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Research article

Changes in soils of Central Yakutia cryolithozone under the influence of anthropogenic and thermokarst processes

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Abstract: Soils of arable lands abandoned from agricultural use more than three decades ago were studied within the Central Yakutian Plain at sites located in the zone of the ice complex. Under conditions of climate change, the degradation of the ice complex occurs on abandoned arable lands due to an increase in the depth of seasonal soil thawing. The melting of ground ice underlying large areas of former arable land causes subsidence and deformation of the surface, accompanied by the formation of initial thermokarst landforms. These are revealed as combinations of convex rounded mounds (up to 5–9 m in diameter) and a polygonal network of depressions above thawing ice wedges (0.5–1.5 m deep). The formation of a specific thermokarst microrelief results in changes in the redistribution of moisture on the surface and within the soil, as well as in thawing depth; thus, the water-permafrost regime of thermokarst-affected soils begins to acquire distinct features. As a result, the previously homogeneous soil cover—represented by cultivated pale solonetzic soils of abandoned fields—transforms into a mosaic combination of soils. This includes patches of dark cryogenic solonetz soils on the tops of mounds and light gleyic solonetz soils in the bottoms of depressions, adjacent to typical light solonetz soils developing along the slopes of the microrelief. The main changes affecting the soil cover and soil properties of the studied sites at the initial stages of thermokarst relief dynamics were identified. In particular, the major morphological changes in soil profile structure and the dynamics of such indicators as bulk density, acidity, and field moisture at different elements of the cryogenic microrelief were examined. A significant lightening of the upper soil layers on the slopes of the mounds and in the depressions between them was observed as a result of increased moisture compared to the drier soils of the convex parts of the microrelief. A comparison between cultivated soils and background forest soils was also carried out.

Keywords: Cryolithozone; Central Yakutia; arable lands; thermokarst; soil transformation; permafrost pale soils; permafrost solonetz

1. Introduction

The Republic of Sakha (Yakutia) is the largest federal subject of the Russian Federation, covering an area of 3083.5 million km², which accounts for 18.03% of the total territory of Russia (Figure 1). The region is located within the zone of continuous permafrost, which extends hundreds of meters deep. The main feature of frozen soils is the presence of ice wedges within them, where the thickness reaches 50–60 m [1].

Global climate warming has significantly changed the situation in permafrost regions, where it has largely contributed to the intensification of cryogenic processes that lead to irreversible degradation of permafrost landscapes (Figure 1) [2]. The rate and pace of landscape transformation resulting from these processes serve as indicators for assessing the response of permafrost to climate warming [3,4]. Alongside natural factors, anthropogenic drivers also play a significant role, including forest fires and logging, increasing population density, ignoring the ecological carrying capacity of lands, inappropriate land management practices, and excessive exploitation of land resources, all negatively affecting soil conditions [5]. These factors have a particularly destructive impact on the soils of the cryolithozone [6,7].

Central Yakutia is one of the northernmost centers of high-risk agriculture, constrained by harsh climatic conditions, permafrost, and a short growing season [8,9]. Since the 1950s–1960s, natural forest lands in Central Yakutia have been converted into arable fields through forest stubbing [10,11]. Following forest stubbing, natural biogeochemical cycles become disrupted, and the soil thawing depth increases. Since the creation of these arable lands, an increasing degree of soil salinization has been observed. Under the dominance of an evaporative water regime in soils within a semiarid climate, the accumulation of water-soluble salts in the surface soil layers of open areas intensifies over time [12].

As a result of the country's political transformation and the collapse of large collective agricultural enterprises in the early 1990s, these arable lands were abandoned. In the early 1980s, the total area of arable land in Yakutia amounted to approximately 140 million ha, whereas at present, only up to 49.3 million ha are cultivated annually [13–17]. Arable lands created on former forest territories within the cryolithozone provided only a short-term increase in agricultural productivity immediately after stubbing, followed by a long-term decline associated not only with nutrient depletion but also with soil compaction [10]. Without annual cultivation, arable lands located on ice-rich permafrost soils began to degrade on a large scale (Figure 1).

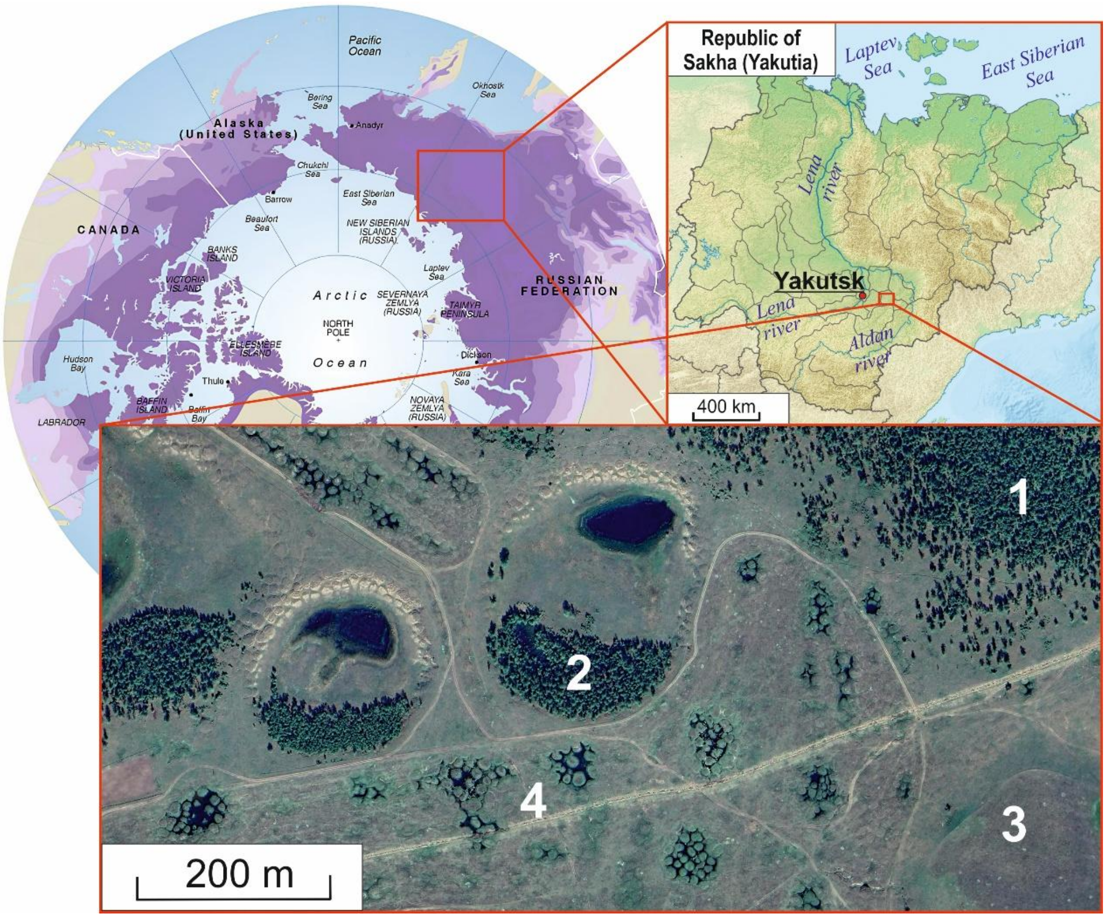

Figure 1. Location of the study area and degradation of abandoned arable lands in the permafrost zone. 1: larch forest, 2: birch forest, 3: abandoned arable land not affected by thermokarst process, 4: byllars–thermokarst affected area.

