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Organic carbon and nutrients (N, P) in surface soil horizons in a non-glaciated catchment, SW Spitsbergen

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Abstract: Organic carbon, nitrogen, and phosphorus in the soils of the High Arctic play an important role in the context of global warming, biodiversity, and richness of tundra vegetation. The main aim of the present study was to determine the content and spatial distribution of soil organic carbon (SOC), total nitrogen (N_{tot}), and total phosphorus (P_{tot}) in the surface horizons of Arctic soils obtained from the lower part of the Fuglebekken catchment in Spitsbergen as an example of a small non-glaciated catchment representing uplifted marine terraces of the Svalbard Archipelago. The obtained results indicate that surface soil horizons in the Fuglebekken catchment show considerable differences in content of SOC, N_{tot}, and P_{tot}. This mosaic is related to high variability of soil type, local hydrology, vegetation (type and quantity), and especially location of seabird nesting colony. The highest content of SOC, N_{tot}, and P_{tot} occurs in soil surface horizons obtained from sites fertilized by seabird guano and located along streams flowing from the direction of the seabird colony. The content of SOC, N_{tot}, and P_{tot} is strongly negatively correlated with distance from seabird colony indicating a strong influence of the birds on the fertility of the studied soils and indirectly on the accumulation of soil organic matter. The lowest content of SOC, N_{tot}, and P_{tot} occurs in soil surface horizons obtained from the lateral moraine of the Hansbreen glacier and from sites in the close vicinity of the lateral moraine. The content of N_{tot}, P_{tot}, and SOC in soil surface horizons are strongly and positively correlated with one another, *i.e.* the higher the content of nutrients, the higher the content of SOC. The spatial distribution of SOC, N_{tot}, and P_{tot} in soils of the Hornsund area in SW Spitsbergen reflects the combined effects of severe climate conditions and periglacial processes. Seabirds play a crucial role in nutrient enrichment in these weakly developed soils.

Key words: Arctic, Svalbard, soil organic carbon, nitrogen, phosphorus, Cryosols.

Introduction

The High Arctic is characterized by a predominance of permafrost-affected soils, which are known as Cryosols, according to the WRB classification system (IUSS Working Group WRB 2014), and Gelisols, according to the Soil Taxonomy (Soil Survey Staff 1999). According to both the WRB and Soil Taxonomy, Cryosols/Gelisols are defined as soils containing permafrost within one meter from the soil surface and lack cryoturbation or within two meters providing evidence of cryoturbation (Bockheim *et al.* 2006). These soils are a very important carbon sink in the context of global climate change due to a very slow mineralization rate of soil organic matter (SOM) and low activity of soil microorganisms associated with severe climate conditions (*e.g.* Opaliński 1991; Klimowicz *et al.* 1997; White *et al.* 2002). It was recently estimated that organic carbon stocks in 0–2 m depth of Cryosols from northern circumpolar permafrost region are 827±108 Pg and in 0–3 m depth, the stocks in the Cryosols are 1035±150 Pg (Hugelius *et al.* 2014). High Arctic soils contain 34±16 Pg SOC and 24±8 Pg in the 0–3 m and 0–1 m depth ranges, respectively (Hugelius *et al.* 2014). However, the continually increasing air temperature in the world, known as global warming, may lead in the nearest future to a higher rate of mineralization of soil organic matter and may help release a large amount of carbon dioxide, nitrogen oxide, and methane into the Earth's atmosphere. Thus, Arctic soils will be an important carbon and nitrogen source contributing to further warming of the global climate due to a higher concentration of greenhouse gases (CO_2, NO_x, CH_4) in the atmosphere, all of which are released from soils thanks to the decomposition of organic matter (Lal 2004; Paré and Bedard-Haughn 2012; Zubrzycki *et al.* 2013, 2014). On the other hand, an increase in SOM mineralization and the release of nitrogen may increase plant productivity leading to greater carbon sequestration on non-glaciated surfaces of polar regions (Paré and Bedard-Haughn 2012). In addition, the global warming is responsible for primary accumulation of organic carbon and total nitrogen in surface of recently deglaciated areas (*e.g.* Kabała and Zapart 2012).

