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RESEARCH ARTICLE

Soils and vegetation of the permafrost floodplain of the small river Tenyakha (Messoyakha basin, Western Siberia)

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Abstract

The soils and vegetation of Arctic floodplains are vulnerable to global warming because, in addition to climate change, they are affected by the changing hydrological regime of rivers. However, for river floodplains in large Arctic regions, such as the Yamalo-Gydan ecoregion, even descriptive field studies are still very incomplete. Therefore we studied the vegetation and soils of the floodplain of the small Tenyakha River in the south of the Gydan Peninsula. Two types of floodplain are described. The first type is represented by a floodplain on channel slopes. The second is a meander with ridges and depressions in between. Plant communities of the first type of floodplain have a higher diversity of higher plants than communities of the second type. Plant communities of microtopographic depressions and concave slopes have a lower diversity of vascular plants. The soil-forming deposits are predominantly sandy. According to the WRB, almost all the soils studied are classified as Fluvisols, except for one, classified as Arenosol, which is present in modern aeolian deposits on the floodplain ridge. All soils within two meters of the surface contain permafrost. There are soils with a humus horizon more than 20 cm thick (Gleyic Orthofluvic Fluvisol (Epiarenic, Endosiltic, Ochric)). The Munsell value of these soils is the same as that of the humus horizons of the zonal soils of the southern taiga and subtaiga. We have not detected a distinct effect of climate change on the soils. Further research is needed to confirm this.

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Keywords
Yamalo-Gydan ecoregion, meander, riverside floodplain, higher plants, Fluvisol, Arenosol, tundra, humus A horizons

Introduction

Recent studies have shown that Subarctic floodplain vegetation is changing as a result of global warming (Frost et al. 2023). This is due not only to improved climatic conditions for vegetation, but also to changes in river hydrological regimes (Mann et al. 2010), fertility, and the amount of river suspended matter settling on the surface of flooded soils (Krickov et al. 2018).

The amount of alluvium deposited on the floodplain surface depends mainly on the following factors (according to Makkaveev 1955): the degree of surface roughness, determined by the heterogeneity of the nanorelief and the type of vegetation; the age of the floodplain; the distance from the river bed; the duration and intensity of flood and spring flood processes; the concentration of suspended matter in the water. Floodplain processes have a dual focus: on the one hand, the floodplain is a place of accumulation of alluvium when flow intensity and water level decrease; on the other hand, when the erosive capacity of the flow increases, the flow of suspended matter with the river water increases (Alekseevsky 1998).

The most dynamic part of the floodplain is the riverside. The most intensive deposition of coarse alluvium occurs in the riverside, often on top of previously formed soils. Despite the fact that floodplains are widespread in the subarctic low tundra, our understanding of their ecosystem change under climate warming remains limited. This is due to the inaccessibility of the region and less intensive research compared to other terrestrial biomes (Zhu et al. 2024).

The soils and vegetation of floodplains of many tundra regions, such as the Yamalo-Gydan Ecoregion, remain poorly understood even from the standpoint of primary inventory and photographic records. Future detailed studies of soil and vegetation dynamics in Arctic floodplains require surveys with broad spatial coverage. Ground-based studies are needed to explain the direction and magnitude of tundra vegetation productivity trends derived from the Normalized Difference Vegetation Index (NDVI) (Tassone et al. 2024).

For future environmental monitoring, it is necessary to ensure a high spatial coverage of published field data in different regions of the Arctic. Research is underway to address this issue (Syso et al. 2024). An example is the work of I.D. Makhatkov and B.A. Smolentsev (2022) on the forest-tundra of southwestern Taimyr, in which primary materials were published with descriptions, photographs, and coordinates. Reference can also be made to the study by D.A. Sorochinskaya and N.B. Leonova (2020), which also presents extensive studies on the productivity of plant communities, including floodplain communities. Recently, there has been a growing interest in studying various aspects of river floodplain ecology in Western Siberia within the taiga zone (Interesova et al. 2023; Mikhaleiko et al. 2023; Vorobyev et al. 2024). Obviously, the floodplains of tundra rivers also deserve close attention.

In the tundra zone, the greatest biodiversity of higher plants is characteristic of the slopes of river valleys and their floodplains (Chinenko et al. 2018; Chernykh et al. 2022; Ivanova and Borisova 2020; Sorochinskaya et al. 2021; Neshataev 2023), especially their riverbeds, where the most specific soil-forming conditions for the tundra zone develop. In the context of global climate change, the transformation of the hydrological and hydrochemical regimes of rivers will be particularly pronounced in the riverbed floodplain. In this regard, the study of river floodplains and especially their riverside is an important task in the primary survey of poorly studied areas and in the study of the soil and vegetation cover of river valleys (Loiko et al. 2023).

It can be noted that the flora and soil cover of the Yamalo-Gydan ecoregion, especially the southern part of the Gydan Peninsula, are poorly studied, while the central part of this peninsula has been better studied (e.g. Telyatnikov et al. 2021). For example, the avifauna in the south of the Gydan Peninsula has been studied noticeably better (Korobitsyn and Tyutenkov 2023). The southern boundaries of the Gydan Peninsula have recently been described on the basis of landscape data in the work of O.A. Klimanova and E.Yu. Kolbovsky (2018). Recently there has been active industrial development in the area, which can significantly alter natural landscapes. Due to insufficient soil and vegetation studies, it will be difficult in the future to assess the extent and nature of the technogenic impact on nature in the process of natural resource development.

The soils and flora of the floodplains of small rivers in the tundra zone of Western Siberia remain poorly studied. The floodplain of one of the largest rivers in the Yamal-Gydan ecoregion, the Taz River, borders the south-western part of the Gydan Peninsula. The vegetation of this floodplain has been studied from its source to the confluence with the Panchatka River (Titov and Potokin 2001). The vegetation and soils of the floodplains of the lower reaches of the Taz River in the southern tundra have been studied in the most general terms (Natural conditions... 1972; Pismarkina and Byalt 2016; Glazunov and Nikolaenko 2018). The tundra landscapes and vegetation of the Pur-Taz interfluve have been studied (Zarov et al. 2022). Inventory studies of the soils and vegetation of the floodplains of the lower reaches of the Taz River and its small tributaries were carried out (Loiko et al. 2023). Information on the role of alluvial soils of small river valleys in the structure of the land cover was obtained for the territory of the Taz Polar Region, located on the left bank of the lower course of the Taz River (Smolentsev and Makhatkov 2024).

In order to obtain the first data on the soil and vegetation cover of small river floodplains in the south of the Gydan Peninsula, in the southern tundra subzone, we studied the flora and soils of the floodplain of the Tenyakha River (a tributary of the Bolshaya Kharvutayakha River, the Messoyakha River basin). The objectives of the work included studying the morphology and classification of soils, the species composition of higher plants and the relationship between them and soil formation conditions.

The results of the study not only provided information on the diversity of vascular plants and soils, but also described successions in the floodplains of small tundra rivers. In the context of changing hydrological processes under global warming, these data can be used as a basis for planning soil and vegetation monitoring.

