POLISH POLAR RESEARCH
vol. 37, no. 3, pp. 361–377, 2016 doi: 10.1515/popore-2016-0019

Texture and geochemistry of surface horizons of Arctic soils from a non-glaciated catchment, SW Spitsbergen

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Abstract: Physical and chemical properties of Arctic soils and especially the properties of surface horizons of the soils are very important because they are responsible for the rate and character of plant colonization, development of vegetation cover, and influence the rate and depth of thawing of soils and development of active layer of permafrost during summer. The main aim of the present study is to determine and explain the spatial diversity of selected physical and chemical properties of surface horizons of Arctic soils from the non-glaciated Fuglebekken catchment located in the Hornsund area (SW Spitsbergen) by means of geostatistical approach. Results indicate that soil surface horizons in the Fuglebekken catchment are characterized by highly variable physical and chemical properties due to a heterogeneous parent material (marine sediments, moraine, rock debris), tundra vegetation types, and non-uniform influence of seabirds. Soils experiencing the strongest influence of seabird guano have a lower pH than other soils. Soils developed on the lateral moraine of the Hansbreen glacier have the highest pH due to the presence of carbonates in the parent material and a lack or presence of a poorly developed and discontinuous A horizon. The soil surface horizons along the coast of the Hornsund exhibit the highest content of the sand fraction and SiO_2. The surface of soils occurring at the foot of the slope of Ariekammen Ridge is characterized by the highest content of silt and clay fractions as well as Al_2O_3, Fe_2O_3, and K_2O. Soils in the central part of the Fuglebekken catchment are depleted in CaO, MgO, and Na_2O in comparison with soils in the other sampling sites, which indicates the highest rate of leaching in this part of the catchment.

Key words: Arctic, Svalbard, texture, chemical composition, surface layer, Cryosols.

Introduction

The physical and chemical properties of Arctic soils (permafrost-affected soils) and especially the properties of the surface horizons of the soils are important, as they are responsible for the rate and character of plant colonization and development of vegetation cover (Klimowicz and Uziak 1996a; Skiba *et al.* 2002; Moreau *et al.* 2008; Walker 2012). Furthermore, the quantity, quality, community structure, and activity of soil microorganisms and soil fauna, which occur mainly in the upper part of the soil profile, also depend on soil physical and chemical properties (Moorhead *et al.* 2003; Carson *et al.* 2007; Rousk *et al.* 2010; Banning *et al.* 2011; Świtoniak *et al.* 2014). Surface soil horizons are also characterized by the highest content of soil organic carbon and nitrogen and the concentration of organic carbon and nitrogen in soils is highly related to other soil physical and chemical parameters such as texture (mainly clay fraction content), mineral composition (mainly quantity and quality of clay minerals), moisture, pH, and the content of common and less common chemical elements (Schimel *et al.* 1994; Balesdent *et al.* 2000; Sjögersten *et al.* 2006; Xu *et al.* 2016; Szymański *et al.* 2016). The physical and chemical properties of soils affect the rate and depth of thawing of the upper part of soil profile and the development of an active layer of permafrost during summer as well as the susceptibility of soil material to cryoturbation, frost heave, solifluction, and gelifluction (Wójcik and Marciniak 1987; Klimowicz and Uziak 1996b; Hinkel *et al.* 2001; Szymański *et al.* 2013, 2015; Mishra and Riley 2014; Bockheim 2015). Therefore, detailed knowledge on the physical and chemical properties of surface horizons of soils is needed in order to understand ecological processes and relationships between environmental components in the High Arctic.

The main aim of the present study was to determine and explain the spatial diversity of selected physical and chemical properties of surface horizons of Arctic soils from the non-glaciated Fuglebekken catchment located in the Hornsund area (SW Spitsbergen) by means of geostatistical approach. The presented results may be useful in environmental studies and especially in studies of the active layer thickness of permafrost and circulation of elements in the Arctic environment.

Study area

The study area is located in a close proximity to the Polish Polar Station (77°00'N; 15°33'E), along the northern coast of Hornsund (Isbjørnhamna) in the southern part of Wedel Jarlsberg Land, SW Spitsbergen (Fig. 1). The study was carried out in the small, non-glaciated catchment of Fuglebekken stream (area ~1.5 km^2) located on the coastal plain, in the eastern part of Fuglebergsletta