Over the past 50 years, the region has experienced ongoing climate warming. Since the late 1980s, a sharp shift toward higher mean annual air temperatures has been observed in Central Yakutia [18,19]. The first signs of degradation of ice-rich permafrost due to climate change began to appear around the same time, as a result of the formation of subsurface holes caused by thawing of the upper parts of ice wedges. The massive activation of thermokarst, leading to the formation of initial polygonal depression microrelief, was caused by a significant increase in ground temperatures in the late 1980s and early 1990s. Since the mid-2000s, permafrost degradation with thawing of ice wedges has been widely observed in treeless areas of the ice complex [6]. As a result of degradation processes, the surfaces of abandoned arable lands have experienced mosaic subsidence of 0.5–1.5 m or more. The average rate of soil subsidence in abandoned arable lands was estimated at 3.9 cm/year [20]. This leads to irreversible transformation of both landscapes and soil cover. Especially significant soil transformations are occurring in the most agriculturally developed areas of the republic, within the Lena–Amga interfluve. At present, intensive degradation of the ice complex is observed there, accompanied by the formation of initial alas depressions (byllars) and, in some places, young thermokarst lakes (dyuedya) (Figure 1). Thus, the thermokarst degradation of the soil cover on arable lands has been converting large areas of agricultural lands into disturbed terrain for the past three to four decades.

The aim of this study is to investigate changes in the morphogenetic characteristics of soils resulting from the thawing of the underlying ground ice during the initial stages of thermokarst development on abandoned arable lands in the cryolithozone. To achieve this aim, the following questions were investigated: (1) How are thawing depth and soil moisture changes on the top, slope, and bottom of byllars compared between forest soils and abandoned arable lands? (2) What changes occur in the system of soil horizons and morphological properties of soils in degraded areas? (3) Which soil processes lead to the complexity of the soil cover of agricultural lands disturbed by thermokarst?

2. Materials and methods

The study area is located in the central part of the Lena–Amga interfluve, in the vicinity of Churapcha village. According to geomorphological zoning, this corresponds to the level of the Abalakh medium-altitude accumulative–erosional terrace [21]. The terrace is composed of Quaternary deposits: the upper part consists of loamy and sandy loam lacustrine–alluvial sediments containing ice wedges with a thickness of 50–60 m, while the lower part is formed by sandy alluvium [2]. Permafrost deposits within the study area are characterized by relatively high ice content, with the index ranging from 0.26 to 0.47 [22]. Partial degradation of ground ice in the Holocene led to the formation of thermokarst alas relief. In terms of soil regionalization, the study area lies within the Lena–Tatta district of the Central Yakutian taiga–alas soil province [23]. The dominant soils include permafrost forest solodic soils, pale carbonate soils, and pale solodized loamy soils [24], while thermokarst depressions are characterized by a complex of alas soils [12].

The typical taiga vegetation in the region consists of various forms of larch forests dominated by *Larix cajanderi* L. and frequently distinguished birch stands containing steppe elements [25,26]. The climate of the Lena–Amga interfluve is sharply continental, characterized by very low winter and high summer temperatures and relatively low precipitation [27].

Over the past 30 years, Central Yakutia has shown one of the highest trends in the increase of mean annual air temperature in Russia, reaching 0.06 °C per year [28,29]. While in the 1960s–1970s climate warming was not yet so distinct, in the 1980s, it became clearly evident [30].

Climatic data for the study area were obtained from the reports of the nearest meteorological station in Churapcha. The data series begins in 1936 and continues to the present. The mean annual temperature for the entire period is −10.6 °C, and the long-term average annual precipitation is 268.2 mm. At this station, two distinct shifts in mean annual air temperature have been observed, as reported by Desyatkin [19]. Taking the period from 1936 to 1987 as the baseline, the mean annual temperature, including interannual fluctuations, was −11.4 °C, which closely corresponds to the climatic norm of 1961–1990 (−11.1 °C). To accurately reflect modern warming, the Russian Hydrometeorological Center now uses the 1991–2020 climatic norm, which gives a long-term mean temperature in Churapcha of −9.6 °C. Within this period, two shifts of mean annual temperature increases have been recorded in the study area: the first, with warming of 1.1 °C since the late 1980s, and the second, from 2007 to the present, with an increase of 2.6 °C relative to the 1961–1990 baseline (Figure 2). Such an increase in mean annual temperatures has had a significant impact on permafrost thawing in the region and on the subsidence of the surfaces of abandoned arable lands.

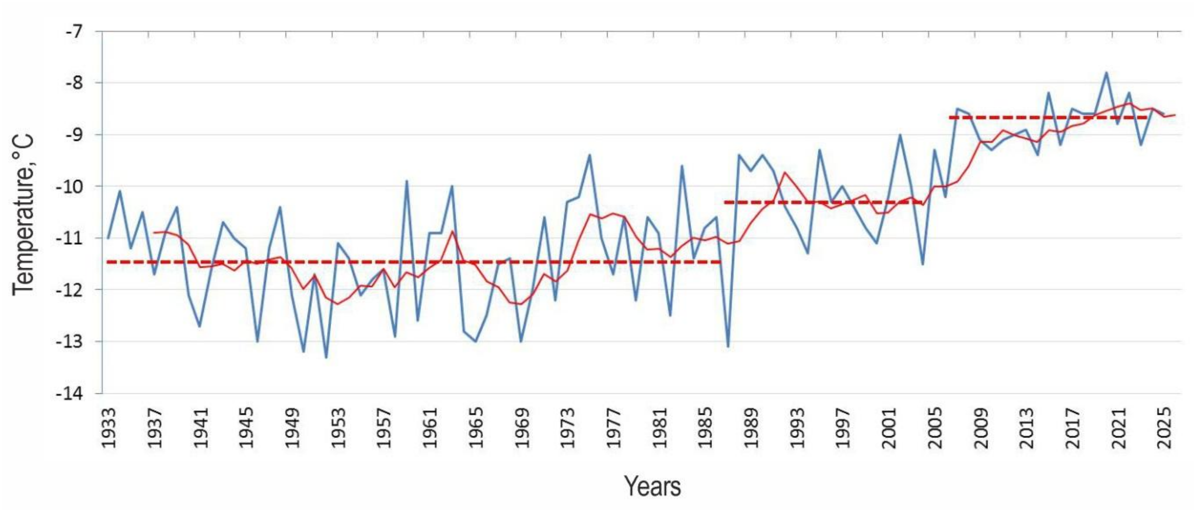

Figure 2. Increase in mean annual air temperature at the Churapcha meteorological station. The red dashed line indicates shifts in mean air temperatures. Mean annual air temperature baseline 1933–1987, shifts 1988–2006, and 2007–present day.

Due to the increase in air temperature in Central Yakutia, the depth of seasonal soil thawing is increasing everywhere [31]. When the depth of seasonal thawing reaches the upper boundary of the ice complex wedges, their melting begins, which leads to the appearance of initial forms of thermokarst alas formation in the form of byllars. The emergence of such hummock–depression polygonal microrelief on the flat surface of abandoned arable lands causes the transformation of the previously homogeneous soil cover.