Madan *et al.* (2007) showed that both content and availability of nutrients, especially nitrogen and phosphorus, play an important role in species richness, diversity and productivity of tundra vegetation in High Arctic ecosystems. Moreover, the influence of the availability of nitrogen on tundra vegetation is higher when phosphorus is also present and available to plants in comparison with areas without this element (Madan *et al.* 2007). Thus, it is very likely that the areas being fertilized by seabirds are potentially the most susceptible to changes in vegetation cover due to higher supply of nitrogen and phosphorus. According to the literature, atmospheric deposition of nitrogen in Arctic areas is negligible (Solheim *et al.* 1996; Madan *et al.* 2007). It was estimated that this type of deposition ranges from 0.1 to 0.5 g N m^{-2} a^{-1} (Woodin 1997; Skrzypek *et al.* 2015). However, the supply of nitrogen and phosphorus is probably much higher in areas being fertilized by seabirds (Solheim *et al.* 1996; Zwolicki *et al.* 2013).

Many studies concerning the content and dynamics of SOC as well as nutrients such as nitrogen and phosphorus have been conducted at selected sites (plots), and can be described as strongly spatially limited (*e.g.* Solheim *et al.* 1996; Bardgett *et al.* 2007; Madan *et al.* 2007; Paré and Bedard-Haughn 2012). On the other hand, studies concerning the content and spatial distribution of these key elements in soils in polar regions are very rare (Fritsen *et al.* 2000). Taking into consideration that polar regions (tundra landscapes) are very heterogeneous even on a small scale, *i.e.* dry sites *vs.* wetland sites, flat sites *vs.* sloping sites, bare sites *vs.* highly vegetated sites occurring in close proximity to each other (Sjögersten *et al.* 2006; Paré and Bedard-Haughn 2012; Migała *et al.* 2014), it is important to conduct several studies at the catchment scale. Such studies would generate more complete data on the local environment and relationships between its various components. Furthermore, this research scale is also very important in studies on the soil organic carbon and nitrogen content, because as shown by Jones *et al.* (2000), Welker *et al.* (2000), McFadden *et al.* (2003), and Sjögersten *et al.* (2006), some soils may act as carbon and nitrogen sinks and other, adjacent soils may serve as carbon and nitrogen sources in the context of the emission of greenhouse gases and climate change. Since carbon and nitrogen storage estimates for permafrost-affected soils are very important (*e.g.* Tarnocai *et al.* 2009; Hugelius *et al.* 2010, 2014; Kuhry *et al.* 2013; Zubrzycki *et al.* 2013; Ping *et al.* 2015), and many Arctic areas are not readily available for scientific studies, it is necessary to conduct this type of research in representative and readily accessible areas of the Arctic and extrapolate the obtained results to other areas with a similar natural environment (Zubrzycki *et al.* 2014).

The main aim of this study was to determine the content and spatial distribution of SOC, N_{tot}, and P_{tot} in the surface horizons of Arctic soils from the lower part of the Fuglebekken catchment in Spitsbergen. Since the study area is very similar to many flat raised marine terraces occurring in Svalbard, the presented results could be extrapolated to other similar sites as well as could be used in future studies for comparison purposes and monitoring of soil organic carbon, nitrogen, and phosphorus content in relation to climate change.