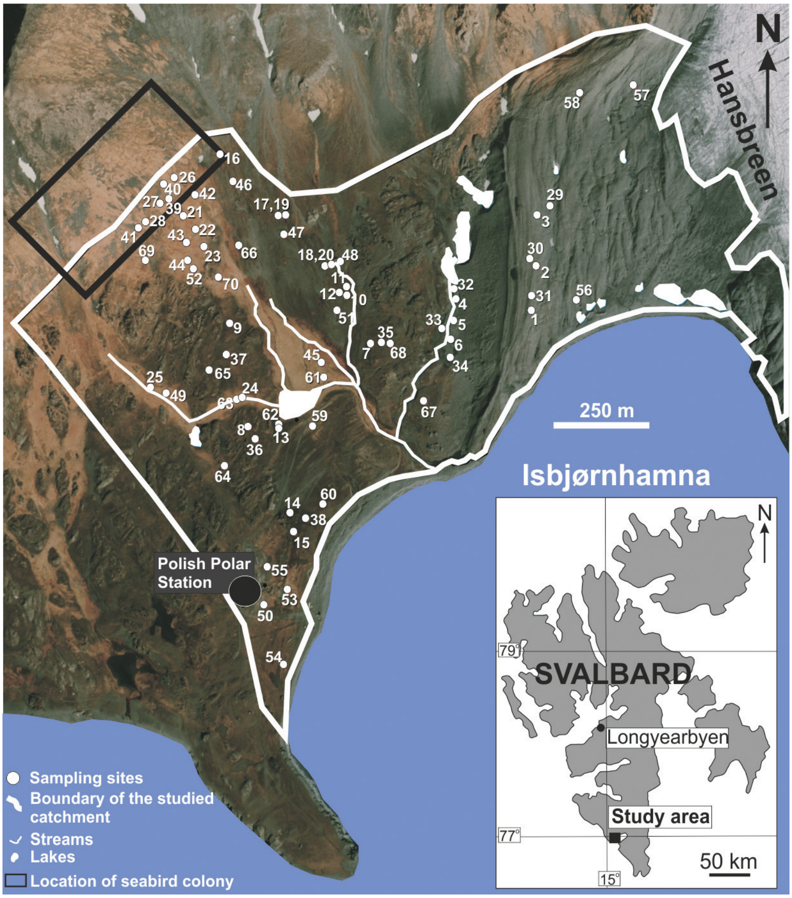

Fig. 1. Location of the area and the sampling sites in the lower part of the Fuglebekken catchment. Basemap from Kolondra (1995).

(Fig. 1). The bedrock in the area of the Fuglebekken catchment is composed mainly of metamorphic schist, paragneiss, quartzite, amphibolite, and marble (Czerny *et al*. 1993; Majka *et al*. 2010), which are covered with unsorted and mostly coarse-grained marine deposits (Szerszeń 1965; Szymański *et al*. 2013, 2015). The eastern part of the study area is limited by the rolling, ice-cored lateral moraine of the Hansbreen glacier. Haplic Cryosols, Reductaquic Cryosols, Hyperskeletic Cryosols, Turbic Cryosols, and Leptic Regosols Ornithic are the prevailing soil units in the area (Szymański *et al*. 2013, 2015; Migała *et al*. 2014). Haplic Cryosols are covered with dry lichen-heath tundra vegetation, with *Cetraria delisei*, *Ochrolechia frigida*, *Salix polaris*, *Saxifraga oppositifolia*, and *Polytrichastrum alpinum* being the most common local species. Wet moss tundra vegetation, with a predominance of *Sanionia uncinata*, *Warnstorfia sar-*

mentosa, *Straminergon stramineum*, and *Aulacomnium palustre*, occurs along the Fuglebekken stream and its tributaries. Turbic Cryosols are characterized by scarcity of vegetation and are covered mainly by cyanobacteria mats. Ornithocoprophilous tundra vegetation, featuring *Chrysosplenium tetrandrum* and *Cochlearia groenlandica* as the prevailing species, is present in the northwestern part of the study area (Dubiel and Olech 1992; Wojtuń *et al*. 2013; Skrzypek *et al*. 2015). Detailed data on the soils and tundra vegetation of the study area are presented by Szymański *et al*. (2013, 2015, 2016), Wojtuń *et al*. (2013), Migała *et al*. (2014), and Skrzypek *et al*. (2015). The study area experiences suboceanic climate conditions with a mean annual air temperature of -4.2^{o}C and mean precipitation of 450 mm per year (Marsz and Styszyńska 2007). The mean annual temperature of the top one meter of the ground in the study area is between -2.0 and -3.0^{o}C (Marsz 2013).

Methods

The exact location of the sampled sites is shown in Fig. 1 and other data on the sites can be found in Szymański *et al*. (2016). Samples from surface soil horizons (uppermost 10 cm) were collected in plastic bags and immediately air dried. After drying, the samples were gently crushed, and sieved through a 2 mm sieve. All laboratory analyses were conducted on the fine earth material (fraction <2 mm). The texture was determined using the hydrometer method (silt and clay fractions) and wet sieving (sand fraction) (Gee and Bauder 1986). Soil pH was measured via potentiometry in deionized water (1:2.5 w/v ratio) using a glass electrode (Thomas 1996). Chemical composition of the soil samples (*i.e*. content of SiO_2, Al_2O_3, CaO, MgO, K_2O, Na_2O with a detection limit of 0.01% and Fe_2O_3 with a detection limit of 0.04%) was determined by Inductively Coupled Plasma – Emission Spectrometry (ICP-ES) after digestion of the samples using lithium metaborate/tetraborate and dilute nitric acid at Acme Labs (Vancouver, BC, Canada).

Soil data (*i.e*. pH, content of sand, silt, and clay fractions, SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O) were correlated with each other using Spearman's correlation coefficient with the help of Statistica 12 software (Statsoft 2014).

