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ECOLOGY

Vegetation and Soils of Tundra Landscapes in the Pur–Taz Interfluvial Region

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Abstract—The landscape diversity of the tundra area in the Pur–Taz interfluvial region are analyzed using field and remote sensing data. For each land unit (microlandscape), botanical, microrelief, and soil descriptions are produced, projective covers of plant species are estimated, and seasonal soil thawing depths are defined. Additionally, the water table levels, pH, and electrical conductivity (EC) of peatland waters are measured in waterlogged microlandscapes.

Keywords: vegetation, soils, landscapes, microlandscapes, satellite images, tundra ecosystems, Pur–Taz interfluvial region

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INTRODUCTION

Modern climatic changes are most clearly manifested in arctic and subarctic latitudes (Bindoff et al., 2013); in the permafrost zone, these changes activate adverse cryogenic processes (Kizyakov and Leibman, 2016). Vast tundra areas of western Siberia are exposed to significant anthropogenic pressure due to the intense development of hydrocarbon deposits and expansion of reindeer farms (Detter, 2017; Callaghan et al., 2019). Analysis of the response of the tundra ecosystems of western Siberian to climatic and anthropogenic impacts requires comprehensive studies. However, many tundra regions still remain poorly researched due to their harsh climatic conditions, high waterlogging, and lack of developed transport infrastructure. A number of publications have presented data on the phytocoenotic and structural features of the vegetation cover (Meltser, 1984; Telyatnikov, 2003; Magomedova et al., 2006) and thermokarst processes (Pavlov, 2008; Moskovchenko et al., 2017) typical for the northwestern part of Siberia; descriptions of individual soil profile pits were produced for this region (Khrenov, 2011; Gentsch et al., 2015); and its peatland types were identified and described (Liss et al., 2001; *Gidrologiya*..., 2009). Palynological data collected on the basis of core samples from exploration wells made it possible to assess changes in the climatic conditions and vegetation over the sediment formation period (the deposits are up to 400 m thick) in the northwestern part of Siberia (Peteet et al., 1998; Volkova, 1999). Some publications have analyzed the degrees of anthropogenic impact on natural landscapes in the northwestern regions of Siberia (Kornienko and Yakubson, 2011; Soromotin and Brodt, 2018).

In tundra ecosystems of the cryolithozone, the vegetation cover significantly affects the thermal regime of the underlying perennially frozen rocks (Tyrtikov, 1980; Pavlov, 2008). Therefore, the response to climatic changes in the cryolithozone manifested in the dynamics of the seasonally thawed layer and the temperature of perennially frozen rocks significantly depends both on the type of vegetation cover and its state and on the parameters of the perennially frozen rocks in the ecosystems studied. Earlier studies (Khimenkov and Vlasov, 2007; Pavlov and Malkova, 2010) have shown that climatic trends and trends in the parameters of the seasonally thawed layer and perennially frozen rocks may not coincide depending on the landscape conditions. Analysis of trends in the parameters of the soil–ground stratum in the cryolithozone determined by natural and technogenic factors requires studies of the diversity of the modern landscape in this zone, as well as of the vegetation and soil cover parameters.

In the framework of this study, the spatial pattern of tundra landscapes in the Pur–Taz interfluvied region was analyzed and microlandscapes featuring homogeneous vegetation cover, uniform surface microrelief, and similar soil cover have been distinguished. For each microlandscape, botanical, surface relief, and soil descriptions were produced and the

