One Ecosystem 6: e68408
doi: 10.3897/oneeco.6.e68408

OPEN ACCESS

Research Article

Morphological features, productivity and pollution state of abandoned agricultural soils in the Russian Arctic (Yamal Region)

Timur Nizamutdinov[‡], Evgeny Abakumov[‡], Evgeniya Morgun[§]

‡ Department of Applied Ecology, Faculty of Biology, St. Petersburg State University, Saint Petersburg, Russia
§ Arctic Research Centre of YANAO, Salekhard, Russia

Corresponding author: Timur Nizamutdinov (timur_nizam@mail.ru)

Academic editor: Bastian Steinhoff-Knopp

Received: 07 May 2021 | Accepted: 05 Aug 2021 | Published: 09 Aug 2021

Citation: Nizamutdinov T, Abakumov E, Morgun E (2021) Morphological features, productivity and pollution state of abandoned agricultural soils in the Russian Arctic (Yamal Region). One Ecosystem 6: e68408. https://doi.org/10.3897/oneeco.6.e68408

Abstract

Recently, questions about the return of the concept of Arctic agriculture in order to promote sustainable development of the northern regions and ensure food security have been raised more often. The re-involvement of previously-used and abandoned soils into agricultural usage can provide an essential contribution for the development of the Arctic regions. We conducted a comprehensive research of soils with different levels of abandonment in the central part of the Yamal Region (Russia) and compared their morphological features, chemical and physical properties, fertile qualities and the level of contamination with heavy and trace metals to background soils of the region. It has been noted that there are no evident features of cryoturbation processes in the profiles of abandoned agricultucal soils and regular changes in the redox regime, as a consequence of the presence of reductimorphic spots in the soil profiles, have been recorded. Soil organic matter (SOM) stock in the topsoil of abandoned soils is estimated as medium and has a similar level to the stocks of total organic matter in the agricultural soils of the Arctic circumpolar region (Norway, Sweden, and Finland). Statistically significant differences in the content of nutrients between abandoned and background soils were recorded which indicates stability of the soil nutritional state during different abandoned states. Particularly notable are the differences between the content of available forms of phosphorus. The results of the study revealed significant differences between soils of various periods of abandonment and the background soils of the Yamal Region. Abandoned soils can be used for ground and greenhouse agriculture, these soils having a high level of fertility and are not limited for use in agriculture by the level of contamination with heavy and trace metals. According to the character of trace metal contamination, abandoned and background soils are evaluated as uncontaminated on the base of Z_c and I_{geo} indices values. Reuse of the previously abandoned soils can undoubtedly become the basis for increasing agricultural production and ensuring food security in the Yamal Region.

Keywords

postagrogenic soils, permafrost, nutrients, pollution status, Arctic

Introduction

The development of the agricultural sector of economy in the Arctic Regions is inextricably linked to the sustainable development and stable economic growth, not only in individual regions, but also in the country as a whole (Maximova 2018). Nowadays, in the Russian Federation there are many global development projects associated with the Arctic Region, such as the Northern Sea Route and natural resources exploration of the northern regions. Undoubtedly, the development of global projects in the Arctic zone is impossible without providing food security for the regions of this circumpolar region. This issue is receiving more and more attention nowadays (Alekseeva 2017, Abakumov and Morgun 2020, Abakumov et al. 2020b). During the Soviet Union times, there were practices of introducing northern farming (Khantimer 1974, Purtov 1994, Vavilov 1931, Basharin 1990, Naumov et al. 2020), which, with the use of modern technologies, can become a mainstay in terms of food security and sustainable development of the Arctic.

The development of the Arctic zone is recognised by all countries with northern territories. The issues of agricultural use are widely discussed at the international level, within the framework of The Circumpolar Agricultural Association (Soppela 2020). Although the climatic conditions of the Arctic latitudes are severe, there are a number of countries that have experience in successful agricultural practices in polar environments. The experience of farming in Alaska is well known (Gasser 1948, Lewis et al. 1987). On the Kenai Peninsula (Alaska), potatoes and various types of vegetables were successfully cultivated, well known small farms in the vicinity of Anchorage, as well as in the Tanana and Matanuska Valleys where potatoes and vegetables were planted (Stevenson et al. 2014, Francis 1967, Gasser 1948). Norway has also been active in introducing agriculture under Arctic conditions (Elstrand 1979). Farms in northern Norway exist around the towns of Brensholmen and Austein, where forage crops for cattle were grown (Vorren 2005, Sjögren and Arntzen 2013). In the vicinity of the Finnish city of Revoniemi, cereals and potatoes were farmed (Jokinen 1997). The experience of northern farming in Sweden and Canada is also known (Elstrand 1979).

In Russia, polar agriculture began to develop intensively in the late 18th and early 20th centuries (Alekseeva 2017, Purtov 1994, Naumov et al. 2020). In Tsarist times, Arctic farming was practised by the Cossacks and exiled migrants, who mixed with the indigenous population and passed on their agricultural experience (Naumov et al. 2020, Purtov 1994). Before that period, the indigenous peoples inhabiting the polar regions were mainly engaged in reindeer herding, fishing and hunting (Morgun and Abakumov 2019). The development of polar agriculture is largely related to the partial transition of indigenous peoples from a nomadic to a sedentary lifestyle. The impetus for the application of scientific and systematic approach to polar agriculture can be considered the adoption of the *Concept of Northern Farming*. This concept was formed by N.I. Vavilov in 1931 and included the planned steps to implement the "northernisation" of agriculture in the USSR (Vavilov 1931, Eichfeld 1933). After that, polar agriculture began to actively develop in the Murmansk Region, the Republic of Karelia, the Komi Republic, the Arkhangelsk Region, the Yamal-Nenets Autonomous District and the Republic of Sakha (Yakutia) (Alekseeva 2017, Khantimer 1974, Purtov 1994, Basharin 1990, Naumov et al. 2020).

The foundation of the Yamal zonal vegetable experimental station of the Soviet-Union Academy of Agricultural Sciences in 1932 was the beginning of the active development of agriculture in the Yamal-Nenets Autonomous District (YANAO) (Khantimer 1974, Eichfeld 1933, Chistyakova 2015). There were also arable plots in the region, which, when amended with manure, yielded a stable crop of potatoes, cabbage and turnips. The development of agriculture in the region progressed rapidly until the collapse of the Soviet Union. In the crisis years of 1990s - 2000s, the agro-industrial sector fell into decline and now it is actively recovering. At present, however, the current number of large agricultural enterprises is still few. Today, the agricultural sector in YANAO grows mainly potatoes and vegetables (Morgun and Abakumov 2019).

Recently, abandoned permafrost affected soils are of considerable interest in terms of assessing the post-agrogenic transformation of soils under cryogenic conditions. This is of particular interest because it is important to determine the ability of soils with various degrees of abandonment to retain fertility, especially in Arctic conditions (Nizamutdinov et al. 2021a, Abakumov et al. 2020a, Kalinina et al. 2009). The study of these soils could be a step towards returning the overgrown soils into agricultural use, which will contribute to the development of the Yamal Region in the framework of the programme "Socio-economic development of the Arctic zone of the Russian Federation until 2025" (Maximova 2018), as well as ensuring food supply of the Arctic Regions.

Therefore, our goal in this study is to assess the specificity of postagrogenic transformation of recently-abandoned agricultural soil in the permafrost conditions of the Yamal Region. The study objectives are:

1. to study morphological features of soils previously used for agriculture;
2. to assess the main physical, chemical and agrochemical properties of the abandoned soils;
3. to characterise the degree of pollution by trace metals.

The study results can become the basis for sustainable development of a strategy for planning future agriculture in the studied areas.

Material and methods

Regional settings

The Yamal-Nenets Autonomous District (YANAO) is located in the Arctic zone in the northern part of the West Siberian Plain and covers a wide area of 769250 km^2. More than half of the region is located above the Arctic Circle (Fig. 1). YANAO is located in three climatic zones: Arctic, subarctic and temperate. Landscape zonation is characterised by taiga, forest-tundra and tundra zones (Chistyakova 2015).

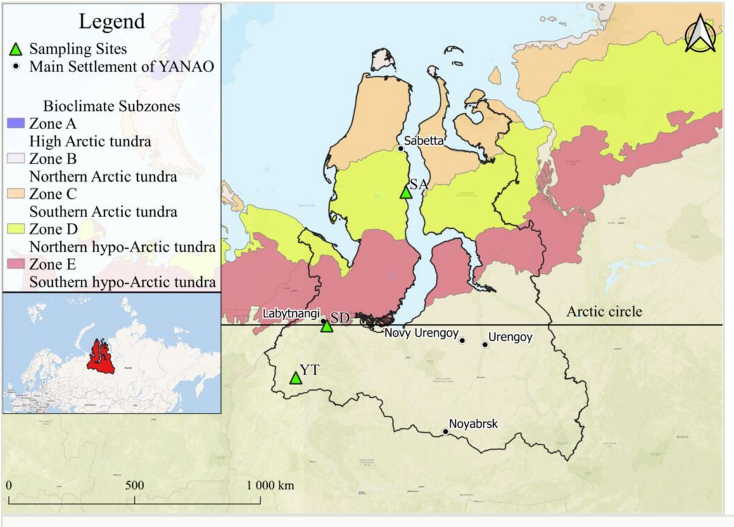

Figure 1.

Sampling sites (Team et al. (2003)).

The climatic conditions of the Yamal Region are highly variable in spatial dimension. The Arctic tundra zone (the northern part of the Yamal and Gydan Peninsulas) is characterised by long harsh winters, with frost lasting up to 220 days (Kozin and Bakulin 1996). Average temperatures: January, −27°C; July, 3.4-4.5°C (1961–1990). Precipitation is less than 200 mm per year. The depth of snow cover is 20-25 cm. The central part of the peninsulas (up to the Arctic Circle) is in subarctic climatic conditions. Stable snow cover lasts up to 210 days, with snow cover depth of 35-50 cm. Average temperatures: January, −22°C; July, 8-13°C (1961–1990). Vegetation period duration is up to 44 days (Kvashin 1999). The southern part of the region is in a temperate climate zone. Stable snow cover lasts up to 190 days, snow cover depth up to 70-80 cm. The average temperature in January is, −23°C, in July, 14-16°C (1961–1990) (Kozin and Bakulin 1996, Kvashin 1999, Pavlov and Malkova 2005).

The research is based on the analysis of soil samples taken in different areas of the YANAO (Fig. 1).