Study area

The study area is located along the northern coast of the Hornsund fjord in the southern part of Spitsbergen (Fig. 1). The study was carried out on marine terraces (elevation from 2 to 30 m a.s.l.), raised during Holocene (Lindner *et al.* 1991) in the small, non-glaciated catchment of the Fuglebekken stream (area ~1.5 km^2) in close proximity to the Polish Polar Station (77^{o}00'N; 15^{o}33'E; 10 m a.s.l.) and on a

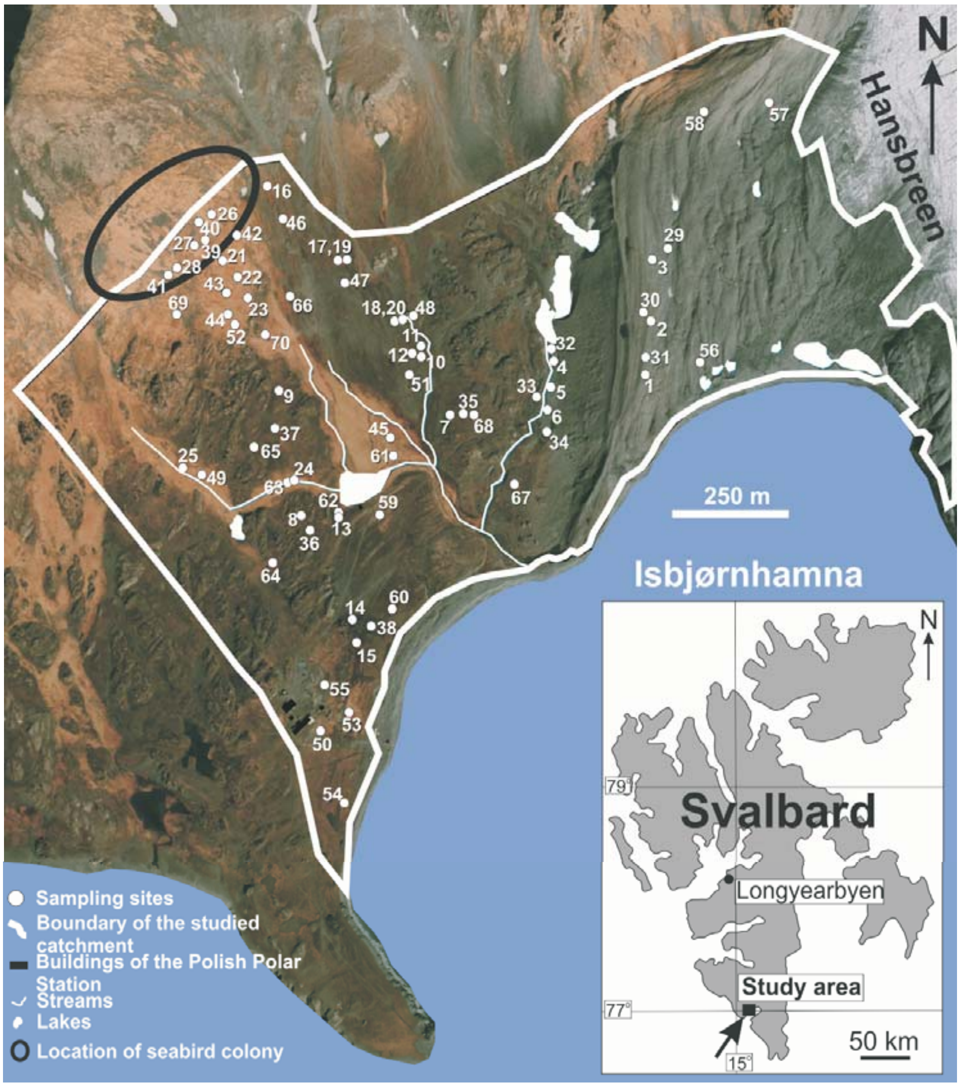

Fig. 1. Location of the studied area and the sampling sites in the lower part of the Fuglebekken catchment. Basemap from Kolondra (1995).