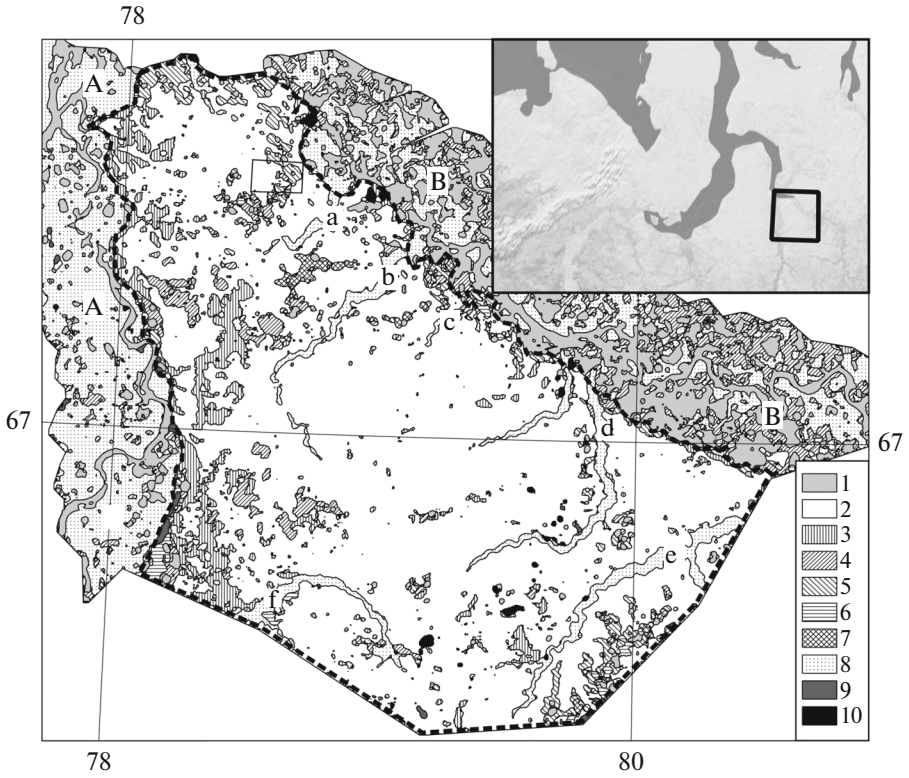


Fig. 1. Schematic map of the study area. The dashed line outlines the tundra area in the Pur–Taz interfluvial region. The Yarneto key site is outlined by a thin solid line. Ground surface categories: (1) water surface, (2) plakors, (3) slopes with shrub thickets, (4) khasyreys, (5) grass–sphagnum hollows, (6) sedge fens, (7) polygonal–fissure complexes, (8) river floodplains ((A) Pur River, (B) Taz River, (a) Vesakoyakha River, (b) Lukyyakha, River (c) Syambotayakha River, (d) Bolshaya Kheikha River, (e) Yuredeiyakha River, and (f) Nadosalyakhadyta River), (9) sandy deposits, and (10) infrastructural facilities.

seasonal soil thawing depths and physicochemical properties of peatland waters (acid–base conditions and electrical conductivity) were determined.

MATERIALS AND METHODS

Tundra ecosystems of the Pur–Taz watershed are located in the continuous permafrost region (Pavlov, 2008), in the south-tundra subzone of western Siberia (Liss et al., 2001). The study area (Fig. 1) is some 7000 km^2 in size (~12% of the Pur–Taz interfluvial area). According to the typological map of wetlands (Romanova et al., 1977), polygonal and flat–hummocky oligotrophic peatlands are typical for the region studied, the degree of waterlogging of which reaches 15%. The regional climate is sharply continental. Analysis of monitoring data collected at the Tazovsky meteorological station (www.rp5.ru) for the period of 2005–2017 shows that the region studied features a negative mean annual air temperature (–6.5°C). The coldest month is January (mean monthly air temperature –25.4°C), and the warmest month is July (mean monthly air temperature +15.4°C). The annual sum of positive temperatures is 1320°C. The mean annual amount of precipitation is 570 mm; its major part (55%) falls in the summer–autumn season. The growing season duration is some 100 days. The study area is located in the humid zone; excessive moistening is determined by a low evaporation capacity (240 mm per year).

The spatial pattern of tundra landscapes was analyzed using both space images with various spatial resolutions (Golubyatnikov et al., 2015) and field data collected on the Yarneto key site (67°22′–67°25′ N, 78°29′–78°41′ E) located in the studied region. Landsat 8 (medium spatial resolution 30 m/pixel) and WorldView-2 (high spatial resolution 2 m/pixel) satellite images were used in this study. The Landsat-8 image covers the entire study area in the Pur–Taz interfluvial region; the WorldView-2 image depicts the key site. The images were interpreted using the QuantumGIS and GRASS geoinformation software. Comparison of landscapes from the Landsat-8 image with microlandscape types distinguished in the WorldView-2 image made it possible to determine the areal shares of the studied microlandscapes in each landscape.

In the course of field studies conducted on the Yarneto key site (~40 km^2 in size) in the years 2013–2017, landscapes and microlandscapes distinguished as a result of interpretation of the satellite imagery were

Table 1. Areas of ground surface categories in the tundra area of the Pur–Taz interfluvial region

Ground surface category	S, $\times 1000$ km^2	Q_{reg}, %	Q^*_{reg}, %	Q_{key}, %	Q^*_{key}, %
Water surface	0.13	1.9	7.3	2.8	9.8
Plakors	3.82	55.9	29.3	48.2	27.7
Slopes with shrub thickets	1.11	16.2	27.7	7.4	21.2
Khasyreys	0.49	7.1	4.9	8.0	5.2
Grass–sphagnum hollows	0.38	5.6	9.6	23.5	17.1
Sedge fens	0.21	3.1	2.1	3.8	2.8
Polygonal–fissure complexes	0.15	2.3	11.2	6.3	16.2
River floodplains	0.37	5.4	5.4	–	–
Sandy deposits	0.06	0.9	0.9	–	–
Infrastructural facilities	0.11	1.6	1.6	–	–

S is the area, Q_{reg} and Q^*_{reg} are areal shares in the interfluvial area studied, and Q_{key} and Q^*_{key} are areal shares on the key site. The S, Q_{reg}, and Q_{key} values were computed based on the medium-resolution Landsat-8 satellite image. The Q^*_{key} values were computed based on the high-resolution WorldView-2 satellite image. The Q^*_{reg} values were computed based on the Landsat-8 and WorldView-2 satellite images.

