communities described by us should be noted. Although it was previously noted that one specific feature of the development of primary successions in the sandy quarries of the northern taiga of Western Siberia is the absence of plants of this family (Koronatova and Milyaeva, 2011).

The combination of the species of the early stages of sandy outcrops overgrowing in the forest-tundra zone is very close to the floral composition of the initiators of the overgrowth oversand surfaces in the subzone of the northern taiga. Obviously, the succession in dry and humid open sandy areas begins with the appearance of widespread mezo- and xeromesophilous (in some cases, hygromesophilous) herbaceous plant species, trees, and shrubs, which have certain adaptations for spreading diasporas (anemochory) and fixation on drift substrate (rhizome or turf grass, woody forms with developed and deeply penetrating root systems with a long-lasting main root). Under conditions of the permanently acting factor associated with the activity of wind, which inhibits vegetation restoration, the species of indigenous communities, buried beneath a layer of sand at blowing sites or destroyed during quarry development may probably reappear in these areas only at later stages of succession.

CONCLUSIONS

Anthropogenic oversanding is a widespread phenomenon in the northern regions of Western Siberia. Its causes are the open mining of mineral resources, primarily of construction materials (sand), and the construction of linear engineering structures. The successions that start on anthropogenic sand outcrops could be both of primary (ecogenetic) or secondary (regenerative) types. A small number of higher plants and lichens species (from 2 to 11 species) of indigenous or secondary biocenoses participate in the initial stages of the overgrowth of the sandy substrates. Plant species are mainly anemochore and zoochoric rhizome or firm-bunch widely distributed grasses or shrubs with a predominantly ruderal, less frequent, stress-tolerant, phytocoenotic strategy or transitional types of strategies, violent—ruderal and ruderal—stress-tolerant. Less common in the vegetation of the initial stages of succession are woody and shrubby plants, whose survival in such extreme conditions is extremely low. Plants form open communities, the plant cover of which does not exceed 50%; more often this index is much lower. The communities var. *Juncus trifidus* of the association *Arctostaphylo alpini-Empetretum hermaphroditi* class *Loiseleurio-Vaccinietea* were identified on the moistened sandy outcrops of the forest tundra and northern taiga of Western Siberia. The early stages of xerosere succession are represented by communities *Festuca polesica* (*Loiseleurio-Vaccinietea/Koelerio-Corynephoretea*), *Festuca polesica-Hieracium pseudoarctophilum* (*Koelerio-Corynephoretea*), and *Calamagrostis epigeios-Bromopsis inermis* (*Artemisietea vulgaris*). The plant species composition of the initial stages of successions on the sandy surfaces of neighboring natural zones is similar, which is due to the participation of widespread species—initiators of overgrowth adapted to drift-sand substrates in the vegetation restoration.

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