Maps of the spatial distribution of sand, silt, and clay fractions, SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, and Na_2O contents in the surface soil horizons and the pH values were created by the inverse distance weighting (IDW) deterministic interpolation method – with the 3rd power function modifying the distance weights (Lu and Wong 2008). An ESRI ArcMap environment was used to perform the interpolation calculation with an assumed resolution of 2.5 m.

Results

Physical properties of the surface horizons. — Almost all of the surface soil horizons are characterized by sand, sandy loam, and loamy sand texture classes with a clear prevalence of the sand fraction (up to 96%; mean value of 66%) (Table 1). The presence of silt loam, silt, and loam texture classes were determined only at selected sites. In general, the lowest content of the sand fraction – ranging from 3% to 50% – occurs in surface soil horizons in the north-central part of the catchment at the foot of the slope of the Ariekammen ridge, while the highest content of this fraction (from 65% to 96%) occurs in the southwestern part of the area (Fig. 2A). The content of the silt fraction in the surface soil horizons ranges from 3% to 87%, with the mean at 30% (Table 1), and the spatial distribution of this fraction is opposite compared to the distribution of the sand fraction (Table 1, Figs 2A and 2B). This finding is confirmed by a very large and negative correlation coefficient (r = -0.99) (Table 2). The content of the clay fraction is very low in the surface horizons, ranging from 0% to 14%, with a mean of 5% (Table 1). The lowest content of the clay fraction (from 0% to 5%) occurs in the southwestern part of the Fuglebekken catchment, while the highest content of this fraction (from 7% to 14%) was determined in the north-central part – at the foot of the slope of the Ariekammen ridge (Fig. 2C). The content of the clay fraction is also strongly and negatively correlated with the content of the sand fraction (r = -0.88), while positively correlated with the silt fraction (r = 0.83) (Table 2).

Table 1

Selected physical and chemical properties of the surface soil horizons.

No.	Proportion of fraction (%)			pH in H_2O	Chemical composition (%)						
	Sand	Silt	Clay		SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O
1	60	33	7	8.1	55.91	16.24	7.59	2.76	3.94	3.32	1.60
2	57	38	5	8.0	56.55	16.04	7.36	2.77	3.96	3.18	1.67
3	60	34	6	8.1	55.00	16.25	7.68	2.83	4.44	3.58	1.72
4	76	20	4	7.7	70.30	12.29	6.02	1.91	1.27	1.53	1.50
5	72	26	2	7.7	65.56	14.00	6.96	2.33	1.43	1.80	1.47
6	39	56	5	7.6	59.12	16.84	7.67	3.13	1.22	2.36	1.47
7	81	16	3	5.4	65.12	12.13	5.86	1.92	1.03	1.51	1.31
8	87	12	1	5.6	66.04	12.83	5.98	2.06	1.02	1.48	1.39
9	n.a.	n.a.	n.a.	4.9	41.64	12.68	5.30	2.11	1.07	1.49	1.04
10	n.a.	n.a.	n.a.	6.3	57.22	17.48	8.46	3.47	1.01	2.52	1.07
11	n.a.	n.a.	n.a.	6.5	57.27	17.39	8.42	3.35	1.10	2.51	1.17

Table 1 – continued

No.	Proportion of fraction (%)			pH in H_2O	Chemical composition (%)						
	Sand	Silt	Clay		SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O
12	n.a.	n.a.	n.a.	7.1	57.72	17.53	8.39	3.34	1.18	2.55	1.26
13	88	10	2	6.8	69.39	11.89	5.25	1.88	1.25	1.47	1.36
14	96	4	0	6.9	82.31	6.48	3.90	0.99	0.62	0.83	0.75
15	92	7	1	7.4	75.90	7.92	5.08	1.23	1.50	1.52	0.90
16	13	80	7	7.3	46.10	19.46	11.15	3.67	1.79	3.01	1.11
17	n.a.	n.a.	n.a.	7.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
18	31	58	11	7.1	52.51	18.60	9.51	3.68	1.08	2.56	0.92
19	n.a.	n.a.	n.a.	7.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
20	36	54	10	7.1	54.41	17.83	9.25	3.45	1.14	2.46	0.97
21	23	69	8	6.6	43.91	17.54	9.77	3.23	1.85	2.68	1.14
22	n.a.	n.a.	n.a.	5.8	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
23	n.a.	n.a.	n.a.	6.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
24	n.a.	n.a.	n.a.	6.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
25	n.a.	n.a.	n.a.	5.8	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
26	n.a.	n.a.	n.a.	5.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
27	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
28	n.a.	n.a.	n.a.	5.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
29	61	31	8	8.2	54.86	16.30	7.78	2.88	4.41	3.41	1.60
30	55	38	7	8.5	53.51	16.55	7.91	2.97	4.40	3.74	1.64
31	71	25	4	8.4	56.92	15.48	7.19	2.71	4.70	2.94	1.69
32	89	6	5	7.2	72.16	11.52	5.92	1.73	1.37	1.41	1.53
33	69	27	4	7.7	66.07	13.89	6.69	2.41	1.38	1.85	1.43
34	95	2	3	7.4	75.13	10.52	4.94	1.56	1.13	1.24	1.53
35	90	7	3	5.9	69.50	12.00	5.82	1.79	1.05	1.36	1.52
36	83	12	5	5.3	62.91	14.77	6.48	2.31	1.01	1.83	1.82
37	85	12	3	5.9	65.23	14.02	6.90	2.27	1.12	1.73	1.64
38	93	5	2	7.3	78.92	8.46	4.20	1.45	0.63	1.06	0.98
39	n.a.	n.a.	n.a.	5.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
40	n.a.	n.a.	n.a.	4.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
41	n.a.	n.a.	n.a.	5.3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
42	n.a.	n.a.	n.a.	6.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
43	n.a.	n.a.	n.a.	6.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
44	n.a.	n.a.	n.a.	6.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
45	n.a.	n.a.	n.a.	6.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
46	12	82	6	7.3	47.20	19.25	11.07	3.67	1.74	3.17	1.14