rolling, lateral moraine of the Hansbreen glacier (elevation up to 60 m a.s.l.), which occurs in the eastern part of the study area (Fig. 1). Metamorphic schist, paragneiss, marble, quartzite, and amphibolite form the main bedrock of the study area (Czerny *et al.* 1993; Majka *et al.* 2010). However, unsorted and mostly coarse-grained marine deposits showing variable lithological and mineralogical composition serve as the parent material of soils occurring on uplifted marine terraces (Szymański *et al.* 2015). The studied area is characterized by a predominance of Haplic Cryosols, Hyperskeletic Cryosols, and Turbic Cryosols (Szymański *et* *al.* 2013, 2015; Migała *et al.* 2014). Haplic Cryosols and Hyperskeletic Cryosols are formed from coarse and very coarse deposits (stone and gravel) containing small amounts of fine earth material (mainly the sand fraction). Turbic Cryosols show higher amounts of fine fractions (especially silt) and lower amounts of stone and gravel in comparison with Haplic Cryosols and Hyperskeletic Cryosols. In addition, Turbic Cryosols are characterized by specific micro-relief on the surface (*i.e.* stony circles, polygons or stripes surrounding loamy material) and lack of easily discernible horizonation of the soil profile indicating strong cryoturbation (Szymański *et al.* 2013, 2015). Haplic Cryosols and Hyperskeletic Cryosols serve as habitats for dry lichen-heath tundra vegetation with *Cetraria delisei*, *Ochrolechia frigida*, *Salix polaris*, *Saxifraga oppositifolia*, and *Polytrichastrum alpinum* being the most popular species. Wet moss tundra vegetation occurs along the Fuglebekken stream and its tributaries and is characterized by a predominance of *Sanionia uncinata*, *Warnstorfia sarmentosa*, *Straminergon stramineum*, and *Aulacomnium palustre*. Turbic Cryosols are covered mainly by cyanobacteria mats. At sites occupied by colonies of little auks (*Alle alle*) and in their close vicinity, so-called nitro-coprophilous tundra or ornithocoprophilous tundra vegetation can be observed. The two most common vascular plant species at such sites are *Chrysosplenium tetrandrum* and *Cochlearia groenlandica* (Dubiel and Olech 1992). More details concerning the soils and tundra vegetation of the study area can be found in Szymański *et al.* (2013, 2015), Wojtuń *et al.* (2013), and Migała *et al.* (2014). The mean annual air temperature (MAAT) in the study area is -4.2°C ranging from -11.3°C in January to +4.4°C in July and total annual precipitation (TAP) is 450 mm (Marsz and Styszyńska 2007; Migała *et al.* 2008), see also Hornsund GLACIOTOPOCLIM Database 2014 (http://www.glacio-topoclim.org retrieved on 9 November 2015). However, the MAAT and TAP in the study area vary greatly from year to year. Mean annual relative air humidity in the study area was 80% and days with snow cover was about 250 per year (data for period 1979–2013) (Hornsund GLACIOTOPOCLIM Database 2014). According to Miętus and Filipiak (2004) and Migała *et al.* (2004), ground in the vicinity of the Polish Polar Station (the site is located atop Haplic Cryosols) thaws to an average depth of 1.75 m, but varies from 1.39 to 2.02 m depending on weather conditions in each particular season. Mean annual ground temperature (MAGT) of the top one meter is between -2.0 and -3.0°C (data for period 2000–2009 from site located atop Haplic Cryosols) (Marsz 2013).

Materials and methods

Soil samples from surface horizons (the uppermost 10 cm) were collected during the summer of 2011 and 2013. The exact location of the collected samples is shown in Fig. 1 and the environmental details concerning each of the studied sites

Table 1

Environmental characteristics of the studied sites.