During field activities in the summer of 2020, we identified various abandoned agricultural sites. Several research sites were selected in which soil pits were established (Fig. 1). The pits were dug down to the permafrost horizon. Soil samples for chemical, agrochemical and physicochemical analysis were taken every 10 cm (when the horizon thickness is less than 10 cm or falls on the horizon boundary, samples were taken from each genetic horizon). The description of the seven sampling sites is given in Table 1.

Table 1.

Basic data about sampling sites.

Sampling Site	Sampling code	Soil type	N	E
Priuralsky District, YANAO				
Salekhard, agrostation field	SD1	Abandoned Soil (14 years of abandonment)	66.52713	66.65490
Tundra outside the city of Salekhard	SD2	Background Soil	66.32603	66.39632
Shuryshkarsky District, YANAO				
Yamgort village, agro-farm field	YT1	Abandoned Soil (2 years of abandonment)	64.94554	64.35480
Yamgort village, private vegetable garden	YT2	Abandoned Soil (2 years of abandonment)	64.94015	64.36350
Northern Taiga beyond the village of Yamgort	YT3	Background Soil	64.94550	64.36379
Yamalsky District, YANAO				
Sayakha village, private vegetable garden	SA1	Abandoned Soil (3 years of abandonment)	70.17046	72.52002
Tundra outside Sayaha village	SA2	Background Soil	70.16091	72.47588

Currently, the agricultural areas in the region are not much developed. In the process of field research and interviews with the local population, we have identified several interesting sites that have recently been abandoned. Of particular interest are private vegetable gardens, which, in some cases, have been cultivated for more than 25 consecutive years. These data are, in many aspects, unique because private farming in Arctic conditions is extremely rare.

The first sampling site (SD) was the field of the experimental Yamal agricultural station (Salekhard, Priuralsk District, YANAO). Here, since 1932, work has been carried out to study the adaptation of various crop species to the conditions of the Far North (Fig. 2). Unfortunately, since 2007, the activity of the station was stopped and was not renewed in 2019 in full. The background for this area was the soils of mature tundra outside the city of Salekhard.

Figure 2.

Sampling sites (Photos: E. Morgun, 2020)

a: SD1
b: SD2

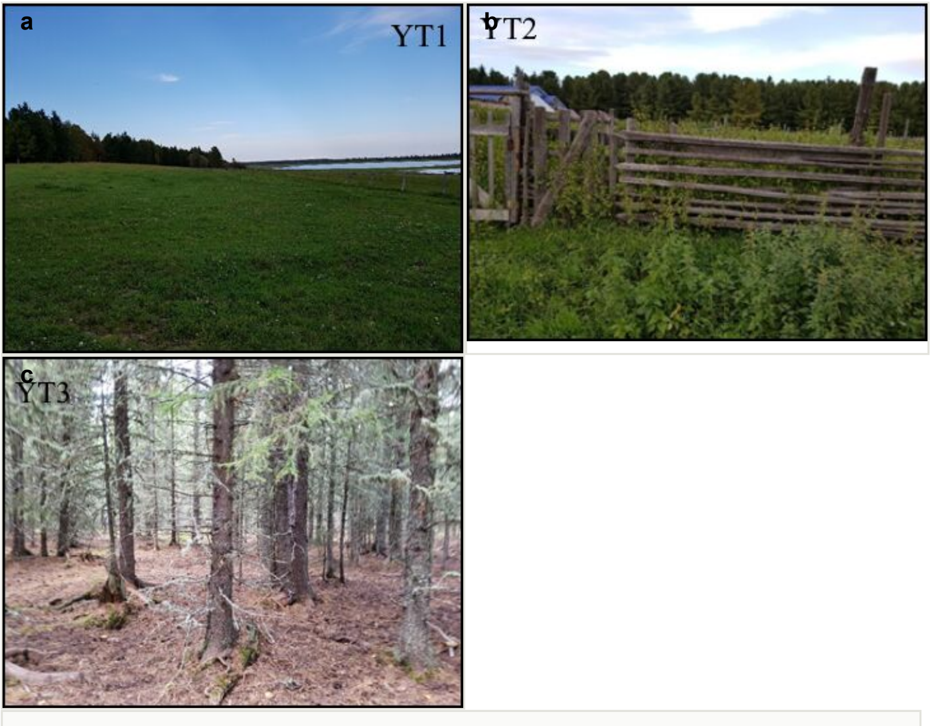

Figure 3.

Sampling sites (Photos: E. Morgun, 2020)

a: YT1
b: YT2
c: YT3

The second sampling site (YT) is located in the Shuryksharskiy District of YANAO, in the village of Yamgort. Three soil profiles were established (Fig. 3). The first one was on the territory of an abandoned private vegetable garden; the vegetable garden had been continuously cultivated for 25 years, with regular application of mineral fertilizers (ash, cow and horse manure). This site was predominantly a potato-growing area. Now the vegetable garden is abandoned and there have been no agricultural activities for more than 2 years. The landowners noted that the territory of the vegetable garden was subjected to flooding three times in 25 years. The second sample was taken on the territory of the abandoned field of the agricultural company "Muzhevskoe". Potatoes and oats were rotated growing in this site. From 2019 to the present, the field has been abandoned and unused. The background for this area provided the soils of mature northern taiga outside the village. Photos of the sampling locations are presented on the .

The third sampling site (SA) is in the Yamalsky District of YANAO. Two soil profiles were established. The first, in the village of Sayakha - the northernmost settlement of the Yamalsky District (Fig. 4). Sampling was conducted in the territory of an abandoned urban ecosystem in the private plot's yard. This area has not been used for 2 years. The background for this area was soils beyond the settlements in a mature tundra area.

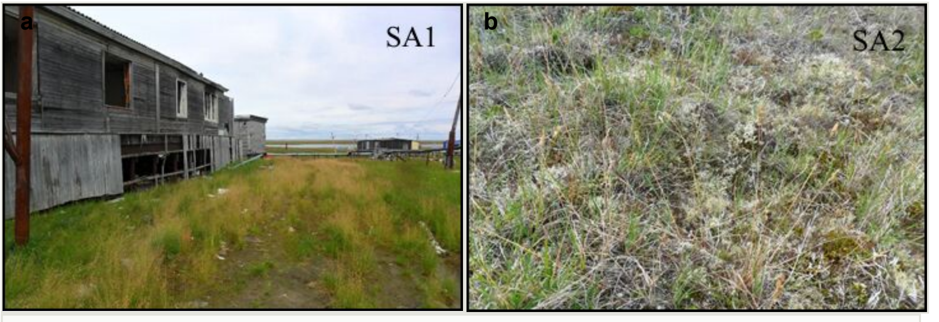

Figure 4.

Sampling sites (Photos: E. Morgun, 2020)

a: SA1
b: SA2

Laboratory analyses and data processing

After sampling, the soils were transported to the laboratory of the Department of Applied Ecology, St. Petersburg University. The samples were air dried, grounded and passed through a 2 mm sieve. The pH values of soil solution were measured by the using a pH-meter-millivoltmeter pH-150MA (Produced in Belarus). Soil solution was prepared in the ratio of 1:2.5 with water or 1M calcium chloride ($CaCl_2$) (Black et al. 1965). Basal soil respiration was evaluated by measuring carbon dioxide (CO_2) in sodium hydroxide. Incubation of CO_2 was conducted for 10 days in plastic sealed containers (Jenkinson and Powlson 1976). The particle size distribution of the soil was determined by the sedimentation (pipette) method (Kachinsky 1958, Jackson and Saeger Jr 1935). Soil organic carbon (SOC) content was determined by the Tyurin method, based on the oxidation of soil organic matter with a mixture of potassium dichromate and concentrated sulphuric acid (Bel'chicova 1965, Walkley and Black 1934). SOC content was converted in soil organic matter (SOM) values by a factor of 1.724 according to Loges (1883). Soil organic matter (SOM) stocks (volumetric concentrations) were estimated by the Orlov et al. (2005) method according to the following formula:

$$SOMStock, t \times ha^{-1} = C \times h \times d \quad (1)$$

where: C - SOM content, %; h - depth of the soil horizon, cm; d - soil compaction density, g×cm^{-3}.

The content of available forms of ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3-N) were determined using potassium chloride solution (ISO 2003). The content of mobile potassium and phosphorus was determined by the Kirsanov method (GOST 2003, Mulvaney and Sparks 1996). The method is based on the extraction of mobile compounds of phosphorus and potassium from the soil with a solution of 0.2 M hydrochoric acid (HCl).

The content of trace metals was determined following to the standard ISO 11047-1998 “Soil Quality-Determination of Cadmium (Cd), Cobalt (Co), Copper (Cu), Lead (Pb), Manganese (Mg), Nickel (Ni) and Zinc (Zn) in Aqua Regia Extracts of Soil - Flame and Electrothermal Atomic Absorption Spectrometric” method with an Atomic absorption spectrophotometer Kvant 2M (Moscow, Russia) (ISO 1998).

The Geoaccumulation Index (I_{geo}) allows us to classify seven levels of soil contamination, from Practically unpolluted ($I_{geo} \leq 0$) to Extremely polluted ($I_{geo} > 5$) (Müller and Furrer 1994,Jiang et al. 2019). The generic calculation formula is as follows:

$$Igeo = log_2[C_n / 1.5 B_n] \quad (2)$$

where: C_n – the measured concentration of the element in soil, B_n – the geochemical background value.

Total soil contamination index (Z_c), which is most commonly used in Russia to assess the dergree of soil contamination, was calculated according to the method of Hygienic evaluation of soil in residential areas (1994) (GN 1994). The value of this index has four levels, from acceptable pollution category (Z_c < 16) to extremely hazardous pollution category (Z_c > 128) (GN 1994).

$$Zc = (\sum_{(i=1)}^{n} Kc) - (n-1) \quad (3)$$

where: *Kc* – concentration coefficient of the i-th chemical element; *n* – number of evaluated elements.

$$Kc = C_i / C_b \quad (4)$$

where: C_i – the measured concentration of the element in soil; C_b – the geochemical background value.