Materials and methods

In the southern tundra subzone of the Gydan Peninsula, grass-dwarf shrub-moss-lichen and moss-shrub tundra communities are widespread. Peatland ecosystems are represented by sedge-cotton grass-moss and dwarf shrub-moss-lichen communities of polygonal frozen bogs. Meadow and shrub communities alternate in river floodplains (Ilyina et al. 1985; Magomedova et al. 2006). Highly productive plant communities are formed in the basins of drained thermokarst lakes (Loiko et al. 2020).

The studies were conducted in the middle reaches of the Tenyakha River (Fig. 1). According to landscape zoning, the area belongs to the Messoyakha subprovince of the southern tundra subzone of the Gydan province of the Yamal-Gydan tundra region (Atlas... 2004). According to the soil-ecological zoning of Russia (Map... 2020), the research area belongs to the subzone of tundra gley soils and podburs of the subarctic tundra, West Siberian tundra province. The territory is part of the Tazovsky-Gydansky district, whose soils have a variable soil texture from sandy to clayey, binomials and marine sediments are often found.

The climate in the south of the Gydan Peninsula is continental, with long, harsh winters and relatively short, cool summers. The average air temperature in January is between -27 and -28°C. The warmest month is July, with average air temperatures of 12–14°C. On some summer days, the air temperature can rise to 27–30°C. The average annual air temperature is between -9.5 and -10.5°C (Trofimova and Balybina 2014). Precipitation is 350 mm. A stable snow cover usually forms by the end of the first ten days of October and melts completely by the beginning of June. The snow cover reaches its maximum height at the end of April. Frequent snowstorms are also observed, resulting in an extremely uneven distribution of snow depths, from practically bare edges to 1–2 m (and more) snowdrifts in areas where alder bushes grow and at the bottom of tundra ravines (Geocrology... 1989).

The flat interfluve areas adjacent to the Tenyakha River valley have a gentle slope with a series of steps to the north-west. The highest elevations of the interfluve areas reach 40 meters above sea level. The water lines of the rivers have elevations of about 15 meters. The upper part of the Tenyakha catchment area is a flat peaty plain with elevations above 40 m, into which the Tenyakha valley and its tributaries are deeply incised. In this part, the river valley has the appearance of a picturesque hilly landscape cut by deep ravines. The incision of the gorges reaches 25 m (Fig. 2). The Tenyakha catchment area in its middle reaches is a flat plain with a lower elevation of 20–30 m above sea level. Here the Tenyakha valley widens and meanders appear near the river (Fig. 3).

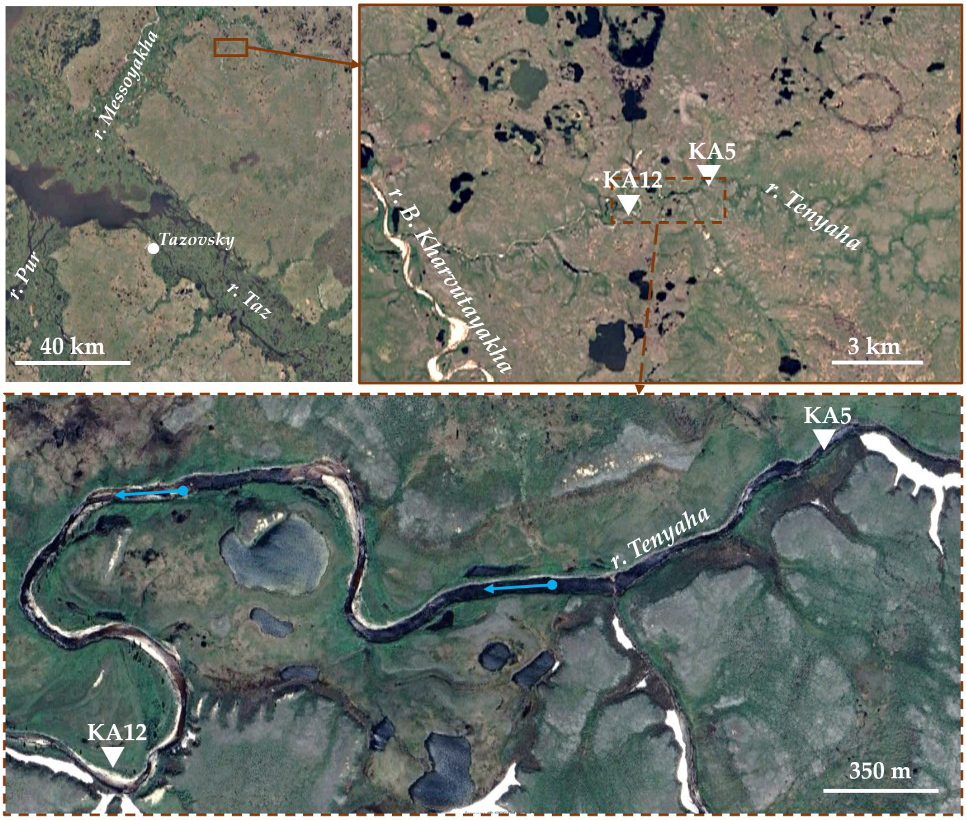

Figure 1. Location of the studied key areas (KA5 and KA12).

In the upper reaches of the Tenyakha, the riverbed is deep and narrow, 20–50 m wide and up to 6–7 m deep. The floodplain is the slope of the riverbed. In spring, the water can briefly flood the adjacent terrace, as evidenced by tufts of dry grass, but this does not affect the vegetation on the terrace. In the middle reaches, where the valley widens, the river meanders and a ridged floodplain emerges. The height of these ridges above the low water level of the river is 2–3 meters.

The treeless nature of the interfluve favours the redistribution of snow by wind – in winter thick snowdrifts form in gullies, on valley slopes and in the riverbed part of the floodplain. This affects plant and soil diversity. Winter conditions under the snow are milder, but in summer the soils warm up less due to later thawing.

Due to the combination of two floodplain types in the middle reaches of the Tenyaha River, we have established two key areas here (Fig. 1). KA5 is used to characterize the vegetation and soils of the floodplain on the slopes of the deep channel of the Tenyaha River (Fig. 4), and KA12 is used to characterize the rugged floodplain terrace (Fig. 5). At KA5 we set up two work sites. At each site, the soil profile was opened by digging a pit and the vegetation was described. At KA12 we established four work sites and examined three additional soil profiles without describing the vegetation. In addition, route observations of vegetation cover and floodplain structure were carried out in the floodplain to determine the representativeness of the selected key areas.

We carried out the fieldwork in the third ten-day period of July 2024. This year was characterised by a two-week delay in the start of the growing season, which allowed us to record the maximum number of flowering plants during the work. Reconnaissance studies were carried out to identify the geomorphological features of the Tenyakha River floodplain, on the basis of which geomorphological conditions were typified and locations for key sites and work sites were selected.

We studied soil profiles by digging soil pits, cutting and photographing their front walls, identifying soil horizons and describing them morphologically, followed by sampling. We carried out the geobotanical descriptions on 10x10 m plots or within natural contours, with small phytocenosis sizes from the side of the front walls of the dug soil pits. The description was performed by tiers.

