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Morphology and properties of permafrost-affected soils under different tundra vegetation in central Spitsbergen

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Abstract: The main aim of this study was to determine the morphology, physical, and chemical properties of permafrost-affected soils under different types of tundra in the central part of Spitsbergen. This is a preliminary part of detailed studies focused on the relationship between tundra vegetation and permafrost-affected soils in the Spitsbergen. The obtained results indicate that all the studied soils represent an early stage of formation and the main soil-forming process present in these soils is cryoturbation. Most of the studied soils are shallow and contain a high content of coarse rock fragments. Tundra vegetation type plays controlling role in the development and structure of surface soil horizons. All the studied soils are characterized by loamy texture and acidic or slightly acidic reaction, and these properties are not very different under various tundra vegetation types. The contents of soil organic matter are strongly dependent on the type of tundra vegetation. The highest soil organic matter content occurs at sites with well-developed vegetation such as heath and wet moss tundra. The high carbon-to-nitrogen ratio for the surface soil horizons of the majority of the studied soils indicates that organic matter is poorly decomposed under all the studied tundra vegetation types. This is most likely related to low activity of soil microorganisms in the harsh High Arctic environment. However, the lowest carbon-to-nitrogen ratio was noted for surface soil horizons at sites covered with Arctic meadow, and this indicates that there occur the optimum conditions for soil organic matter decomposition.

Keywords: Arctic, Svalbard, soil organic matter, heath and pioneer tundra, Cryosols.

Introduction

Soil is the most external part of the Earth's surface, which is formed due to weathering of rocks and constitutes one of the most important elements of the environment. Importantly, it plays a key role in many processes in terrestrial ecosystems, such as the sorption of water and nutrients (Brady and Weil 2004). Soil morphology and properties are related to soil-forming factors, *i.e.*, parent material, relief, living organisms (vegetation and animals), human activity, climate, and time. In permafrost-affected soils, one of the most important among such processes is cryoturbation. It is responsible for the formation of patterned ground and cryogenic alteration in deeper horizons, namely the mixing of material, disruption of soil horizons, and formation of organic intrusions (Bockheim and Tarnocai 1998; Ping *et al.* 1998; Bockheim *et al*. 2006). The formation of patterned ground and occurrence of cryoturbation in soils are also influenced by the climate, soil physical properties, hydrology, topography, and vegetation (Walker *et al*. 2004, 2008). Another common feature of soils in the Arctic region is the early formation and accumulation of organic matter due to the harsh climate conditions and low rate of soil organic matter degradation.

Soils in Arctic regions constitute a huge reservoir of organic carbon and therefore are crucial players in the global carbon cycle (Post *et al*. 1990; Lehmann and Kleber 2015; Schuur *et al*. 2015). It was estimated that the content of organic carbon in the Northern Circumpolar Arctic soils is about 1035 Gt (Hugelius *et al.* 2014). In addition, soil organic matter (SOM) may be responsible for positive feedback to climate change because of release of large amounts of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), from the soil into the atmosphere during SOM decomposition, which in turn can be accelerated by a changing climate (White *et al*. 2004; Andersen and White 2006; Kuhry *et al*. 2013; Zubrzycki *et al*. 2013). Furthermore, substantial climate warming in the High Arctic in recent few decades has led to many important changes in the natural environment of this region (Serreze and Barry 2011; Przybylak *et al*. 2014; Piskozub 2017). Warmer summers and longer growing seasons strongly affect the tundra environment by accelerating the development of the vegetation cover (Tape *et al*. 2006; Post *et al*. 2009).

The central part of Spitsbergen (Svalbard archipelago) is especially suitable for study of the relationship between vegetation and soil, because this is where the best-developed (highly heterogeneous) tundra vegetation occurs, which is due to the mildest ambient climate conditions (Johansen and Tømmervik 2014). Additionally, a detailed tundra vegetation map of this part of Spitsbergen, *i.e.*, Nordenskiöld Land, is currently available, hence the area occupied by each type of tundra vegetation is easily traceable (Johansen and Tømmervik 2014). Despite the aforementioned circumstances and availability of a number of detailed environmental studies carried out in the central part of Spitsbergen, there is still a lack of information about soils under different types of tundra vegetation.

Environmental research conducted to date has focused on vegetation, hydrology, sediments, and climate conditions (Bryant 1982; Killingtveit *et al.* 2003; Johansen and Tømmervik 2014; Nordli *et al*. 2014). Strictly pedological studies carried out in this part of Spitsbergen touched several issues as well. Changes in soil temperature and their impact on the decomposition of soil organic matter in soils near Longyearbyen were studied by Brooker and van der Wal (2003). The origin of heavy metals and radionuclides in the soil and plants near Longyearbyen was studied by Kłos *et al*. (2017). The relationship between the decreasing concentration of organic carbon in soil and increasing elevation was studied by Weiss *et al*. (2017). Szymański *et al*. (2019b) analyzed the physical and chemical properties of surface horizons in the town of Longyearbyen. Wojtuń *et al.* (2019) examined the concentration of trace elements in surface horizons and vegetation. Gilbert *et al*. (2019) analyzed properties of the soil and temperature regime in the soils and permafrost of Adventdalen. Polyakov *et al*. (2019) examined the molecular composition of humic substances in soils in the Grønfjorden area (western part of Nordenskiold Land). Recently, Szymański *et al*. (2022) conducted detailed mineralogical studies of permafrost-affected soils in Adventdalen and mountains in the vicinity of Longyearbyen.

