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SOIL TEMPERATURE REGIME IN POSTAGROGENIC ECOSYSTEMS UNDER THE EXPANSION OF SELF-RESTORING SUCCESSION OF TUNDRA VEGETATION (EUROPEAN NORTH-EAST OF RUSSIA)

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The peculiarities of soil temperature regime and occurrence of permafrost table in the postagrogenic meadow ecosystems developing in the cryolithozone in the European north-east of Russia in the context of the self-restoring tundra vegetation succession expansion have been investigated (2009–2016). A comparative analysis of the studied parameters with those pertained to meadow (agrogenic) ecosystems in the period of their agricultural development (1996–1999) is provided. Recent increase in the temperature of loamy Anthrosols and Stagnosols/Cryosols (gleyzems) is associated with the permafrost table depth changing from relatively shallow to below 2 m as a result of climate change-driven activation of the self-restoring tundra vegetation succession. Specifically, within the observation sites located on the river terrace and watershed, the increased soil temperature during the study period has prompted an increase in the active layer thicknesses from 1.5 to 1.8 m and from 1.8 to 2.0 m, respectively.

Soil temperature regime, permafrost, postagrogenic ecosystems, self-restoring succession of tundra vegetation

INTRODUCTION

Agricultural development of the areas subsumed into tundra ecosystems which commenced in the second half the 20th century was largely prompted by a rapid population growth in the Vorkuta industrial district within the cryolithozone in European NE Russia [*Archegova et al., 2013*]. Under severe subarctic climate coupled with discontinuous permafrost, perennial artificial meadows were cultivated as a fodder base for local livestock [*Kotelina et al., 1985*]. With liquidation of the state agricultural farms late in the 1990s, both soil fertilization and haymaking ceased on the artificial meadows. For some time afterwards (during the 2000s) the meadows continued to function as stable postagrogenic ecosystems [*Panyukov, 2013; Kovaleva et al., 2017*], however, active colonization of the artificial meadows by the tundra vegetation began already in the second decade of the 21st century. In the "warm" East-European permafrost zone, changes in the vegetation cover strongly affect both soil temperatures and permafrost table depth [*Malkova, 2010*]. Thus far, very few research works have addressed soil temperature regime of the meadow ecosystems within the cryolithozone [*Desyatkin and Desyatkin, 2017; Zheng et al., 2017*].

Effects of the agricultural development on soil temperature regime of the tundra ecosystems during summer in the European North was studied by A.V. Kononenko [*1986*] who established that the extinction of natural vegetation and peaty surface horizons have entailed a drastic change in the soil temperature regime of agricultural lands. In her paper, I.B. Archegova [*2007*] provides an in-depth analysis of the temperature regime of long-term seasonally freezing soils of the agrogenic and postagrogenic tundra ecosystems in comparison with their virgin counterparts.

Agrogenically transformed soils that formed in the period of agricultural development of the tall-shrub tundra sites have become colder, than virgin soils, with the temperature parameters approaching regional permafrost-affected soils during their latest agricultural years (1996–1999).

The purpose of this paper is to study the Anthrosols temperature regime dynamics and variability of the permafrost table depth prompted by the activation of self-restoring tundra vegetation succession in postagrogenic ecosystems in the European NE Russia. A comparative analysis of the studied parameters with those of the intact tundra ecosystems located in similar landscape conditions provided indicators for the periods of postagrogenic (2009–2016) and agricultural (1996–1999) functioning of the tundra ecosystems.

OBJECTS OF RESEARCH

The research area is characterized by a severe subarctic climate and massive-island distribution of permafrost [*Ershov and Kondratieva, 1997*]. The main climatic parameters for the periods of 1996–1999 and 2009–2016 were derived from the Vorkuta weather station data listed in Table 1.