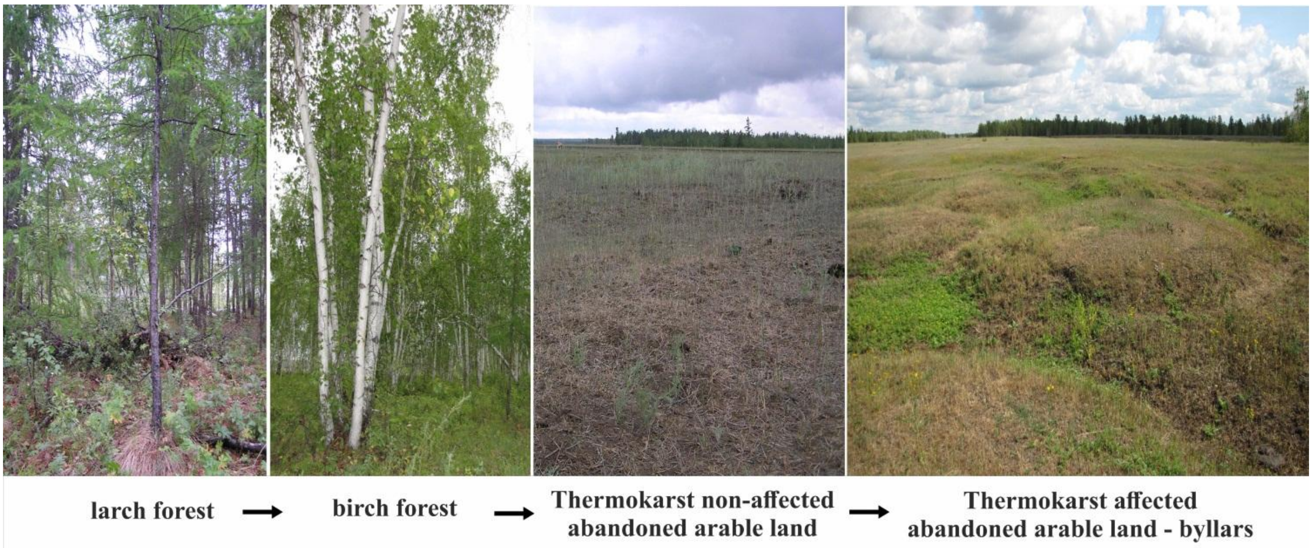

Figure 3. General view of study sites.

Field studies investigating the influence of the initial thermokarst landforms formation (byllars) on the morphogenetic characteristics of soils were conducted on an abandoned arable land located 1.5 km southeast of the village of Churapcha. The field had been abandoned in the early 1990s. Byllars are small mounds up to 5–6 m in diameter with subsidence features and a polygonal network of shallow depressions above ice wedges (0.5–1.5 m deep), formed as a result of thawing of the upper part of the ice complex [32]. Control soil pits showing the soil profile structure in areas without signs of ice complex degradation or anthropogenic disturbance were made in larch and birch forests (soil pits C-10.12 and C-09.12) (Figure 3). Due to the presence of natural vegetation cover and a thermally insulating litter layer, despite climate warming, the permafrost here remains stable [33]. Additional soil pits characterizing soils after forest stubbing and their transformation into postagrogenic soils were located on a recently cultivated field (C-08.12), at the top of a byllar (C-01.12), on the slope of a byllar (C-02.12), and at the bottom of the depression between byllars (C-03.12), where the soils are most affected by cryogenic degradation and transformation (Figure 3). In all six soil pits, the parent material is represented by calcareous loesslike loam.

Morphological descriptions of the soil profiles and measurements of thawing depths were conducted in the field by digging soil pits. Designation of soil horizons and soil names followed the Russian Soil Classification (RSC) [34], Guidelines for Soil Description of Food and Agriculture Organisation (FAO) [35], and the World Reference Base for soil resources (IUSS WG WRB) system [36]. Physical soil samples were taken from every horizon and air-dried. Bulk density, pH, soil moisture, and particle-size distribution were determined in the samples taken with a cutting ring of 100 cm^3 in volume from each soil horizon. The bulk density was determined by the gravimetric method. The pH of soil water suspensions (1:2.5) was measured with an F-8 pH meter (Horiba, Japan). Soil moisture was measured by the thermostatic gravimetric method. Particle size was evaluated using the Kachinsky method. Cation exchange capacity and exchangeable bases were determined by the ammonium acetate method using a mechanical vacuum extractor (Model 24VE). The concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+ in the solution were measured on an atomic emission spectrometer with inductively coupled plasma Spectro CirosCCD (Germany, Spectro Analytical Instruments GmbH). Statistical analysis of the described parameters was conducted using the linear Pearson correlation coefficient.

3. Results

3.1. Soil morphology in areas not affected by thermokarst processes

Soil pit C-10.12 (Figure 4) was located in a larch forest 2 km southeast of Churapcha village. The vegetation cover is represented by a larch forest with a mixed herbaceous and dead ground cover. The tree layer is dominated by *Larix cajanderi* Mayr., with the participation of young *Betula pendula* Roth. The shrub layer includes *Rosa acicularis* Lindl., *Spiraea media* Schmidt, and *Salix bebbiana* Sarg. The herb–shrub layer is uniform and sparse (~40% cover). The dominant species are *Limnas stelleri* Trin., *Rubus saxatilis* L., and *Festuca lenensis* Drob. Among forest species, *Vaccinium vitis-idaea* L. and *Lathyrus humilis* (Ser.) Spreng are present. The moss–lichen layer is poorly developed (less than 5% cover) and is represented by *Aulacomnium turgidum* (Wahlenb.) Schwägr. and *Cladonia amaurocraea* (Flörke) Schaer.

The microrelief is uneven, with frost cracks and small elevations around tree trunks. According to the RSC, the soil is identified as permafrost pale solodic surface cryoturbated soil; according to the international WRB, it is classified as turbic protocalcic cambic cryosol (siltic, sodic). The soil profile formula according to the FAO system is Oi–OA–E/Bw1–E/Bw2–Bk–BCk–Ck. The depth of seasonal thawing reached 118 cm. At the top of soil profile C-10.12, there is a litter layer composed of larch needles and birch leaves with a thickness of approximately 3 cm, with occasional thin moss layers. Beneath is the located horizon OA, a compacted layer of partially decomposed plant residues interwoven with roots and with admixture of light loam, containing traces of past fires in the form of charcoal inclusions. As a result of post-fire turbation processes, the subsequent albic and cambic horizons are mixed, forming an E/Bw horizon. In the upper part, this layer is composed of very dense medium loam of pale color with grayish-brown spots. The lower part of the mixed layer is characterized by a decrease in the number of pale spots and the appearance of ochre mottles due to illuviation processes. The protocalcic horizon (Bk), with a thickness of 10–15 cm, is represented by heavy loam that strongly reacts with HCl. Due to the uneven relief, the presence of frost cracks, and post-fire turbation, the boundaries between the horizons have an irregular, tongue-shaped pattern. The transitional horizon (BCk), occurring at a depth of 33(37)–62 cm, is represented by light grayish-brown heavy loam with a yellowish tint and occasional organic streaks. With increasing depth, the influence of microrelief on horizon boundaries weakens, and the boundary with the underlying horizon becomes almost flat. A distinctive feature of the parent material horizon (Ck) is the presence of cryogenic platy structure in the soil (Figure 4; Table 1).