All in all, only very limited data exist about soils in this area, and those available are essentially devoid of comparative context that takes into account the heterogeneity of tundra vegetation. The main aim of this study is to determine the morphological, physical, and chemical properties of permafrost-affected soils under different types of tundra vegetation in the central part of Spitsbergen. This is a preliminary part of detailed studies focused on the relationship between tundra vegetation and permafrost-affected soils in the warmest part of this island.

Study area

The study area is located in the central part of Spitsbergen (Svalbard archipelago), in the close vicinity of the town of Longyearbyen (Fig. 1). It is characterized by the presence of sedimentary rocks ranging in their age from the Permian to the Eocene (Dallman *et al*. 2001). The bedrock of this area belongs to the Carolinefjellet Formation dating back to the Cretaceous and consists primarily of clastic sedimentary rocks such as black shale, mudstone, sandstone, and siltstone. In addition, sedimentary rocks belonging to the Firkanten, Basilika, and Grumantbyen Formations are present in the area (Dallman *et al*. 2001). The floors of river valleys such as the Adventdalen and Longyeardalen are filled with glaciofluvial and fluvial deposits transformed by aeolian and cryoturbation processes (Bryant 1982; Christiansen 2005; Watanabe *et al*. 2017; Szymański *et al*. 2022).

The central part of Spitsbergen is characterized by a milder and drier climate, relative to other areas located at similar latitudes, due to atmospheric circulation

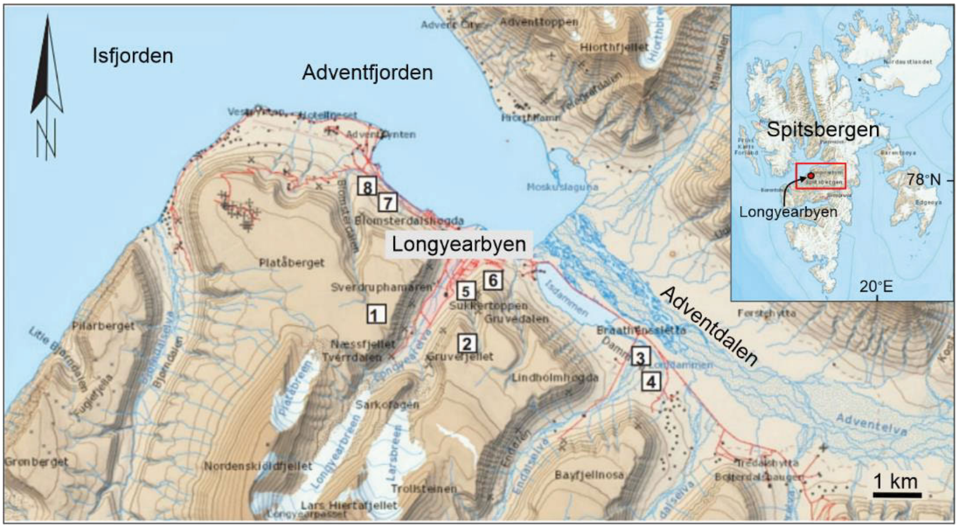

Fig. 1. Location of the study area and sampling sites/profiles 1 to 8.

and warm ocean currents flowing from the south along the western coast of Svalbard (Ziaja 2002). The mean annual air temperature in the study area is around −6°C and total annual precipitation is 190 mm, of which *ca.* 60% occurs in the form of snow (Christiansen 2005; Eckerstorfer and Christiansen 2010; Førland *et al*. 2011; Watanabe *et al*. 2017). The snow cover in Adventdalen is thin (around 30 cm) due to the occurrence of strong southeasterly winds that make its accumulation difficult (Christiansen 2005). It is also worth mentioning that the annual air temperature in this area has increased by 2.6°C over the past 100 years (Nordli *et al*. 2014).

In Adventdalen, the soil temperature at a depth of 2 cm fluctuated during the year between about 15°C (in summer) and −23°C (minimum in January), and strongly depended on air temperature (Watanabe *et al*. 2017). Moreover, freezing temperatures at a depth of 2 cm remained at that level for more than six months (from mid-October to the end of May) (Watanabe *et al*. 2017). According to Watanabe *et al*. (2017), the top of permafrost in Adventdalen occurs at a depth of 100 cm. The temperature at the top of permafrost remains around 0°C for six months (from July to the end of December), while the minimum annual temperature usually occurs in the middle of February and reaches −15°C (Watanabe *et al*. 2017). Studies carried out by Christiansen *et al.* (2005) indicate that permafrost thickness ranges between 100 m and 300 m in the Breinosa massif.

The vegetation in the study area is very heterogeneous, even at the local scale (Johansen and Tømmervik 2014). Heath tundra featuring *Salix polaris*, *Cassiope tetragona*, and *Dryas octopetala* is usually located on the lower parts of hillslopes. Moist tussock tundra and Arctic meadows with grasses and forbs occur mainly in river valleys. Wet moss tundra, mires, and marshes are located in small depressions across valley floors as well as on gentle slopes and are characterized by the shallow occurrence of groundwater. The highest parts of mountains as well as plateaus in the study area are covered with pioneer tundra characterized by discontinuous biological soil crusts (BSC), without any plant species or with only very few vascular plant species present (Johansen and Tømmervik 2014).

Methods

Fieldwork was conducted in July 2018 and July 2021. Representative study sites for each tundra vegetation type were selected on the basis of available vegetation maps (Johansen and Tømmervik 2014) and were characterized by presence of plants and vegetation formations characteristic for each type of tundra.