identified on the ground and botanical and soil cover descriptions produced. Geobotanical studies were performed in accordance with the standard methodology (*Polevaya geobotanika*, 1964). Sampling plots 5 × 5 m in size were established with an eightfold replication in microlandscapes of the same type located in different parts of the key site. On each sampling plot, vegetation descriptions were produced; projective covers of plant species estimated visually; and the seasonally thawed layer depth and peatland water level, acidity, and electrical conductivity measured. Test holes were dug near sampling plots to produce soil cover descriptions. The soil names are provided in accordance with the classification of soils of Russia (*Klassifikatsiya*..., 2004) and the international classification of soil resources (IUSS..., 2015). The depth of the seasonally thawed layer in each microlandscape was measured with a graduated metal probe at the end of July. The peatland water level in waterlogged microlandscapes was measured with a tape measurer. The acidity and electrical conductivity of peatland waters were measured with a Hanna 98129 portable pH conductometer (Hanna Instruments, United States).

RESULTS AND DISCUSSION

The interpretation of the Landsat-8 satellite image made it possible to distinguish ten ground surface categories in the Pur–Taz interfluvial area under study (Table 1): six key landscape types, lakes, sandy deposits, river floodplains, and infrastructure (settlements, roads, etc.). The interpretation was performed with a 92% accuracy. Analysis of the medium-resolution satellite image showed that tundra landscapes on flat-topped elevations occupy ~72% of the interfluvial area under study. Landscapes in depressions occupy 20% of the study area. River floodplains, sand deposits, and infrastructure occupy ~8% of the region (these categories are excluded from the study). Based on the interpreted image, a map of the distinguished terrain categories was produced for the tundra area in the Pur–Taz interfluvial region. Figure 1 shows an aggregated sketch map of the map produced.

Lakes play a significant role in the carbon balance and affect the regional climate (Schilder et al., 2013; Golubyatnikov and Mammarella, 2018). Accordingly, these natural objects are distinguished in this study into a separate category: water surface. The lakes of the study region are mostly of thermokarst origin (Zemtsov, 1976; Kravtsova and Rodionova, 2016), shallow (usually 1–2 m deep, rarely up to 3.5 m), and from 1500 m^2 to 2 km^2 in size. The lake shores are mostly gentle, but can also form ledges 2–4 m high. Bottom sediments in most lakes are represented by peat–mineral deposits and consist of mineral layers of various granulometric compositions and thicknesses alternating with redeposited peat interlayers. Silt and sapropel deposits are noted in some lakes.

Tundra Landscapes of the Interfluvial Territory

A significant portion of the interfluvial area under study is occupied by flat-topped elevations with mineral soils: *plakors*. The ground cover of this landscape is predominated by lichens; herbaceous communities (grasses, sedges, and rushes), sphagnum mosses, ericaceous dwarf shrubs, and dwarf birches and willows are widespread. The most elevated sites are occupied by alder thickets. On the border with forest-tundra zone both individual larch trees and sparse larch forest sites of small area are observed.

Numerous slopes that dissect uplands are occupied by *shrub communities*. Willow stands are formed in the lower parts of the slopes near watercourses. Shrub thickets predominated by dwarf birch are widespread in the upper parts of the slopes. The shrubs reach the maximum height in narrow ditch-like erosional depressions. Mosses predominate in the ground cover of the slopes; forb species and reed grass are widespread. The slope network is most dense between the floodplains of the Bolshaya Kheikha and Yuredeiyakha rivers in the southern part of the studied interfluvial region and in areas adjacent to the Pur River floodplain.

Polygonal–fissure complexes feature a sophisticated structure: elevated polygons alternate with ditch-like fissures separating the polygons. Polygon surfaces are usually covered by small tussocks; in some cases, they are smooth. Polygons have four-, five-, and six-sided, as well as heptagonal, shapes; the side size is 5–14 m. The fissures are 1–3 m wide. Rather wide areas with hollows are formed at the intersections of fissures. The vegetation of polygons consists of lichens, sphagnum mosses, ericaceous dwarf shrubs, and dwarf birches. In fissures, vegetation is represented by moisture-loving grass–moss communities consisting of sphagnum mosses, sedges, cotton-grass, and sparse andromeda individuals. Peat deposits in polygons are usually 1.5–2 m thick; sometimes, more than 3 m thick. This landscape type is most widespread in the southeastern part of the Pur–Taz interfluvial region and in areas adjacent to the Taz River floodplain in catchment basins of the Vesakoyakha, Lukyyakha, and Syambotayakha rivers.