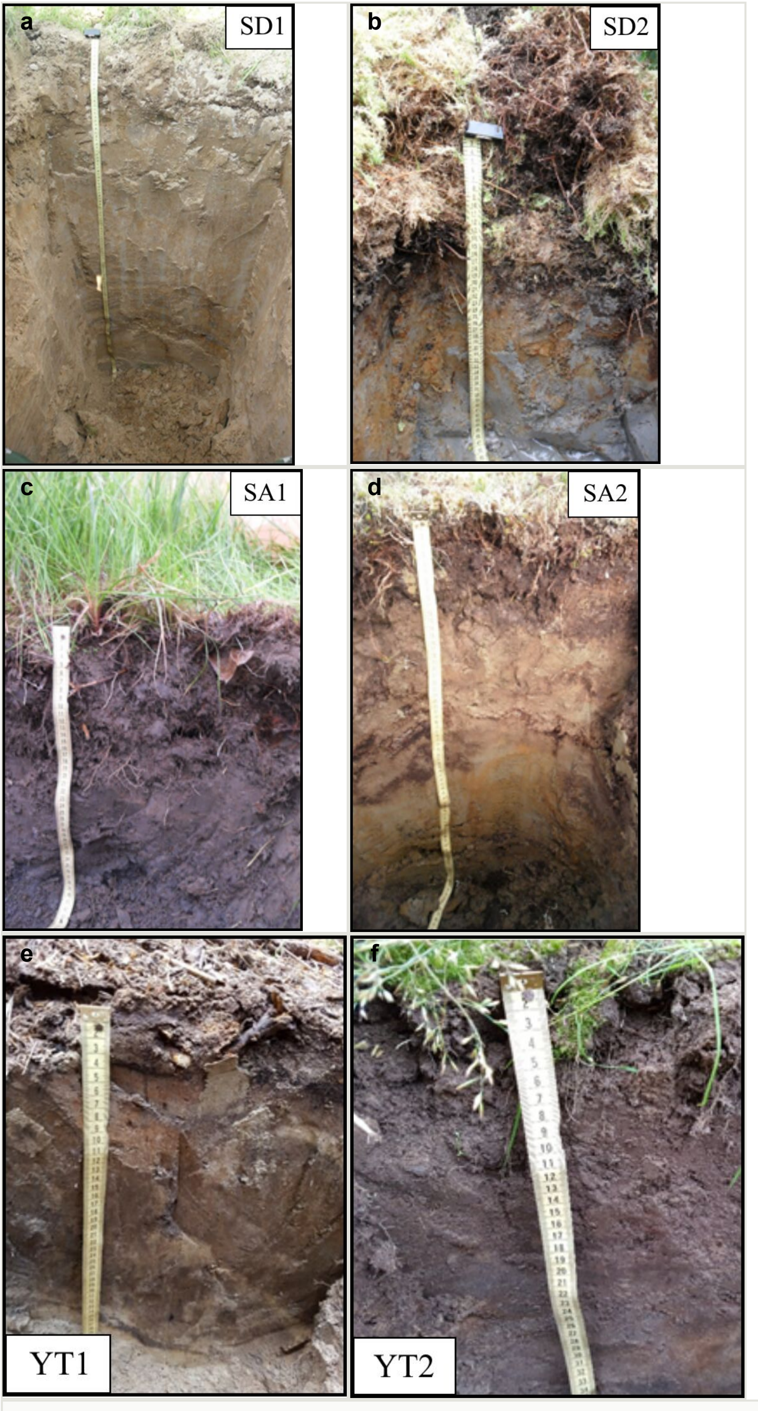

Figure 5.

Diversity of studied soils (Photos: E. Morgun 2020)

The value of this index has four levels, from acceptable pollution category (Z_c < 16) to extremely hazardous pollution category (Z_c > 128) (GN 1994).

Detailed contamination level values according to the I_{geo} and Z_c index values are shown in Suppl. material 1.

Statistical treatment and data visualization was performed using StatSoft Statistica v12.0, Prism GraphPad 9.0.0 and QGIS v3.16 software.

Results and discussions

Soil morphology

Soils diagnostics were performed using the International Soil Classification System (World Reference Base for Soil Resources (WRB 2014)). The studied soils are mainly represented by reference groups of *Cryosols* and *Podzols*. Previously, it was thought that plaggen (post-agricultural) soils can be preserved only in temperate latitudes, but studies of northern soils of Arkhangelsk Region revealed the ability of soils to maintain fertility in northern latitudes (Kalinina et al. 2009). Abandoned agricultural soils reached a depth of up to 140 cm. There is low decomposed organic matter in the superficial horizons (Fig. 5 SD1, SA1, YT1, YT2). There are no signs of cryoturbation and the transitions between diagnostic horizons are gradual. Abandoned soils contained anthropogenic artefacts (glass shards, slag and pieces of polyethylene). Background soils are more strongly enriched in organic matter of different degrees of decomposition (Fig. 5 SD2, SA2). Signs of cryoturbation processes are observed amongst pristine soils, which are most pronounced in the SD2 profile; other background soils (SA2 and YT3) are less turbed.

In most of the studied soils (abandoned and background), there are marked reductimorphic features, indicating a regular change in the redox regime in individual soil horizons. All of the studied soils are underlain by permafrost, with detailed soil descriptions presented in Table 2.

Table 2.

Morphological characteristics of the soils.

Sampling site	Soil name, WRB (2014)	Soil Horizons	Depth, cm	Description of soil horizons
SD1	Plaggic Podzol (Turbic)	Ap	0-23	Live roots, humid, antropogenic artefacts, blocky-prozmatic structure. Gradual distinction, wavy topography
		Bg1	23-31	Humid, roots, prismatic structure. Gradual distinction, wavy topography
		Bg2	31-41	Humid, reductimorphic colours of the gleyic colour pattern, prismatic structure. Gradual distinction, wavy topography
		Cg1	41-121	Humid, reductimorphic colours of the gleyic colour pattern, platy-crubly structure. Gradual distinction, smooth topography

Sampling site	Soil name, WRB (2014)	Soil Horizons	Depth, cm	Description of soil horizons
		Cg2	121-143	Humid, unstructured, non-consolidated
		C⊥	143-…	Permafrost
SD2	Turbic Cryosol	O	0-13	Slightly decomposed organic material, wet
		Ag	13-26	Reductimorphic colours of the gleyic colour pattern, live roots, wet, unstructured. Gradual distinction, smooth topography
		Cg1	26-37	Wet, unstructured. Gradual distinction, smooth topography
		Cg2	37-55	Gleyic colour pattern, very wet, unstructured
		C⊥	55-…	Permafrost
SA1	Urbic Technosol	Au	0-19	Wet, unstructured, live roots, accumulation of organic matter, antropogenic artefacts. Gradual distinction, smooth topography
		Cgu	19-40	Reductimorphic colours of the gleyic colour pattern, antropogenic artefacts, very wet
		C⊥	40-...	Permafrost
SA2	Reductaquic Cryosol	Oa	0-14	Live roots, accumulation of organic matter, humid, unstructured. Abrupt distinction, wavy topography
		Cg1	14-41	Roots, dark humus spots. Humid, lumpy structure. Abrupt distinction, wavy topography
		Cg2	41-73	Reductimorphic colours of the gleyic colour pattern, wet, unstuctured
		C⊥	73 - …	Permafrost
YT1	Plaggic Podzol (Turbic)	Ap	0-27	Live roots, humid, blocky-crumbly structure. Clear distinction, smooth topography
		Bgd	21-48	Humid, hard, crumbly structure, reductimorphic colours of the gleyic colour pattern
		C⊥	48-...	Permafrost
YT2	Plaggic Podzol (Turbic)	A	0-21	Organic matter, live roots, dry, compacted, granular-blocky structured. Gradual distinction, smooth topography
		Bg	21-41	Reductimorphic colours, humus spots, humid, compacted
		C⊥	41-...	Permafrost
YT3	Plaggic Podzol (Turbic)	Oa	0-4	Dry, live roots, unstructured, non-consolidated. Clear distinction, smooth topography
		Ar	4-37	Roots, humid, ferrous spots, white powder, platy structure. Clear distinction, wavy topography
		Cg	37-40	Gleyic colour pattern, wet, compacted, platy structured, live roots
		C⊥	40-...	Permafrost

Key physico-chemical and agrochemical properties of study soils

The main information about the physical and chemical properties of the studied soils is given below, with more details being seen in Table 3. All of the studied soil samples recorded acid reaction, pH values being highly variable and ranging from strongly acidic to weakly acidic (3.99 - 6.67). Exchangeable acidity values (pH $CaCl_2$) is traditionally lower in comparison with pH H_2O, with values ranging from 3.01 to 6.11. In most cases, soil acidity increases with depth; this can be explained by the processes of podzolisation in the soil profile. The greatest variation of pH values was recorded in the abandoned soils; this can be explained by the fact that, as a result of land abandonment, fertilization (carbonate compounds, or ash in the case of private plots) was stopped, which led to acidification of the superficial horizons.

Table 3.

The main physico-chemical parameters of the studied soils.

Sampling site	Soil name WRB (2014)	Soil Horizons	Depth, cm	pH (H_20)	pH ($CaCl_2$)	Basal Respiration mg CO_2/ 100g/day	SOM, %	SOM Stock, t×ha^{-1}	SOM stock in soil profile, t×ha^{-1}	SOM stock in topsoil (0 - 20 cm), t×ha^{-1}
SD1	Plaggic Podzol (Turbic)	Ap	0-23	4.95	3.61	46.20	3.2	86	127	76
		Bg1	23-31	4.37	3.02	52.80	0.9	10		
		Bg2	31-41	4.35	3.01	48.40	0.5	7		
		Cg1	41-121	5.17	4.09	31.68	0.2	22		
		Cg2	121-143	5.99	5.36		0.1	2		
		C⊥	143-…	-	-	-	-	-		
SD2	Turbic Cryosol	O	0-13	-	-	-	24.2	433	528	398
		Ag	13-26	5.51	5.21	30.80	4.6	85		
		Cg1	26-37	5.38	4.52	48.40	0.3	4		
		Cg2	37-55	5.68	4.77	44.00	0.2	6		
		C⊥	55-…	-	-	-	-	-		
SA1	Urbic Technosol	Au	0-19	5.97	5.51	52.80	5	124	124	88
		Cgu	19-40	6.67	6.11	44.00	3.1	88		
		C⊥	40-...	-	-	-	-	-		
SA2	Reductaquic Cryosol	Oa	0-14	-	-	117.33	32	659	895	599
		Cg1	14-41	4.39	3.75	44.00	4.6	186		
		Cg2	41-73	5.50	4.69	61.60	0.9	50		
		C⊥	73 - …	-	-	-	-	-		
YT1	Plaggic Podzol (Turbic)	Ap	0-27	5.15	4.46	90.20	2.8	113	140	86
		Bgd	21-48	5.81	4.88	59.40	0.7	26		

Sampling site	Soil name WRB (2014)	Soil Horizons	Depth, cm	pH (H_20)	pH ($CaCl_2$)	Basal Respiration mg CO_2/ 100g/day	SOM, %	SOM Stock, t×ha^{-1}	SOM stock in soil profile, t×ha^{-1}	SOM stock in topsoil (0 - 20 cm), t×ha^{-1}
		C⊥	48-...	-	-	-	-			
YT2	Plaggic Podzol (Turbic)	A	0-21	5.31	4.44	30.80	4.2	134	386	126
		Bg	21-41	5.1	4.63	48.40	9	252		
		C⊥	41-...	-	-	-	-	-		
YT3	Plaggic Podzol (Turbic)	Oa	0-4	3.99	3.41	30.80	6.3	34	227	114
		Ar	4-37	4.06	4.11	22.00	3.56	181		
		Cg	37-40	5.56	4.68	52.80	2.5	12		
		C⊥	-	-	-	-	-	-		

The level of basal respiration of soils is not homogeneous, varying greatly depending on the depth in the soil profile. Expectedly high values were obtained for the topsoil horizons of the background soils, as they are the most abundant in organic matter.