Study sites 1 and 2 were located on Platåberget Mt. and Sukkertoppen Mt., respectively (Fig. 1). Both of these sites were covered with pioneer tundra vegetation characterized by the occurrence of discontinuous BSC and very few vascular plant species. Study sites 3 and 4 were located on the floor of the Adventdalen valley (Fig. 1), where Arctic meadow with grasses and forbs are present. Study sites 5 and 6 were covered with heath tundra featuring *C. tetragona* and *D. octopetala*, and located on the lower part of the slope of Sukkertoppen Mt. (Fig. 1). The sites 7 and 8 with wet moss tundra vegetation were located on the lower part of the slope of Platåberget Mt. (Fig. 1). A general view of the selected study sites as well as the morphology of representative soil profiles are shown in Fig. 2.

Representative soil profiles were excavated and described at each study site according to Jahn *et al.* (2006). Soil samples were collected from each genetic horizon from all soil profiles and placed in plastic bags. The collected soil samples were air-dried and transported to the laboratory. The samples were then gently crushed and sieved through a 2 mm sieve. All living parts of plants were removed manually from the samples before further analysis. The sand content was determined by wet sieving, whereas the content of the silt and clay fractions was determined using a hydrometer (Gee and Bauder 1986). Soil pH was measured in deionized water in a 1:2.5 ratio (w/v) using a glass electrode (Thomas 1996). The concentration of total carbon (TC) and total nitrogen (TN) was determined (in triplicate and then averaged) using gas chromatography via a Vario Micro Cube CHN elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). The soil samples used for the TC and TN determination were ground in a mortar to homogenize them before analysis. The obtained TC content was assumed to be soil organic carbon (SOC) content, because all of the studied soils did not contain carbonates.

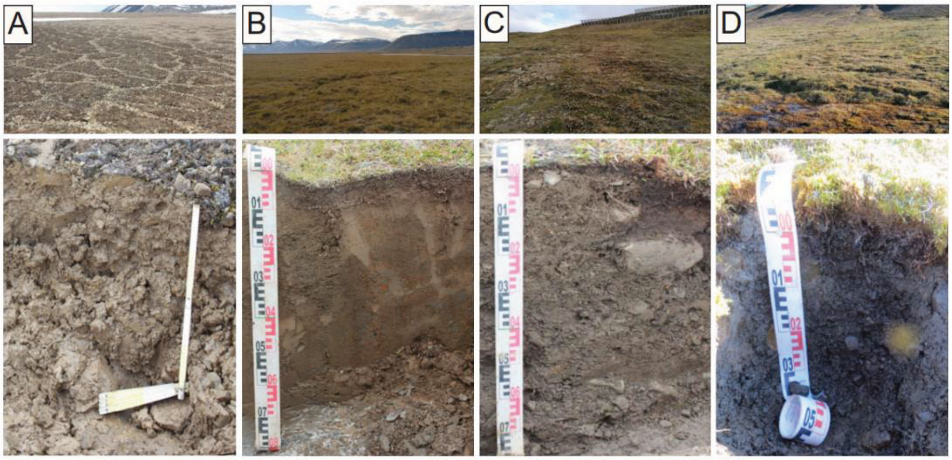

Fig. 2. Overall view of the land cover types and landforms of the study sites in central part of Spitsbergen as well as the soil profiles of the study sites: pioneer tundra with biological soil crust (BSC) on the Plataberget Mt. (**A**), Arctic meadow in the Adventdalen valley (**B**), heath tundra vegetation on the Sukkertopen Mt. (**C**), and mosses tussock tundra in the footslope of Sverdruphamaren (**D**).

Results and interpretations

Soil morphology and physical properties. — All of the studied soils were classified as Cryosols according to the World Reference Base for Soil Resources due to the occurrence of evidence of cryoturbation and shallow presence of permafrost (Watanabe *et al.* 2017; IUSS Working Group WRB 2022). Detailed results are presented in Table 1.

Cryoturbation features such as broken and discontinuous soil horizons as well as patterned ground morphology of the soil surface occurred in six of the studied soil profiles, *i.e.*, those from sites 1–6, covered with pioneer tundra, Arctic meadow, and heath tundra (Figs. 3 and 4). The mixing and segregation of material in soils were the result of cyclic freeze and thaw processes, which is the common characteristic for soils occurring in the High Arctic (*e.g.*, Bockheim and Tarnocai 1998; Walker *et al.* 2004, 2008; Bockheim *et al.* 2006; Ugolini *et al.* 2006; Szymański *et al.* 2015). Only at two of the studied sites (*i.e.*, sites 7 and 8), which were characterized by a very shallow occurrence of groundwater and covered with wet moss tundra, the effects of cryoturbation in the soil profile were not observed. However, the morphology of soil surfaces, featuring many low mounds (so-called thufurs) and depressions, indicated also the occurrence of freeze and thaw processes at these sites (Fig. 3).

The majority of the studied profiles were characterized by a high content of coarse rock fragments. Especially soils occurring under pioneer tundra (sites 1 and 2), heath tundra (sites 5 and 6), and wet moss tundra (sites 7 and 8) contained a large amount of coarse rock fragments (Table 1). The fragments were

Table 1.

Classification, location, and morphology of the studied soils as well as prevalent plant species at the studied sites. Abbreviations: r – strong reduction; g – stagnic conditions; f – frozen soil; i – organic material in an initial state of decomposition; @ – evidence of cryoturbation; I – layers containing >75% ice; H – organic or organotechnic layer, not forming part of a litter layer, water saturation >30 consecutive days in most years or drained; A – mineral horizon at the mineral soil surface or buried, contains organic matter that has at least partly been modified *in situ*, soil structure and/or structural elements created by cultivation in ≥50% (by volume, related to the fine earth), *i.e.*, rock structure, if present, in <50% (by volume); C – mineral layer, unconsolidated (can be cut with a spade when moist), or consolidated and more fractured than the R layer, no soil formation; R – consolidated rock.