Soils[a]	Microtopography/ pattern ground	Parent material	Plant community[b]	Texture	Wetness	Cryoturbation	No. of study sites
Haplic Cryosols	flat	marine deposits	lichen-herb-heath	sand/loamy sand	dry	no	4–9, 32–38, 13–20, 46–48, 50, 53–55, 59–60, 62, 65, 67–68
Hyperskeletic Cryosols	rolling	lateral moraine	geophytic initial	sand/loamy sand	dry/ moist	no	1–3, 29–31, 56–58
Turbic Cryosols	stony circles or stripes	marine deposits	polygonal	sandy loam/silt loam	moist	yes	10–12, 51, 64, 66
Reductaquic Cryosols	flat	marine deposits	wet moss	sand/loamy sand	wet	no	21–25, 43–45, 49, 52, 61, 63, 70
Leptic Regosols Ornithic	irregular	rocky debris	ornithocopro-philous	sandy loam	moist	no	26–28, 39–42, 69

a – according to the WRB 2014, b – according to Szymański *et al.* (2013).

are summarized in Table 1. The soil samples were taken from sites that differed in: (1) soil type (Haplic Cryosols, Reductaquic Cryosols, Hyperskeletic Cryosols, Turbic Cryosols, Leptic Regosols Ornithic), (2) relief (flat raised marine terrace, lateral moraine), (3) degree of wetness (dry, moist, wet), and (4) tundra vegetation type (geophytic initial, polygonal, lichen-herb-heath, wet moss, ornitocoprophilous) (Table 1). Initial soils (Lithic Leptosols) occurring on rock outcrops in the study area were not taken into consideration due to their highly variable soil properties, which lead to considerable problems with interpolation. After collection, the samples were air dried, gently crushed using a wooden rolling pin, and sieved through a 2 mm steel sieve. All the laboratory analyses were done in the fine earth material (fraction < 2 mm). The content of soil organic carbon was determined (in duplicate and then averaged) via rapid dichromate oxidation technique (Nelson and Sommers 1996). The content of N_{tot} (in triplicate and then averaged) was determined by means of a Vario Micro Cube CHNS elemental analyzer. P_{tot} content (in duplicate and then averaged) was determined using molybdenum blue after sample ignition at 550°C (Radojević and Bashkin 2006).

Environmental data (content of SOC, N_{tot}, P_{tot}, C/N ratio, and distance of the sites from the center of the seabirds colony) were correlated with each other using Spearman's correlation coefficient (level of significance at $p < 0.05$). All calculations were done using Statistica ver. 12 software.

Maps of the spatial distribution of SOC, N_{tot}, and P_{tot} content in surface horizons were produced using the inverse distance weighting (IDW) deterministic interpolation method with the 3rd power function modifying the distance weights (Lu and Wong 2008). The interpolation was calculated in an ESRI ArcMap environment with an assumed resolution of 2.5 m.

Results and discussion

Content and spatial distribution of soil organic carbon and total nitrogen. — The content and spatial distribution of SOC and N_{tot} in the surface horizons of Cryosols from the lower part of the Fuglebekken stream catchment are shown in Table 2 and Figs 2 and 3, respectively. In spite of the very small surface area of the studied catchment (~1.5 km^2), differences in the content of SOC and N_{tot} in the surface horizon of the studied soils are very large. The lowest content of SOC (3.4–4.7 g kg^{-1} with a mean of 4.2 g kg^{-1}) and N_{tot} (0.3–0.6 g kg^{-1} with mean of 0.5 g kg^{-1}) is at the surface horizons of soils (Hyperskeletic Cryosols, Hyperskeletic Leptosols) from the eastern part of the study area, which is occupied by a lateral moraine of the Hansbreen glacier. The low content of SOC and N_{tot} in this part of the Fuglebekken catchment is related to very sparse surface vegetation due to locally severe climate conditions associated with the close vicinity of the glacier and a quite high instability of the ground due to the thawing of the ice core occurring inside the moraine. In addition, in this part of the catchment, the soils are formed from very stony parent material containing only a very small amount of fine earth material making such sites unfavorable for plant colo-