Two types of peatland landscapes were identified in depressions of the studied region. A significant part of peaty depressions are occupied by oligotrophic and oligotrophic–mesotrophic *grass–sphagnum hollows*. Sphagnum mosses form a continuous cover in hollows. Sedges and cotton-grass are widespread. *Sedge fens* are formed in waterlogged areas with stagnant waters. The peatland water level in this landscape is close to the peat deposit surface. A part of the landscape area is covered by water. Vegetation is represented mainly by sedges. Sphagnum mosses and ericaceous dwarf shrubs grow only on rare tussocks. Grass–sphagnum hollows and sedge fens are typical for areas adjacent to the floodplain of the Taz River and its tributaries. Significant areas are occupied by these landscapes, both in the southeastern part of the interfluvial region and on the Taz Estuary banks. In addition, such landscapes occur along the Pur River floodplain.

Basins of drained thermokarst lakes (*khasyreys*) represent a typical landscape of tundra areas in the Pur–Taz interfluvial region (Loyko et al., 2018). After drainage of a lake, water can be retained in depressions of its bottom, thus, forming small shallow lakes. Along with highly productive herbaceous communities, sphagnum mosses, cotton-grass, and sedges are widespread in lake basins. At this initial stage of khasyrey formation, hollows are formed in the lake basins, and frost heaving occurs resulting in the formation of small (20–40 cm) elevations covered by sphagnum mosses, lichens, and ericaceous dwarf shrubs. A similar khasyrey development stage in the tundra in the northeastern part of European Russia was described by D.A. Kaverin et al. (2014). Excessive moistening of the area together with thermokarst and frost heaving processes contribute to the formation of palsas up to 3 m high in basins of drained lakes, as well as hollows of varying degrees of waterlogging and small lakes (i.e., the transition from the initial formation stages into a fully developed khasyrey form is observed). Dwarf birches, green mosses, and lichens grow on palsas. Vegetation of hollows surrounding palsas consists mainly of sedges and oligotrophic moss species. Basins of drained lakes are widespread throughout the study area. Khasyreys occupy significant areas north of the Vesakoyakha River, in the central western part of the interfluvial region bounded by the Pur, Vesakoyakha, and Lukyyakha rivers, and in the southwestern part of the interfluvial region between the Pur, Lukyyakha, and Nadosalyakhadyta rivers.

Descriptions of Microlandscapes

Tundra landscapes of the Pur–Taz interfluvial region were analyzed based on an high-resolution WorldView-2 image of the Yarneto key site and field data. The analysis conducted made it possible to distinguish 20 microlandscapes in the study area and compute areas occupied by each microlandscape (Table 2).

The water surface is subdivided into three microlandscapes: deeper parts of the lakes lacking emergent vegetation (*deep water*), shallow parts with sparse emergent vegetation or without it (*shallow water*), and *wetland ponds*. The reaction of waters in the studied lakes and ponds varies from acidic to slightly acidic (pH 3.5–6.3). Such pH values are typical for south-tundra lakes (*Gidrologiya*..., 2009; Golubyatnikov and Kazantsev, 2013). The electrical conductivity of lake waters varies in the range of 5–38 μS/cm. The low values of this parameter indicate a poor mineral composition of waters in the reservoirs studied.

Lichen communities grow on sandy loam soils developing on the most well-drained plakors. Lichens *Cladonia stellaris*, *C. rangiferina*, *Alectoria ochroleuchia*, *Cetraria cucullata*, and *C. nivalis* form a nearly continuous (projective cover 90–100%) cover. The dwarf-shrub layer is 5–15 cm high. Its projective cover is 10–20%, and it is formed by *Ledum palustre*, *Vaccinium uliginosum*, *Arctous alpina*, *Betula nana*, and *Salix* spp. Herbaceous communities formed by gramineous species (*Poa arctica* and *Calamagrostis* spp.), *Carex arctosibirica*, and *Juncus* spp. form sparse clumps. The microlandscape features sandy loam cryogenic cryoturbated tundra podzolized brown soils (Dystric Arenosols (Gelic, Protospodic, Protostagnic)).

Table 2. Characteristics of tundra microlandscapes in the Pur–Taz interfluvial region

Microlandscape type	Q_{key}, %	Q_{reg}, %	WL, cm	STL, cm	pH	EC, μS/cm
Deep water	2.7	2.1	–	–	4.1–6.3	5–34
Shallow water	1.5	1.7	–	–	3.5–6.1	9–31
Wetland ponds	5.6	3.5	–	–	3.9–4.7	8–38
Lichen communities on plakors	1.7	1.9	–	>70	–	–
Shrub–lichen communities on plakors	15.0	16.9	–	>35	–	–
Shrub–cotton-grass–lichen communities on plakors	11.0	10.5	–	23–29	–	–
Shrub–green-moss communities on slopes	13.3	16.8	–	30–50	–	–
Dwarf birch thickets on slopes	7.9	10.9	–	32–50	–	–
Lichen–moss–shrub communities on peatland polygons	7.3	6.2	–	28–30	–	–
Lichen–shrub communities on peatland polygons	1.6	1.1	–	25–28	–	–
Moss–shrub communities on peatland polygons	6.3	3.3	12–22	29–33	3.2–3.5	49–64
Frost-shattered fissures between polygons	1.0	0.7	3–17	31–45	3.8–4.2	21–43
Sedge–shrub–sphagnum hollows	1.2	0.5	17–24	25–28	4.3–4.9	22–39
Sedge–cotton-grass–sphagnum hollows	2.9	1.0	10–25	24–31	3.4–4.9	28–52
Waterlogged sedge–cotton-grass–sphagnum hollows	13.1	8.1	3–8	35–48	3.8–4.4	16–21
Sedge–sphagnum fens	0.2	0.1	8–10	35–40	4.2–4.5	14–20
Shrub–sedge–moss fens	0.4	0.3	0–10	29–46	4.3–4.7	8–30
Sedge–cotton-grass fens	2.1	1.7	–10...2	48–55	4.2–5.1	6–8
Waterlogged sphagnum hollows in khasyreys	3.2	2.1	5–12	31–42	3.8–4.2	23–33
Shrub–moss communities on palsas	2.0	2.8	–	15–36	–	–