Soil horizon	Depth (cm)	Color (dry state)	Structure	Roots	Consistence	Moisture	Vegetation
Profile 1. Reductaquic Turbic Cryosol (Biocrustic Epic Eutric Loamic Ochric Thixotropic) – Platåberget Mt. (78°12'28"N, 15°32'08"E; 467 m a.s.l.)							
A	0-0.5	2.5 Y 4/3	n.a.*	n.a	n.a.	n.a.	lichens, cyanobacteria, mosses
C@1	0.5-15	2.5 Y 6/3	platy	common	soft	very wet	
C@2	15-30	2.5 Y 6/3	platy	few	soft to slightly hard	moist	
C@3	30-50	2.5 Y 6/3	massive	absence	slightly hard	moist	
Cf	50+		n.a.	absence	n.a.	n.a.	
Profile 2. Protic Turbic Cryosol (Biocrustic Eutric Ochric Siltic Thixotropic) – Sukkertoppen Mt. (78°12'37"N, 15°39'26"E; 373 m a.s.l.)							
AC@	0-20	2.5 Y 4/3	granular, platy	few	moder-ately hard to slightly hard	moist	lichens, cyanobacteria, *Saxifraga cespitosa*
Cg@1	20-45	2.5 Y 6/3	angular blocky	common	moderately hard	moist	
Cg@2	45-85	2.5 Y 6/3	angular blocky	common	moderately hard to hard	moist	
R	85+		n.a.	n.a.	n.a.	n.a.	
Profile 3. Turbic Cryosol (Eutric Humic Siltic) – Adventdalen (78°11'39"N, 15°51'11"E; 7 m a.s.l.)							
A1	0-2	2.5 Y 4/3	granular	many	slightly hard	slightly moist	grasses, *Salix polaris*, *Saxifragaces-pitosa*, *Alopecurus ovatus*
A2	2-4	2.5 Y 3/3	granular	many	slightly hard	slightly moist	
A3	4-9	2.5 Y 4/3	granular, fibrous	many	moderately hard to slightly hard	slightly moist	
Cg@1	9-18	2.5 Y 5/3	platy, granular	few	moderately hard	slightly moist	

Table 1 – *continued.*

Soil horizon	Depth (cm)	Color (dry state)	Structure	Roots	Consistence	Moisture	Vegetation
Cg@2	8-35	2.5 Y 4/3	platy, granular	few	moderately hard to hard	slightly moist	
Cg@3	35-55	2.5 Y 4/3	prismatic, platy	common	moderately hard to hard	moist	
Cg@4	55-70	2.5 Y 4/3	prismatic, platy	common	hard	moist	
Cf	70-80	2.5 Y 4/3	lenticular	absence	very hard	wet	
I	80+		suspended	n.a.	very hard	n.a.	
Profile 4. Turbic Glacic Cryosol (Amphisiltic Eutric Epiloamic Humic Raptic) – Adventdalen (78°11'39"N, 15°51'11"E; 5 m a.s.l.)							
A1	0-1	2.5 Y 4/3	granular	many	soft	slightly moist	grasses, *Salix polaris*, *Saxifraga cespitosa*, *Alopecurus ovatus*
A2	1-3	2.5 Y 3/3	granular, fibrous	many	soft	moist	
A@	3-11	2.5 Y 4/3	platy, granular	common	soft	moist	
Cg@1	11-17	2.5 Y 4/3	platy, granular	common	soft to slightly hard	moist	
AC@1	17-28	2.5 Y 4/3	platy, granular	common	slightly hard	slightly moist	
Cg@2	28-35	2.5 Y 4/3	angular blocky, platy	common	slightly hard	slightly moist	
AC@2	35-50	2.5 Y 4/3	angular blocky, platy	few	slightly hard to soft	slightly moist	
Cg@3	50-70	2.5 Y 4/3	angular blocky, platy	common	slightly hard to soft	slightly moist	
Cf	70-80	2.5 Y 4/3	massive	absence	hard	wet	
I	80+		n.a.	n.a.	n.a.	n.a.	
Profile 5. Protic Turbic Cryosol (Eutric Folic Humic Loamic) – Sukkertoppen Mt. (78°13'02"N, 15°39'17"E; 64 m a.s.l.)							
Oi1	10-8	n.a.	n.a.	n.a.	n.a.	n.a.	*Cassiope tetragona*, *Salix polaris*, *Polygonum viviparum*, *Oxyria digyna*
Oi2	8-0	n.a.	fibrous	many	soft	moist	
C@1	0-25	2.5 Y 4/3	granular, subangular blocky	few	soft	moist	
C@2	25-50	2.5 Y 4/3	granular, subangular blocky	common	soft	moist	