Soil pit C-09.12 (Figure 4) was examined in a birch forest, 1.6 km southeast of Churapcha village. Vegetation cover is represented by a birch forest with a forb-rich ground layer. The tree layer is composed of *Betula pendula* Roth, with a minor admixture of *Larix cajanderi* Mayr. The shrub layer includes *Salix bebbiana* Sarg., *Rosa acicularis* Lindl., and *Spiraea media* Schmidt. The herb–dwarf shrub layer is well developed, with a total cover of 40%–50%. Dominating species are *Calamagrostis langsdorffii* (Link) Trin., *Limnas stelleri* Trin., and *Bromopsis inermis* (Leyss.) Holub. Among forbs, *Sanguisorba officinalis* L., *Artemisia tanacetifolia* L., and *Pulsatilla angustifolia* Turcz. dominate. The moss layer is weakly developed, with a cover of approximately 5% *Amblystegium serpens* (Hedw.) Bruch. and *Ceratodon purpureus* (Hedw.) Brid.

The microrelief is relatively even, with slight elevations around tree trunks. According to the RSC, the soil is identified as permafrost pale solodic cryoturbated soil; according to the international WRB, it is classified as turbic calcic cambic cryosol (siltic, sodic). The soil profile formula according to the FAO system is Oi–OA–E/Bw@–E/Bw/Bk@–Bw/Bk@–BCk–Ck. The depth of seasonal thawing reached 138 cm. Beneath the litter and forest floor, a thin folic organic horizon has formed, consisting of plant residues at different stages of decomposition mixed with light loamy material. Below this layer there are three horizons with clear signs of cryoturbation, determined as swirling structures. Due to cryoturbation processes, the first horizon represents a mixture of albic and cambic horizons (E/Bw@). It occurs at a depth of 3(7)–13(16) cm and is the lightest in color. Cryoturbation also caused a slight incorporation of organic material from the overlying horizon, visible as brown and grayish-brown spots and coatings. This horizon differs from the two underlying ones in the absence of reaction to HCl and by its relatively lighter texture (medium loam). Below lies a horizon where fragments of albic, cambic, and calcic horizons are mixed (E/Bw/Bk@) at a depth of 13(16)–22(30) cm, with the heaviest texture among these layers (light clay), being the darkest of the three cryoturbated horizons. Here, a small amount of organic material has also been incorporated in the form of brown spots, coatings, and charcoal inclusions. Due to the mixing with carbonate-rich material, the soil begins to react with HCl starting from this horizon. Additionally, due to an old crack on the right side of the profile, the boundary has a tongue-like, infiltrated appearance. The third cryoturbated horizon occurs between 22(30) and 36(45) cm and consists of heavy loam with a light grayish-brown color and a pale tint where cambic and calcic materials are mixed (Bw/Bk@). Also, weak ochre mottles are observed. The reaction with HCl is noticeably stronger in this third cryoturbated layer than in the overlying ones. The transitional horizon (BCk) occurs at a depth of 36(45)–83 cm and is represented by light grayish-brown heavy loam with a yellowish tint and occasional iron mottles (Figure 4; Table 1). The parent material horizon (Ck) consists of heavy loam with a platy structure and shows a weak reaction to HCl.

Soil pit C-08.12 (Figure 4) was sampled on abandoned arable land not affected by thermokarst processes, located 2.0 km southeast of Churapcha village. Vegetation cover is represented by a forb–grass meadow. The total projective cover is approximately 70%. The dominant species are *Elytrigia repens* (L.) Nevski, *Leymus chinensis* (Trin.) Tzvelev, *Artemisia commutata* Besser, and *Tanacetum vulgare* L. Less abundant species include *Artemisia jacutica* Drobow, *Crepis tectorum* L., and *Potentilla anserina* L.

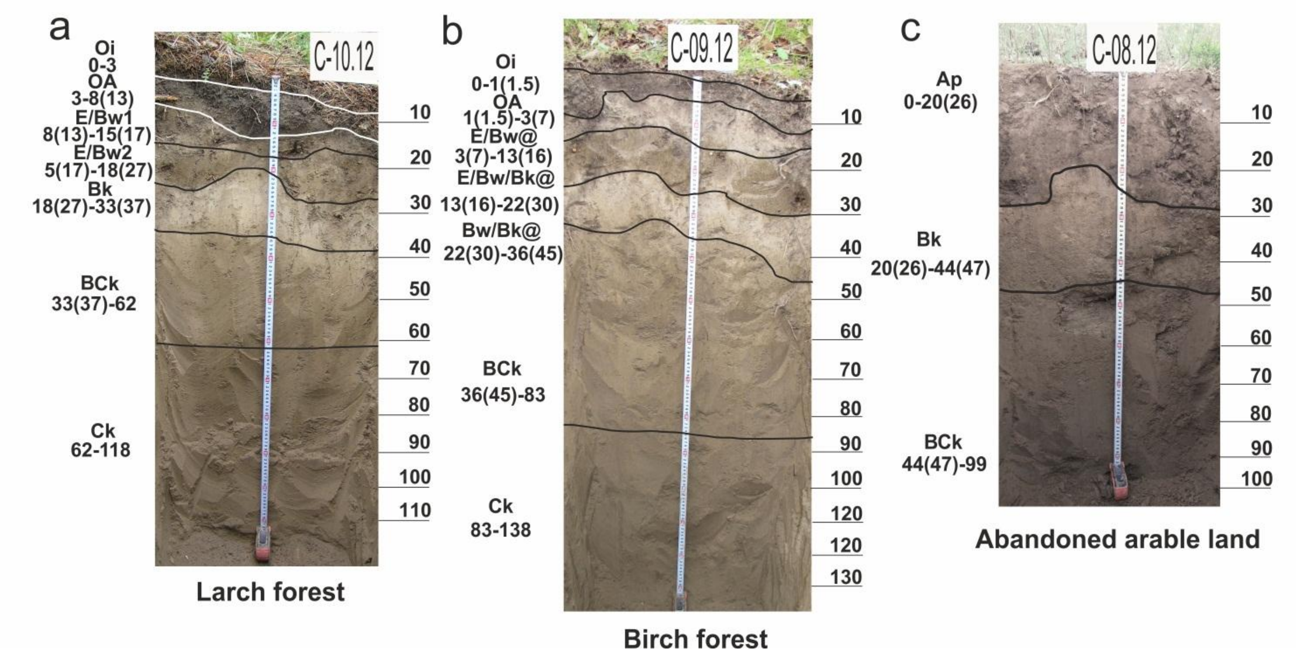

Figure 4. Morphological structure of the soil profiles: a) profile in the larch forest (C-10.12); b) profile in the birch forest (C-09.12); c) profile on abandoned arable land (C-08.12). Left of profile: horizon index and depth; right of profile: soil depth.

The microrelief is flat, with local slight waviness and no slope. It is assumed that the soil of the profile made on the abandoned arable land was originally a permafrost pale solodic soil. According to the RSC, the soil is identified as permafrost pale postagrogenic soil; according to the international WRB, it is classified as anthaquic sodic cambisol (siltic, protocalcic). The soil profile formula according to the FAO system is Ap–Bk–BCk. The depth of seasonal thawing reached 152 cm. The agrohumus and agroabrasion horizons are turbated and mixed as a result of relatively recent agricultural cultivation, which leads to a certain homogenization of the upper horizons, typical for arable lands [37]. As a result, the three upper horizons of the original permafrost pale solodized soil—organic, eluvial, and metamorphic horizons—were transformed into a plowed arable layer (Ap). Characteristic features of agrogenic (postagrogenic) soils are present, including cracks and streak-like infiltrations of organic matter, beginning at a depth of 7 cm, as well as a compacted and very dense plowed layer. The soil begins to react with HCl already in the upper horizons. Below lies the relatively undisturbed accumulative-carbonate horizon (Bk), which shows a stronger reaction to HCl. Like the rest of the profile, this horizon consists of heavy loam. Rust-colored mottles are present in the upper part of the horizon. The transitional horizon (BCk) occurs at a depth of 44(47)–99 cm and is characterized by lower compaction; it tends to crack and break apart easily (Figure 4; Table 1).