Q_{key} is the areal share on the key site, Q_{reg} is the areal share in the studied interfluvial area, WL is the peatland water level, STL is the seasonally thawed layer, and pH/EC are the acidity and electrical conductivity of peatland and lake waters.

Shrub–lichen communities occupy flat tops of plakors. The microrelief features spots of squeezed out mineral ground (medallion-like spots). Dwarf shrubs *Arctous alpina* and *Empetrum hermaphroditum* grow along edges of these spots. Lichens *Cladonia stellaris*, *C. rangiferina*, *Alectoria ochroleuchia*, *Cetraria cucullata*, and *C. nivalis* form a continuous cover. The dwarf-shrub layer 15–20 cm high. Its projective cover is 45%, and it is formed by *Ledum palustre* with the participation of *Betula nana* and rare *Salix glauca*, *S. phylicifolia*, and *Vaccinium uliginosum* individuals. Alder (*Duschekia fruticosa*) occurs on elevations. In microlandscape parts with poor drainage, separate *Eriophorum scheuchzerii* and *E. vaginatum* clumps are observed. The soil cover is formed by taiga gley cryogenic soils with humus cutans and sandy loam podzolized brown soils within spots (Reductaquic Turbic Cryosols (Loamic, Thixotropic), Dystric Arenosols).

Plakor *shrub–cotton-grass–lichen communities* occur on poorly drained sites adjacent to lakes or waterlogged hollows. The microlandscape features a tussocky relief formed by cotton-grass mounds 20–30 cm high (50% of the area). The herbaceous layer consists mainly of *Eriophorum vaginatum* (projective cover 60–70%) and *Rubus chamaemorus* (10%). The dwarf-shrub layer (projective cover 40%) is represented by *Ledum palustre* with the participation of *Betula nana*. Spaces between tussocks are covered by the lichens *Cladonia stellaris*, *C. rangiferina*, and *Cetraria cucullata* (projective cover 75–80%) with an admixture of mosses *Sphagnum fuscum*, *Sph. lenense*, *Sph. balticum*, *Polytricum strictum*, and *Dicranum* spp. (15–20%). Peat–gley cryogenic cryoturbated soils (Histic Reductaquic Turbic Cryosols (Loamic, Thixotropic)) are typical for this microlandscape.

Descriptions of the vegetation cover in the central part of the Taz Peninsula produced by N.V. Kobeleva (2012) indicate that plant communities of tundra plakors in the Pur–Taz interfluvial region are also typical for tundra plains of the Taz Peninsula.

Shrub–green-moss communities occupy gentle slopes of plakors. The shrubs *Betula nana* (projective cover 75%) and *Salix glauca* (5–15%) form dense thickets up to 60 cm high. Sparse *Ledum palustre* and *Vaccinium uliginosum* individuals occur under their canopy. The ground cover is predominated by green mosses *Hylocomium splendes* and *Pleurozium schreberi* (projective cover up to 45%); lichens *Cladonia arbuscula*, *C. stellaris*, and *C. rangiferina* occur as well. Soils of this microlandscape are represented by loamy cryogenic peaty–gleyic soils (Reductaquic Turbic

Cryosols (Siltic, Thixotropic), Reductaquic Cryosols (Loamic, Thixotropic)).

Dwarf birch thickets occupy steep slopes of plakors. Dwarf birch with an admixture of *Salix glauca* and *S. saxatilis* forms thickets up to 2.5 m high (projective cover 75–90%). The thin grass–dwarf-shrub layer (up to 20%) consists mainly of *Ledum palustre*, *Vaccinium vitisidaea*, *Equisetum palustre*, *Rubus arcticus*, and *R. chamaemorus*. Mosses *Sphagnum girgensohnii*, *Anlacomnim palustris*, *Hylocomium splendes*, *Pleurozium schreberi*, and *Palytrichum strictum* cover 90–100% of the soil surface. The soils are the same as in the previous microlandscape.