During the study, 6 simplified geobotanical descriptions of plant communities were made, indicating the type of community, dominants and a complete list of species growing in it (Table 1).

In order to identify the plants, they were herbarised. All collected herbarium specimens were transferred to the P.N. Krylov Herbarium (TK) of Tomsk State University for storage. Herbarisation was carried out according to the rules of herbarium (Gureeva 2013). The collected herbarium was identified according to the "Flora of Siberia" (1987–2003) and collection of TK.

Figure 2. The Tenyaha River valley in its upper reaches.

Figure 3. The Tenyaha River valley in its middle reaches.

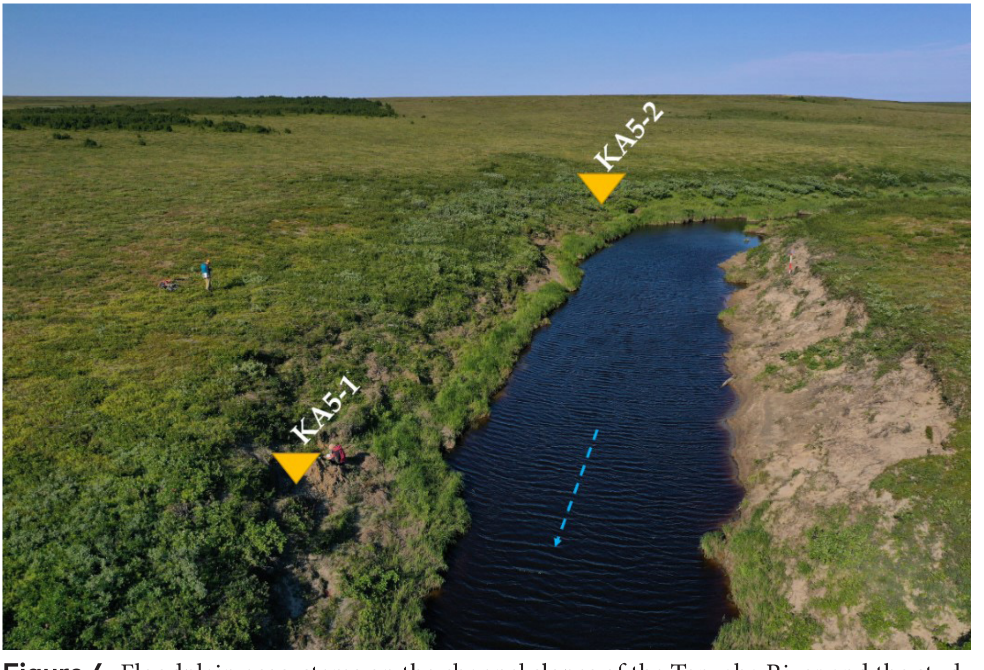

Figure 4. Floodplain ecosystems on the channel slopes of the Tenyaha River and the studied sites in the key area KA5.

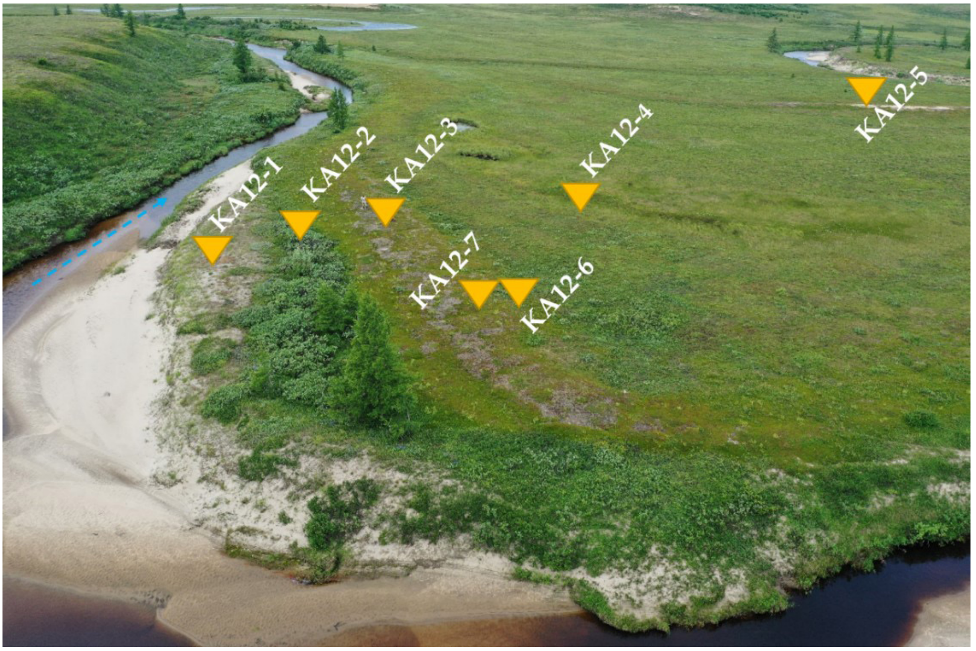

Figure 5. Overview photograph of the floodplain of the Tenyakha River and the key area KA12.

Table 1. List of identified species of higher plants in the floodplain of the Tenyaha River

Site number. Relief.	Number of species	List of plant species at research sites
		Key area 5 (KA5). Floodplain on channel slopes
KA5-1. Steep, straight in cross-section channel slope	35	*Equisetum arvense*, *Juniperus communis* L., *Carex aquatilis*, *Eriophorum vaginatum*, *Trisetum molle*, *Alopecurus pratensis*, *Festuca rubra*, *Deschampsia espitosa* (L.) P. Beauv., *Salix pulchra*, *Salix glauca*, *Betula nana*, *Rubus arcticus*, *Rosa acicularis*, *Polemonium caeruleum*, *Bistorta vivipara*, *Bistorta elliptica* (Willd. ex Spreng.) Kom., *Galium boreale*, *Chamaenerion angustifolium* (L.) Scop., *Arctous alpina* (L.) Nied., *Vaccinium uliginosum*, *Geranium krylovii*, *Linnaea borealis*, *Ranunculus propinquus*, *Trollius asiaticus*, *Astragalus subpolaris* Boriss. & Schischk., *Vicia cracca* L., *Hedysarum arcticum*, *Pedicularis sudetica* Willd., *Solidago lapponica*, *Antennaria dioica* (L.) Gaertn., *Achillea impatiens*, *Tanacetum bipinnatum*, *Erigeron elongatus* Ledeb., *Cerastium arvense* L., *Rumex acetosa* L.
KA5-2. Concave in cross-section channel slope. Steepness from gentle to sloping	22	*Equisetum arvense*, *Carex aquatilis* Wahlenb., *Alopecurus pratensis* L., *Trisetum molle* Kunth, *Luzula multiflora* (Ehrh.) Lej. subsp. *sibirica* Krecz., *Salix pulchra* Cham., *Salix glauca*, *Betula nana*, *Rosa acicularis*, *Rubus arcticus*, *Polemonium caeruleum* L., *Bistorta vivipara*, *Vaccinium uliginosum*, *Veratrum lobelianum* Bernh., *Ranunculus propinquus* C.A. Mey., *Trollius asiaticus* L., *Hedysarum arcticum*, *Geranium krylovii* Tzvelev, *Galium boreale* L., *Pyrola rotundifolia* L., *Solidago lapponica* With., *Achillea impatiens* L.