The SOM content of abandoned soils is significantly different from its content in the background soils. Within the same study area, differences of more than 8 times were recorded. For example, for the sample SD1 in the upper 10 cm layer of soil, SOM content is - 3.2%, on the contrary, in the sample SD2, it is - 24.2 %. These results are quite logical, since in natural soils, there are active processes of accumulation of organic matter due to the necrosis of plants and accumulation of plant debris.

Analysis of the of SOM stock levels in soil profiles also revealed significant differences between abandoned and background soils. The maximum stock for the background soils was found at *Reductaquic Cryosol* in point SA2; here the stock is estimated at 895 t×ha^{-1}, for the whole soil profile. For the abandoned soils, this value is significantly lower, 386 t×ha^{-1} for *Plaggic Podzol (Turbic)* in point YT2. However, from the point of view of agriculture, the content of SOM in the topsoil horizons (0-20 cm) is much more important (Fig. 6). Here, similarly to the results for the whole profile, the abandoned soils differ significantly from the background ones. The maximum stock in the layer 0-20 cm amongst the abandoned soils is also noted in the point YT2, amongst the background soils in the point SA2.

It is necessary to emphasize that the longer the soil has been abandoned, the lower the level of SOM stock in it. For example, at point SD1 (abandoned since 2007), the stock of SOM in the layer 0-20 cm is estimated at 76 t×ha^{-1} and at point YT2 (abandoned in 2019), the stock in the same layer is estimated at 126 t×ha^{-1}. Undoubtedly, such differences in SOM reserves are associated with abandonment of soils, because the processes of accumulation of leaf litter and, consequently, humus formation have been disrupted by past agricultural practices. Restoration of natural vegetation cover (especially trees) in Arctic conditions is very slow and, as can be seen in Figure 5, at point SD1 in 14 years of abandonment, it has not accumulated much SOM. In abandoned soil scenarios, multidirectional processes of organic matter accumulation can take place. Both accumulation of organic matter in the litter (humification) and removal of organic matter into the organo-mineral horizons (dehumification). Therefore, the dynamics of humus content in the abandoned soils of distant regions should be investigated in more detail in the nearest future (Unc et al. 2021).

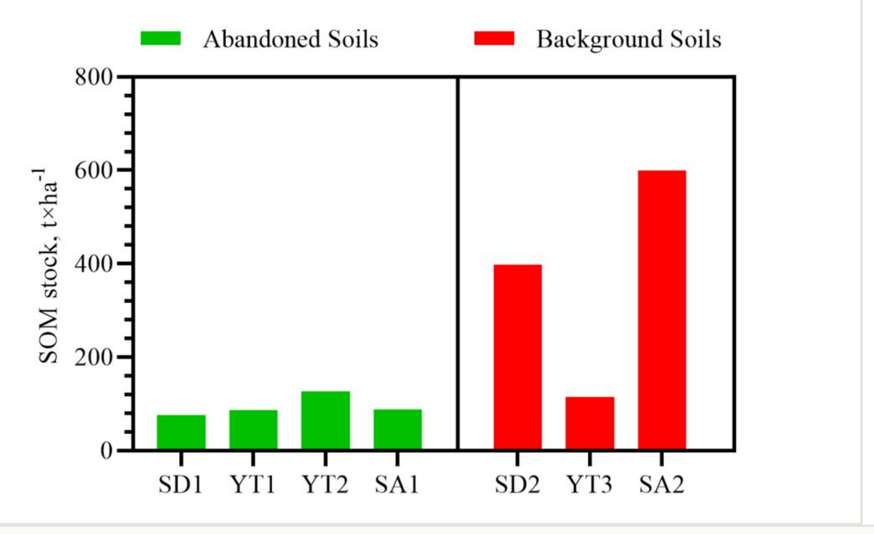

Figure 6.

SOM stock in topsoil 0-20 cm.

According to the Orlov et al. (2005) classification, the stock of SOM in the 0-20 cm layer for abandoned soils is characterized by medium (100-150 t×ha^{-1}) to very low (< 50 t×ha^{-1}) (Kiryushin and Ivanov 2005). SOM stock in our research is similar to the typical stock of organic matter in the northern agricultural soils of Norway, Sweden and Finland. In these countries, the SOM stock in the northernmost agricultural soils is estimated at 70 to 200 t×ha^{-1} (mean values for topsoil horizon 0-30 cm) (Lugato et al. 2014, Rusco et al. 2001). For soils in northern Canada, the SOM stock is 118 t×ha^{-1} in the northern Arctic and 240 t×ha^{-1} in the southern Arctic in the 0-50 cm horizon (Hossain et al. 2007).

Analysis of the particle size distribution of soils produced very interesting results. As is known, the particle size distribution of fine-grained soils is one of the basic characteristics of soils. The fractional structure of soil has a great impact on soil formation and agro-productive features of soils (Bridgeman et al. 2007). Particle size distribution affects the processes of migration, transformation and accumulation of organic matter in the soil (Arrouays et al. 2006, Keller and Håkansson 2010), it also determines properties such as moisture capacity and water infiltration (Kravchenko and Zhang 1998, Nasta et al. 2009) and is crucial in the formation of air and thermal regime of the soil (Shein 2005). It is also confirmed that the content of clay particles greatly contributes to the accumulation of various chemical compounds in the soil, including heavy and trace metals (Lavado et al. 1998, Harbison 1986, Yu and Li 2011, Gupta and Chen 1975).

As can be seen in Figs 7, 8, in all the studied soils, in the particle size distribution, the proportion of sandy fraction dominates (except SD1). In the SD1 soil profile up to a depth of 50 cm, the particle size distribution is characterized as sandy clay; deeper into the soil profile, the particle size distribution changes to clay (WRB 2014). In the deeper horizons, closer to the permafrost, the sandy fraction content increases, up to 95% at a depth of 100 cm.

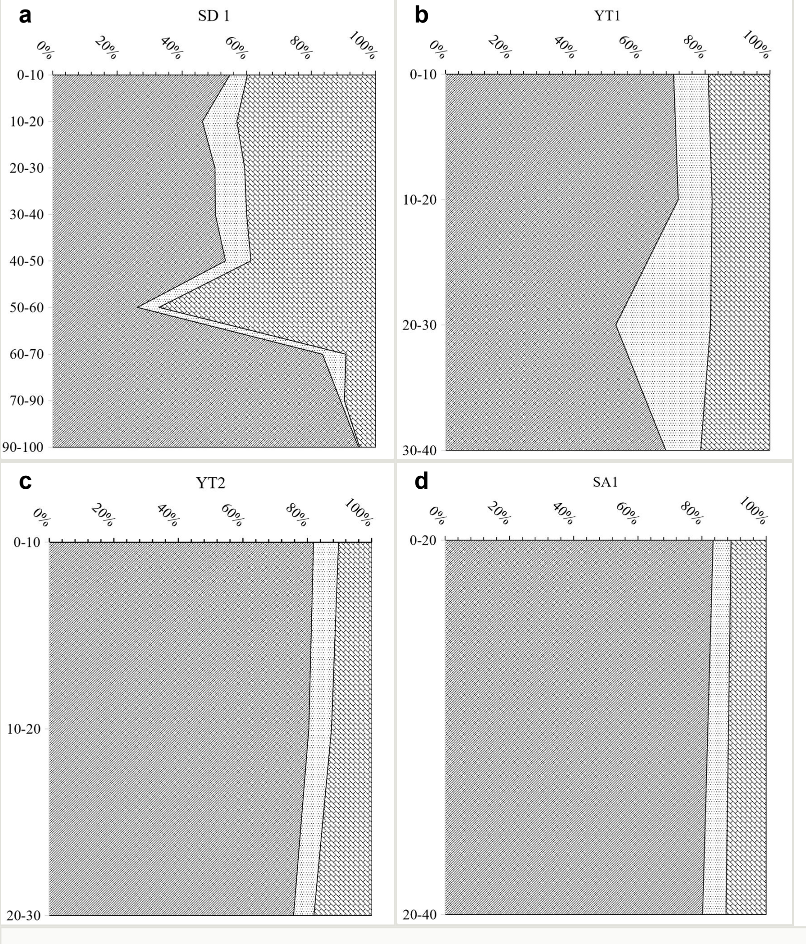

Figure 7.

Particle size distribution of abandoned soil (Legend included in Figure 8).

a: SD1
b: YT1
c: YT2
d: SA1

Other abandoned soils contain a much lower content of clay fractions compared to sample SD1, but show also an increase in the proportion of clay fraction with depth. In samples YT1 and YT2, the proportion of clay fraction in the lower horizons reaches to 17-20%. The particle size distribution of the soil is described as sandy clay loam and sandy loam for both samples, respectively.