Unlike plant communities growing on slopes of south-tundra plakors in the Taz Peninsula (Valeeva and Moskovchenko, 2009), the grass–dwarf-shrub layer in the studied region is predominated by *Ledum palustre*, *Vaccinium vitisidaea*, *Equisetum palustre*, *Rubus arcticus*, and *R. chamaemorus*.

Lichen–shrub communities on peatland polygons occupy the border zones of polygonal–fissure complexes. The microrelief is small-tussocky; the tussocks are 10–15 cm high and occupy 40–50% of the microlandscape area. The dwarf-shrub layer is concentrated on tussocks and consists of *Ledum palustre* (projective cover 30%) with a slight admixture of *Betula nana* individuals (up to 5%). Mosses *Sphagnum fuscum* and *Sph. capillifolium* occur on tussocks in sparse patches (projective cover 2–3%). The herbaceous layer is represented by *Rubus chamaemorus* (projective cover up to 30%). Spaces between tussocks area occupied by fruticose lichens *Cladonia stellaris* and *C. stygia* with the participation of *C. rangiferina*, *C. amaurocraea*, and *Cetraria cucullata*. The microlandscape is characterized by peat–oligotrophic cryogenic, sometimes residual-eutrophic soils (Dystric Epifibric Cryic Histosols, Dystric Hemic Cryic Histosols, Murshic Hemic Epicryic Histosols).

Lichen–moss–shrub communities on peatland polygons occur in central parts of polygonal–fissure complexes. This microlandscape features a small-tussocky relief. Tussocks occupy 35–40% of the microlandscape area. Lichens *Cladonia stellaris* and *C. stygia* form a continuous cover between tussocks. On tussocks, vegetation is represented by the mosses *Sphagnum fuscum* and *Sph. capillifolium* (projective cover 10–20%), lichens *Cladonia stellaris* and *C. stygia* (up to 15%), and grass–dwarf-shrub communities consisting of *Rubus chamaemorus* (up to 20%), *Ledum palustre* (60%), and *Betula nana* (up to 25%). The soils are the same as in the previous microlandscape.

Moss–shrub communities on peatland polygons occur in marginal parts of polygons affected by water–thermal erosion. The moss cover (projective cover 90–100%) consists mainly of *Sphagnum fuscum*, *Sph. balticum*, and *Sph. lenense*. Lichens *Cladonia stellaris* and *C. stygia* occur in sparse patches (5–10%). The herbaceous layer with a sward density of 10–30% consists of *Rubus chamaemorus*. The thin dwarf-shrub layer (5–20%) is represented by *Andromeda polifolia*, *Ledum palustre*, and *Betula nana*. The microlandscape features oligotrophic cryogenic peaty soils (Dystric Epifibric Endohemic Cryic Histosols).

Frost-shattered fissures between polygons are small trenches (1–3 m wide) formed as a result of frost cracking. The mosses *Sphagnum balticum*, *Sph. lindbergii*, *Sph. jensenii*, and *Sph. majus* form a continuous cover. The projective cover of *Carex rotundata* and *Eriophorum russeolum* reaches 20–35%. *Betula nana* and *Andromeda polifolia* occur rarely. The soil cover is formed by oligotrophic cryogenic peaty soils (Dystric Epifibric Cryic Histosols); the ice vein usually occurs at depths over 50–70 cm.

Sedge–shrub–sphagnum hollows are formed along the boundaries of polygonal–fissure complexes in drainage zones of these peatlands. The vegetation cover is predominated by *Carex rotundata* (projective cover 50%). The low level of peatland waters contributes to the growth of thickets consisting of *Betula nana* (up to 50%), *Salix glauca*, *Andromeda polifolia*, *Chamaedaphne calyculata*, and *Vaccinium myrtillus* (up to 15%). The mosses *Sphagnum obtusum* and *Sph. balticum* form a continuous cover. This microlandscape features oligotrophic cryogenic peaty soils (Dystric Fibric Cryic Histosols).

Sedge–cotton-grass–sphagnum hollows occur both in the border zone between the polygonal–fissure complex and the depressions and between heaving mounds in developed khasyreys. The relief is formed by small (some 10 cm high) tussocks that cover up to 50% of the microlandscape surface. The mosses *Sphagnum balticum*, *Sph. obtusum*, and *Sph. riparium* form a continuous cover. The herbaceous layer (projective cover 85%) is represented by *Carex rotundata* and *Eriophorum russeolum*. *Betula nana*, *Salix glauca*, *Andromeda polifolia*, and *Ledum palustre* occur sparsely. The soils are the same as in the previous microlandscape.

Waterlogged sedge–cotton-grass–sphagnum hollows are a typical microlandscape of areas in the central parts of the depressions. *Eriophorum russeolum* and *Carex rotundata* predominate in the grass cover (projective cover 30–55%). *Andromeda polifolia* occurs sparsely. Mosses form a continuous cover predominated by *Sphagnum balticum*, *Sph. lindbergii*, *Sph. jensenii*, and *Sph. majus*. Small parts of the microlandscape are covered with water. The microlandscape features oligotrophic cryogenic peaty soils (Dystric Fibric Cryic Histosols).