Site number. Relief.	**Number of species**	**List of plant species at research sites**
Key area 12 (KA12). Wide floodplain with a series of riverside levees (ridges) of different ages		
KA12-1. First riverside levee	24	*Equisetum arvense*, *Festuca rubra*, *Festuca ovina* L., *Poa arctica* R. Br., *Salix glauca*, *Salix phylicifolia* L., *Salix nummularia* Anderss., *Rosa acicularis*, *Bistorta vivipara*, *Aster sibiricus* L., *Solidago lapponica* With., *Tanacetum bipinnatum*, *Artemisia tilesii* Ledeb., *Chamaenerion angustifolium*, *Linnaea borealis* L., *Conioselinum tataricum* Hoffm., *Galium boreale*, *Campanula rotundifolia* L., *Cerastium arvense*, *Parnassia palustris* L., *Hedysarum arcticum*, *Aconogonon ocreatum*, *Rumex acetosa, Rumex graminifolius* Lamb.
KA12-2. An elongated depression between the first and second levees from the riverbed	10	*Equisetum arvense*, *Salix glauca*, *Salix gmelinii* Pall., *Betula nana*, *Rubus arcticus*, *Achillea impatiens*, *Viola epipsiloides* Á. Löve & D. Löve, *Vaccinium uliginosum*, *Bistorta vivipara*, *Carex* sp.
KA12-3. Second from the bed of the Tenyaha River is a riverside levee	24	*Equisetum arvense*, *Salix glauca*, *Salix nummularia*, *Betula nana*, *Rubus arcticus*, *Tanacetum bipinnatum*, *Armeria maritima* (Mill.) Willd., *Chamaenerion angustifolium*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea* L. ssp. *minus* (Lodd.) Hultén, *Empetrum nigrum*, *Arctous alpina*, *Campanula rotundifolia*, *Stellaria peduncularis* Bunge, *Hedysarum arcticum*, *Astragalus subpolaris*, *Aconogonon ocreatum*, *Bistorta elliptica*, *Luzula multiflora* subsp. *sibirica*, *Arctagrostis latifolia* (R. Br.) Griseb., *Calamagrostis langsdorffii* (Link) Trin., *Trisetum molle*, *Festuca rubra*, *Hierochloe alpina* (Sw.) Roem. & Schult.
KA12-4. Peaty, waterlogged depression in the central part of the floodplain	10	*Salix myrtilloides* L., *Betula nana*, *Comarum palustre* L., *Ranunculus gmelinii* DC., *Pedicularis sudetica*, *Luzula wahlenbergii* Rupr., *Sparganium hyperboreum* Laest. ex Beurl., *Eriophorum vaginatum*, *Carex rotundata* Wahlenb., *Carex chordorrhiza* Ehrh.

To quantify the differences in the plant communities, the beta diversity index was calculated using the Bray-Curtis dissimilarity (Bray-Curtis index). The Bray-Curtis index quantitatively measures the degree of difference between two samples (communities) based on the counts for each of them (Bray, Curtis 1957).

The index was calculated according to the formula:

$$BCij = 1 - 2\ Cij / (Si + Sj),$$

where Cij is the sum of common species for samples i and j, Si and Sj are the total number of species for samples i and j, respectively.

It should be clarified that in the formula for calculating the Bray-Curtis index, the indicator Cij implies the sum of smaller values for species common to two samples. However, since simplified geobotanical descriptions were carried out during the study, without taking into account the projective cover of species, the calculation of the Bray-Curtis index was carried out with the assumption that in this case the index describes to a greater extent the taxonomic differences of the described sites. The values obtained by calculating the Bray-Curtis dissimilarity range from 1 to 0, with 1 representing the most different communities and 0 representing identical communities.

In the laboratory, bulk monoliths were prepared from collected soil samples, which helped to clarify the morphological characteristics of the soil horizons. The classification and diagnosis of soils were carried out using photographs of the front walls of soil pits, profile formulae, soil descriptions and samples taken in the field. The Classification of Soils of Russia (Shishov et al. 2004) and the Field Guide to Soils of Russia (Field... 2008) were used to determine the classification affiliation of soils. In addition, the International Soil Classification System WRB (IUSS... 2022) was used. Logical-interpretive processing of the collected photographic material, descriptions of soils, vegetation and relief was carried out using the comparative geographical method and the concept of hydrological continuum (Doretto et al. 2020).

Results

In the upper and part of the middle reaches of the Tenyaha River, the floodplain is confined to the steep slopes of the riverbed. Rich shrub-herbaceous communities develop on the slopes. Shrub cover increases with the age of channel slope stabilisation. The proportion of herbaceous parcels is higher in conditions of geomorphologically more active slopes.

Four types of slope floodplains can be distinguished:

- Scree-Talus. The most geomorphologically active slopes are the least widespread. They are just beginning to be covered with grass. The vegetation cover is minimal.
- The slopes with landslide terraces are beginning to be covered with birch, less often with willow. They occupy no more than the first two percent of the entire length of the channel slope. They have the greatest diversity and saturation of herbaceous species per unit area. The transverse and longitudinal profiles are straight.
- Slopes with landslide terraces in an advanced stage of overgrowth, a typical option. There are many willows and dwarf birches up to 100 cm high. The diversity of herbs is lower than in the previous type. Slopes of this type occupy more than 70% of the length of the channel slopes.
- Slopes are concave in cross section. They are formed in areas where small ravines flow into the river, through which water flows from the first floodplain terrace. On this type of slope the bushes are up to 160–200 cm high. The most vegetated type of slope.

The key area KA-5 (68.094182° N and 79.323692° E) is located on the slopes of the south-western and south-eastern exposures. The slopes extend from the low-water line of the Tenyakha River to the edge with the first floodplain terrace. The difference from the edge to the water's edge is 4 metres. The slopes of the second and fourth types are characterised by sections (Table 2).

Below is a description of the soils and vegetation.

Soil profile KA5-1 is described in the middle part of the south-eastern slope, with a steepness of 10–15° (Table 2). Cover of herbs is 60–70%. The diversity of higher plants at this point is the highest among all the studied plant communities of the Tenyahi floodplain (Table 1). The share of shrubs is insignificant, the most abundant here are *Tanacetum bipinnatum* (L.) Sch. Bip., *Aconogonon ocreatum* (L.) H. Hara and *Festuca rubra* L.