The study area is a gently rolling plain with a surface blanket of silty clay-loams not exceeding 10 m in thickness [*Petrov et al., 2010*]. According to the geobotanical zoning, this area belongs to the Vorkuta tundra district of the shrub (southern) tundra subzone [*Ogureeva, 1991*]. Shrub (crowberry and willow) and low shrub tundra communities are commonly developed on the watershed sites. Sedge and flat-topped hummocky mires tend to occupy flat areas and depressions [*Khantimer, 1974*]. Given a largely impeded drainage of the soil cover, Histic Cryosols and Histosols predominate within its structure, whereas Stagnosols are widespread on the drained massifs [*Dobrovolsky et al., 2010*]. The permafrost table depth in clay-loamy soils is differentiated depending on the type of vegetation cover, varying accordingly from 0.7–0.8 to 2.0–3.0 m and more [*Mazhitova, 2008*]. Cryosols are widespread on summits exposed to the wind, sloping hills, ridges and terraces covered by moss-shrubby vegetation. The anchoring type of permafrost (i.e. seasonally frozen soil layer merges with permafrost table) typifies permafrost-affected soils [*Ershov, 1988*]. The permafrost table is not detected within the upper 2–3 meters of the strata beneath the cover of tall shrub vegetation, where discontinuous type of permafrost is established [*Shamanova, 1964*].

Anthrosols developed in areas of the postagrogenic tundra ecosystems, which are represented by perennial artificial meadows overgrown with natural tundra vegetation were chosen as the research objects. Stagnosols/Cryosols of the natural tundra ecosystems are considered as their virgin counterparts (Table 2). In these soils, the topmost horizon (T or O) is immediately underlain by gley horizon (G). Anthrosols have a limited distribution and were first studied in detail in the vicinity of the city of Vorkuta [*Shishov et al., 2004*]. These differ from the undisturbed (virgin) Stagnosols/Cryosols by a soddy horizon (AY) occurring in the upper part of the soil profile (Table 2). Mineral horizons occurring below 20 cm have preserved the natural undisturbed layered structure. Whatever the soil type, a gley horizon in the middle part of the profile is underlined by a cryometamorphic horizon (CRM), gradually passing into the soil-forming deposits (C). The studied soils are developed on drained clay-loamy sloping hills. At this, two pairs of soil profiles formed in areas dominated by low- and tall-shrub vegetation, respectively, are considered. The study sites 1 and 2 are located at a distance of 400 m from each other, 10 km north-east of Vorkuta (the Ayach-Yaga natural boundary) on the riverine sloping hill featured by the predominance of dwarf-crowberry

Table 1. **Climatic parameters according to the Vorkuta weather station**

Hydrological years	Mean annual air temperature, °C	Sums of temperatures, °C·day		Air frost number	Annual mean precipitation, mm
		TDD	FDD		
1995/96	–5.8	835	–2905	0.65	426
1996/97	–5.2	828	–2693	0.64	366
1997/98	–8.0	1004	–3878	0.66	583
1998/99	–8.4	881	–3930	0.68	541
1995–1999	–6.8	887	–3351	0.66	479
2009/10	–7.0	995	–3542	0.65	776
2010/11	–4.1	1098	–2562	0.60	668
2011/12	–2.3	1370	–2182	0.56	642
2012/13	–4.8	1200	–2951	0.61	438
2013/14	–5.5	924	–2862	0.64	623
2014/15	–3.8	1184	–2566	0.60	517
2015/16	–1.1	1637	–2018	0.53	419
2009–2016	–4.1	1201	–2669	0.60	583

Table 2. **Characteristics of the investigated sites**

Investigated site No. and type	Topography characteristics	Plant community	Shrub layer		Moss layer		Soil name and structure**
			Average height*, cm	Projective cover*, %	Average height*, cm	Projective cover*, %	
1. Postagrogenic	SE – facing drained riverine sloping hill	Mixed grass-red fescue grass meadow	30 ± 25	20	2	55	Anthrosol Gleyic Stagnic: AY (0–5) – Bh (5–8) – G (8–28) – CRM (28–75) – C crm (75–100) – C crm (100–110) – G (110–147)
2. Undisturbed (virgin)		Dwarf-shrub herbaceous grass-shrub moss tundra	30 ± 8	30–50	2	85	Histic Cryosol Reductaquic: T (0–12) – G (12–70) – CGcrm (70–110) – CG (110–120+)
3. Postagrogenic	Drained summit of watershed sloping hill	Mixed grass-bluegrass meadow	41 ± 50	20	1	35	Anthrosol Gleyic Stagnic: AY (0–3) – ABg (3–10) – G (10–22) – CRM (22–60+)
4. Undisturbed (virgin)		Willow tall-shrub-moss tundra	125 ± 25	60–70	7	70	Gleyic Stagnosol: O (0–5) – Gtx (5–30) – CRM (30–89+)

* Measurements were performed in September 2016.