Table 1 – continued

No.	Proportion of fraction (%)			pH in H_2O	Chemical composition (%)						
	Sand	Silt	Clay		SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O
47	n.a.	n.a.	n.a.	7.2	48.09	16.96	8.97	3.31	1.41	2.37	0.83
48	7	79	14	7.3	48.38	20.30	10.46	4.12	0.98	2.83	0.77
49	n.a.	n.a.	n.a.	6.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
50	91	8	1	7.2	69.80	8.00	4.60	1.30	2.70	1.90	1.00
51	56	37	7	7.1	58.80	16.90	8.20	3.20	1.30	2.40	1.30
52	n.a.	n.a.	n.a.	6.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
53	82	14	4	7.2	68.70	6.90	3.80	1.10	1.50	1.10	0.90
54	95	4	1	7.4	60.30	7.60	6.20	1.30	6.60	3.30	0.80
55	77	20	3	7.9	63.95	13.28	7.15	2.28	1.68	2.61	1.62
56	52	39	9	8.0	57.05	15.29	7.14	2.61	4.35	3.00	1.69
57	83	16	1	7.8	60.60	15.50	7.00	2.60	3.20	2.40	1.80
58	66	26	8	8.0	55.70	14.50	6.70	2.80	6.80	2.20	1.60
59	n.a.	n.a.	n.a.	5.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
60	95	3	2	7.4	77.87	8.27	4.56	1.42	0.97	1.25	0.97
61	n.a.	n.a.	n.a.	6.2	45.05	17.87	9.83	3.41	1.45	2.69	1.09
62	70	24	6	5.8	57.40	13.00	5.70	2.20	1.40	1.60	1.30
63	71	25	4	7.1	62.20	14.60	7.30	2.60	1.60	2.20	1.80
64	72	23	5	7.1	60.70	15.10	7.50	2.60	1.70	2.50	1.80
65	n.a.	n.a.	n.a.	6.3	57.40	16.80	7.60	2.90	1.90	2.70	1.80
66	54	39	7	7.2	57.00	17.90	9.10	3.30	1.40	2.40	1.40
67	3	87	10	8.1	56.29	19.24	8.21	3.39	1.00	2.70	1.45
68	63	31	6	6.2	63.50	13.80	6.60	2.30	1.20	1.90	1.40
69	n.a.	n.a.	n.a.	6.5	30.50	12.70	7.00	2.30	2.40	2.40	0.80
70	n.a.	n.a.	n.a.	6.8	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

n.a. – not analyzed

Chemical properties of the surface horizons. — Soil pH of the surface horizons is listed in Table 1 and presented in Fig. 3A. Soils with the lowest pH of the surface horizons (from 4.1 to 6.3 in distilled water) occur in the northwestern part of the Fuglebekken catchment and along streams flowing from the direction of the seabird colony. Soils with the highest pH (from 7.9 to 8.5 in distilled water) were identified in the eastern part of the area, which is occupied by a lateral moraine of the Hansbreen glacier.

The surface soil horizons are mainly composed of SiO_2 (30.5% to 82.3%; mean of 59.9%), Al_2O_3 (6.5% to 20.3%; mean of 14.4%), Fe_2O_3 (3.8% to 11.2%; mean of 7.2%), and K_2O (1.0% to 4.1%; mean of 2.5%) (Table 1). The content