Three microlandscape types are present in depressions on sites with stagnant waters. The herbaceous layer of *sedge–sphagnum fens* is predominated by *Carex chordorrhiza*; *C. limosa* and *Eriophirum russeolum* are also present (projective cover 50%). The moss *Sphagnum obtusum* forms a continuous cover. Open waters occupy 5–10% of the microlandscape area.

The soil cover is formed by oligotrophic cryogenic peaty soils (Dystric Fibric Cryic Histosols). In *shrub–sedge–moss fens*, *Carex chordorrhiza*, *C. limosa*, *C. rotundata*, *Eriophorum russeolum*, and *E. angustifolium* form a tall grass cover (projective cover 20%). The fen water level is above the peat surface in 10–20% of the microlandscape area. The low-growing dwarf-shrub layer consists of *Andromeda polifolia* (projective cover 10–70%). *Betula nana* occurs sparsely. The ground cover (60%) is formed by sphagnum (*Sphagnum obtusum*), green mosses (*Warnstorfia exannulata* and *Polytrichum jensenii*), and liverworts (*Scapania paludicola*). The microlandscape features oligotrophic cryogenic peaty soils (Dystric Epifibric Histosols). The vegetation cover of *sedge–cotton-grass fens* is formed by *Carex chardorrhiza* and *Eriophorum russeolium* (projective cover 40–70%). A significant part of the microlandscape area is covered by water. The soil cover is formed by alluvial peaty–gley soils (Dystric Gleyic Histic Fluvisols). It must be noted that green mosses and liverworts are not mentioned in the vegetation cover descriptions produced in south-tundra bogs of the Taz Peninsula (Valeeva and Moskovchenko, 2009).

Waterlogged sphagnum hollows are typical for khasyreys at their initial development stages. Small parts of the microlandscape are covered by water. Mosses *Sphagnum balticum*, *Sph. lindbergii*, *Sph. jensenii*, and *Sph. majus* form a continuous cover in areas not covered by water. The herbaceous layer (projective cover 15%) is predominated by *Carex rotundata*, *C. limosa*, and *Eriophorum russeolum*. *Sphagnum obtusum*, *Sph. riparium*, and *Sph. squarrosum* predominate on small sites along slightly manifested watercourses and near wetland ponds; the herbaceous layer is formed by *Carex aquatilis*, *C. chordorrhiza*, *Eriophorum angustifolium*, and *E. russeolum*; *Comarum palustre* occurs sparsely. The microlandscape features peaty gley cryogenic soils on lacustrine alluvium (Histic Reductaquic Histosols).

Shrub–moss communities occupy the surfaces of large (2–3 m high) palsas. A shrub layer with a closeness of 75–90% is formed by dense *Betula nana* thickets (more than 1.5 m high) with insignificant participation of *Salix glauca*. The moss cover (projective cover 80–100%) consists of *Sphagnum fuscum*, *Hylocomium splendes*, *Pleurozium schreberi*, *Aulacomnim palustris*, *Polytrichum strictum*, and *P. commune*. Lichens (*Cladonia stellaris* and *C. rangiferina*) occur in rare spots. The soils are represented by cryozems (Folic Cryosols (Loamic, Thixotropic), Cryosols (Loamic, Thixotropic)).

In different microlandscapes of the region studied, the peatland water level occurs at different depths (Table 2). In fens, the water level can be registered on the surface of peat deposits. The lowest peatland water level (24–25 cm) is observed in hollows located along the boundaries of polygonal mires. The reaction of peatland waters in the region studied is acidic (pH 3.2–5.1); their electrical conductivity is low (from 6–8 to 52–64 μS/cm).

Measurements of the seasonally thawed layer depths in microlandscapes of the key site (Table 2) showed that the greatest thaw penetration depth (more than 70 cm) is typical for well-drained plakor sites with lichen communities. On poorly drained plakor sites with shrub–cotton-grass–lichen communities, the thickness of the seasonally thawed layer does not exceed 30 cm. The maximum thaw penetration depth in peat deposits of polygons (29–33 cm) is typical for microlandscapes with moss–shrub communities. In frost-shattered fissures separating polygons, the seasonally thawed layer is 31–45 cm. In fen microlandscapes, the thaw penetration depth varies in the range from 29 to 55 cm. In hollows, the seasonal thawed layer reaches 24–31 cm; in waterlogged hollows, its depth increases to 42–48 cm. In soils of khasyrey microlandscapes, the thaw penetration depth varies from 15 to 42 cm.

Comparison of Landscapes and Microlandscapes

All landscapes types identified in the tundra area of the Pur–Taz interfluvial region using the medium-resolution Landsat-8 image are present on the Yarneto key site. Data on the microlandscape areas obtained on the basis of the high-resolution WorldView-2 image were used to determine the areas of all landscapes studied on the key site. Data on the areal shares of the studied landscapes on the key site (based on the Landsat-8 and WorldView-2 images) are provided in Table 1.