Table 1 – *continued.*

Soil horizon	Depth (cm)	Color (dry state)	Structure	Roots	Consistence	Moisture	Vegetation
Profile 6. Turbic Cryosol (Abruptic Eutric Humic Loamic Raptic) – Sukkertoppen Mt. (78°13'03"N, 15°39'10"E; 61 m a.s.l.)							
A1	0-3	2.5 Y 4/3	granular, fibrous	many	soft	moist	*Dryas octopetala*, *Cassiope tetragona*, *Salix polaris*, *Polygonum viviparum*, *Oxyria digyna*, *Cerastium arcticum*
A2	3-10	2.5 Y 3/3	granular	many	soft	moist	
A3	10-20	2.5 Y 4/3	granular, subangular blocky	many	soft	moist	
C@1	20-40	2.5 Y 4/3	angular blocky	many	slightly hard	moist	
C@2	40-60	2.5 Y 4/3	angular blocky	few	hard	moist	
C@3	60-80	2.5 Y 4/3	angular blocky	few	hard	very moist	
Profile 7. Skeletic Reductaquic Cryosol (Eutric Humic Loamic) – slope of Platåberget Mt. (78°13'45"N, 15°34'34"E; 53 m a.s.l.)							
H	3-0	n.a.	fibrous	n.a.	n.a.	wet	mosses
A	0-5	2.5 Y 4/3	granular, fibrous	many	soft	wet	
Cr1	5-20	2.5 Y 4/2	subangular blocky	few	moderately hard	wet	
Cr2	20-32	2.5 Y 4/2	subangular blocky	few	moderately hard	wet	
Profile 8. Protic Reductaquic Cryosol (Dystric Humic) – slope of Platåberget Mt. (78°13'51"N, 15°34'05"E; 47 m a.s.l.)							
H	5-0	n.a.	fibrous	few	soft	wet	mosses
Cr	0-10	2.5 Y 4/3	subangular blocky	many	soft	wet	

* Not analyzed.

angular and ranged in size from 2 mm to 100 mm. The rock-fragment content at these sites ranged from 2% to 60% and increased with depth. The absence of rock fragments at sites 3 and 4 covered with Arctic meadow was caused by the location of these profiles on the floor of the Adventelva river valley, which was covered with a thick layer of aeolian deposits shielding glaciofluvial and fluvial sediments (Bryant 1982). The high content of coarse rock fragments is typical of soils elsewhere in Svalbard, *e.g.*, Kaffiöyra (Pilchta 1993), Bellsund (Klimowicz *et al.* 1999), Calypsostranda (Świtoniak *et al.* 2014), Sørkappland (Szymański *et al.* 2019a), and Hornsund (Szymański *et al.* 2015).

Soil profiles at sites 1 and 2, found under pioneer tundra, exhibited a very initial and poorly developed A horizon (site 1) or only an AC horizon (site 2)

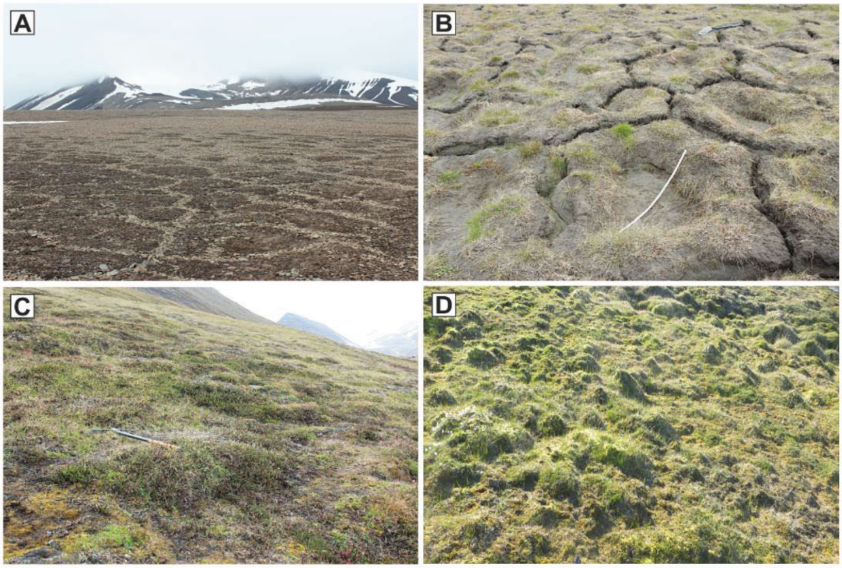

Fig. 3. Soil surface characteristics at selected studied sites: patterned ground at site 1 (**A**); patterned ground at site 3 (**B**); solifluction lobes at site 6 (**C**); small thufurs at site 8 (**D**).

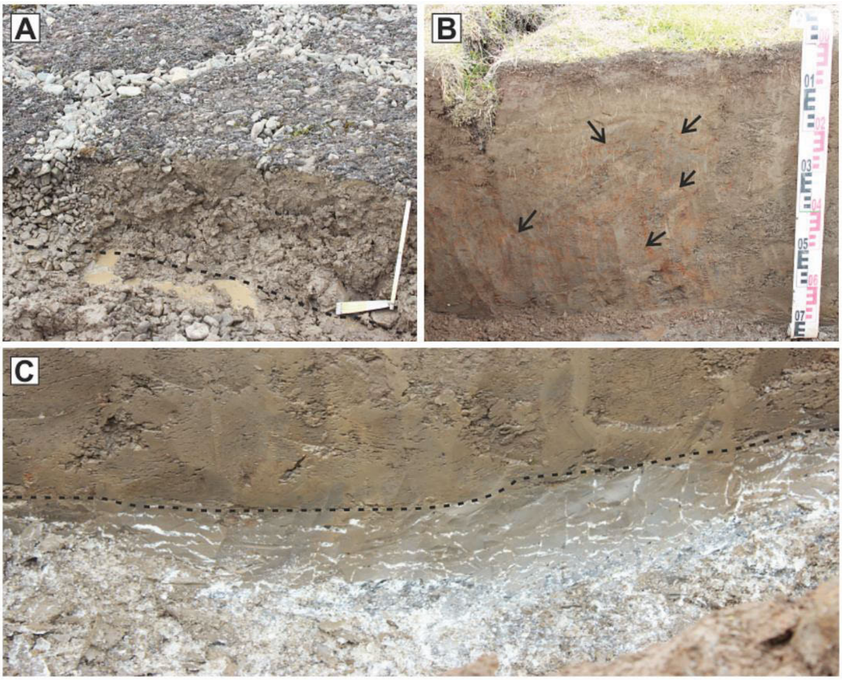

Fig. 4. Soil profile at site 1 with marked contact of unfrozen and frozen parts of soil (black broken line) at 50 cm (late July 2018) (**A**); evidences of cryoturbation in soil profile at site 3 in the form of discontinuous and deformed thin orange layers marked with black arrows (**B**); contact of unfrozen and frozen parts of soil profile at site 4 at a depth of 80 cm (black broken line) with ice veins and lenticular structure above massive ice (late July 2018) (**C**).