3.2. Soil morphology in an arable land area disturbed by thermokarst processes

The soils of the byllars represent areas of transformed cultivated soil cover affected by the initial stages of thermokarst degradation, with traces of a former plow horizon. Below are descriptions of soil profiles made on a small byllar within an old abandoned arable land along the top–slope–depression transect.

Soil profile C-01.12 (Figure 5) was examined at the top of the byllar, located 1.5 km southeast of the village of Churapcha on arable land abandoned 30 years ago. The vegetation is represented by dry grassland meadows with evidence of domestic animal activity. The total projected cover of herbaceous vegetation is 40–50%. The dominant species is *Leymus chinensis* (Trin.) Tzvelev, *Elytrigia repens* (L.) Nevski, and *Carex duriuscula* C.A. Mey.

The surface of the byllar is covered with partially infilled frost cracks up to 10 cm wide. According to the RSC, the soil is identified as permafrost dark cryoturbated postagrogenic solonetz; according to the international WRB, it is classified as calcic solonetz (loamic, turbic). The soil profile formula according to the FAO system is Oi–AEp–AEp/Btn@–Bk@–BCk–Ck. The depth of seasonal thawing reached 161 cm. The entire soil profile consists of heavy loam. On the soil surface, a layer of poorly decomposed felt-like material from herbaceous plant residues has accumulated. As a legacy of past agricultural use, the profile shows a former plow horizon (AEp) of brownish-gray color with dark-brown streaks, with a thickness of 6–7 cm. Beneath the former plow layer lies a cryogenically mixed layer composed of a compacted subplow layer and the textured natric horizon AEp/Btn@, which is the darkest layer in the profile, extending to a depth of 14–27 cm. This layer also shows the most pronounced cryogenic cracks, along which humified material has flowed, forming tongues and pockets. The accumulative-carbonate horizon (Bk@) consists of pale loam that reacts strongly with HCl, with a thickness of 47–56 cm. The transitional horizon (BCk) is dense, moist, nutty and cloddy, carbonate-rich, and loamy. The parent material horizon (Ck) is gray, moderately compacted, cloddy, moist, and of medium loam texture (Figure 5; Table 1).

Soil pit C-02.12 (Figure 5) was located on the slope of the same byllar. Grassland meadows with a mix of grasses and herbs are also well-developed, showing signs of domestic animal activity, particularly cattle and horses, in the form of grazing and trampling. The dominant species are *Elytrigia repens* (L.) Nevski, *Artemisia commutata* Besser, and *Carex duriuscula* C.A. Mey.

Table 1. Properties of the studied soil profiles.

Horizon (cm)	Depth (cm)	Thawing depth (cm)	Bulk density (g/cm^3)	pH	Moisture (%)	(Mg^{2+} + Na^{+})/Sum	Particle size (%) (mm)	
							<0.001	Σ<0.01
Larch forest C-10.12								
OA	3–8(13)	118	0.58	6.46	30	0.67	15.6	28.2
E/Bw1	8(13)–15(17)		1.23	7.3	2.8	0.69	10.3	33.6
E/Bw2	15(17)–18(27)		1.15	7.76	7.9	0.55	27	46.6
Bk	18(27)–33(37)		1.22	9	9.3	0.69	21.7	45.4
BCk	33(37)–62		1.34	9.48	14.9	0.78	22.5	44.6
Ck	62–118		1.36	9.46	15.6	0.79	21.8	44.3
Birch forest C-09.12								
OA	1(1.5)–3(7)	138	0.56	6.78	40.9	0.73		
E/Bw@	3(7)–13(16)		1.27	6.76	7.9	0.67	11.9	34
E/Bw/Bk@	13(16)–22(30)		1.27	8.05	11.6	0.61	34.4	52.3
Bw/Bk@	22(30)–36(45)		1.29	8.64	11.8	0.6	24.2	49.9
BCk	36(45)–83		1.35	9.2	15.2	0.8	24.2	47
Ck	83–138		1.47	9.01	16.4	0.81	24.2	45
Abandoned arable land C-08.12								
Ap	0–20(26)	152	1.37	8.42	7.3	0.71	19.7	44.2
Bk	20(26)–44(47)		1.25	8.89	17.8	0.77	26.2	49.5
BCk	44(47)–152		1.32	8.94	18.2	0.81	22.9	45.8
Top of byllar C-01.12								
AEp	2–6(7)	161	1.19	9.5	30	0.87	22.9	44.2
AEp/Btn@	6(7)–14(27)		1.38	9.69	22.7	0.89	24.2	48.7
Bk@	14(27)–70(74)		1.31	9.66	23	0.83	25	42.5
BCk	70(74)–113 (117)		1.27	9.6	23.5	0.84	24.2	47
Ck	113(117)–161		1.19	9.54	29.1	0.86	22.9	47.8
Slope of byllar C-02.12								
AEp	2(3)–9(20)	171	1.27	9.15	14	0.83	20.5	42.9
AEp/Btn@	9(20)–20(28)		1.46	8.69	13.6	0.62	7.4	29.1
Btn@	20(28)–34 (40)		1.24	9.54	24.5	0.88	31.1	53.1
Bk@	34 (40)–47(56)		1.49	9.64	24.9	0.84	29.9	48.2
BCk	47(56)–110(115)		1.49	9.6	26.4	0.83	23.8	42.1
Ck	110(115)–171		1.44	9.06	23.3	0.74	23.7	44.6
Depression between the byllars C-03.12								
AEp	2–8(18)	156	1.25	6.19	17	0.57	14.8	36.4
AEp/Btn@	8(18)–23(30)		1.39	7.34	13.8	0.64	18.9	43.3
Btn@	23(30)–52(60)		1.31	8.65	20.6	0.75	37.2	55.6
Bk	52(60)–78(81)		1.31	8.9	25.1	0.71	26.6	50.3
BCgk	78(81)–110(113)		1.36	8.96	27.3	0.72	24.2	48.7
Cgk	110(113)–156		1.04	8.92	49.7	0.72	24.6	45.8

The slope of the byllar is covered with partially infilled frost cracks up to 10 cm wide. According to the RSC, the soil is classified as permafrost light postagrogenic solonetz; according to the international WRB, it is classified as calcic solonetz (albic, loamic, turbic). The soil profile formula according to the FAO system is Oa–AEp–AEp/Btn@–Btn@–Bk@–BCk–Ck. The depth of seasonal thawing reached 171 cm. In the upper part of the AEp horizon with fragments of albic material, there is a layer enriched with roots and plant residues, up to 2–3 cm thick. The former plow heavy loamy horizon itself has a light-gray color with a brownish tint. The underlying mixed layer (AEp/Btn@) also appears light in color due to the presence of albic material, becoming light loamy. The natric horizon (Btn@) occurs at a depth of 20(28)–34(40) cm and transforms into the light clay. Unlike profile C-01.12, cryogenic processes here are less pronounced, resulting in more horizontally differentiated layers, but the presence of spots and irregular boundaries indicates ongoing cryoturbation processes (Figure 5; Table 1).