Table 2. List of studied sites, soils and vegetation

Site number	Geomorphological position and key area	Geographical coordinates	Soil name according to the Classification of Soils of Russia (2004, 2008)	Soil name according to WRB 2022	Plant community
KA5. Floodplain on the slopes of the deep channel of the Tenyakha River					
KA5-1	Second type of slope. The slope is steep, straight in both transverse and longitudinal directions. There are solifluction nanoterraces, separated in places by settling cracks parallel to the riverbed	68.09418° N 79.32369° E	Allyuvial'naya gumusovaya gleyevataya peschano(40)-srednesuglinistaya	Gleyic Orthofluvic Fluvisol (Epiarenic, Endosiltic, Ochric)	Willow-forb-grass meadow
KA5-2	Slope of the fourth type. Concave in cross section. The slope is gentle in the upper part and sloping in the lower part. The place where an intermittent stream flows into the slope	68.09474° N 79.32548° E	Sloisto-allyuvial'naya grubogumusirovannaya gleyevataya peschano(20)-tyazhelosuglinistaya	Pantofluvic Fluvisol (Epiarenic, Endoloamic, Ochric)	Dwarf birch-willow forb-sedge
KA12. Wide floodplain with a series of riverside levees (ridges) of different ages					
KA12-1	The top of the young riverside levee (the first from the river bed)	68.089285° N 79.294789° E	Sloisto-allyuvial'naya peschanaya	Pantofluvic Fluvisol (Arenic)	Willow-forb-grass sparse meadow
KA12-2	An elongated depression between the floodplain ridges (the first and second riverside levees)	68.089415° N 79.294960° E	Sloisto-allyuvial'naya gumusovaya gleyevataya peschano-legkosuglinistay	Stagnic Pantofluvic Fluvisol (Ochric)	Horsetail-forb willow
KA12-3	The second from the manual riverbed riverside levee-ridge	68.089523° N 79.294918° E	Sloisto-allyuvial'naya gumusovaya peschanaya	Pantofluvic Fluvisol (Arenic, Ochric)	Willow-lichen-dwarf shrub-arctus tundra meadow with elements of mixed grasses
KA12-4	Peaty, waterlogged depression in the central part of the floodplain	68.089775° N 79.295003° E	Allyuvial'naya torfyano-gleyevaya merzlotnaya srednesuglinistaya	Histic Pantofluvic Fluvisol (Loamic, Gelic)	Cotton grass-dwarf birch-sedge-sphagnum fen

Site number	Geomorphological position and key area	Geographical coordinates	Soil name according to the Classification of Soils of Russia (2004, 2008)	Soil name according to WRB 2022	Plant community
KA12-5	A long-standing ridge on the central floodplain with evidence of aeolian transformation	68.090681° N 79.293841° E	Podbur opodzolennyy malomoshchnyy peschanyy	Brunic Arenosol (Gelic, Nechic)	Lichen-crowberry-arctous tundra
KA12-6	A cryogenic crack that crosses the second riverbed ridge from the riverside levee (ridge). Slope of the ridge	68.089560° N 79.295232° E	Allyuvial'naya gumusovaya grubogumusirovannaya krioturbirovannaya merzlotnaya	Stagnic Pantofluvic Fluvisol (Arenic, Gelic, Ochric, Turbic)	Willow-forb-artous-crowberry tundra meadow
KA12-7	A cryogenic crack that crosses the second riverbed ridge from the riverside levee (ridge). The top of the ridge	68.089529° N 79.295117° E	Sloisto-allyuvial'naya gumusovaya grubogumusirovannaya peschanaya krioturbirovannaya gleyevataya merzlotnaya	Pantofluvic Fluvisol (Arenic, Gelic, Ochric, Turbic)	Lichen-arthus-crowberry tundra meadow

The soil is diagnosed as Gleyic Orthofluvic Fluvisol (Epiarenic, Endosiltic, Ochric). Profile horizons: A(0-8(10))–[A-C]@(8(10)-18(23))–AC~(18(23)-37(40))–Cl~(37(40)-61)–Cg~(61-82+) (Fig. 6). The background of the A horizon has a pale grey hue when wet (according to Munsell 1.1Y/5.3/3.1). Its pattern includes thin layers of pale sandy material and rare small charcoals. The horizon is densely penetrated by the roots of the grass. The texture is sandy loam.

Horizon [A-C]@ is heterogeneous, pale grey (Munsell 0.9Y/5.0/3.1) with light ochre patches and thin whitish layers, increasing in number towards the lower boundary, humified. Contains occasional charcoal, sandy loam in the main mass, coarse sand in lighter layers. The transition is marked by a sharp decrease in the number of grey layers.

Horizon AC~ grayish-pale (Munsell 0.7Y/5.2/3.6) with whitish, light gray layers, brown layers and ochre spots. It is lighter in colour than the overlying horizons, but contains layers of humified material indicating periodic burial of formed humus layers by a fresh portion of alluvium. Sandy, rare roots.

The underlying horizons are the parent rock transformed by gleyization and precipitation of iron (hydr-)oxides. Cl~ is glaucous with numerous ochre and whitish glaucous patches and layers, mostly sandy, sandy loam on gleyed morphons, roots are found. Horizon Cg~ is a glaucous background colour with a small amount of rusty ochre patches. Texture from sandy loam to light loam. Roots are rare.

Soil profile KA5-2 was investigated on a slope with a concave cross section and southern exposure, with a slope angle of 5–10° (Table 2). The soil was diagnosed as

Pantofluvic Fluvisol (Epiarenic, Endoloamic, Ochric) (Fig. 7). The plant community is shrub-herbaceous. The number of plant species is slightly lower than in site KA5-1, with 23 species (Table 1). However, the cover is higher, reaching 80–90%. There is plant litter on the surface. The profile horizons are A~(0-12(14))–AC~(12(14)-18(22))–Cg(18(22)-31(37))–C~(31(37)-66+).

Figure 6. Southern slope of the Tenyaha River bed and Gleyic Orthofluvic Fluvisol (Epiarenic, Endosiltic, Ochric) (soil profile KA5-1).

Figure 7. Southern slope and Pantofluvic Fluvisol (Epiarenic, Endoloamic, Ochric) (soil profile KA5-2).

Horizon A is grayish-brown (0.4Y/4.5/2.1 according to Munsell) with pale yellow and whitish interlayers. Consists of alternating buried grayish humified and light sandy layers. Densely penetrated by roots. Single charcoal is found. AC is light brown (10.1YR/4.2/2.2) with pale yellow and brown spots. There is stratification. Sandy. Cg is heterogeneous olive-pale (1.3Y/6.0/3.1) with glaucous, ochre and brown spots, the horizon contains large grayish-brown morphons, their abundance increases along the lower boundary of the horizon, which is apparently associated with the burial of the former soil. Medium loam. The parent rock C~ is light brown with bluish spots having a rusty-ocher border. The deposit has a slate-platy structure. Heavy loam.

Despite the rather similar geomorphological location, the two described profiles differ significantly in their morphology. The A-horizon of the KA5-1 profile is developed significantly better than in the KA5-2 profile. In the soil of the KA5-2 site, the upper horizon is represented by a system of isolated layers, reflecting the alternation of cycles of sedimentation of large clarified alluvium and accumulation of humus fine earth.