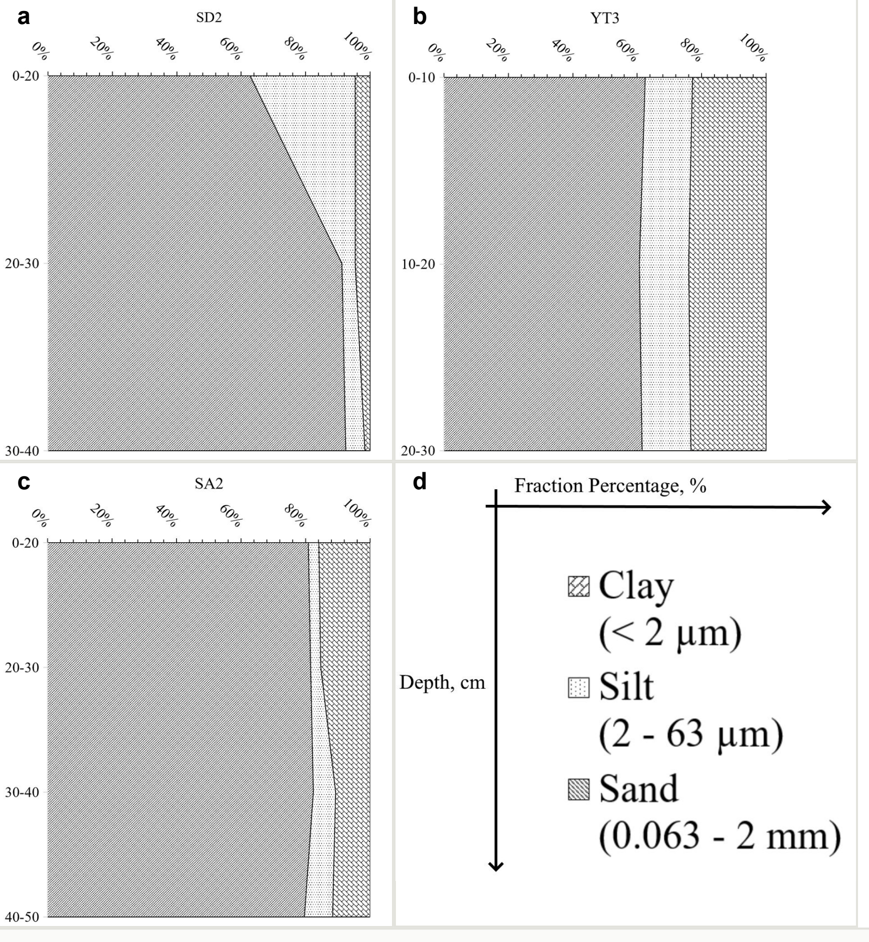

Figure 8.

Particle size distribution of background soils.

a: SD2
b: YT3
c: SA2
d: Legend

In all background soils, the proportion of clay particles does not change or even decreases along the soil profile (sample SD2). In all background soils, the proportion of sandy fraction in the fine-grained soil dominates. This distribution of fractions will have an impact on the degree of association of organic matter (Kononova 2013, Kemmitt et al. 2008). As a rule, organic matter is adsorbed in clay minerals, but the highest level of aeration is possible in soils of sandy particle size distribution (Tiessen et al. 1994). Finding the optimal balance between the degree of aeration of the soil profile and the availability of organic matter to microorganisms determines the mineralization of organic matter in the long term (Kononova 2013, Kemmitt et al. 2008, Leirós et al. 1999).

Nutritional status of the studied soils

Study of the degradation of soil fertility under permafrost conditions is one of the most important aspects in the context of agricultural planning in the Arctic. The content of nutrients in the soil is crucial in assessing the degree of soil fertility (Mineev 2004, Tiessen et al. 1994, Gruhn et al. 2000). Available forms of phosphorus, potassium and nitrogen are considered as the main nutrients for plants (Kudeyarov and Semenov 2006, Kiryushin and Ivanov 2005). Based on the data on the actual content of available forms of nutrients, it is possible to develop measures to create a nutrient regime for various crops (Kiryushin 2007). Organic compounds of phosphorus and nitrogen are part of the soil organic matter (Holford 1997, Kononova 2013), potassium is in the form of insoluble aluminosilicate minerals (Yakimenko 2018) and becomes available to plants only after their weathering. In addition, the ability of the soil to retain mobile forms of nutrients is mainly influenced by its particle size distribution and percentage of clay fraction (Caravaca et al. 1999, Chekmarev et al. 2011, Carlon 2007).

There are few publications on the content of nutrients in the abandoned soils of the Arctic zone. There are data on the content of available forms of nitrogen, phosphorus and potassium for abandoned agricultural soils in the vicinity of Salekhard. In 2018, the content of available forms of phosphorus was estimated as very high (> 250 mg×kg^{-1}) according to the Mineev (2004) assessment scale. Soil enrichment of available potassium and nitrogen is highly variable. Potassium content was estimated by the authors from very high (> 250 mg×kg^{-1}) to low (40-80 mg×kg^{-1}). Available forms of nitrogen in the abandoned soils of the Salekhard City vicinity were mostly estimated as moderate (20-40 mg×kg^{-1}) (Abakumov et al. 2020a). There is also information about the content of available forms of phosphorus and potassium in the soils of northern Norway. In the Province of Tromso, the maximum level of potassium does not exceed 66 mg×kg^{-1} and phosphorus 11.3 mg×kg^{-1} (Arnesen et al. 2007). In agricultural soils in Arctic Norway, the content of organic phosphorus reaches 670 mg×kg^{-1} (Øgaard 1996). Estimated scales of nutritional elements (for available phosphorus and potassium 6 scales, for nitrate and ammoniun nitrogen 4 scales), used in the Russian Federation, based on the works of Mineev (2004) and Gamzikov (1981), are shown in Suppl. material 2.

As can be seen in Fig. 9, the highest concentration of all nutrients in abandoned soils is observed in the topsoil. The content of the available form of phosphorus reaches 935 mg×kg^{-1} in sample YT1 and 569 mg×kg^{-1} in sample SD1. Additionally, for sample SD1, there is a local maximum of phosphorus content in the 60-70 cm horizon, where the highest proportion of clay fraction (Figs 7, 8), the fine-grained soil, was registered. This confirms the thesis that clay particles accumulate nutrients. The content of available phosphorus in the topsoil can be estimated as very high (> 250 mg×kg^{-1}) in soils SD1 and YT1. In samples SA1 and YT2, the content is estimated as moderate (50-100 mg×kg^{-1}). It should be noted that soils SD1 and YT1 were used for industrial cultivation, while SA1 and YT2 were used in private agriculture. Consequently, the soil parameters were controlled at different levels.

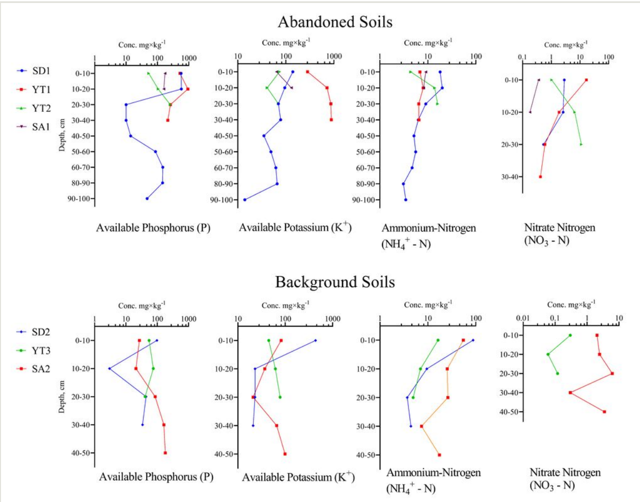

Figure 9.

Nutrients concentration dynamic in soil profiles.

The maximum content of available potassium was recorded in the YT1 abandoned agricultural soil, which was used by an agricultural company. Potassium concentrations range from 284 mg×kg^{-1} in the surface layer, to 885 mg×kg^{-1} at a depth of 40 cm. It is now possible to discuss the incipient migration of potassium along the soil profile, as a consequence of the termination of field exploitation. Similar to the phosphorus content, in the soil of the former experimental agricultural station SD1, a local maximum of potassium content is observed at a depth of 60-70 cm. The content of available potassium is estimated as very high (> 250 mg×kg^{-1}) in the soil (YT1) of the ex-agricultural company in the layer 20-40 cm. Soils of other studied areas can be characterized as moderate (80-120 mg×kg^{-1}) in terms of available potassium content (Fig. 9). The stocks of available phosphorus and potassium in the background soils were significantly different from the content of these elements in the abandoned agrosoils. For potassium and phosphorus, there is a trend of increasing concentrations with depth, which may be due to cryoturbation processes identified at the stage of morphological analysis. Stock of available forms of phosphorus and potassium is characterized as moderate, except for a few local maximums of available potassium in the topsoil horizon of site SD2 and phosphorus content on the deep horizon of 40-50 cm in the soil site SA2.

The content of ammonium nitrogen in abandoned soils is estimated from low (10-20 mg×kg^{-1}) to medium (20-40 mg×kg^{-1}). The maximum level is in the topsoil. Local maximum of 5.6 mg×kg^{-1} in the soil of agrostation SD1 at the depth of 50-60 cm. The nitrate nitrogen content is heterogeneous in all studied abandoned soils. However, there is a decrease in nitrate nitrogen concentrations at the depth of all soil profiles, with the exception of site YT2. Here, the maximum value of 11.2 mg×kg^{-1} was recorded at a depth of 20-30 cm. In most cases, the stock of ammonium nitrogen can be characterized as low (< 10 mg×kg^{-1}), except for the surface horizon 0-10 cm of soil YT1 and the horizon 20-30 cm of soil YT2.

As can be seen, high (r < 0.6) significant correlation coefficients were found between the content of SOM and available forms of nitrogen which suggests that the nitrogen status of these soils is controlled by the content of organic matter (Table 4). It is also important to note the correlation between the dynamics of available forms of phosphorus and potassium, previously identified in the specifics of their distribution in the profile of the soil SD1. The clay content correlates significantly with available forms of potassium and ammonium nitrogen.

Table 4.

Spearman Rank Order Correlations between nutrients, SOM content and clay fraction contents.

Variable	Available Phosphorus	Available Potassium	Ammonium Nitrogen	Nitrate Nitrogen	SOM	Clay Content
Available Phosphorus	1.00	***0.59***	0.25	***0.48***	0.21	0.15
Available Potassium		1.00	0.33	***0.37***	0.23	***0.48***
Ammonium Nitrogen			1.00	***0.62***	***0.83***	***0.43***
Nitrate Nitrogen				1.00	***0.65***	0.31
SOM					1.00	0.16
Clay Content						1.00
Marked (italic/bold) correlations are significant at p <0.05						

Statistical processing of data on the content of nutrients in the topsoil of abandoned and background soils (Table 5) also revealed some statistically significant differences between them.

Table 5.

Statistical analysis of nutrients concentrations in topsoil (0 - 20 cm).

	Abandoned soils			Background soils			ANOVA Aband. vs. Backg.	
	Me	SD	n	Me	SD	n	F	*p*
Available Phosphorus	387.25	310.74	8	46.50	35.94	6	***5.55***	***0.03***
Available Potassium	193.63	225.94	8	114.33	156.39	6	0.85	0.37
Ammonium Nitrogen	11.04	5.60	8	33.56	31.86	6	***8.76***	***0.01***
Nitrate Nitrogen	4.03	5.52	8	0.82	1.14	4	2.31	0.15
Marked (italic/bold) significant F and p values								

The major significant difference was detected between the content of available forms of phosphorus and ammonium nitrogen. The *p*-value < 0.05, which rejects the hypothesis of the similarity of abandoned and background soils. Testing with Fisher's F-criterion also showed that the differences between background and abandoned soils are statistically significant.