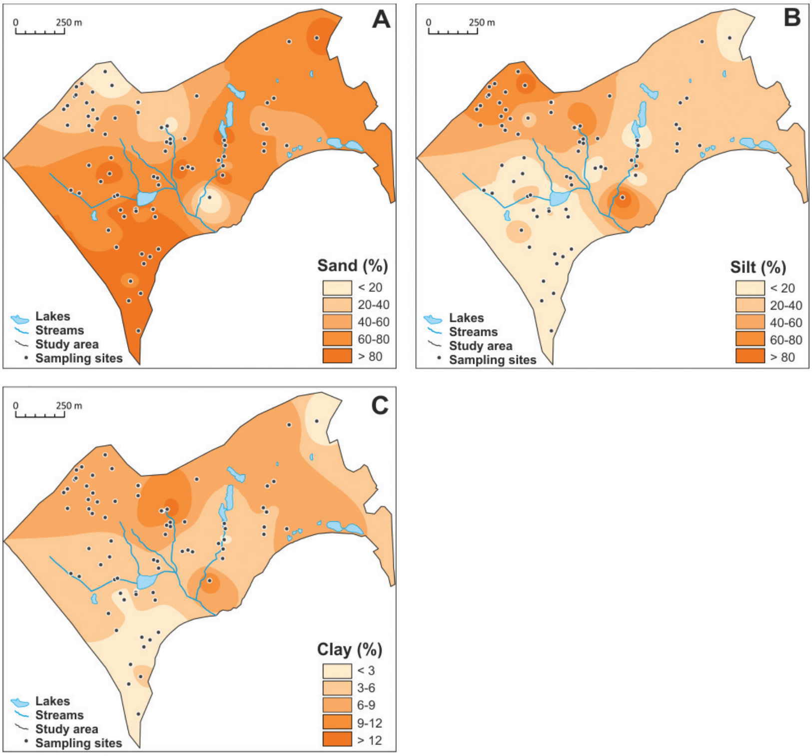

Fig. 2. Content and spatial distribution of sand fraction (**A**), silt fraction (**B**), and clay fraction (**C**) in the soil surface horizons of the lower part of the Fuglebekken catchment.

Table 2

Spearman's rank correlation coefficients between the soil properties.

	Sand	Silt	Clay	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	CaO	Na_2O
pH	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.44	0.53	0.29
Sand		-0.99	-0.88	0.87	-0.92	-0.89	-0.94	-0.70	n.s.	n.s.
Silt			0.83	-0.86	0.92	0.90	0.93	0.71	n.s.	n.s.
Clay				-0.80	0.80	0.75	0.83	0.59	n.s.	n.s.
SiO_2					-0.75	-0.78	-0.78	-0.73	-0.36	n.s.
Al_2O_3						0.96	0.99	0.70	n.s.	n.s.
Fe_2O_3							0.96	0.77	n.s.	n.s.
K_2O								0.70	n.s.	n.s.
MgO									0.59	n.s.
CaO										0.36

n.s. – not significant at the 0.05 level of MgO, CaO, and Na_2O is low, with mean values of 2.3%, 2.0%, and 1.3%, respectively. The lowest content of SiO_2 (from 30.0% to 56.0%) is present in surface horizons in the northwestern part of the study area, while the highest (from 65.0% to 82.0%) occurs in the southwestern part of the catchment and in close vicinity of the lateral moraine of the Hansbreen glacier (Table 1, Fig. 3B). Soils with the lowest content of Al_2O_3 (from 6.5% to 13.0%), Fe_2O_3 (from 3.8% to 7.2%), K_2O (from 1.0% to 2.0%), and Na_2O (from 0.8% to 1.6%) in their surface horizons occur in the southwestern part of the catchment (Table 1, Figs 3 and 4). The highest contents of Al_2O_3 (from 16.0% to 20.3%), Fe_2O_3 (from 9.1% to 11.2%), and K_2O (up to 3.7%) are present in the north-central part of the studied area, *i.e.* at the foot of the slope of the Ariekammen ridge (Table 1, Figs 3 and 4). Soils developed on the lateral moraine of the Hansbreen glacier are characterized by the highest content of MgO (up to 3.7%), CaO (up to 6.8%), and Na_2O (up to 1.8%) in their surface horizons (Table 1, Fig. 4).