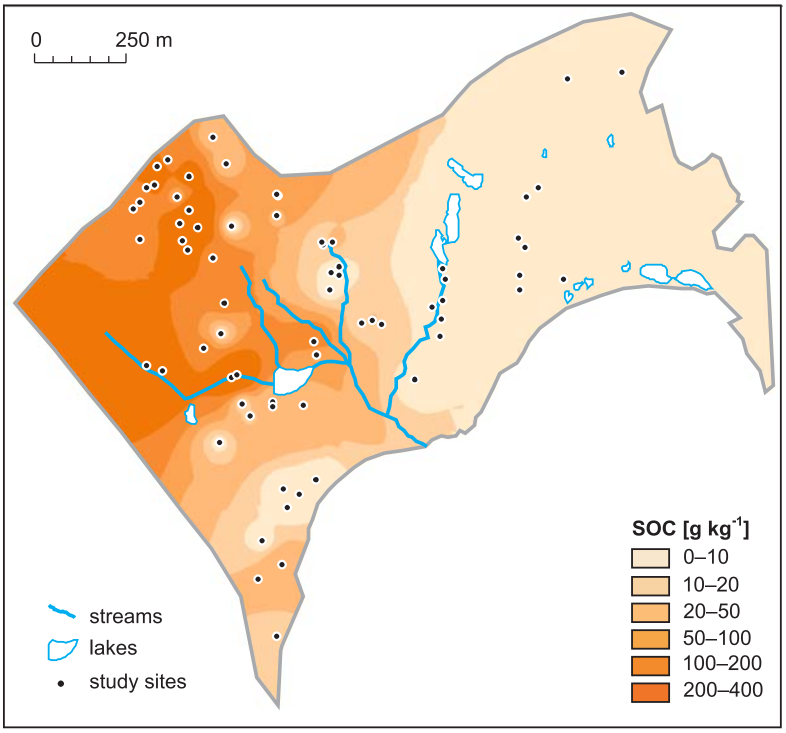

Fig. 2. Content and spatial distribution of soil organic carbon (SOC) in the soil surface horizons of the lower part of the Fuglebekken catchment.

Table 2

Content of soil organic carbon, total nitrogen, total phosphorus, C/N ratio in the surface soil horizons studied and distance of the studied sites from the center of the seabirds colony.

No.	Soil organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Total phosphorus (g kg^{-1})	C/N ratio	Distance from seabird colony (m)
1	4.7	0.5	0.6	9	1049
2	4.2	0.3	0.4	14	1045
3	4.7	0.6	0.6	8	1047
4	5.1	0.6	0.5	9	850
5	5.5	0.6	0.6	9	857
6	9.1	1.1	0.7	8	867
7	21.2	1.9	0.4	11	679
8	17.5	1.6	0.4	11	593
9	109.3	8.1	0.9	13	347
10	7.5	0.8	0.5	9	574
11	8.5	1.0	0.5	9	567
12	7.2	0.8	0.5	9	553
13	15.2	1.8	0.8	8	641
14	4.3	0.6	0.6	7	843
15	8.4	1.0	0.6	8	892
16	25.9	1.8	0.7	14	287
17	95.4	4.4	0.8	22	386
18	14.4	1.2	0.6	12	515
19	99.0	5.1	0.8	19	386
20	13.2	1.2	0.6	11	515
21	53.4	4.6	1.0	12	121
22	367.5	21.7	1.6	17	149
23	331.3	20.4	1.8	16	178
24	370.0	23.3	1.6	16	518
25	357.8	22.9	2.1	16	417
26	146.0	14.0	1.6	10	160
27	198.4	19.1	1.4	10	27
28	133.7	13.2	1.5	10	26
29	4.1	0.4	1.0	10	1079
30	4.0	0.5	1.0	8	1029
31	3.7	0.5	1.0	7	1044
32	3.2	0.4	0.7	8	838
33	5.2	0.7	0.8	7	836
34	3.4	0.4	0.7	9	883
35	10.4	1.1	0.5	9	702
36	9.8	1.1	0.8	9	631
37	12.0	1.3	1.0	9	405
38	5.6	0.8	0.8	7	876
39	222.8	23.6	2.8	9	86
40	281.8	23.9	2.3	12	132
41	198.2	20.9	2.5	9	1
42	243.1	22.8	3.6	11	172

Table 2 – *continued*.