Site KA5-2 is located on a slope that has a concave cross-section. In spring, water from a stream flowing from the valley slopes flows here. Due to the higher and denser shrub layer, the surface becomes rougher. This, in turn, accelerates the sedimentation of suspended matter during flooding, which promotes the renewal of the mineral matrix and interrupts the formation of the humus horizon. In the conditions of a concave surface, which is also in the shade of shrubs, accumulation of humus slow down.

The KA12 key area is located on the actively growing meander of the Tenyakha River (coordinates: 68.08928°N and 79.29479°E). The meander consists of a series of riverside levees of different ages, alternating with elongated depressions (drops of 1–1.2 m and less) (Fig. 5). In the central part of the meander, the microtopography is leveled where waterlogged permafrost soils are formed. On the latest riverside levees, Brunic Arenosols are formed, and the processes of podzolization and winnowing of sandy deposits begin. On the second riverside levee, soils with cryogenic disturbances associated with the formation of permafrost wedges are encountered.

The key site KA12-1 is on the top of an early riverside levee (first from the riverbed) (Table 2). Plant cover is sparse, no more than 50–60%. It is a herb-grass meadow with low shrubs, the most common of which are *Tanacetum bipinnatum* (L.) Sch. Bip., *Aconogonon ocreatum* (L.) H. Hara and *Festuca rubra* L. (Table 1). The soil profile is diagnosed as Pantofluvic Fluvisol (Arenic) (Fig. 8).

The soil contains the following horizons Ch1~(0-11)–Ch2~(11-23(27))–C3~(23(27)-42–C4~(42-100+). Horizon Ch1~ is represented by a series of brownish pale-coloured sandy layers buried in poorly developed humus horizons. Below this is Ch2~, which has a similar morphology but contains fewer roots. The lower part of this horizon is bounded by a light brown, more silty interlayer just over one cm thick. Horizon C3~ is pale with light grey thin layers and patches of dark brown detritus along root passages. It is the loosest and coarsest sandy horizon. C4~ is represented by layered deposits with alternating pale and light brown thin layers. Roots are rare. Permafrost at 180 cm.

Along the first riverside levee there is a depression with horsetail-forb willow. In this depression, during the flood period, fine fractions of alluvial material are deposited, which is reflected in a fine earth texture. The period of standing water in the depression is also significantly longer than on the riversides (ridges), so the soil is gleyed. The site KA12-2 is associated with this depression. Herb-shrub community. *Betula nana* L. and *Salix glauca* L. dominate, under their canopy there is a significant abundance of *Equisetum arvense* L. and *Rubus arcticus* L., green mosses are noted (Table 1).

The soil of the depression is diagnosed as Stagnic Pantofluvic Fluvisol (Ochric) (Fig. 9) with horizons Ch(0-9)–C~(9-75). The Ch horizon is light grey with seven dark brown interlayers consisting of plant litter buried under the alluvium. The C~ horizon is stratified, represented by a series of buried horizons composed of layers of contrasting morphology: thick bluish-grey interlayers with ochre stains alternate with lighter and more sandy pale grey interlayers.

In profile KA12-2, fragments of buried plant litter are found to a depth of 40 cm, confined to darker layers. Unlike the riverside levee soil, humus formation occurs here, which is expressed in the fragmentary distribution of light-gray humified layers near the surface. Permafrost begins at 120 cm.

On the second levee from the Tenyaha River bed was site KA12-3. It contained a willow-lichen-dwarf shrub-arctus tundra meadow with a predominance of *Empetrum nigrum* L., *Arctous alpina* (L.) Nied. and *Aconogonon ocreatum*. In the soil profile of KA12-3 the horizons are Ch(0-5)–C~(5-90+). In comparison with KA12-1, a light grey humus horizon of about 5 cm thickness is expressed here. The soil is classified as Pantofluvic Fluvisol (Arenic, Ochric) (Fig. 10). The layered deposit, as in the case of the first riverside levee, is represented by a series of buried surface horizons. However, the contrast in thickness and colour of the layers is somewhat reduced. Permafrost begins at a depth of 170 cm.

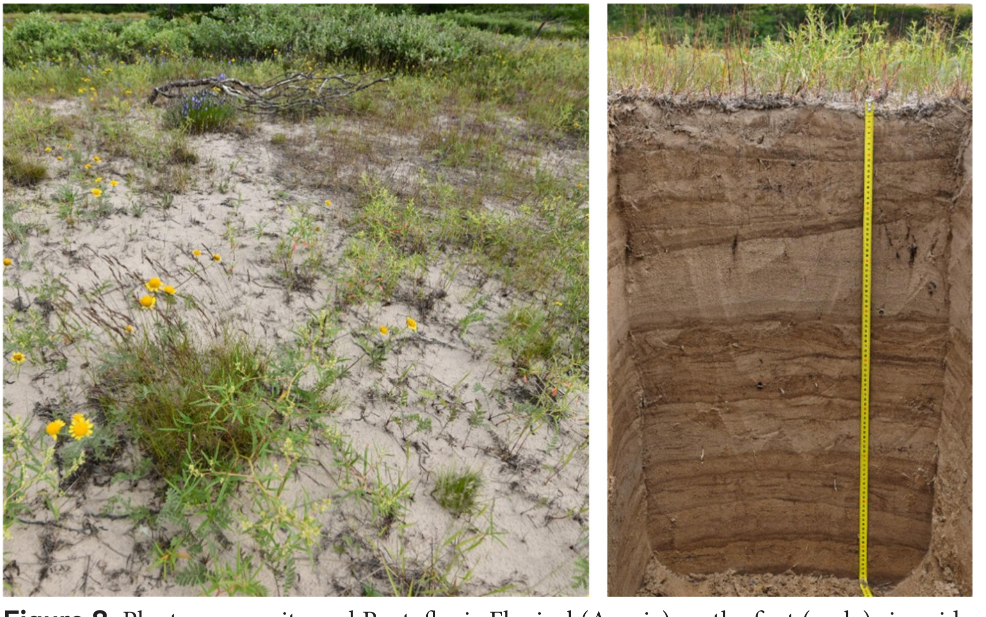

Figure 8. Plant community and Pantofluvic Fluvisol (Arenic) on the first (early) riverside levee of the Tenyayakha River.

Figure 9. Plant community and Stagnic Pantofluvic Fluvisol (Ochric) in the depression between the riverside levees.