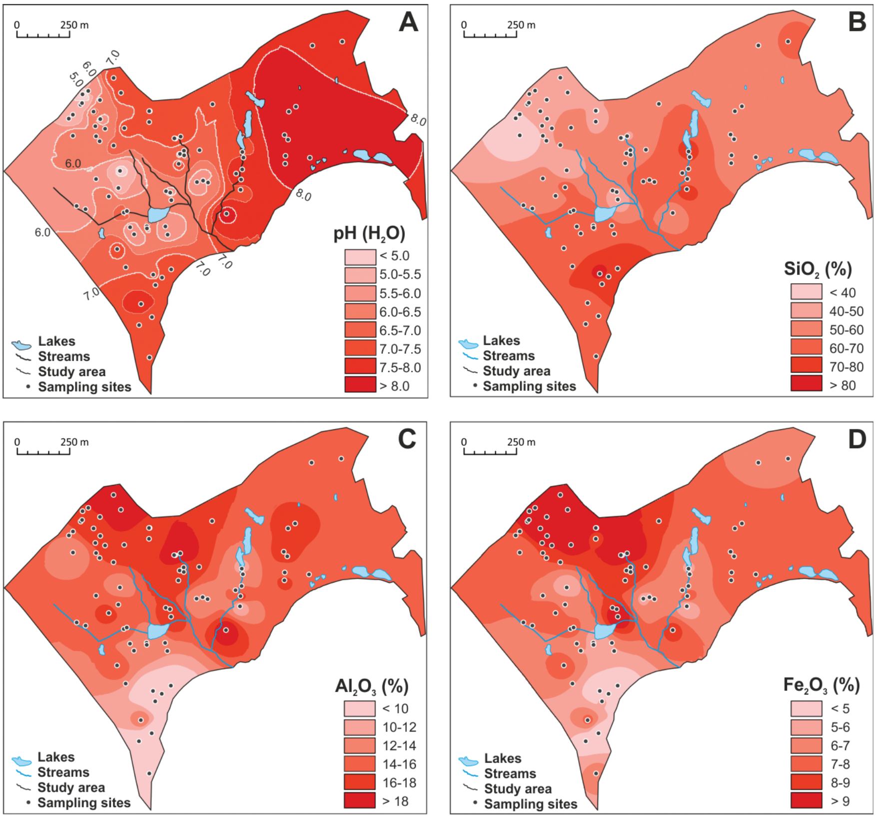

Fig. 3. Reaction (pH in H_2O) (**A**), content and spatial distribution of SiO_2 (**B**), content and spatial distribution of Al_2O_3 (**C**), and content and spatial distribution of Fe_2O_3 (**D**) in the soil surface horizons of the lower part of the Fuglebekken catchment.

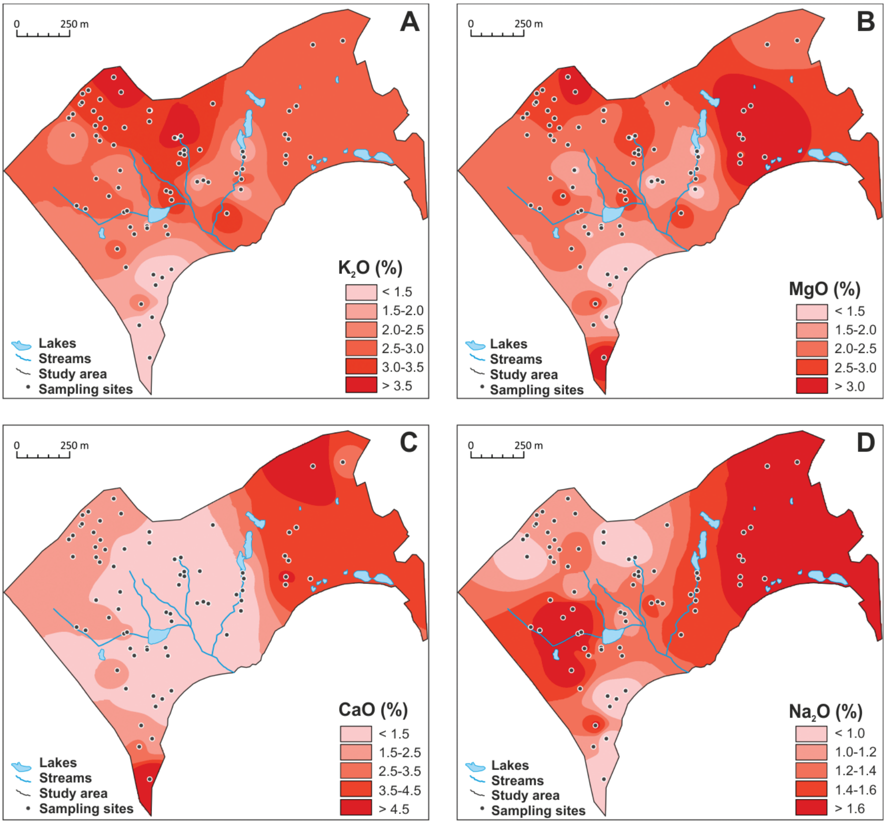

Fig. 4. Content and spatial distribution of K_2O (**A**), MgO (**B**), CaO (**C**), and Na_2O (**D**) in the soil surface horizons of the lower part of the Fuglebekken catchment.

In addition, high contents of MgO and CaO in the surface horizons of soils developed from marine deposits containing carbonates were noted in the most southwestern part of the area (Figs 4B and 4C). Soils containing the lowest amounts of CaO (below 1.5%) and MgO (below 2.5%) occur in the central and southern parts of the area (Table 1, Fig. 4). It should be noted that some soils occurring at the seabird colony and in its close vicinity contain slightly higher amounts of CaO in their surface horizons than soils in the central part of the area. The lowest content of Na_2O (below 1.3%) occurs in the northwestern and southwestern parts of the area (Table 1, Fig. 4D). However, it should be stressed that the spatial distribution of Na_2O, and also MgO, is the most random among the studied compounds.