(Table 1). This was related to the low biomass supply from very sparse, pioneer vegetation occurring at these sites (Fig. 2). Moreover, the shallow presence of the C horizon in these soil profiles indicated a low degree of soil development. By contrast, both soil profiles, *i.e.*, those from sites 3 and 4, found under Arctic meadow exhibited a clearly better developed A horizon. This was connected with the well-developed vegetation cover at these sites and higher supply of biomass to the soil in relation to soils covered with pioneer tundra (Fig. 2). Soils covered with heath tundra were characterized by the occurrence of a thick organic horizon (site 5) or thick A horizon (site 6). This was also related to the well-developed vegetation cover and this vegetation supplied high amount of organic matter to the soil. In soil profiles under wet moss tundra vegetation, an organic horizon (sites 7 and 8) underlain by an A horizon (site 7) occurred. The presence of a thin H horizon in these soils most likely was connected with the high wetness of these sites. Furthermore, mosses, which were the main part of the vegetation at these sites, are resistant to decomposition (Gerdol *et al*. 2007; Osono *et al.* 2012; Riis *et al.* 2016). The morphology of the studied soils indicates an early stage of formation, which is typical of soils occurring in Spitsbergen, *e.g.*, in Hornsund (Szymański *et al.* 2015), on the Bellsund coast (Klimowicz *et al*. 1999), and in Recherchefjorden (NW part of Wedel Jarlsberg Land) (Hanaka *et al.* 2019).

The studied soils covered with pioneer tundra (sites 1 and 2) were characterized by the occurrence of a platy and granular structure in surface horizons (Table 1). Most likely this was related to frequent freeze and thaw events (Van Vliet-Lanoë 2010). Deeper horizons of soils covered with pioneer tundra exhibited an angular blocky or massive structure (Table 1). The soil structure at sites 3 and 4 found under Arctic meadow was very similar to the structure of soils covered with pioneer tundra vegetation; however, in deeper horizons of soils found under Arctic meadow, a prismatic structure additionally occurred (Table 1). The prismatic structure in deeper soil horizons is most likely connected with the wetting and drying of soil material due to freezing and thawing, and this type of structure is very common in soils with a silt loam texture (*e.g.*, Szymański *et al.* 2011). Moreover, a fibrous structure occurred in some A horizons in soils found under Arctic meadow, which indicated that some part of organic residue had not been strongly transformed by soil microbes (Table 1). Most likely, this was related to a strong influx of organic residues from well-developed vegetation (Arctic meadow) and strong cryoturbation (Bockheim and Tarnocai 1998; Palmtag *et al.* 2016). Soils found under heath tundra (sites 5 and 6) and wet moss tundra (sites 7 and 8) exhibited a mainly fibrous structure in their organic and A horizons (Table 1). Most likely, this was due to an accumulation of large amounts of organic residue originating from well-developed vegetation cover and lower rate of its decomposition, because of the low susceptibility to biodegradation of mosses and *C. tetragona* residues. Additionally, high moisture of soils covered with wet moss tundra (Table 1) and occurrence of anaerobic conditions hampers decomposition of organic matter by soil microorganisms (Gilbert and Mitchell 2006; Kulichevskaya *et al.* 2007).

All of the studied soils were characterized by loamy texture (from sandy loam to silt loam). Sand, silt, and clay content ranged from 25% to 65%, 16% to 66%, and 7% to 18%, respectively (Table 2). Soils covered with pioneer tundra (sites 1 and 2) were characterized by a loam and silt loam texture (Table 2). The parent material of these soils was the weathering residue of mudstone and sandstone,

Table 2.

Chemical and physical properties of the studied soils. Abbreviations as in Table 1.

	Depth	pH	SOC	TN	C/N	Skeleton	Sand	Silt	Clay	Texture
	(cm)	(H_2O)	(%)	(%)		(%)	(%)	(%)	(%)	
Profile 1										
A	0-0.5	4.33	14.87	0.42	35	0	n.a.*	n.a.	n.a.	n.a.
C@1	0.5-15	5.31	0.87	0.06	14	30	44	41	15	loam
C@2	15-30	5.47	0.47	0.05	10	40	39	44	17	loam
C@3	30-50	5.79	0.36	0.04	9	40	39	43	18	loam
Cf	50+	5.81	0.39	0.04	10	n.a.	n.a.	n.a.	n.a.	n.a.
Profile 2										
AC@	0-20	5.55	0.94	0.09	10	2	53	30	17	sandy loam
Cg@1	20-45	6.51	0.70	0.07	10	5	61	22	17	sandy loam
Cg@2	45-85	6.50	0.70	0.07	10	40	70	19	11	sandy loam
R	85+	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Profile 3										
A1	0-2	5.24	5.09	0.30	17	0	38	53	9	silt loam
A2	2-4	4.88	5.22	0.37	14	0	37	59	4	silt loam
A3	4-9	4.77	2.08	0.15	14	0	33	60	7	silt loam
Cg@1	9-18	4.71	1.98	0.14	15	0	38	53	9	silt loam
Cg@2	8-35	5.09	1.87	0.14	14	0	38	55	7	silt loam
Cg@3	35-55	4.79	1.97	0.14	14	0	33	61	6	silt loam
Cg@4	55-70	4.75	2.07	0.15	13	0	35	58	7	silt loam
Cf	70-80	5.16	2.51	0.19	13	0	25	64	11	silt loam
I	80+	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 2 – *continued.*