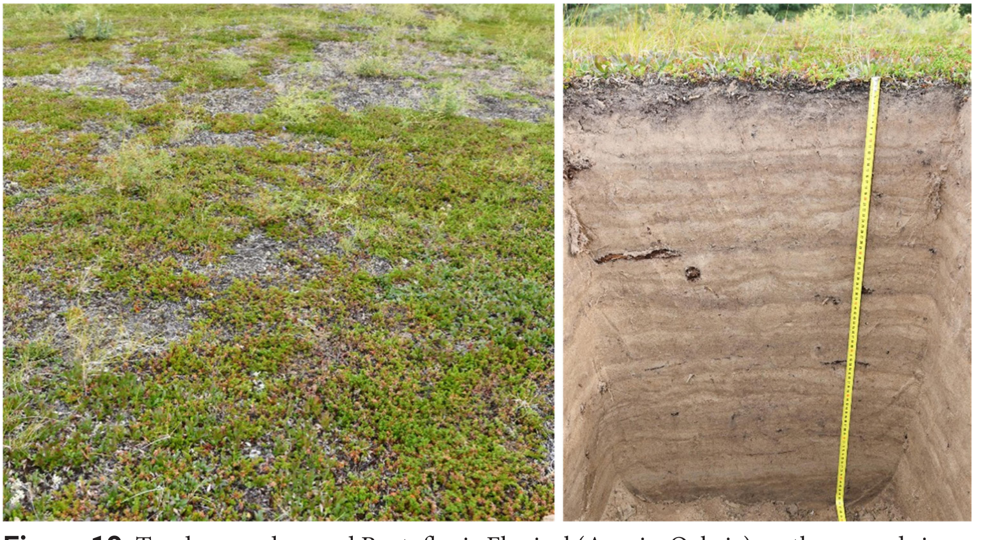

Figure 10. Tundra meadow and Pantofluvic Fluvisol (Arenic, Ochric) on the second riverside levee from the Tenyaha River bed.

Over the centuries of existence of the second riverside levee, cryogenic cracks with epicryogenic ice veins have formed. The heads of these ice veins are at the level of maximum seasonal thaw. The upper horizons slide into these cracks, accumulating organic matter and forming fairly large Oe morphons. Figure 11 shows photographs of soil profiles illustrating the characteristics of the influence of these cracks on soils.

Soils KA12-6 and KA12-7 are located at the foot and at the top of the riverside levee, respectively. They are confined to the same crack running across the riverside levee KA12-6 is classified as Stagnic Pantofluvic Fluvisol (Arenic, Gelic, Ochric, Turbic), consisting of horizons: A~(0-16)–C~(16-36)–Cg~(36-80).

Horizon A~ contains fragments of a buried layer of brown peat, coloured with humus underneath. Sandy. Horizon C~ is pale yellow with grey and brown layers. Cg is pale grey with ochre stains, greyish and whitish layers, the number of rusty ochre and gleyed stains increases towards the bottom of the horizon. Pseudomorphosis along a crack consists of material from overlying horizons and goes deeper than 1 meter. There is an unfilled cavity in the upper part.

Figure 11. Soils of cryogenic cracks transverse to the direction of the extension of the axis of the second river from the Tenyaha riverside levee. On the left is KA12-7 (A) and on the right is KA12-6 (B).

The soil of section KA12-7 is diagnosed as Pantofluvic Fluvisol (Arenic, Gelic, Ochric, Turbic). The undeformed part of the soil profile is similar in morphology to profile KA12-3. The profile formula is A(0-6)–C~(6-70+). In the cryodeformed pedon along the crack, the thickness of the humus horizon is increased by the sliding of material from the soil surface. The lower part of the crack is filled with redeposited sandy material, as in KA12-6.

The soils of the central part of the Tenyaha River meander are waterlogged with active peat accumulation. A sedge-cotton grass-sphagnum fen has been studied here (site KA12-4). *Carex rotundata* Wahlenb. and *Eriophorum vaginatum* L. are dominant. *Betula nana* grows on the hummocks. *Sphagnum* sp. dominates the mosses. The elevation of this site is lower than that of the riverside levee described above, located at a distance of 30 m. The soil profile of the site is diagnosed as Histic Pantofluvic Fluvisol (Loamic, Gelic) (Fig. 12) and has the following horizons Oi(0-28)–CG~(28-35)–CG(35-38+)$\perp$. The thickness of the peat horizon is 28 cm, below which organogenic and mineral gleyed layers alternate. Permafrost occurs at a depth of 35 cm.

In the terrace part of the meander of the Tenyaha River there is an ancient ridge, the upper part of whose alluvial deposits have been aeolian redeposited. This was established by analyzing the morphology and textures of the soil profile studied by section KA12-5 (Fig. 13). The soil is diagnosed as Brunic Arenosol (Gelic, Nechic).

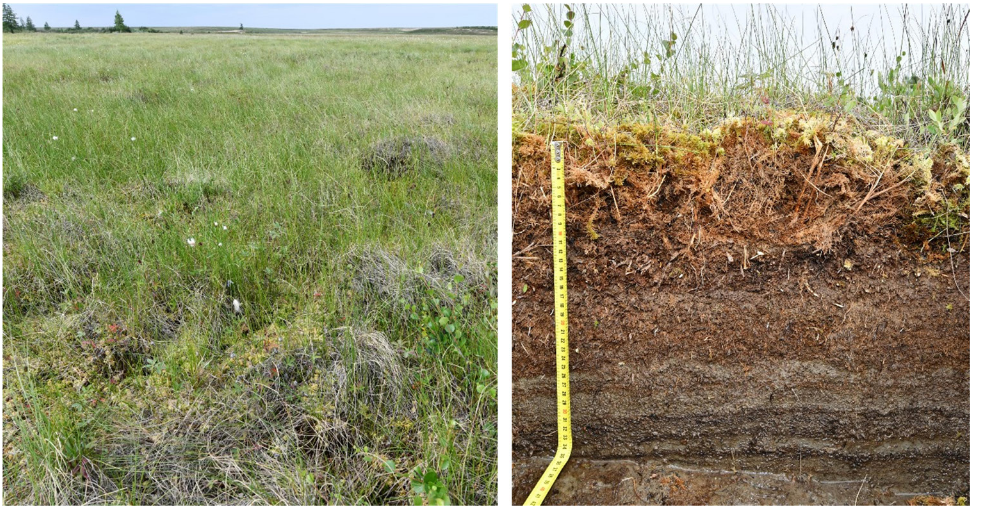

Figure 12. Fen and Histic Pantofluvic Fluvisol (Loamic, Gelic) of the central part of the meander of the Tenyaha River.

Figure 13. Brunic Arenosol (Gelic, Nechic) of the area of aeolian redeposited sands of the ridge of the near terrace floodplain of the Tenyaha River.

In profile KA12-5 there are horizons: I(0-3)–OA(3-5(10))–Bs(5(10)-20)–C~(20-30+). On the surface there are several cm of relatively recent blown-in material from a nearby sand blowdown on the same ridge. Below there is a humus horizon with a large proportion of plant detritus. Mineral grains in this horizon are devoid of (hydr-)oxide coatings, whitish. In the lower part of the humus horizon podzolization is diagnosed. Below there is a pale-ocherous sandy horizon Bs with (hydr-) oxide coatings on the surface of sand grains. Under it there are sandy deposits with an aeolian signature, replaced by alluvial deposits.