No.	Soil organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Total phosphorus (g kg^{-1})	C/N ratio	Distance from seabird colony (m)
43	210.8	18.4	6.2	11	130
44	277.6	24.3	3.6	11	154
45	161.3	13.2	2.7	12	596
46	21.6	1.8	0.9	12	276
47	46.0	2.9	1.0	16	381
48	23.8	1.8	0.9	13	537
49	392.5	12.0	1.1	33	438
50	20.3	2.0	0.9	10	1037
51	7.5	0.8	0.7	9	564
52	275.3	19.4	2.1	14	181
53	39.1	4.1	1.0	10	1023
54	17.3	1.4	1.1	12	1199
55	7.2	0.6	0.9	12	945
56	4.6	0.5	1.1	9	1157
57	4.5	0.5	0.8	9	1349
58	3.4	0.4	0.7	9	1207
59	28.9	1.9	0.8	15	688
60	5.8	0.7	0.8	8	866
61	46.6	4.4	1.7	11	622
62	44.8	3.9	0.8	11	632
63	344.4	21.0	2.6	16	517
64	8.4	1.1	1.0	8	661
65	105.8	10.2	1.6	10	416
66	5.1	0.4	0.8	13	267
67	6.4	0.9	0.9	7	875
68	15.7	1.5	0.7	10	727
69	128.0	14.5	2.2	9	84
70	147.3	13.5	2.5	11	247

nization (Szymański *et al.* 2013). A slightly higher content of SOC and N_{tot} in the surface horizon of the studied soils (Haplic Cryosols) occurs at sites in the close vicinity of the western, terminal part of the lateral moraine of the Hansbreen glacier (content of SOC from 3.2 to 9.1 g kg^{-1} with a mean of 5.3 g kg^{-1} and N_{tot} from 0.4 to 1.1 g kg^{-1} with a mean of 0.6 g kg^{-1}), at sites with sorted patterned ground (Turbic Cryosols) (SOC content 5.1–8.5 g kg^{-1} with a mean of 7.4 g kg^{-1}; N_{tot} content 0.4 to 1.1 g kg^{-1} with a mean of 0.8 g kg^{-1}), and in soils formed from very coarse parent material containing a high amount of stone and gravel and a low amount of fine earth material (Hyperskeletic Cryosols and some Haplic Cryosols) (SOC content 4.3–109.3 g kg^{-1} with a mean of 30.2 g kg^{-1}; N_{tot} content 0.2–10.2 g kg^{-1} with a mean of 2.4 g kg^{-1}). Sites in the close vicinity of the studied moraine were also covered with sparse vegetation – most likely due to a moderately strong influence of the Hansbreen glacier on their microclimate, and this is