Soil profile C-03.12 (Figure 5) was made in the depression between the same byllars. In the depression between byllars, suppressed grasses–Potentilla meadow develop, showing signs of domestic animal activity. The projected cover of the herbaceous layer is 70%. The dominant species are *Potentilla anserina* L., *Elytrigia repens* (L.) Nevski, and *Artemisia commutata* Besser.

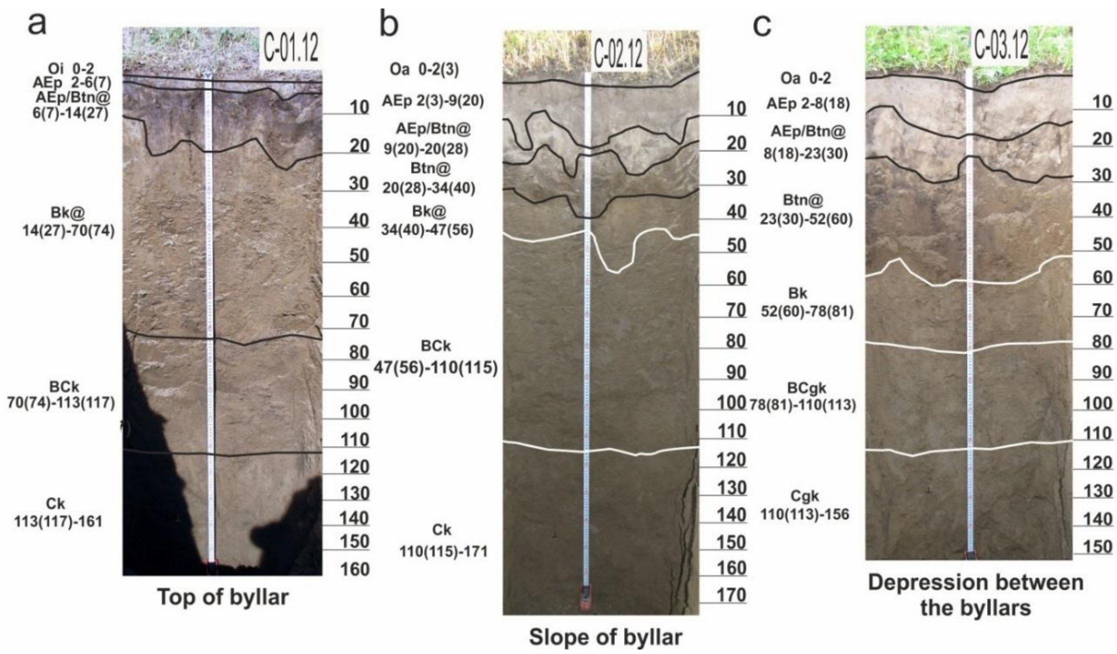

Figure 5. Morphological structure of byllar soil profiles: a) profile on the top of the byllar (C-01.12); b) profile on the slope of the byllar (C-02.12); c) profile at the bottom of the depression between the byllars (C-03.12). Left of profile: horizon index and depth; right of profile: soil depth.

The bottom of the depression between the byllars (4–5 m in diameter) is covered with partially infilled frost cracks up to 10 cm wide. According to the RSC, the soil is classified as a permafrost light solonetz with slight signs of gleying below 80 cm; according to the international WRB, it is classified as calcic stagnic solonetz (albic, loamic, turbic). The soil profile formula according to the FAO system is Oa–AEp–AEp/Btn@–Btn@–Bk–BCgk–Cgk. The depth of seasonal thawing reached

156 cm. The profile structure is largely similar to that of profile C-02.12, with main differences being the thickness and depth of the intermediate layers in the depression soil. These layers are located deeper and are slightly more vertically extended in the profile. Evidence of former plowing is present. The eluvial horizon, mixed with fragments of the heavy loamy natric horizon (AEp/Btn@) due to cryoturbation, is well visible and has a characteristic light-gray color with a pale tint and dark spots. The natric horizon, brown in color, occurs at a depth of 23(30)–52(60) cm, with a thickness of approximately 29–30 cm and becomes light clay (Figure 5; Table 1).

In all soils studied on the byllars, the former plow horizon is also relatively thin compared to soils from other abandoned arable lands, which may be due to a combination of factors, including low-intensity agricultural practices (shallow plowing) and the enhanced effect of water erosion in conditions of relief deformation. The thinnest plow horizon is observed at the top of the byllar, which may be related to surface deformation and cracks that have led to erosion and degradation of the plow layer.

3.3. Some properties of the studied soils

As the most informative soil properties during thermokarst transformation, dynamic indicators, such as bulk density, pH, field moisture, and particle size distribution were studied (Table 1).

3.3.1. Bulk density

Soil bulk density is considered to depend on the properties of the materials forming the solid phase: particle-size distribution, structure, and organic matter content. This parameter has been defined as dynamic [38,39]. On cultivated lands, the soil is usually loosest immediately after tillage and then gradually compacts; after some time, its density reaches an equilibrium. During thermokarst transformation, caused by the melting of subsoil ice wedges, some areas subside, while others on polygonal surfaces may retain their original position in the initial stages of degradation. By studying soil density profiles across different landform positions at the early stages of thermokarst, it is possible to determine the impact of subsoil ice degradation on the spatial and vertical variability of soil density.

For the soil profiles C-10.12 and C-09.12, located in a larch forest and a birch stand, the upper organic layer has a relatively low bulk density of 0.56–0.58 g/cm³. Below this, data vary slightly. In the larch forest soil, the underlying lightened horizon shows an increase in compaction to 1.23 g/cm³, followed by a decrease at a depth of 15–18 cm (Table 1). The increased density in the upper part of the eluvial horizon may be associated with trampling. With increasing depth, bulk density rises gradually, reaching a maximum of 1.36 g/cm³ in the over-permafrost layer, which is typical of pale soils under natural taiga vegetation [5]. In the birch forest soil, the three cryoturbated layers beneath the thin organic layer have approximately similar density values, ranging from 1.27 to 1.29 g/cm³. Below, as in the larch forest soils, density continues to increase, reaching a maximum in the over-permafrost horizon (Ck). However, here the values are significantly higher, up to 1.47 g/cm³, likely due to a heavier particle-size composition. In the abandoned arable land profile (C-08.12), the highest bulk density (1.37 g/cm³) is found in the former plow horizon (Ap) with a thickness of 20 cm, especially in the lower part (Table 1). Below this, there is a slight decrease in density, but values remain similar to the calcic and transitional horizons (Bk, BCk) of soils under the larch and birch forests.

Soil bulk density parameters at the top of the byllar are characteristic of the dark permafrost solonetz soils. On the surface, there is a thin 2–6(7) cm layer with a density of 1.19 g/cm³. Below this lies a significantly denser AEp/Btn@ horizon (1.38 g/cm³). Since this layer was diagnosed as solonetzic, the high density is associated with both increased exchangeable sodium content and anthropogenic factors. In the underlying Bk@ and BCk horizons, bulk density gradually decreases. The over-permafrost horizon (Ck) in this profile has the lowest density (1.19 g/cm³) (Table 1). On the other hand, in the soil profile on the slope of the byllar, high density is observed in the upper 20 cm (1.26–1.47 g/cm³), while density in the natric horizon (Btn) at a depth of 20–40 cm decreases to 1.24 g/cm³. The genetic horizons in the lower half of the slope profiles also show relatively high values (1.44–1.49 g/cm³) (Table 1). The soils of the depressions are very similar in density and distribution to the soils at the top of the byllar, showing a notable decrease in density in the over-permafrost part of the profile.