Analysis of the medium- and high-resolution satellite images (Landsat-8 and WorldView-2, respectively) of the key site shows that the use of highly detailed satellite images significantly enhances the accuracy of areal estimates of the objects studied. It is necessary to note that the spatial resolution of the Landsat-8 image is insufficient for the identification of small natural objects, such as wetland ponds, small peat polygons and hollows, frost-shattered fissures, etc. Comparison of the satellite images used in this study shows that landscape boundaries identified on the key site based on the Landsat-8 image partially encompass microlandscapes not typical for these landscapes. For instance, plakor microlandscapes occupy only 47% of the plakor area in the Landsat-8 image: 27% of this area is occupied by microlandscapes of plakor slopes, 23% by peatland microlandscapes, and 3% by water bodies and palsas. Based on the WorldView-2 satellite image, the areas occupied by slopes with shrub thickets and polygonal–fissure complexes on the key site exceed the areas of these landscapes in the Landsat-8 image by 2.9 and 2.6 times, respectively. According to the WorldView-2 image, the areas of plakors, grass–sphagnum hollows,

and sedge fens are 26–42% less than the areas of these landscapes in the Landsat-8 image.

Comparison of the medium- and high-resolution satellite images of the key site made it possible to determine the areal shares of the microlandscapes studied within the boundaries of each landscape distinguished in the medium-resolution image. Based on the results obtained, the areas of all microlandscapes were computed for the entire Pur–Taz interfluveial area studied (Table 2). These data made it possible to estimate areas of various groups of microlandscapes and adjust the areas of landscapes (Table 1) computed for the tundra area of the interfluvial region based on the Landsat-8 satellite image. According to the estimates produced, ~35% of the wetland area in the region studied is occupied by waterlogged hollow microlandscapes. Polygonal–fissure complexes constitute a significant part of the wetlands in the study area (~31% of the peatland area). Lakes and wetland ponds occupy 7% of the study area in the Pur–Taz interfluvial region. The estimates produced indicate that the shallow zone of lakes constitutes up to 44% of their total area. Microlandscapes on plakors and their slopes occupy 57% of the tundra area in the Pur–Taz interfluvial region. Large palsas (more than 2 m in height) are quite rare and occupy no more than 3% of the study area.

CONCLUSIONS

Field data and Landsat-8 and WorldView-2 satellite images made it possible to analyze the spatial pattern of landscapes in the tundra area of the Pur–Taz interfluvial region. This study has demonstrated that the use of high-resolution space imagery significantly enhances the accuracy of areal estimates of the ground objects studied in comparison with data obtained using medium-resolution satellite imagery. The analysis conducted shows that wetland microlandscapes occupy 36% of the tundra area in the Pur–Taz interfluvial region. The estimates produced indicate that plant communities on sandy–loam and loamy soils of plakors occupy a significant part (46%) of the region studied.

Lichen and shrub–lichen communities grow on well-drained flat-topped elevations with mineral soils. Poorly drained plakor sites are occupied by shrub–cotton-grass–lichen communities. Shrub thickets are observed on plakor slopes: shrub–green-moss communities up to 60 cm high and high (up to 2.5 m) dwarf birch thickets. Polygons in polygonal–fissure complexes feature microlandscapes such as lichen–moss–shrub communities, lichen–shrub communities, and moss–shrub communities. Frost-shattered fissures separating the polygons represent a separate microlandscape. Three microlandscapes have been distinguished within the peatland landscape of grass–sphagnum hollows: sedge–shrub–sphagnum hollows, sedge–cotton-grass–sphagnum hollows, and waterlogged sedge–cotton-grass–sphagnum hollows. Sedge fens are subdivided into the following microlandscapes: sedge–sphagnum fens, shrub–sedge–moss fens, and sedge–cotton-grass fens. Waterlogged sphagnum hollows are typical for the early khasyrey development stages. Two microlandscapes were distinguished in fully developed khasyreys: shrub–moss communities on palsas and sedge–cotton-grass–sphagnum hollows.

Different microlandscapes feature different depths of the seasonally thawed layer. The greatest thaw penetration depth (more than 70 cm) is observed on plakors under lichen communities. Among the peatland microlandscapes, the greatest depth of the seasonally thawed layer (40–55 cm) is typical for waterlogged hollows and fens. Peat deposits of the polygons thaw by 25–33 cm. In palsas, the seasonally thawed layer varies in the range from 15 to 36 cm.

In the area of the Pur–Taz interfluveial region studied, cryogenic and thermokarst processes in perennially frozen rocks result in the formation of various microrelief forms; these forms have a significant impact on the formation of the vegetation cover and determine its clearly manifested heterogeneous horizontal structure. The obtained data on the composition and structure of the vegetation and seasonally thawed soil layer in regional landscapes can be used to assess the ecological potential of the study area and identify development trends in the tundra vegetation under natural dynamics conditions.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflicts of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

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