Trace metals pollution of study soils

The content of trace metals in soil is one of the limiting factors of agricultural use of soil in Russia and all over the world. The harmful effects of heavy and trace metals on the human health is undoubted. Heavy and trace metals are able to migrate from the soil profile into crop and livestock products, which will lead to harmful effects on human health (Chary et al. 2008, Sharma and Agrawal 2005). The soil cover is the primary environment for the accumulation of heavy metals, including those from the atmosphere and the aquatic environment (Dube et al. 2001, Ross 1994). Trace metals can enter the soil as a result of anthropogenic processes (metallurgy, power generation, coal and oil combustion) that are transferred from the source of contamination over long distances (Duruibe et al. 2007, Mohammed et al. 2011, Yang et al. 2018, Polyakov et al. 2021). Agricultural soils can become contaminated with heavy metals through the use of pesticides and plant growth stimulants (Juvelikyan et al. 2009). Mineral phosphate fertilizers can also contain trace metal impurities (Karpova and Potatueva 2005, Karpukhin and Bushuev 2007).

In the Russian Federation, restrictions on agriculture come with the following total content of trace metals in the soil: Cu – 200; Pb – 125; Zn – 500; Ni – 150; Cd – 3 mg×kg^{-1} (Chernova and Beketskaya 2011). Additionally, in the Russian legislation, there is a system of regulation of the content of heavy and trace metals, based on the character of the acidity reaction of the soil and its particle size distribution - TAC (Tentative allowable concentrations). For sandy and sandy loam soils (which prevail in our study), the TAC values follows: Cu – 33; Pb – 32; Zn – 55; Ni – 20; Cd – 0.5 mg×kg^{-1} (GN 1994); these limits are meant to provide soil safety for public health, but do not restrict agriculture.

The abandoned agricultural soils of the Yamal Region have not been investigated for trace metal contamination until this work. There are a number of publications devoted to the analysis of metal content in urbanized and background soils in the Yamal Region (Belyi Island, the vicinity of Salekhard, the foothills of the Polar Urals) (Alekseev et al. 2016, Alekseev et al. 2017, Tomashunos and Abakumov 2014, Moskovchenko et al. 2019, Nizamutdinov et al. 2021). In most cases, the authors characterize background soils as uncontaminated, with the content of heavy metals in soils being largely similar to the results of the analysis given in this paper. The highest level of contamination of soils with trace metals is given for the topsoil of Technosols of Salekhard, Kharsaim and Aksakarka. In the soils of these settlements, there were high recorded concentrations of Zn (up to 234 mg×kg^{-1}), Cu (up to 142 mg×kg^{-1}) and Ni (up to 98 mg×kg^{-1}) (Alekseev et al. 2016, Alekseev et al. 2017).

As can be seen from the results of the analysis reported in Fig. 10, all of the soil samples investigated are not limited for agricultural use in terms of trace metals content. There are single excedances of TAC for Ni in the abandoned soils of area YT1, here the recorded concentrations of Ni are up to 53 mg×kg^{-1}. In addition, in the background soils, excedances of TAC for Ni are recorded, for example, in the study area YT3, where concentrations of this metal reach 27 mg×kg^{-1}.

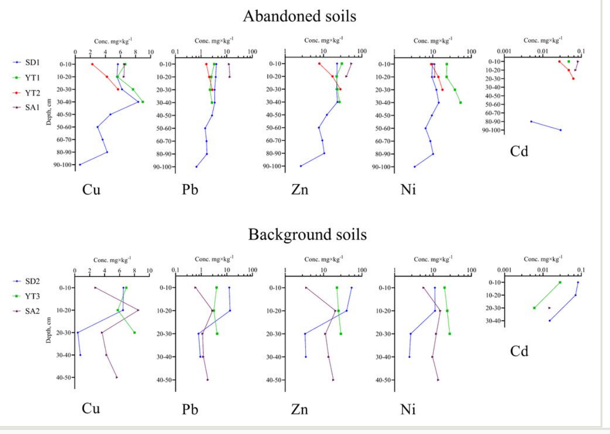

Figure 10.

Trace metal concentration dynamic in soils profiles.

For abandoned soils, there is a trend of increasing metal concentrations along the soil profile. This phenomenon can be explained by the processes of illuviation of clay particles. These are known to be the main accumulators of heavy and trace metals in the soil (Gupta and Chen 1975, Lavado et al. 1998). This fact can be confirmed by the results of the correlation analysis of our data. In Table 6, we can see the correlation matrix of the relationship between the concentrations of trace metals and the percentage of clay fraction in the studied soils. All the studied trace metals, except Cd, have a significant correlation relationship with the proportion of clay fraction in the soil This is due to the extremely low Cd content of the soils, because we could not capture the exact level of Cd content, even though the detection limit was quite low (> 0.005 mg×kg^{-1}).

Table 6.

Spearman Rank Order Correlations between trace metals and clay fraction content.

Variable	Cu	Pb	Zn	Ni	Cd	Clay
Cu	1.00	***0.82***	***0.88***	***0.83***	0.03	***0.53***
Pb		1.00	***0.89***	***0.65***	0.25	***0.55***
Zn			1.00	***0.79***	0.33	***0.44***
Ni				1.00	-0.03	***0.52***
Cd					1.00	-0.32
Clay						1.00
Marked (italic/bold) correlations are significant at p <0.05						

To assess the pollution status of soils in the Russian Federation, the index Z_c is widely used (index of total soil contamination) and we also applied the calculation of the I_{geo} geoaccumulation index, which is widely used in scientific research. To calculate both indices, information on the background concentration of pollutants (geochemical background value) is required. For a qualitative assessment of the degree of heavy and trace metal contamination of soils in the Yamal Region, we used background concentration values for sandy soils of Russia published by Chernova and Beketskaya (2011) and soils of the Island of Belyi published by Moskovchenko et al. (2019). According to these sources, background concentrations of trace metals in pristine soils are as follows: Cu – 9; Pb – 15; Zn – 32; Ni – 13; Cd – 0.0071 mg×kg^{-1} (Chernova and Beketskaya 2011, Moskovchenko et al. 2019).

Assessment of the degree of soil contamination using the total concentration index *(Z_c)* showed that the pollution status of soils is characterized as permissible for all studied soil samples *(Z_c < 16)*. Detailed values of the Z_c index are presented in Suppl. material 1. The soils are suitable for any agricultural crops (MU 1999).

Assessment of the level of contamination with trace metals, using the index of geoaccumulation *(I_{geo})*, showed that, in most cases, the character of contamination of soil profiles with trace metals is estimated as uncontaminated *(I_{geo} < 0)* for Cu, Pb and Zn. For Ni in a number of soil horizons, contamination is estimated as unpolluted to moderately polluted *($0 < I_{geo} < 1$)*, for example, the abandoned soil YT1 at a depth of 20-30 cm. Pollution of soil with cadmium is estimated as the most significant, the character of pollution in a number of soil horizons being estimated as moderately to strongly polluted *($2 < I_{geo} < 3$)*. This level of contamination is registered in the layer 0-20 cm in the background soil SD2, as well as in the whole profile of the abandoned soil SA1. More detailed values of the index I_{geo} can be seen in Suppl. material 1.

Table 7.

Statistical analysis of heavy and trace metals concentrations in topsoil (0-20 cm).

	Abandoned soils			Background soils			ANOVA Aband. vs. Backg.	
	Me	SD	n	Me	SD	n	F	*p*
Cu	5.36	1.48	8	6.16	1.89	6	0.12	0.74
Pb	5.39	4.74	8	6.07	5.45	6	0.01	0.91
Zn	26.98	14.26	8	27.41	17.34	6	0.08	0.77
Ni	13.85	5.85	8	14.66	6.49	6	0.36	0.56
Cd	0.05	0.02	5	0.06	0.03	3	0.26	0.62

No significant differences detected

A one-factor analysis of variance (ANOVA) was performed to identify statistically significant differences in heavy and trace metal concentrations between abandoned and background soils. Concentrations of trace metals in topsoil (0-20 cm), as the most important from the point of view of soil usage in agriculture, were chosen as the initial data. As can be seen from the results shown in Table 7, significant differences between the contents of various heavy metals are not detected.

The *p*-values in all cases are significantly higher than 0.05, which rejects the hypothesis about the differences between abandoned and background soil on the content of trace metals. Significance test by Fisher's F-criteria also did not confirm any difference between abandoned and background soils.

Conclusions

Based on all of the above, we can summarise that the recently abandoned soils of the Yamal Region retained a high level of fertility. In spite of a different period of abandonment, they are still fundamentally different from the background soils of this Region. The soils, with varying periods of abandonment, ranging from two to fourteen years, retained fairly high levels of nutrient content. Abandoned private vegetable gardens (points YT1 and SA1) can be used for the development of industrial agriculture of open and closed types, due to their high fertile qualities. Since Russia is currently in the process of agricultural re-development of the Arctic territories, the information obtained from the study can provide the basis for strategic planning of agricultural development of the Yamal Region.

As result of analysis of chemical, physical, agrochemical properties and features of soil formation of the recently-abandoned soils in the Yamal Region, the following conclusions can be made:

- Morphological features of cryogenic processes in the abandoned soils are less pronounced, since the soil profile contains an old arable horizon. Arable horizons contribute to more aeration of the soil profile, which leads to a change in the redox properties of the soil. Visible cryoturbation features were observed only in the background soils of the region, but signs of frequent changes in the redox regime were observed in both types of studied soils, which is confirmed by the presence of reductimorphic spots and signs of gleyic colours in the soil profiles. All soils are characterized by a predominantly acidic reaction of the soil solution. There is a decrease of acidity along the soil profile, which could be a sign of podzolisation processes;
- The background soils have a considerably higher SOM stock in the topsoil. For background soils, the SOM stock, according to Orlov's classification in the 0-20 cm layer, is estimated as very high (> 200 $t \times ha^{-1}$) or medium (100-150 $t \times ha^{-1}$), while in the abandoned soils, the SOM stock is estimated mainly as low (50-100 $t \times ha^{-1}$);
- Soils of abandoned agricultural farms strongly differ in the content of nutrients, compared with background soils. The difference in the content of available forms of phosphorus and potassium in the topsoil of abandoned soils is particularly pronounced. The content of these elements in the abandoned soils is estimated as very high (> 250 $mg \times kg^{-1}$), while in the background soils, the content of phosphorus and potassium is moderate. Background soils are characterized by higher content

of ammonium nitrogen compared to abandoned soils. There are also significant correlations between the content of the clay fraction (< 2 μm) in the soil profile and the content of some nutrients. Correlation analysis also confirmed the relationship between the SOM content (which is the main accumulator of nitrogen compounds) and available forms of nitrogen. According to the results of an ANOVA, the differences between background and abandoned soils in the content of available forms of phosphorus and ammonium nitrogen are statistically significant;

- Soils are assessed as uncontaminated in terms of heavy and trace metals pollution, except for isolated cases of Cd contamination. These conclusions were based on the results of the calculation and analysis of the Z_c and I_{geo} indices values. Statistically significant differences between the abandoned and background soils were not detected.