** Indices of soil horizons: O – peaty litter; AY – soddy; T – peaty; G – gleyic; CRM – cryometamorphic; B – transition; C – soil-forming sediment; AB, BC – transitional horizons. Indices of genetic characteristics in the soil horizons: h – humic, g – gleyic, tx – thixotropic, crm – cryometamorphic, after: [*Shishov et al., 2004*].

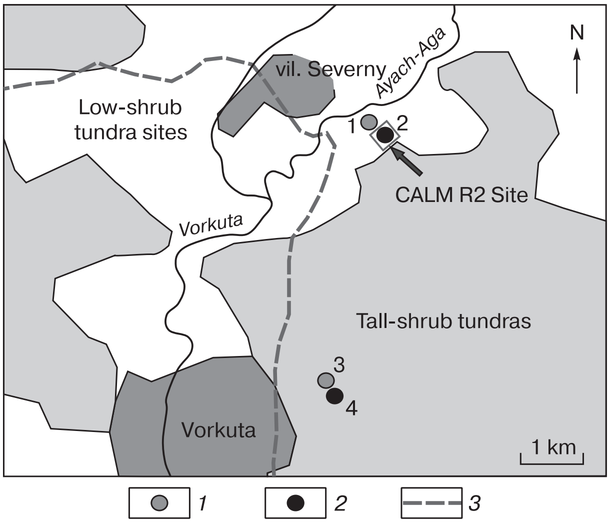

Fig. 1. Geographical position of the objects of study.

The studied sites 1–4: *1* – postagrogenic, *2* – undisturbed (virgin). *3* – road.

vegetation and relatively shallow occurrence (1–2 m) of the permafrost table depth (Fig. 1, Table 2). Sites 3 and 4 are located at a distance of 400 m from each other, 3 km north-east of Vorkuta (the Nerusovey-Musyur natural boundary) on a drained watershed sloping hill covered mainly by tall shrub vegetation in the area of relatively deep occurrence (2 m and more) of the permafrost table.

The four investigated sites satisfactorily represent major types of vegetation communities. With the sites located in the identical landscape conditions, this allows to observe and compare the variations in soil temperature regime, permafrost table depth and vegetation cover of the postagrogenic ecosystems (sites 1 and 3) against their virgin counterparts (sites 2 and 4). The development of soils in the tundra ecosystem within the investigated sites was accompanied by the creation of artificial meadows used as hayfields back in the 1980s and 1990s. Since 1997, their fertilization was suspended, and harvesting of crops became irregular and waned altogether in the 2000s. Artificial meadows have therefore graded into the postagrogenic phase of agro-ecosystems. The abundance, viability and degree of development of the sown grass species have decreased significantly, giving way to the expansion of plant species from the surrounding natural tundra ecosystems – willows, mosses and pioneer lichens. Dense moss and shrub cover have not formed yet, growing as disparate vegetation patches in the postagrogenic ecosystems (Table 2).

RESEARCH METHODS

The minitransects were laid within each investigated site, on the point lines for investigating species composition, height and projective cover of plant canopies, snow cover depth and the permafrost table depth. Minitransects of sites 1, 3, 4 are straight, 50 m long lines with 11 points evenly spaced at 5 m. A hundred-meter minitransect on site 2 was isolated from 11 points from row No. 6 of the CALM R2 monitoring site (Ayach-Yaga) [*Brown et al., 2000*].

The measurements of the permafrost table depth (at the end of the seasonal thawing period) and the snow cover depth (in the third decade of March) were performed using a graduated metal probe 2 m in length. In 1998 and during the period 2009–2016, the active layer thickness and snow cover depth were measured annually in site 2, whereas at sites 1, 3, 4, these parameters were determined only in 1998, 2009 and 2016.