	Depth	pH	SOC	TN	C/N	Skele-ton	Sand	Silt	Clay	Tex-ture
	(cm)	(H_2O)	(%)	(%)		(%)	(%)	(%)	(%)	
					Profile 4					
A1	0-1	5.34	4.29	0.21	20	0	45	47	8	loam
A2	1-3	4.64	4.00	0.25	16	0	42	53	5	silt loam
A@	3-11	4.40	2.16	0.13	17	0	41	52	7	silt loam
Cg@1	11-17	4.52	1.60	0.12	14	0	52	41	7	loam
AC@1	17-28	4.74	1.45	0.11	14	0	48	45	7	loam
Cg@2	28-35	5.34	1.54	0.10	15	0	43	49	8	loam
AC@2	35-50	5.20	1.93	0.15	13	0	38	54	8	silt loam
Cg@3	50-70	5.17	1.94	0.13	14	0	36	55	9	silt loam
Cf	70-80	5.22	1.82	0.14	13	0	n.a.	n.a.	n.a.	n.a.
I	80+	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
					Profile 5					
Oi1	10-8	n.a.	22.21	0.82	27	0	n.a.	n.a.	n.a.	n.a.
Oi2	8-0	5.60	29.82	0.95	31	0	n.a.	n.a.	n.a.	n.a.
C@1	0-25	5.78	3.77	0.27	14	20	39	46	15	loam
C@2	25-50	5.80	3.70	0.30	12	30	40	48	12	loam
					Profile 6					
A1	0-3	5.60	19.32	0.90	21	0	n.a.	n.a.	n.a.	n.a.
A2	3-10	5.97	13.39	0.70	19	0	n.a.	n.a.	n.a.	n.a.
A3	10-20	5.92	4.18	0.31	14	0	30	53	17	silt loam
C@1	20-40	6.26	2.74	0.20	14	20	25	48	27	clay loam
C@2	40-60	6.50	3.11	0.23	14	30	48	16	36	sandy
C@3	60-80	6.70	2.07	0.14	15	50	40	40	20	loam
					Profile 7					
H	3-0	n.a.	n.a.	n.a.	n.a.	0	n.a.	n.a.	n.a.	n.a.
A	0-5	6.50	10.55	0.47	22	20	n.a.	n.a.	n.a.	n.a.
Cr1	5-20	6.01	2.69	0.14	19	40	65	28	7	sandy loam
Cr2	20-32	6.00	2.12	0.14	15	60	61	32	7	sandy loam
					Profile 8					
H	5-0	n.a.	n.a.	n.a.	n.a.	0	n.a.	n.a.	n.a.	n.a.
Cr	0-10	4.80	7.29	0.56	13	20	n.a.	n.a.	n.a.	n.a.

* Not analyzed.

and therefore, the soils were characterized by low clay content. Higher content of silt and sand over clay fraction is common in soils in Svalbard (Plichta 1993; Świtoniak *et al.* 2014; Hanaka *et al.* 2019; Szymański *et al.* 2019a) as well as strongly depends on parent material. A higher content of silt was noted at sites 3 and 4 (Table 2), and it was connected with loess deposits occurring in the floor of the Adventdalen valley (Bryant 1982). Soils covered with heath tundra (sites 5 and 6) exhibited highly variable texture (loam, silt loam, clay loam, and sandy loam). Most likely, this was related to the fact that these soils had formed from mixed slope deposits originating from the weathering residues of sandstone, mudstone, and shale. Soils under wet moss tundra (represented by site 7) were characterized by sandy loam texture and the highest content of the sand fraction, supposedly due to a continuous freshwater supply, which led to the removal of fine particles, *i.e.*, silt and clay fractions, from the soil profile.

Soil chemical properties. — All of the studied soils were very acidic or slightly acidic with pH values ranging from 4.33 to 6.70 (Table 2). This was due to a lack of carbonate in the parent material. In most cases, the soil pH increased with depth due to a lower content of organic matter in the deeper soil horizons and lower concentration of organic acids. Soils under pioneer tundra and Arctic meadow exhibited pH values ranging from 4.3 to 6.5 and from 4.5 to 5.3, respectively (Table 2). Soils under heath tundra were characterized by higher soil pH, which ranged from 5.6 to 6.7. The highest soil pH was noted at site 7, covered with wet moss tundra (pH ranged from 6.0 to 6.5, with the highest pH value in the surface horizon), and this was most likely related to the enrichment of this soil in alkaline cations by stream water flowing in its close vicinity.