Acknowledgements

The authors would like to express their sincere acknowledgements to the researchers of the "Arctic Research Center of YANAO" (Salekhard) for their help in organizing and conducting the fieldwork.

Funding program

This paper is supported by the Ministry of Science and University Education of the Russian Federation under agreement No. 075-15-2020-922 dated 16.11.2020 for providing a Russian federal grant. The grant is intended to provide national support for the establishment and development of the Agro-technologies for the Future World-class Research Centre.

Author contributions

T.N. – laboratory analyses, manuscript writing, statistics; E.A. – data processing, soil diagnostics; E.M. – field survey, data interpretation

Conflicts of interest

The authors declare no conflict of interest.

References

- Abakumov E, Morgun E, Pechkin A, Polyakov V (2020a) Abandoned agricultural soils from the central part of the Yamal region of Russia: morphology, diversity, and chemical properties. Open Agriculture 5 (1): 94-106. https://doi.org/10.1515/opag-2020-0010

- Abakumov E, Zverev A, Morgun E, Alekseev I (2020b) Microbiome of abandoned agricultural and mature tundra soils in southern Yamal region, Russian Arctic. Open Agriculture 5 (1): 335-344. https://doi.org/10.1515/opag-2020-0034
- Abakumov EV, Morgun EN (2020) On the need to create a scientific station for polar agriculture in Yamal. Biosfernoye Khozyaystvo: Teoriya i Praktika 12: 66-74. [In Russian].
- Alekseeva L (2017) The formation of Arctic agriculture in the USSR (Yamal). Bulletin of Nizhnevartovsk State University (2)3-10. [In Russian].
- Alekseev I, Abakumov E, Shamilishvili G, Lodygin E (2016) Heavy metals and hydrocarbons content in soils of settlements of the Yamal-Nenets autonomous Okrug. Gigiena i Sanitariya 95 (9): 818-821.
- Alekseev I, Dinkelaker N, Oripova A, Semyina G, Morozov A, Abakumov E (2017) Assessment of ecotoxicological state of soils of the Polar Ural and southern Yamal. Gigiena i Sanitariya (10)941-945.
- Arnesen G, Beck PS, Engelskjøn T (2007) Soil acidity, content of carbonates, and available phosphorus are the soil factors best correlated with alpine vegetation: evidence from Troms, North Norway. Arctic, Antarctic, and Alpine Research 39 (2): 189-199. https://doi.org/10.1657/1523-0430(2007)39[189:SACOCA]2.0.CO;2
- Arrouays D, Saby N, Walter C, Lemercier B, Schvartz C (2006) Relationships between particle-size distribution and organic carbon in French arable topsoils. Soil Use and Management 22 (1): 48-51. https://doi.org/10.1111/j.1475-2743.2006.00020.x
- Basharin GP (1990) History of Farming in Yakutia (17th century - 1917). Yakutsk [In Russian].
- Bel'chicova N (1965) Determination of the humus of soils by IV Tyurin's method. Agrochemical methods in study of soils. 4th ed. Moscow: Nauka75-102. [In Russian].
- Black CA, Evans D, White J (1965) Methods of soil analysis: chemical and microbiological properties. ASA.
- Bridgeman T, Darvell L, Jones J, Williams P, Fahmi R, Bridgwater A, Barraclough T, Shield I, Yates N, Thain S (2007) Influence of particle size on the analytical and chemical properties of two energy crops. Fuel 86 (1-2): 60-72. https://doi.org/10.1016/j.fuel.2006.06.022
- Caravaca F, Lax A, Albaladejo J (1999) Organic matter, nutrient contents and cation exchange capacity in fine fractions from semiarid calcareous soils. Geoderma 93 (3-4): 161-176. https://doi.org/10.1016/S0016-7061(99)00045-2
- Carlon C (2007) Derivation Methods of Soil Screening Values in Europe: A Review of National Procedures Towards Harmonisation: a Report of the ENSURE Action. EUR-OP [ISBN 9279052381]
- Chary NS, Kamala C, Raj DSS (2008) Assessing risk of heavy metals from consuming food grown on sewage irrigated soils and food chain transfer. Ecotoxicology and Environmental Safety 69 (3): 513-524. https://doi.org/10.1016/j.ecoenv.2007.04.013
- Chekmarev P, Lukin S, Siskevich Y, Yumashev N, Khizhnyakov A (2011) Role of phosphorus in agriculture in Central Chernozem Region. Research and Technical Advances of Agribusiness Sector.
- Chernova O, Beketskaya O (2011) Permissible and background concentrations of pollutants in environmental regulation (heavy metals and other chemical elements). Eurasian Soil Science 44 (9): 1008-1017. https://doi.org/10.1134/S106422931109002X

- Chistyakova NF (2015) Yamal District : encyclopedia. Adm. of Municipal Formation of Yamal District. [in Russian].
- Dube A, Zbytniewski R, Kowalkowski T, Cukrowska E, Buszewski B (2001) Adsorption and migration of heavy metals in soil. Polish Journal of Environmental Studies 10 (1): 1-10.
- Duruibe JO, Ogwuegbu M, Egwurugwu J (2007) Heavy metal pollution and human biotoxic effects. International Journal of Physical Sciences 2 (5): 112-118.
- Eichfeld I (1933) Struggle for the far north. All-Union Institute of Plant Industry [In Russian].
- Elstrand E (1979) Sub-arctic farming. [in Russian].
- Francis KE (1967) Outpost agriculture: the case of Alaska. Geographical Review 496-505. https://doi.org/10.2307/212929
- Gamzikov G (1981) Nitrogen in agriculture of Western Siberia. M.: Nauka[In Russian].
- Gasser G (1948) Agriculture in Alaska. Arctic 1 (2): 74-83.
- GN 21 (1994) Soil, cleaning of settlements, domestic and industrial waste, sanitary protection of soil. [in Russian].
- GOST R (2003) 54650-2011 Soils. Determination of mobile compounds of phosphorus and potassium according to the Kirsanov method in modification CINAO[In Russian].
- Gruhn P, Goletti F, Yudelman M (2000) Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges. Intl Food Policy Res Inst [ISBN 0896296377]
- Gupta SK, Chen KY (1975) Partitioning of trace metals in selective chemical fractions of nearshore sediments. Environmental Letters 10 (2): 129-158. https://doi.org/10.1080/00139307509435816
- Harbison P (1986) Mangrove muds—a sink and a source for trace metals. Marine Pollution Bulletin 17 (6): 246-250. https://doi.org/10.1016/0025-326X(86)90057-3
- Holford I (1997) Soil phosphorus: its measurement, and its uptake by plants. Soil Research 35 (2): 227-240. https://doi.org/10.1071/S96047
- Hossain MF, Zhang Y, Chen W, Wang J, Pavlic G (2007) Soil organic carbon content in northern Canada: A database of field measurements and its analysis. Canadian Journal of Soil Science 87 (3): 259-268. https://doi.org/10.4141/S06-029
- ISO 1 (2003) Soil Quality-Determination of Nitrate, Nitrite and Ammonium in Field Moist Soils by Extraction with Potassium Chloride Solution. International Organisation for Standardisation Geneva.
- ISO D (1998) 11047. Soil quality–determination of cadmium, chromium, cobalt, copper, lead, nickel and zinc in aqua regia extracts of soil-flame and electrothermal atomic absorption spectrometric methods. Berlin: German Institute for Standardization.
- Jackson CE, Saeger Jr C (1935) Use of the pipette method in the fineness test of molding sand. Part of Journal of Research of the N. Ational Bureau of Standards.
- Jenkinson DS, Powlson DS (1976) The effects of biocidal treatments on metabolism in soil—V: A method for measuring soil biomass. Soil Biology and Biochemistry 8 (3): 209-213. https://doi.org/10.1016/0038-0717(76)90005-5
- Jiang F, Ren B, Hursthouse A, Deng R, Wang Z (2019) Distribution, source identification, and ecological-health risks of potentially toxic elements (PTEs) in soil of thallium mine area (southwestern Guizhou, China). Environmental Science and Pollution Research 26 (16): 16556-16567. https://doi.org/10.1007/s11356-019-04997-3

- Jokinen P (1997) Agricultural policy community and the challenge of greening: The case of Finnish agri-environmental policy. Environmental Politics 6 (2): 48-71. https://doi.org/10.1080/09644019708414327
- Juvelikyan KA, Scheglov DI, Gorbunova NS (2009) Methods of control and ranking of contaminated soils. Soil Science and Land Resources Management, VSU
- Kachinsky N (1958) Mechanical and microaggregate composition of the soil, methods for its study. AN USSR, Moscow[In Russian].
- Kalinina O, Chertov O, Nadporozhskaya M, Giani L (2009) Properties of soil organic matter of plaggic anthrosols from Northwest Germany, Northwest and North Russia. Archives of Agronomy and Soil Science 55 (5): 477-492. https://doi.org/10.1080/03650340802637733
- Karpova E, Potatueva Y (2005) Accumulation of heavy metals by winter rye and oat plants under the effect of nitrogen and potassium fertilizers and the long-term aftereffect of phosphorus fertilizers on soddy-podzolic soil. AGROKHIMIIA 4[In Russian].
- Karpukhin A, Bushuev N (2007) Effect of fertilization on the content of heavy metals in soils of long-term field experiments. AGROKHIMIIA 5[In Russian].
- Keller T, Håkansson I (2010) Estimation of reference bulk density from soil particle size distribution and soil organic matter content. Geoderma 154 (3-4): 398-406. https://doi.org/10.1016/j.geoderma.2009.11.013
- Kemmitt S, Lanyon C, Waite I, Wen Q, Addiscott T, Bird NR, O'donnell A, Brookes P (2008) Mineralization of native soil organic matter is not regulated by the size, activity or composition of the soil microbial biomass—a new perspective. Soil biology and Biochemistry 40 (1): 61-73. https://doi.org/10.1016/j.soilbio.2007.06.021
- Khantimer IS (1974) Agricultural development of tundra regions. Acadetiy of sciences of the USSR [In Russian].
- Kiryushin V, Ivanov A (2005) Agroekologicheskaya otsenka zemel, proektirovanie adaptivno-landshaftnykh sistem zemledeliya i agrotekhnologii [Agroecological assessment of lands, designing adaptive-landscape farming systems and agricultural technologies]. Methodological guide. Moscow: Federal State Scientific Institution "Rosinformgrotech[In Russian].
- Kiryushin V (2007) Assessment of land quality and soil fertility for planning farming systems and agrotechnologies. Eurasian Soil Science 40 (7): 785-791. https://doi.org/10.1134/S1064229307070113
- Kononova MM (2013) Soil organic matter: its nature, its role in soil formation and in soil fertility. Elsevier [ISBN 1483185680]
- Kozin VV, Bakulin VV (1996) Geography of the Tyumen region. Yekaterinburg [In Russian].
- Kravchenko A, Zhang R (1998) Estimating the soil water retention from particle-size distributions: a fractal approach. Soil Science 163 (3): 171-179. https://doi.org/10.1097/00010694-199803000-00001
- Kudeyarov V, Semenov V (2006) Agroecological Evaluation of Lands and Design of Landscape-Adaptive Farming Systems and Agrotechnologies: Methodological Recommendations. VI Kiryushin and AL Ivanov, Eds., Moscow: Rosinformagrotekh, 2005. 784 p. AGROKHIMIIA 8.[In Russian].
- Kvashin YN (1999) Geographical Atlas of the Yamal-Nenets Autonomous District. Moscow: Drofa. [in Russian].