Soil profiling and drilling of micro-boreholes for temperature measurements were carried out at each of the investigated site, to study the morphological properties and thermal regime of soils. The long-term soil temperature monitoring studies (2009–2016) were carried out using HOBO U-12-008 digital loggers installed at depths of 0, 20, 50, 100 cm and programmed for 8 measurements daily. The loggers were installed in the middle of minitransects, with the logger sensors placed in a hole 3 cm in diameter drilled to a depth of 100 cm.

The values of soil temperature (0–50 cm), permafrost table depth and snow cover depth for 1997–1998 were used from the database compiled by G.G. Mazhitova. The temperature parameters of soils studied in 1997–1998 while functioning in agrogenic ecosystems, were compared with those in the postagrogenic period (2009–2016).

The values of air temperature and total precipitation required for calculations of climatic parameters were obtained from the Vorkuta weather station. Soil names and horizon indices are given according to the Russian soil classification system [*Shishov et al., 2004*].

RESEARCH RESULTS AND DISCUSSION

Climatic parameters. A gradual increase in the mean annual air temperatures (MAAT) (R^2 = 0.22, $y = 0.1432x - 5.6507$) reported for the postagrogenic period (2000–2016) of the studied meadow ecosystems, was caused primarily by a decrease in the sum of freezing degree days (FDD) (R^2 = 0.24, $y = 42.5x - 3104.6$) (Table 1), while sums of thawing degree days (TDD) changed slightly (R^2 = 0.05, $y = 8.8664x + 1101$). A gradual decrease in the air frost number (AFN) was documented (R^2 = 0.16, $y = -0.0027x + 0.6272$) during the postagrogenic period. A decrease in the AFN values from 0.66 (1996–1999) to 0.60 (2009–2016) attests to the mitigation of climatic conditions in regional zone of isolated permafrost. The monitoring results at the CALM R2 site showed a persistent positive trend (R^2 = 0.53, $y = 2.4141x + 25.148$) for increasing snow cover depth in the period 2000–2016, which significantly contributed to reducing permafrost stability in the region [*Oberman and Schesler, 2009*]. Climate changes over the last decades have obviously become one of the major drivers of the activation of self-restoring tundra vegetation succession at the studied sites [*Elsakov, 2013*].

Vegetation cover. Postagrogenic communities at sites 1 and 3 appear to be physiognomically alike, representing variants of grass meadows (Table 2). The cessation of the agricultural regime in both phytocenoses was followed by the seeded grass layer destruction with simultaneous invasion of species from neighborhood intact communities. Layers of shrub willows (*Salix* sp.) and dwarf birch (*Betula nana* L.) began to form actively at sites 1 and 3 during the period 2009–2016. The height and projective coverage of the shrub and moss layers are significantly lower than those of virgin lands (Table 2).

At virgin sites 2 and 4 the species composition of the shrub layer is identical, with both the communities dominated by dwarf birch with a significant admixture of willows. The height and projective coverage of the shrub layer at site 2 is significantly lower, as compared to site 4 (Table 2). At poorly drained site 2, the projective coverage of the moss layer is 15 % higher, than within drained site 4 (Table 2).

Soil temperature regime. The revealed significant changes in soil temperatures which took place from the second half of the 1990s to 2009–2016 (Table 3). A significant reduction in the FDD sums is observed in both virgin and postagrogenic soils (Table 3). This is likely to be driven by increased winter air temperatures and snow cover depth in the period 2009–2016, as compared to the previous decades. Besides, an increase in snow cover depth entails a combination of more prolific winter precipitation and the expansion of tall-shrub vegetation into the areas of low-growing moss-shrub tundra [*Elsakov and Kulyugina, 2014*]. A particularly strong increase in the overwinter soil temperatures is documented in virgin site 2. The smallest distinctions between the considered periods (1996–1999 and 2009–2016) were observed in virgin soil of site 4 with tall shrub vegetation.

In 2009–2016, soils of the investigated postagrogenic sites were colder in winter, against their virgin counterparts (Table 3). This is accounted for lower height and closure of the shrub canopy largely intensifying snow-retaining effect [*Chigir, 1975*]. In this period, soils from sites 3 and 4 still differ significantly, whereas the profiles of windward sites 1 and 2 are already approaching each other in respect to their winter temperature parameters. This can be explained by less pronounced differences in snow cover depth, height and shrub canopy closure between the investigated sites 1 and 2, against sites 3 and 4 (Table 2, 3). Nevertheless, the differences in the FDD sums in soils between investigated sites 3 and 4 decreased significantly. Thus, in the 1990s, the FDD sums were 8–10 times lower in the meadow soil (depth: 20 cm), than in the willow tundra soils [*Archegova, 2007*], whereas in 2009–2016 this parameter varies in the range from 1.5 to 4 (Table 3).