3.3.2. Soil pH

In profile C-10.12, located in a larch forest, there is a continuous increase in pH values with depth. The upper, thinly developed humus horizon shows the lowest pH value of 6.5 and is weakly acidic. Below this, the layers up to 18 cm are disturbed by cryoturbation and have a slightly alkaline environment (pH 7.3–7.8). Further down, there is a jump in pH in the calcic (Bk) horizon, and below that, pH ranges from 9.0 to 9.5, which is quite typical of the designated soil type (Table 1). In the soil profile formed under birch forest (C-09.12), a similar distribution is observed: the upper part of the soil is weakly acidic, close to neutral (pH 6.8); below 13 cm, it becomes alkaline and strongly alkaline, changing in the range from 8.1 to 9.2. In the profile of soil from abandoned arable land not disturbed by thermokarst processes (C-08.12), the pH distribution is quite uniform throughout the entire profile, ranging from 8.4 to 8.9 (Table 1).

Soils of the byllar show certain differences. The postagrogenic solonetz (C-01.12) at the top of the byllar is characterized by strongly alkaline conditions throughout the profile (pH 9.5–9.7) with no extremes. The soil on the byllar slope (C-02.12) also shows high pH values, slightly decreasing to 8.7 in the lightened layer. The most distinct differences are seen in the soils of the byllar depression (C-03.12), where, due to increased eluviation in the top 20 cm, pH values are nearly neutral (6.2–7.3); pH values in the lower horizons are also slightly lower compared to the soils of the top and slope of the byllar (8.7–9.0) (Table 1).

3.3.3. Soil moisture

In natural forest soils, the highest field moisture is typically recorded in the upper organic horizons. In the birch forest, the moisture content is higher (40.9%) compared to the larch forest (30.0%). The high moisture values in these layers result from weather conditions. Further distribution of soil moisture in profile C-10.12 of the larch forest shows an increasing trend, reaching a maximum of 15.6% in the over permafrost horizon, as a result of moisture influx from the melting permafrost. The soil profile under the birch forest (C-09.12) is more moist, with a similar increasing trend of moisture content with depth. The most moist horizon, as in the larch forest, is the over-permafrost horizon with a value of 16.4% (Table 1). Despite recent rains, the soil of the abandoned arable land (P-08.12) remained quite dry in the upper part (7.3%). In the lower horizons, there is a gradual increase in field moisture values up to 18.2% (Table 1). In the soil at the top of the byllar (C-01.12), moisture content in the 0–5 cm layer reaches 30%, indicating a short-term saturation of the layer with high organic matter content. Below, moisture distribution along the profile is fairly uniform (22.7%–23.5%), with an increase up to 29.1% in the over-permafrost layer. The field moisture in the top 20 cm of the slope and the bottom of byllar soils is below 20%. These indicators are most likely related to differences in grass cover density over different microrelief elements—the denser and taller grass vegetation slightly impedes moisture penetration into the upper soil layers. In the case of such short-term rainfall on dried soils, infiltration into lower horizons is almost absent. Although this situation might change during snowmelt or prolonged rains. At the same time, the distribution of moisture values in the over-permafrost layer across microrelief elements shows a pronounced lateral flow: 29.1% on the byllar and 49.7% in the depression between byllar (Table 1).

3.3.4. The portion of Na^{+}, Mg^{2+} in the sum of exchangeable cations

This parameter characterizes the processes of solodization—the destruction of the mineral part of the soil under the influence of alkaline solutions, accompanied by the accumulation of silica and the removal of amorphous weathering products from the solodized eluvial horizon—and solonetz formation (the process of specific transformation of morphological and other soil properties caused by an increase in the content of exchangeable sodium and magnesium). The soils of the studied territories are distinguished by a fairly high proportion of sodium and magnesium ions in the soil exchange complex (more than 50%), reaching a minimum in the solodized eluvial E horizons (0.55–0.67) and a maximum in the solonetzic Btn horizons (0.75–0.89) (Table 1). The distribution of this parameter in the mineral part of forest solodized soils is predominantly increasing downward through the profile, with a characteristic decrease in the bleached horizon. In the abandoned arable land soil, the differentiation along the profile is less pronounced due to anthropogenic disturbance. The soils of the byllars, despite their close proximity, differ greatly in the distribution of exchangeable sodium and magnesium down the profile, with the highest average values recorded in the soils on the tops of the byllars and the lowest in the lowland between the byllars.

4. Discussion

In the studied area, during the mid-1950s, arable land was created through the stubbing of larch and birch forests. In a natural state, such areas were still classified by A.A. Krasyk [40] as solonetz soils under birch forest, and by V.G. Zolnikov [41] as solonetz podzol soils under larch forests. Later, L.G. Yelovskaya [42] classified these soils as forest sod or permafrost pale soils. Based on these definitions by the founders of Yakut soil science, we recognize the dominance of permafrost solonetzic and solodic soils on the degraded arable lands near the village of Churapcha. Their typical morphological profile, after half a century of cultivation, has acquired cultivated and subcultivated horizons at the surface. The soils of byllars are remnants of these previously cultivated soils.

When comparing the morphological properties of the studied soil profiles, it is possible to identify the changes that occur in soils during the initial stages of alas formation. It should be noted that all studied soils show signs of cryoturbation within the profile. In forest soils, these features are mostly confined to the upper 30–40 cm of the soil, indicating the combined influence of permafrost and pyrogenic processes. In the soils of abandoned arable lands, the genesis of turbations is a combination of anthropogenic and cryogenic influences (Figure 4). When forests are stubbed, soil warming increases, making the soil more sensitive to climatic changes.

Arable soils initially differ significantly from soils of the natural sequence: they lack the litter layer, the organogenic horizon, and the features of the solodic horizon characteristic of pale solodized soils, partially or completely degraded. With an increase in the depth of thawing and the absence of irrigation, rapid salinization of the surface of abandoned arable soils occurs due to the dominance of an evaporative (outflow) soil water regime. The pH quickly reaches values of 8–9 in the upper layers, compared to the natural level of 6–7. Intensive accumulation of exchangeable sodium and magnesium takes place in the upper part of the profile, leading to the formation of a solonetzic horizon. Solonetzic soils and solonetzes are formed.

During the formation of byllars, the disappearance of the shielding layer between the seasonally thawed layer and the surface of the ice complex leads to a transformation of the relief [43]. The appearance of numerous depressions and hummocks causes a redistribution of moisture and changes in the pattern of substance accumulation within the disturbed area. In the soil on the top of the byllar (hillock), under conditions of even greater drying and an intensified evaporative regime during permafrost thawing, solonetzic features become more pronounced. At the same time, the soils on the slopes and in the lowlands, due to periodic moistening caused by the redistribution of precipitation and snowmelt, begin to exhibit signs of solonetz degradation (solodization). As a result, the upper part of the soil begins to intensively lighten (become bleached), characterized by a significant reduction in the proportion of exchangeable sodium and magnesium in the soil exchange complex. Thus, the manifestation of solodic features in the soils of byllars begins to show certain differences depending on their position on different elements of the microrelief (Figure 5). In the soil of the depression, due to greater moisture, the lightening of the upper part of the profile is more pronounced, and the pH of the upper layers again approaches the values characteristic for forest soils. In this profile, the horizon composed of lightened material and the natric horizon are also much thicker, while the calcic horizon occurs approximately 20 cm deeper. This may be explained by the possible "stretching" of these layers during the subsidence of the lower part of the soil profile caused by the degradation of the ice-wedge complex, as well as by the increase in the leaching soil regime. The parent material (horizons Ck or Cgk) in all three byllar profiles is nearly identical in terms of depth of occurrence and color.