According to the calculated Bray-Curtis index for the described sites, the fen site KA12-4 in the inner part of the river meander was the most different from the others (10–0.87). Site KA12-2 in the depression between the ridges also differed significantly from the other sites (0.9–0.69), with the exception of site KA5-2 on the concave slope (0.56). Sites KA12-1 and KA12-3 differ significantly from the other sites (0.94–0.62 and 1–0.62, respectively), with the exception of site KA5-1 (0.56). The most similar channel floodplain sites are KA5-1 and KA5-2 (0.33) (Table 3).

Table 3. Bray-Curtis index values of plant communities of the studied sites

	KA5-1	**KA5-2**	**KA12-1**	**KA12-2**	**KA12-3**	**KA12-4**
KA5-1	0	0.33	0.56	0.69	0.56	0.87
KA5-2	0.33	0	0.70	0.56	0.65	0.94
KA12-1	0.56	0.7	0	0.82	0.63	1
KA12-2	0.69	0.56	0.82	0	0.71	0.90
KA12-3	0.56	0.65	0.63	0.70	0	0.94
KA12-4	0.87	0.94	1	0.9	0.94	0

Discussion

Our study is the first description of floodplain soils for the south of the Gydan peninsula. The soils studied are assigned to the Fluvisol reference soil group, with the exception of one site with Arenosol. Six principal qualifiers and seven supplementary qualifiers were used. No accumulation of thick plant litter was noted due to annual flooding of the soils. At site KA12-2 they occur but are quickly buried by new alluvial deposits.

Previously, the floodplains of small rivers of the Taz tundra, which extends to the left bank of the lower reaches of the Taz River, were similarly studied (Loiko et al. 2023). The floodplain of the lower Taz is of the estuarine delta type (Korotaev 2011). There, small rivers are backed up in spring by the Taz River, which floods earlier than these small rivers because the Taz flows from the south. For this reason, the soils of the floodplains of the previously studied small rivers had a significantly greater number and thickness of loamy layers in the soil profiles, as sedimentation of the fine fraction occurs during this backwater. On the contrary, in the floodplain of the Tenyakha River, the water flow is fast, there is no backwater, therefore the sedimentation of the fine fraction is observed only in the conditions of concave slopes in the places with the greatest coverage of shrubs.

Floodplains are considered as areas of underestimated carbon accumulation, especially considering that climate warming may alter geomorphic processes (Lininger et al. 2019). In the soils considered in this study, soil horizons with high carbon content are divided into three groups - peat, humus with high plant detritus content and humus. The diversity of autochthonous horizons accumulating carbon indicates a high sequestration potential of tundra floodplains.

Peat horizons are formed in the fens of the inner parts of meanders. Humus horizons with a large proportion of detritus predominate in the studied soils. A humus horizon similar to more southern areas was encountered in one site – KA5-1. The soil of this site is diagnosed as Pantofluvic Fluvisol (Epiarenic, Endoloamic, Ochric). The last supplementary qualifier notes the presence of a humus horizon, in this case having a thickness of more than 20 cm. The Munsell value of this horizon is similar to the zonal soils of the southern taiga. Such an A horizon diagnoses the process of humus accumulation in the floodplain tundra environment. According to this characteristic, the soil is rare and can be recommended for inclusion in the potential Red Book of soils of the Yamalo-Nenets Autonomous Okrug. During the study of other floodplains in the south of the Gydan Peninsula, as well as within the Pur-Taz interfluve, we have not yet encountered such soils.

The genesis of the humus horizon at site KA5-1 is due to the warming of the southern slope, the introduction of nutrients with floods, the presence of herbaceous vegetation and dying roots. There is also a constant input of humus material from the upper part of the slope to the middle part. Below, closer to the river, the A horizon disappears, as this part is subject to over-wetting and prolonged flooding, and is also more exposed to erosion processes.

Another significant difference between the floodplain of the Tenyakha River and the previously studied floodplains of small rivers on the left bank of the Taz River (Loiko et al. 2023) is the presence of areas of aeolian processes. Brunic Arenosol (Gelic, Nechic) is formed in such places. The podzolisation process develops in this soil. It is associated both with the bleaching of minerals from (hydr)oxides, which is noted by the additional qualifier Nechic, and with the browning of the central part of the profile due to the accumulation of iron compounds. These soils are very rare for tundra, as the soils of the distribution of sandy soil-forming deposits are usually highly disturbed by cryoturbation. In the floodplains of the larger rivers of the southern Gydan, modern eolian deposits are common.

Permafrost was found within two metres of the surface in all the soils investigated. This distinguishes them from the soils previously studied on the left bank of the Taz River (Loiko et al. 2023), as well as from the soils of stream floodplains south of the Bolshezemelskaya Tundra (Kaverin et al. 2023). The more northerly location of the study area means that permafrost is already forming in the floodplain. As the meander grows, ice veins form on older river banks. According to the soil morphology, their formation in sites KA12-6 and KA12-7 occurred after the formation of the upper humus horizons, i.e. relatively recently.

The two types of floodplain investigated are very different. The soils of key area KA5 are regularly flooded. The soils of the key area KA12, as the meander grows, are not flooded any more, or these waters no longer carry much silt. Therefore, under the conditions of a ridge floodplain, there are ecosystems that are no longer riverbed ecosystems. They either develop peat accumulation processes if they are depressions, or tundra transformation and deflation if they are ridges. As a result of these processes, biodiversity and grass cover decrease, while mosses, lichens and ericoids increase.

The study found no obvious effects of climate warming on the environment of the Tenyaha River floodplain. The levees of different ages had a similar structure. There is no evidence of increased silt transport and deposition on the floodplain. No progressive development of one or more plant species was observed. This does not mean that there are no changes at all; they are not in an explicit form accessible to the comparative geographical method. Previously, it was found that in Alaska, the cover, stature and density of vegetation communities in river floodplains increased over a 30-year period (Frost et al. 2023). Shrubbing of floodplain meadows for various reasons is a common process in the boreal climate (Bork and Burkinshaw 2009; Ivanov et al. 2022). In the ecosystems we studied, shrubs are also a common life form of plants, but it was possible to establish some targeted improvement in their habitus indicators. Landscapes away from major river valleys appear to be more resilient to ongoing global climate change.

Conclusion

Based on the results of the first studies of floodplain soils and vegetation in the south of the Gydan Peninsula, using the Tenyaakha River as an example, data on the taxonomic diversity of soils and plants were obtained. Information was obtained on the geomorphological structure of the river floodplain in the area of the confluence of the upper and lower reaches of the river. Information was obtained on the morphological structure of the soils.

It has been established that rare soils are formed in the environment of river floodplains, in which a humus horizon is developed, the value of which on the Munsell scale corresponds to the A horizons of zonal soils of the southern taiga. Such soils can be included in the Red Book of the Yamalo-Nenets Autonomous Okrug. It is on these soils that the greatest diversity of higher plant species can be found. In the conditions of the ridge floodplain, the presence of deflated areas, as well as overgrown eolian deposits with soils showing signs of podzolization, was noted. Permafrost was found within 2 metres of the soil surface in all the alluvial soils studied.

The work carried out is a reserve for further continuation of the comprehensive study of floodplains in the tundra of Western Siberia. It is the floodplain landscapes that are most vulnerable to change as climate change continues.

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