In 1997–1998, the FDD sum at a depth of 50 cm was higher for site 1, than that for virgin soil of site 2, which accounts for the deepening permafrost table and more intensive summer warming of the agriculturally developed clay-loamy permafrost-affected soil on the windward side of the sloping hill. In 1997–1998, the TDD sums for postagrogenic soils of site 3 were lower, than for site 4, which is explained by a significant “accumulation” of winter cold. Unfortunately, the lack of data for that period precluded comparison of the summer temperature conditions at sites 1 and 2. However, the permafrost table depth dynamics have prompted an inference that the TDD sums were lower for postagrogenic soils from site 1, than for site 2. This is consistent with the results of previous research conducted by A.V. Kononenko [*1986*], who documented the best summer warming of Anthrosols within the cultivated sites in comparison with their virgin counterparts. The impact of land ploughing on higher intensity of summer heating of soils is associated with the destruction of organogenic horizons [*Shamanova, 1964*].

The TDD sums in soils considerably increased during 2009–2016, as compared to the period of agricultural development (Table 3). In 2009–2016, the postagrogenic soils from site 3 continued to warm up in the summer, rather less thoroughly, against virgin soils, which is explained by incomplete recovery of the shrub layer there (Tables 2, 3). The upper horizons of Anthrosols (0–20 cm) (site 1) remain colder during the summer, than their virgin counterpart, however their TDD sums are comparable at depths of 50–100 cm (Table 3). A less intensive summer warming of Anthrosols was also a result of the formation of a dense heat-insulating grassy mat as a product of slow biological transformation of dead biomass [*Archegova et al., 2009*].

The available data on the mean annual soil temperature (MAST) in the investigated sites over the time spanning the 1990s are intermittent. Thus, I.B. Archegova [*2007*] reported a decrease in the MAST for site 3, against virgin soils, however providing no precise values. In 1997–1998, positive MASTs were observed in the non-permafrost-affected Stagnosols (site 4), whereas soils from sites of 2 and 3 were characterized by negative MASTs (Table 3). In the period 2009–2016, soils of both the postagrogenic and virgin ecosystems are characterized by predominantly positive MASTs. According to this annual parameter, soils of the postagrogenic ecosystems remain generally colder, than their virgin analogs. Soils from the windward sites 1, 2 are colder, than those formed

Table 3. **Soil temperature parameters, permafrost table depth and snow cover depth within the investigated sites**