- Lavado R, Rodriguez M, Scheiner J, Taboada M, Rubio G, Alvarez R, Alconada M, Zubillaga M (1998) Heavy metals in soils of Argentina: comparison between urban and agricultural soils. Communications in Soil Science and Plant Analysis 29 (11-14): 1913-1917. https://doi.org/10.1080/00103629809370081
- Leirós M, Trasar-Cepeda C, Seoane S, Gil-Sotres F (1999) Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biology and Biochemistry 31 (3): 327-335. https://doi.org/10.1016/S0038-0717(98)00129-1
- Lewis CE, Pearson RW, Thomas WC (1987) Agricultural development in Alaska. Polar Record 23 (147): 673-682. https://doi.org/10.1017/S0032247400008378
- Loges G (1883) Mittheilungen aus dem agriculturchemischen Laboratorium der Versuchs-Station Kiel: III. Ueber die Bestimmung des Humus in Ackererden. Die Landwirthschaftlichen Versuchs-Stationen 28 (1883): 229-245.
- Lugato E, Panagos P, Bampa F, Jones A, Montanarella L (2014) A new baseline of organic carbon stock in European agricultural soils using a modelling approach. Global Change Biology 20 (1): 313-326. https://doi.org/10.1111/gcb.12292
- Maximova D (2018) Sustainable development of the Russian Arctic zone: challenges & opportunities. Arctic Yearbook 2018.
- Mineev V (2004) Agrochemistry. M.: Kolos[In Russian].
- Mohammed AS, Kapri A, Goel R (2011) Heavy Metal Pollution: Source, Impact, and Remedies. In: Khan MS, Zaidi A, Goel R, Musarrat J (Eds) Biomanagement of Metal-Contaminated Soils. Springer Netherlands, Dordrecht, 27 pp. [ISBN 978-94-007-1914-9]. https://doi.org/10.1007/978-94-007-1914-9_1
- Morgun EN, Abakumov EV (2019) Agricultural research and crop yields in the Yamal-Nenets Autonomous District: retrospective analysis (1932-2019). Nauchnyy vestnik Yamalo-Nenetskogo Avtonomnogo Okruga 3: 4-9. [In Russian]. https://doi.org/10.26110/ARCTIC.2019.104.3.001
- Moskovchenko D, Shamilishvilly G, Abakumov E (2019) Soil Biogeochemical Features of Nadym-Purovskiy Province (Western Siberia), Russia. Ecologia Balkanica 11 (2).
- MU 21 (1999) Hygienic evaluation of soil in residential areas. [in Russian].
- Müller G, Furrer R (1994) Schwermetalle in den Sedimenten der Elbe und ihrer Zuflüsse. Die Elbe im Spannungsfeld zwischen Ökologie und Ökonomie 69-77. https://doi.org/10.1007/978-3-322-83425-6_6
- Mulvaney R, Sparks D (1996) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America Book Series 1123.
- Nasta P, Kamai T, Chirico GB, Hopmans JW, Romano N (2009) Scaling soil water retention functions using particle-size distribution. Journal of Hydrology 374 (3-4): 223-234. https://doi.org/10.1016/j.jhydrol.2009.06.007
- Naumov A, Akimova V, Sidorova D, Topnikov M (2020) Agriculture and land use in the North of Russia: Case study of Karelia and Yakutia. Open Geosciences 12 (1): 1497-1511. https://doi.org/10.1515/geo-2020-0210
- Nizamutdinov T, Abakumov E, Morgun E, Loktev R, Kolesnikov R (2021a) Agrochemical and Pollution Status of Urbanized Agricultural Soils in the Central Part of Yamal Region. Energies 14 (14). https://doi.org/10.3390/en14144080
- Nizamutdinov T, Morgun E, Pechkin A, Kostecki J, Greinert A, Abakumov E (2021b) Differentiation of Trace Metal Contamination Level between Different Urban Functional Zones in Permafrost Affected Soils (the Example of Several Cities in the Yamal Region, Russian Arctic. Minerals 11 https://doi.org/10.3390/min11070668

- Øgaard AF (1996) Effect of phosphorus fertilization on the concentration of total and algal-available phosphorus in different particle-size fractions in Norwegian agricultural soils. Acta Agriculturae Scandinavica B-Plant Soil Sciences 46 (1): 24-29.
- Orlov D, Sadovnikova L, Sukhanova N (2005) Khimiya pochv (Soil chemistry). Moscow: Vysshaya Shkola [In Russian].
- Pavlov AV, Malkova GV (2005) Current Climate Changes in the North of Russia: Album of Small Scale Maps. Novosibirsk: Geo [In Russian].
- Polyakov V, Nizamutdinov T, Abakumov E, Morgun E (2021) Soil Diversity and Key Functional Characteristics of Yakutsk City: Largest Urbanized Cryogenic Worlds Ecosystem. Energies 14 https://doi.org/10.3390/en14133819
- Purtov G (1994) Sel'skohozyajstvennoe osvoenie Obskogo Severa [Agricultural development of the Ob North]. Novosibirsk, RASKHN. Sib. otd-nie. NIISKH Sev. Zaural'ya [In Russian].
- Ross SM (1994) Toxic metals in soil-plant systems. Wiley Chichester [ISBN 0471942790]
- Rusco E, Jones RJ, Bidoglio G (2001) Organic matter in the soils of Europe: Present status and future trends. Institute for Environment and Sustainability, Joint Research Centre
- Sharma RK, Agrawal M (2005) Biological effects of heavy metals: an overview. Journal of Environmental Biology 26 (2): 301-313.
- Shein E (2005) Soil physics course. Moscow: Publishing House of Moscow State University [In Russian].
- Sjögren P, Arntzen JE (2013) Agricultural practices in Arctic Norway during the first millennium BC. Vegetation History and Archaeobotany 22 (1): 1-15. https://doi.org/10.1007/s00334-012-0346-2
- Soppela P (2020) Preface to the Special Issue on the 10th Circumpolar Agriculture Conference 2019. Open Agriculture 5 (1): 912-913. https://doi.org/10.1515/opag-2020-0091
- Stevenson KT, Alessa L, Kliskey AD, Rader HB, Pantoja A, Clark M, Giguère N (2014) Sustainable agriculture for Alaska and the circumpolar North: Part I. Development and status of northern agriculture and food security. Arctic271-295. https://doi.org/10.14430/arctic4402
- Team CM, Walker DA, Trahan NG (2003) Circumpolar Arctic vegetation map. US Fish and Wildlife Service
- Tiessen H, Cuevas E, Chacon P (1994) The role of soil organic matter in sustaining soil fertility. Nature 371 (6500): 783-785. https://doi.org/10.1038/371783a0
- Tomashunos V, Abakumov E (2014) The content of heavy metals in soils of the Yamal peninsula and the Bely Island. Gigiena i sanitariia 93 (6): 26-31.
- Unc A, Altdorff D, Abakumov E, Adl S, Baldursson S, Bechtold M, Cattani DJ, Firbank LG, Grand S, Gujnsdttir M, Kallenbach C, Kedir AJ, Li P, McKenzie DB, Misra D, Nagano H, Neher DA, Niemi J, Oelbermann M, Overgrd Lehmann J, Parsons D, Quideau S, Sharkhuu A, Smreczak B, Sorvali J, Vallotton JD, Whalen JK, Young EH, M Z, Borchard N (2021) Expansion of Agriculture in Northern Cold-Climate Regions: A Cross-Sectoral Perspective on Opportunities and Challenges. Front. Sustain. Food Syst 5 (663448). https://doi.org/10.3389/fsufs.2021.663448

- Vavilov N (1931) Problem of Northern Agriculture, materials of the Leningrad Emergency Session of Academy of Sciences of the USSR 25–30 XI1931. Leningrad, Publishing House of Academy of Sciences, 15p[In Russian].
- Vorren K (2005) Farm development at the Arctic cereal limit in northern Norway—continuity and discontinuities. Vegetation History and Archaeobotany 14 (3): 161-170. https://doi.org/10.1007/s00334-005-0016-8
- Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37 (1): 29-38. https://doi.org/10.1097/00010694-193401000-00003
- WRB IWG (2014) World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report 106.
- Yakimenko VN (2018) Potassium forms in soil and methods of determination. The Journal of Soils and Environment 1 (1): 25-31. [In Russian]. https://doi.org/10.31251/pos.v1i1.5
- Yang Q, Li Z, Lu X, Duan Q, Huang L, Bi J (2018) A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment. Science of the Total Environment 642: 690-700. https://doi.org/10.1016/j.scitotenv.2018.06.068
- Yu S, Li X (2011) Distribution, availability, and sources of trace metals in different particle size fractions of urban soils in Hong Kong: implications for assessing the risk to human health. Environmental Pollution 159 (5): 1317-1326. https://doi.org/10.1016/j.envpol.2011.01.013

Supplementary materials

Suppl. material 1: Detailed soil contamination characteristics based on Igeo and Zc indices doi

Authors: Nizamutdinov, Abakumov, Morgun
Data type: Contamination level
Download file (18.59 kb)

Suppl. material 2: Estimated scales of nutrient content in soil doi

Authors: Nizamutdinov, Abakumov, Morgun
Data type: Nutrients assesing scale
Download file (13.11 kb)