Discussion

Physical properties of the surface horizons. — The majority of the soils, except those developed on the lateral moraine of the Hansbreen glacier and from the rock debris on the slope of the Ariekammen ridge, were formed from marine deposits covering terraces uplifted during the Holocene (Szerszeń 1965; Lindner *et al*. 1991; Szymański *et al*. 2013). Given that the marine deposits are composed of rock fragments and mineral grains of highly variable size, from stone to clay fractions (Szerszeń 1965; Salvigsen *et al*. 1990; Skiba *et al*. 2002; Szymański *et al*. 2013, 2015), soils developed from these materials also feature variable content of stone, gravel, sand, silt, and clay fractions. However, almost all the soil surface horizons are characterized by a prevalence of the sand fraction in the fine earths (Table 1). This is related to hard rocks, *i.e*. metamorphic schist, paragneiss, quartzite, amphibolite, and marble, occurring in the area, very limited chemical weathering in severe Arctic climate conditions, and a prevalence of physical weathering (Szerszeń 1965; Czerny *et al*. 1993; Szymański *et al*. 2015). Also, the highest content of the sand fraction in soils of the southwestern part of the area, along the northern Hornsund coast, and its gradual decrease towards the slope of the Ariekammen may be related to the nature of material sedimentation in the coastal area during the period when the marine terraces were still below sea level. Most likely, the sedimentation of finer material, *i.e*. containing more silt and clay fractions and less of the sand fraction, had occurred closer to the previous coastline due to weaker wave action. Coarser material, *i.e*. containing fewer silt and clay fractions and more of the sand fraction, was deposited farther from the coast, towards Hornsund, due to stronger wave action. This finding is supported by the highest content of the silt and clay fractions in the surface horizons in the north-central part of the area (Figs 2B and 2C). The higher content of the silt and clay fractions obtained at the foot of the slope of the Ariekammen may be also the effect of surface runoff during spring and early summer when the snow cover on the south-facing slopes of the Ariekammen is thawing as well as the effect of the subsequent accumulation of these fractions just below the slope (Szerszeń 1965). However, sites with both higher and lower content of sand, silt, and clay fractions do occur at some locations in the study area, which may be attributed to very localized differences in sedimentation and/or contemporary periglacial processes such as cryoturbation, frost heave, solifluction, gelifluction, and aeolian processes. The content of sand, silt, and clay fractions in surface horizons of soils developed on the lateral moraine of the Hansbreen glacier is also very heterogeneous due to the heterogeneous nature of the parent material of the soils and its geographic variations (*e.g*. Knight *et al*. 2000; Midgley *et al*. 2013; Ewertowski and Tomczyk 2015).

Soil physical properties, such as texture, porosity, and bulk density, play an important role in the heat propagation in the ground (Hinkel *et al*. 2001; Migała *et al*. 2014; Wilhelm and Bockheim 2016). Wilhelm and Bockheim (2016) have recently shown that sandy soils along the western Antarctic Peninsula are characterized by the highest rate of thawing. Thus, basing only on the texture of the soils, it is expected that in the sites within the Fuglebekken catchment, where the content of sand fraction is the highest, the active layer thickness will be also the highest, *i.e*. along the northern coast of the Hornsund. On the other hand, the active layer, *i.e*. thickness will be the lowest in the sites showing the highest content of silt and especially clay fraction, *i.e*. in the foot of the slope of the Ariekammen ridge.

Chemical properties of the surface horizons. — The spatial variability of pH of the surface soil horizons clearly indicates the effect of seabird guano on soil chemistry. In the soil environment, initially alkaline bird guano is converted into nitrate and oxalic acid, which are responsible for a decrease in soil pH (Tatur and Myrcha 1983, 1984; Tatur 1989). Soils found along the streams flowing away from the bird colony are also characterized by lower pH in comparison with soils in the other sites, indicating the migration of nitrate and oxalic acid with stream water (Fig. 3A). The second reason for the lower pH in soils in this part of the catchment is the occurrence of soils (Reductaquic Cryosols and Histic Turbic Cryosols) with the best developed organic horizons containing organic acids (Szymański *et al*. 2013). Soils with the highest pH had developed on the moraine of the Hansbreen glacier in the eastern part of the study area. The soils contain carbonates (from 4.7% to 10.5%, data not shown) and are covered with sparse vegetation, which supplies a very small amount of organic material and organic acids to the soil. Thus, the presence of carbonates and the lack or presence of only a very initial and discontinuous A horizon are two main reasons for the highest pH of these soils.

The chemical composition of soils is associated with the mineral composition of their parent material, chemical weathering, and various soil-forming processes. All the soils are developed from heterogeneous parent material (marine deposits, moraine of glacier, rock debris) and this is the reason for the diversity of soil chemical composition. Chemical weathering in soils in the study area is very weak and the main soil-forming processes are as follows – cryoturbation, accumulation of organic matter, leaching, and gleyic processes (Szerszeń 1965, 1974; Szymański *et al*. 2013, 2015, 2016). This is in agreement with results obtained by Etzelmüller and Sollid (1991) in the Kongsfjorden area, Skiba *et al*. (2002) in the western region of Sørkappland, Klimowicz and Uziak (1996b) and Klimowicz *et al*. (2009) in the Bellsund area, as well as Kabała and Zapart (2009, 2012) in the proglacial area of the Werenskioldbreen glacier.

SiO_2 is the main component of many silicates and aluminosilicates, which happen to be the most common minerals in many soils, also in the High Arctic, thanks to the high resistivity of these minerals to weathering in the soil environment. The highest SiO_2 content is present in soils in the southwestern part of the study area due to the highest content of the sand fraction in these soils, which is dominated by quartz. This is supported by a strong and positive correlation coefficient for the content of the sand fraction and SiO_2 (Table 2). The lowest content of SiO_2 was determined in soils obtained from the seabird colony and its close vicinity, as the surface horizons of these soils are characterized by fairly well-developed organic horizons as well as a relatively low amount of mineral material (Szymański *et al*. 2013, 2016). The second reason for the lowest content of SiO_2 in these soils is the lower content of the sand fraction and higher content of the silt and clay fractions, which contain apart from quartz also other minerals. The correlation coefficients for the content of the silt and clay fraction and SiO_2 were found to be large and negative (r = -0.86 and -0.80, respectively) (Table 2).