Hydrological years	Annual mean temperature, °C				Sums of temperatures, °C·day								Permafrost table depth, cm	Snow cover depth, cm
					TDD				FDD					
					Depth, cm									
	0	20	50	100	0	20	50	100	0	20	50	100		
1. Postagrogenic site														
1997–1998*	–	–	–	–	–	–	–	–	–	–	–850	–	–	–
2009/10	0.1	–	–	–	567	–	–	–	–549	–	–	–	150	28
2010/11	0.8	–	–	–	779	–	–	–	–483	–	–	–	–	–
2011/12	1.5	0.8	–	–	1073	708	517	35	–287	–184	–	–	–	–
2012/13	0.8	0.3	0.3	0.1	933	589	353	128	–638	–468	–233	–77	–	35
2013/14	1.1	0.6	0.5	0.3	669	405	231	99	–287	–202	–68	–4	–	–
2014/15	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2015/16	2.3	1.6	1.0	–	1199	785	372	33	–366	–198	–	–	180	39
2. Undisturbed (virgin) site														
1997–1998*	–	–3.2	–	–	740	269	–	–	–2062	–1460	–1401	–	71	39
2009/10	0.2	0.0	–0.3	–	541	266	101	–	–474	–253	–202	–	106	–
2010/11	1.0	0.7	0.6	–	743	452	419	–	–385	–206	–197	–105	102	36
2011/12	2.1	1.3	1.3	–0.2	935	518	525	43	–169	–57	–57	–	105	42
2012/13	1.4	0.5	0.5	0.0	900	429	414	72	–402	–241	–224	–79	107	53
2013/14	1.0	–	0.6	0.1	582	–	315	44	–211	–88	–90	–13	101	91
2014/15	2.2	1.3	0.9	0.1	1045	563	355	0	–252	–109	–32	–6	100	71
2015/16	3.0	1.5	1.0	0.1	1526	694	434	64	–453	–164	–71	–25	106	44
3. Postagrogenic site														
1997–1998*	–0.5	–0.4	–0.4	–	1107	786	515	–	–1083	–919	–720	–	170	43
2009/10	–0.4	–	–0.2	–0.2	570	–	413	283	–636	–	–417	–286	180	70
2010/11	1.0	–	0.7	0.5	879	–	582	394	–506	–	–331	–219	–	–
2011/12	2.0	–	–	–	1207	–	–	–	–212	–	–	–	–	–
2012/13	1.6	1.6	1.6	1.6	1168	812	695	613	–571	–243	–148	–	–	81
2013/14	2.2	–	–	1.7	983	–	–	818	–172	–	–	–	–	–
2014/15	2.4	2.5	2.3	2.3	1079	927	842	814	–227	–40	–17	–	–	–
2015/16	–	–	–	–	–	–	–	–	–	–	–	–	200	72
4. Undisturbed (virgin) site														
1997–1998*	–	1.6	1.6	–	–	749	684	–	–355	–187	–95	–	>200	79
2009/10	1.5	–	1.4	1.6	779	–	671	637	–247	–	–146	–54	>200	110
2010/11	–	–	2.1	2.1	–	–	844	792	–483	–	–81	–22	–	–
2011/12	2.3	2.0	–	–	1220	1039	–	–	–151	–49	–51	–9	–	–
2012/13	2.2	2.3	2.1	–	1081	955	818	–	–262	–112	–98	0	–	100
2013/14	2.0	2.0	–	–	922	766	–	–	–176	–52	0	0	–	–
2014/15	2.6	2.5	2.5	2.4	999	952	905	860	–33	–24	–1	0	–	–
2015/16	3.3	3.2	3.0	2.8	1236	1180	1110	1018	–18	–13	0	0	>200	80

Note. Dash is used for non available data.
* After G.G. Mazhitova.

on the downwind massifs (sites 3, 4), which is due to the region-specific differentiation of geocryological conditions [*Oberman and Schesler, 2009*]. The differences in the annual and summer temperature parameters between these two groups of soils tend to aggravate with depth (Table 3).

Permafrost. The dominance of dwarf-crowberry vegetation in concert with shallow occurrence of permafrost (up to 1 m) and affiliated destruction of heat-insulating peat horizon during the agricultural development of site 1 favored the permafrost table lowering down to a depth 1.5 m. However, complete thawing of permafrost did not occur since meadow ecosystems continued to function under relatively low snow cover depth and strong winter soil cooling. In the presence of a surface heat-insulating peat horizon, shallow occurrence of permafrost at site 2 can be considered as climate-responsive and ecosystem-protected one [*Shur and Jorgenson, 2007*]. Permafrost ceased to be ecosystem-protected at site 1 due to the degradation of organogenic surface horizon as a result of the land plowing, remaining therefore mainly climate-responsive. In 2009–2016, the self-restoring succession activation against the background of climate mitigation contributed to a further lowering (from 1.5 to 1.8 m) of the permafrost table at site 1.

At site 4, the permafrost table was undetectable down to a depth of 2 m. Tall shrub canopy closure retaining a considerable amount of snow, assisted by a thin peaty horizon are liable for a relatively mild soil temperature regime and, accordingly, the absence of permafrost within the soil profile. The destruction of tall-shrub vegetation during the agricultural development at site 3 had led to the intensified overwinter soil cooling and a rise in the permafrost table (to a depth of 1.5 m) in 1990–2000 [*Mazhitova and Lapteva, 2004*]. In 2009–2016, successional changes in the vegetation cover have intensified snow accumulation, which, along with the reported climate mitigation during the winter-time, have ultimately caused the thawing of previously aggraded permafrost to a depth of 2 m.