The soil organic carbon (SOC) content in the studied soils ranged from 0.36% to 29.82% (Table 2). The highest content of SOC occurred in organic and A horizons and was substantially different under various tundra vegetation types. In soils under pioneer tundra, SOC content ranged from 0.39% to 14.87% (Table 2). The obtained results for soils covered with pioneer vegetation are similar to those obtained by Szymański *et al.* (2015) for Turbic Cryosol covered with BSC in Hornsund. Much higher content of SOC in the A horizon at site 1 was most likely associated with the very well-developed BSC at this site. The SOC content in soils covered with Arctic meadow (sites 3 and 4) ranged from 1.45% to 5.09% (Table 2). The highest SOC content was noted in soils covered with heath tundra (sites 5 and 6). The vegetation cover at these sites was very well developed and consisted mainly of vascular plants such as *D. octopetala* and *C. tetragona*, which provided a lot of organic residues to the soil. Moreover, a large number of roots in soils occurred under heath tundra (Table 1), which enriched the soils with organic matter. The higher SOC content in soils under heath tundra relative to soils under Arctic meadow was associated with lower susceptibility to degradation of *C. tetragona* in comparison with grasses and other vascular plants (Hobbie and Gough 2004; Sarneel *et al.* 2020). The SOC content in surface horizon at site 5 are similar to SOC content recorded in the research carried out by Hanaka *et al.* (2019) in Wedel Jarlsberg Land. However, the content of SOC in the surface horizon at site 6 is much higher than in the abovementioned study due to the locally better developed heath tundra. The high content of SOC in A and organic horizons in profiles from sites 7 and 8 (Table 2) under wet moss tundra was associated with the high wetness of these sites and low decomposability of moss-derived litter (Gerdol *et al.* 2007; Osono *et al.* 2012; Riis *et al.* 2016). A study conducted by Szymański (2017) in the eastern part of the Fuglebergsletta shows a slightly higher content of SOC (with a mean value of 20.26%) than results obtained in the present study. This may be caused by locally better developed wet moss tundra in Fuglebergsletta due to little auk impact (*Alle alle*) (Szymański *et al.* 2015).

Total nitrogen (TN) content in the studied soils ranged from 0.04% to 0.95% (Table 2). The lowest content of TN was noted in soils under pioneer tundra (ranged from 0.04% to 0.42%). However, the unexpectedly high content of TN in the A horizon of soil profile from site 1 may be a result of the presence of a well-developed cyanobacterial mat at the surface of this profile (Fig. 2). In soils under Arctic meadow, TN content ranged from 0.10% to 0.37%. The highest content of TN was noted in the A and O horizons of soil profiles from sites 5 and 6, under heath tundra (Table 2). Most likely this was due to the very well-developed vegetation cover at these sites. The content of TN in surface horizons in soil under heath tundra at sites 5 and 6 are similar to result obtained by Hanaka *et al.* (2019) in Wedel Jarlsberg Land. High content of TN occurred at sites 7 and 8, under wet moss tundra, and this was related to the high wetness of these sites, which hampers decomposition of soil organic matter (Lang *et al.* 2009; Hagemann and Moroni 2015). TN content in surface horizons of soils under wet moss tundra was slightly lower in comparison to results obtained for other parts of Svalbard, *e.g.*, the Fuglebergsletta coastal plain (Szymański 2017). This may be caused by a lack of soil fertilization via bird droppings in the soils studied herein.

The C/N ratio for the studied soils was highly variable and ranged from 9 to 35 (Table 2). A broad range of C/N ratios may indicate different stages of development of the studied soils. The high value of the C/N ratio may be due to the harsh climate conditions and low activity of soil microorganisms in such conditions (Dai *et al.* 2002; White *et al.* 2004). The lowest C/N ratio was noted for soil profiles from sites 1 and 2 found under pioneer tundra. This was due to the occurrence of cyanobacterial mats, which exhibit an ability to fix nitrogen from the atmosphere (Steppe *et al.* 1996; Stal *et al.* 2010) as well as due to a low supply of organic matter from sparse vegetation in the area. Only in the surface horizon at site 1 did a high C/N ratio occur due to the well-developed BSC on the soil surface. The highest C/N ratio was noted for soils under heath tundra (sites 5 and 6) (Table 2). This was related to the low decomposability of organic residue derived from *C. tetragona* (Hobbie and Gough 2004), influx of large amounts of organic matter from the very well-developed vegetation cover, and low activity of soil microorganisms in the ambient harsh environment.

Conclusions

All of the studied soils are characterized by being in the early stage of formation. The main soil-forming process in these soils is cryoturbation and all of the studied soils were classified as Cryosols. Most of the studied soils are shallow and contain a high content of coarse rock fragments. The highest content of rock fragments occurs in soils covered with pioneer and wet moss tundra. Soils covered with Arctic meadow do not contain rock fragments. Content of rock fragments and soil texture strongly depend on local parent rocks and weathering conditions. However, tundra vegetation type has a strong impact on the development and structure of surface soil horizons, *i.e.,* organic and A horizons. The obtained results indicate that all of the studied soils are characterized by loamy texture and acidic or slightly acidic reaction with pH ranging from 4.3 to 6.7, and these properties are not very different under various tundra vegetation types. The content of SOC and TN is strongly dependent on the type of tundra vegetation. The highest SOC and TN contents occur at sites with well-developed vegetation such as heath and wet moss tundra, while soils covered with pioneer tundra vegetation exhibit the lowest content of SOC and TN. The high C/N ratio noted for the surface soil horizons of the majority of the studied soils indicates that organic matter is poorly decomposed, which most likely is related to the low activity of soil microorganisms in the studied harsh High Arctic environment. However, the lowest C/N ratio was noted for surface soil horizons found at sites 3 and 4 covered with Arctic meadow, and this indicates that there occur the best conditions for SOM decomposition. To summarize, the type of vegetation has a strong impact on soil organic matter and the structure of surface soil horizons. Other soil properties strongly depend on parent material and local conditions, and there is no direct relationship between vegetation and, *e.g.*, texture.

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