The spatial distribution of Al_2O_3, Fe_2O_3, and K_2O in the soil surface horizons is very similar, *i.e*. the highest content of these elements was determined in surface soil horizons in the north-central part of the studied catchment, and this is related to the content of the silt and clay fractions in the soils (Figs 2B and 2C). Al_2O_3, Fe_2O_3, and K_2O serve as the main components of clay minerals such as illite, chlorite, vermiculite, and smectite. These minerals prevail in the finest fractions of the soils (Szymański *et al*. 2015). This finding is supported by large and positive correlation coefficients for these elements and silt and clay fractions (Table 2). On the other hand, the lowest content of these elements was noted in soils in the southwestern part of the area, characterized mostly by sandy soils with a high prevalence of quartz (Fig. 2A). Slightly higher or lower content of Al_2O_3, Fe_2O_3, and K_2O at select sites in comparison with adjacent sites is related to local differences in the mineral composition of the soil horizons and/or the higher or lower content of organic matter in surface soil horizons (Szymański *et al*. 2015, 2016).

The central part of the catchment is characterized by a lower amount of CaO (Fig. 4C). On one hand, this is related to a lack of carbonates in these soils (Szymański *et al*. 2013), and on the other, this is the effect of the dissolution of mineral and organic constituents containing Ca in the waters of the Fuglebekken stream and its tributaries as well as their confluence with Hornsund. This part of the area is also characterized by a prevalence of Reductaquic Cryosols and Histic Turbic Cryosols covered with a carpet of moss (Szymański *et al*. 2013, 2016), and this fact may serve as another reason for the lowest content of CaO in the area due to more organic surface horizons in comparison with soils in the other sites. The slightly higher content of CaO in selected surface horizons of soils found at the seabird colony and its close vicinity may be related to guano deposition, as shown by Fugler (1985) and Kosakowski *et al*. (2014), who observed that bird guano does contain significant amounts of Ca. The highest content of CaO occurs in soils containing carbonates, *i.e*. soils developed on the lateral moraine of the Hansbreen glacier in the eastern part of the study area and soils developed from marine deposits found in the most southeastern part of the catchment.

The spatial distribution of MgO and Na_2O in the soils is the most random of all the compounds studied (Figs 4B and 4D). The highest content of MgO is present in soils developed on the lateral moraine of the Hansbreen glacier and identified in the southwestern part of the catchment indicating the weakest weathering in these soils due to the presence of carbonates and sparse vegetation (Kabała and Zapart 2012). The high content of MgO in soils in the north-central part of the study area is most likely related to a higher content of minerals containing Mg such as amphibole, biotite, and chlorite, occurring in the silt and clay fractions of these soils (Szymański *et al*. 2015). The lowest content of MgO was determined in surface soil horizons in the central and southern parts of the catchment (Fig. 4B); in some cases, this is related to a higher content of the sand fraction (sites along the Hornsund coast), and in other cases, with a higher organic matter content and the leaching of Mg (sites along local streams). The highest content of Na_2O in soils developed on the lateral moraine indicates that the soils are not strongly weathered, while the lowest content of Na_2O in soils found across the seabird colony and its vicinity results from advanced leaching on one hand and higher content of organic matter on the other. The low content of Na_2O in soils in the southwestern part of the study area is related to a prevalence of sandy soils at these sites and a predominance of SiO_2 in these soils.

Conclusions

Soil surface horizons in the Fuglebekken catchment are characterized by highly variable physical and chemical properties due to a heterogeneous parent material (marine sediments, moraine, rock debris), tundra vegetation types, and non-uniform influence of seabirds. Soils experiencing the strongest influence of seabird guano have a lower pH than other soils. Soils developed on the lateral moraine of the Hansbreen glacier have the highest pH due to the presence of carbonates in the parent material and a lack or presence of a poorly developed and discontinuous A horizon. The soil surface horizons along the coast of the Hornsund exhibit the highest content of the sand fraction and SiO_2. The surface of soils occurring at the foot of the slope of the Ariekammen ridge is characterized by the highest content of silt and clay fractions as well as Al_2O_3, Fe_2O_3, and K_2O. Soils in the central part of the Fuglebekken catchment are depleted in CaO, MgO, and Na_2O in comparison with soils in the other sampling sites, which indicates the highest rate of leaching in this part of the catchment.

Acknowledgements. — This study was supported by the Polish State Committee for Scientific Research via Grant No. N N304410139. Krzysztof Migała from the Department of Climatology and Protection of Atmosphere at the University of Wrocław is thanked for help during field studies. We wish to thank Cezary Kabała and Tony R. Walker for their helpful reviews. Language editing was done by Grzegorz Zębik.

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Received 3 March 2016
Accepted 4 July 2016