CONCLUSION

In the period of artificial meadows cultivation and extensive use (1980–1990s) both soil temperatures and permafrost table depth in the clay-loam tundra soils of watershed areas were differentiated, depending on the landscape position of ecosystems. The destruction of dwarf-crowberry vegetation and heat-insulating peat horizon during the agricultural development of areas with shallow occurrence of permafrost (1.0 m) provoked an increase in soil temperature and permafrost thawing to a depth of 1.5 m. On the contrary, the destruction of snow-retaining tall-shrub layer in areas with deeper permafrost (2 m and below) have caused a decrease in soil temperature and permafrost aggradation to a depth of 1.5 m.

In the period of self-restoring succession activation (2009–2016), higher mean annual air temperatures (−4.1 ± 1.8 °C) and lower frost number (0.60 ± 0.03) were observed in the postagrogenic ecosystems, as compared to the period of their agricultural development. There was observed a positive trend ($R^2 = 0.53$) for an increase in the average snow cover depth (56 ± 20 cm). Climate warming entails successional changes of the tundra vegetation in postagrogenic ecosystems, which is favorable for developing of shrub (closure: 0.2, height: 30–40 cm) and moss (closure: 3.5–5.5, height: 1–2 cm) layers. At this, however, seeded grassland tends to be thinning.

In 2009–2016, compared to the latest 1990s, there was a significant increase in TDD and, particularly, FDD sums in soils of postagrogenic and virgin tundra ecosystems. The distinctions in FDD sums between soils of the seeded meadow and undisturbed ecosystems significantly decreased (1.5–4 times) in the postagrogenic period, as compared to the agricultural period (8–10 times). However, soils of postagrogenic sites remain colder in winter, than virgin soil, which is accounted for lesser snow accumulation with sparse shrub vegetation of the overgrown meadows.

In the summer-time, soils of postagrogenic ecosystems remain generally colder, than their virgin counterparts, which is explained by their significant overwinter cooling and by the formation of heat-insulating grass mat in the wake of hay-cutting activities. Anthrosols, as well as their virgin analogues, are characterized by predominantly positive mean annual temperatures. In postagrogenic ecosystems, the increased soil temperature prompted the permafrost table lowering over the period of 2009–2016 by 0.2–0.3 m, regardless of landscape position of the investigated sites. Thus, an increase in soil temperature of postagrogenic ecosystems and affiliated lowering of the permafrost table have triggered the activation of self-restoring natural tundra vegetation succession, against the background of current climate changes.

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References

Archegova, I.B., 2007. Thermal regime of tundra soils under reclamation and restoration of natural vegetation. Pochvovedeniye (Eurasian Soil Science), No. 8, 954–960.

Archegova, I.B., Kuznetsova, E.G., Likhanova, I.A., Panyukov, A.N., Khabibullina, F.M., Osadchaya, G.G., 2009. Ecological principles of nature management and restoration in the North. Syktyvkar, Komi Scientific Center Ural Branch of the RAS, 176 pp. (in Russian)

Archegova, I.B., Panyukov, A.N., Andrianov, V.A., 2013. Opportunities and economic feasibility of agriculture in the tundra. In: The North and the Market: the Establishment of an Economic Order, No. 1, pp. 12–15. (in Russian)

Brown, J., Hinkel, K.M., Nelson, F.E., 2000. The Circumpolar Active Layer Monitoring (CALM) program: Research designs and initial results. Polar Geography 24 (3), 165–258.

Chigir, V.G., 1975. Heliothermozone and some cryogenic features of soils in the southern part of the West Siberian Plain. In: O.V. Makeev (Ed.). Soil Cryogenesis and Amelioration of Cold and Frozen Soils. Institute of Agrochemistry and Soil Science, Moscow, pp. 170–173. (in Russian)

Desyatkin, R.V., Desyatkin, A.R., 2017. Temperature regime of solonetzic meadow-chernozemic permafrost-affected soil in a long-term cycle. Eurasian Soil Science 50 (11), 1301–1310.