The soils are underlain by permafrost, with only slight differences in the depth of its occurrence—161 cm on the top, 171 cm on the slope, and 156 cm in the depression, meaning that the active-layer thawing in the depression is the least pronounced (Figure 5). It should be noted that there are significant differences in the total projective cover of the herbaceous vegetation across the elements of the permafrost microrelief: on the top and slope of the byllar, the projective cover is 20–30% lower than in the depressions between the byllars. The high projective cover in the depression is achieved due to the vigorous growth of *Potentilla anserina*, which is associated with soils with excessive moisture. This promotes the intensification of organic matter accumulation on the soil surface. Thus, the soils in the depression are slightly better thermally insulated than those on the slopes and top, which explains the reduced thawing depth under increasing soil moisture. At the same time, overall, thawing depth, except for the byllar depression, shows a moderately positive correlation with soil moisture (r = 0.69, where r is the Pearson correlation coefficient), and a strong negative correlation with the total thickness of the litter and coarse humus horizon (r = −0.84). But no significant dependencies on the other parameters were found.

A comparison of soil pH with other studied soil parameters reveals that pH values have a positive correlation with the proportion of exchangeable sodium and magnesium accumulated in the soil exchange complex (r = 0.73). Therefore, solonetz formation is a factor contributing to increased soil alkalinity.

The bulk density values and their distribution along the soil profile in the larch and birch forest are approximately the same and show a tendency to increase with depth. Comparison with other parameters shows that bulk density distribution in the profile of forest soils correlates reasonably well with the distribution of physical clay (<0.01 mm) (r = 0.63). But in abandoned arable land soils, the significant relationship with particle size composition disappears due to mechanical disturbances (r = −0.24). Positive extremes appear in the upper part of the abandoned arable land soil, within the plow and subplow horizons, resulting from the formation of a plow pan, livestock grazing, and solonetz formation. In the soil formed on the top of the byllar and in the depression, bulk density decreases with depth, whereas in the profile located on the slope of the byllar, density increases downward along the profile. We assume that for the top and for the depression, this is related to the collapse and loosening of the lower part of the soil profile due to the thawing of ice-rich fragments of the ice complex. In contrast, in the slope soil, vertical compression may have occurred during the formation of the byllar, which led to compaction. Thus, thermokarst transformation leads to uneven soil bulk density across different parts of the site, which affects its aeration and drainage capacity in areas with cryogenic microrelief.

The distribution of field moisture along the profile in forest soils is almost identical; however, soils under birch forest are generally more moist. The profile of the abandoned arable land, which is currently used for livestock grazing, is characterized by low moisture values due to the absence of a litter layer that protects against evaporation and the relatively limited infiltration of water into the compacted upper part of the soil. With the development of thermokarst, the surface subsides, forming a negative landform, and the degree of subsidence increases each year. Thus, soils of cryogenic microrelief, despite intensive evaporation, possess relatively larger moisture reserves due to runoff from the surrounding elevated relief elements (the sources of moisture being precipitation and water released during permafrost melting). Therefore, it is natural that even during very dry summers, high moisture is preserved in the lower part of the soil profile of depressions between the byllars, creating conditions for the development of gleying. Over time, moisture accumulation in these depressions will increase, and eventually they will be filled with water and expand, further lowering the overall level of the thermokarst-disturbed surface. This process will ultimately lead to the formation of a thermokarst lake, and later an alas.

Thus, the following mechanism of soil cover and property transformation during byllar formation can be identified:

- Top of byllar: dominance of the evaporative water regime during underground ice melting and desiccation → increase in exchangeable sodium and magnesium in the upper part of the profile → formation of a dark solonetzic horizon → transformation of pale cultivated soil into dark solonetz.

- Slope and depression between byllars: additional moisture supply due to runoff → weakening of the evaporative regime, strengthening of the leaching regime → eluviation (solodization) combined with solonetz formation → formation of a light solodic horizon in the upper part of the profile and deepening of the carbonate horizon → formation of light solonetz or solodic soil.

- Depression between byllars: accumulation and stagnation of moisture → gleying process.

5. Conclusions

Climate change in Central Yakutia is causing degradation of the ice complex. Thermokarst degradation is particularly pronounced in cleared, burnt, and abandoned arable lands—areas where the thermal insulation functions of the vegetation cover are significantly weakened.

The typical undisturbed forest soils of the study area are represented by permafrost pale solodized cryoturbated soils [turbic protocalcic cambic cryosol (siltic, sodic)], characterized by a thin organogenic layer, the presence of a clear solodic horizon in the upper part of the profile, and a suspended calcic horizon in the middle part of the profile, as well as cryogenic and pyrogenic turbations. The soils of abandoned arable land in the study area are represented by postagrogenic variations of this forest soil type [anthaquic sodic cambisol (siltic, protocalcic)], characterized by a uniform alkaline reaction across the profile, agrogenic homogenization of the upper part of the profile, and signs of salinization.

The formation of byllars on abandoned arable lands in Yakutia marks the beginning of an irreversible process of soil degradation and erosion. Thus, the soils of the byllar top are previously cultivated arable soils transformed into highly alkaline permafrost-affected dark cryoturbated postagrogenic solonetz [calcic solonetz (loamic, turbic)]. On the slope of the byllar, permafrost-affected light postagrogenic solonetz [calcic solonetz (albic, loamic, turbic)] are formed. In the depressions between byllars, less alkaline permafrost-affected light solonetz with weak signs of gleying [calcic stagnic solonetz (albic, loamic, turbic)] were described. The difference in the nature of moisture due to changes in topography and thawing depth greatly influenced the structure of soil profiles located only 2–3 m from each other. In the soil of the byllar top, which is drier, a characteristic dark natric horizon of small thickness is formed. This is due to an increase in the evaporative regime and the rise of salts with ascending waters of thawing permafrost. In slope and depression soils, under relatively humid conditions, the lightening process is more pronounced—an eluvial horizon with a total thickness of approximately 26–28 cm, washed by alkaline solutions, is formed.

Thus, as a result of successive degradation processes, over a short period of time, some areas of abandoned cropland experienced an irreversible soil profile complexity. Thus, typical permafrost pale forest soils were transformed during agricultural development into pale cultivated solonetzic soils, which, after the formation of thermocrast microrelief forms, evolved into a mosaic combination of dark and light solonetz soils with varying degrees of solonetz formation and solodization depending on their position in the microrelief. It was found that the soil moisture in the byllars is higher than in forests and abandoned arable lands due to the melting of permafrost and moisture accumulation. The thaw rate in such soils is significantly deeper and directly depends on the presence of the organogenic heat-insulating layer on the soil surface and its thickness; the soil density of the byllars has a very uneven distribution due to mechanical disturbances of anthropogenic and thermokarst nature.

Author contributions

N. Filippov: Formal analysis, Investigation, Visualization; R. Desyatkin: Conceptualization, Funding acquisition, Supervision; A. Ivanova: Formal analysis, Methodology, Writing—original draft, Writing—review & editing; P. Fedorov: Investigation; M. Nikolaeva: Investigation; A. Desyatkin: Conceptualization, Investigation, Visualization, Writing—original draft, Writing—review & editing.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare they have no conflict of interest.

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