Dobrovolsky, G.V., Taskaev, A.I., Zaboeva, I.V. (Eds.), 2010. Soil Atlas of the Komi Republic. Komi Republican Printing House, Syktyvkar, 356 pp. (in Russian)

Elsakov, V.V., 2013. The materials of satellite images for chlorophyll index values analysis of tundra phytocenoses. Issledovanie Zemli iz Kosmosa (Studying the Earth from Space), No. 1, 60–70.

Elsakov, V.V., Kulyugina, E.E., 2014. The vegetative cover of the Yugra Peninsula under conditions of climate fluctuations during the recent decades. Issledovanie Zemli iz Kosmosa (Studying the Earth from Space), No. 3, 65–77.

Ershov, E.D. (Ed.), 1988. Geocryology of the USSR. European Territory of the USSR. Nedra, Moscow, 358 pp. (in Russian)

Ershov, E.D., Kondratieva, K.A. (Eds.), 1997. Geocryological Map of the USSR (scale 1:2 500 000). Kart. predpriyatie, Vinnitsa, 16 sheets. (in Russian)

Khantimer, I.S., 1974. Agricultural development of the tundra. Nauka, Leningrad, 227 pp. (in Russian)

Kononenko, A.V., 1986. Hydrothermal Regime of the Taiga and Tundra Soils in the Northeast European Russia. Nauka, Leningrad, 144 pp. (in Russian)

Kotelina, N.S., Archegova, I.B., Ivanov, V.A., Nazarova, V.I., 1985. Fodder production in the Far North. Vestnik Selskokhozyaistvennykh Nauk (J. Agricultural Sciences), No. 7, 78–83.

Kovaleva, V.A., Deneva, S.V., Panyukov, A.N., et al., 2017. Soil fungi as components of postagrogenic phytocenoses in tundra. Bulletin of the Institute of Biology of Komi Science Center (IB Komi SC UB RAS), No. 3, 7–14.

Malkova, G.V., 2010. Mean-annual ground temperature monitoring on the steady-state-station “Bolvansky”. Kriosfera Zemli (Earth’s Cryosphere), XV (3), 3–14.

Mazhitova, G.G., 2008. Soil temperature regimes in the discontinuous permafrost zone in the East European Russian Arctic (in Russian). Eurasian Soil Science 1 (41), 48–62.

Mazhitova, G.G., Lapteva, E.M., 2004. Trans-Ural Polar Tour. Guidebook. Institute of Biology Komi SC RAS, Syktyvkar, Russia, 53 pp.

Oberman, N.G., Shesler, I.G., 2009. Modern and forecasted changes in cryological conditions in the northeast European Russian Federation. Problems of the North and the Arctic of the Russian Federation. Scientific-inform. Bull., issue 9, 96–106. (in Russian)

Ogureeva, G.N., 1991. Botanical-Geographical Zoning of the USSR. Moscow University Press, Moscow, 188 pp. (in Russian)

Panyukov, A.N., 2013. Restoration succession on fallow in the conditions of East European tundra. Intern. J. Applied and Basic Research, No. 8 (2), 235–238. (in Russian)

Petrov, O.V., Morozov, A.F., Chepkasova, T.V., et al. (Eds.), 2010. Map of Quaternary deposits on the Territory of the Russian Federation (scale 1:2 500 000). VSEGEI, St. Petersburg, 1 sheet. (in Russian)

Shamanova, I.I., 1964. Seasonal freezing and thawing of soils and rocks. In: N.G. Bobov, L.A. Bratsev (Ed.). Geocryological Conditions of the Pechora Coal Basin. Nauka, Moscow, pp. 88–118. (in Russian)

Shishov, L.L., Tonkonogov, V.D., Lebedeva, I.I., Gerasimova, M.I. (Eds.), 2004. Russian Soils Classification and Diagnostics. Oykumena, Smolensk, 342 pp. (in Russian)

Shur, Y.L., Jorgenson, M.T., 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes, 18, 7–19, DOI: 10.1002/ppp.582.

Zheng, D., Van Der Velde, R., Su, B., et al., 2017. Evaluation of noah frozen soil parameterization for application to a Tibetan Meadow Ecosystem. J. Hydrometeorol., No. 18 (6), 1749–1763, DOI: 10.1175/JHM-D-16-0199.1.

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