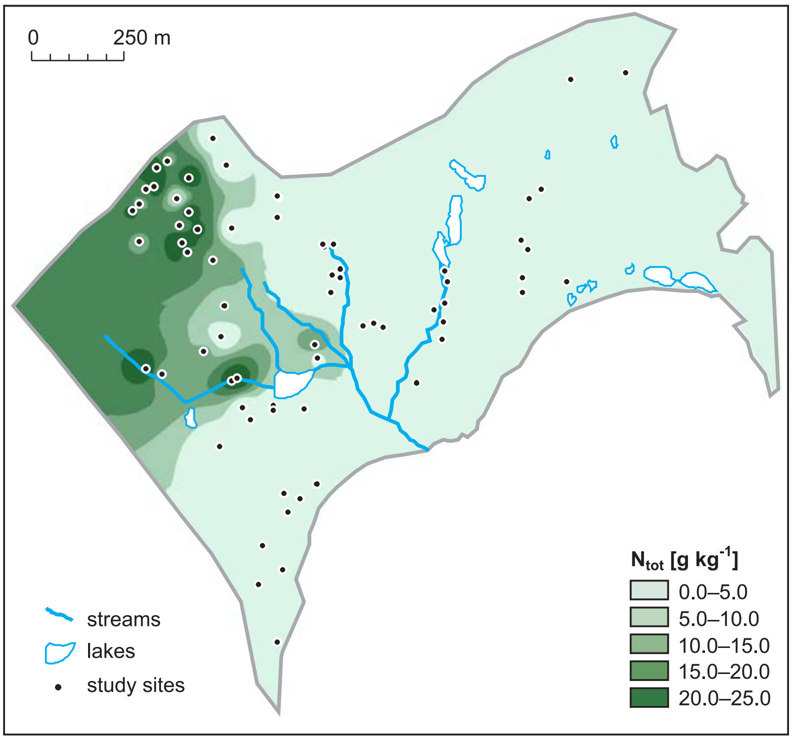

Fig. 3. Content and spatial distribution of total nitrogen (N_{tot}) in the soil surface horizons of the lower part of the Fuglebekken catchment.

the first potential reason for the low content of SOC and N_{tot} in soils from this site. The second reason for the low content of SOC and N_{tot} could be solifluctional and/or aeolian deposition of organically poor soil material from the adjacent moraine. Areas with sorted patterned ground (*i.e.* Turbic Cryosols) are characterized by sparse vegetation because of intense soil mixing related to cryoturbation (Bölter 2011; Szymański *et al.* 2015). At cryoturbated sites, the soil surface is covered only with discontinuous cyanobacterial mats with only a few vascular plants present (*Saxifraga* sp.) (Szymański *et al.* 2013). The scarcity of vegetation at sites featuring soils containing very high amounts of the coarse fraction and small amounts of fine earth material (Hyperskeletic Cryosols and some Haplic Cryosols) is the effect of the high aridity of such sites, which are covered only with lichens (*Cetrariella delisei*, *Ochrolechia frigida*, *Cladonia* sp.).

At sites, where the surface horizon contains a higher amount of fine earth material or in the close vicinity of ephemeral, small ponds, vegetation coverage is better developed and the content of SOC and N_{tot} at such sites is also higher (up to 110.0 g kg^{-1} and up to 10.0 g kg^{-1}, respectively). This is most likely related to more moisture at such sites and occurrence of water for a longer period of time, both of which favor accumulation of soil organic matter. The highest content of SOC (up to 392.5 g kg^{-1}

with a mean of 232.8 g kg^{-1}) and N_{tot} (up to 24.3 g kg^{-1} with a mean of 17.7 g kg^{-1}) in the surface horizons of soils in the Fuglebekken catchment occurs in its northwestern part, where Leptic Regosols Ornithic prevail, and along the Fuglebekken stream and its western tributaries, where Reductaquic Cryosols prevail (Figs 2 and 3).

The northwestern part of the studied catchment is occupied by a large seabird colony (Fig. 1). The birds (little auks) are responsible for the fertilization of soils and the development of lush vegetation. Soils (Reductaquic Cryosols) along the studied streams are covered with a continuous carpet of moss – mainly *Sanionia uncinata*, *Warnstorfia sarmentosa*, *Straminergon stramineum*, and *Aulacomnium palustre* – which supply large amounts of organic matter that is slowly decomposable by microorganisms due to severe Arctic climate conditions and the substantial wetness of the aforesaid soils (White *et al.* 2002; Sjögersten *et al.* 2006; Szymański *et al.* 2013). This finding is in accordance with research results presented by Bardgett *et al.* (2007) who were also able to show that moist soils contain higher amounts of organic matter than soils from dry sites in a High Arctic ecosystem. The highest content of N_{tot} at sites along the Fuglebekken stream is also most likely associated with the transport of dissolved nitrogen in the water of the streams originating in the large seabird colony (*Alle alle*) located on the southern slope of the Ariekammen mountain (Krzyszowska 1985; Opaliński 1991). Local enrichment of surface horizons in SOC and N_{tot} at selected sites in the studied catchment may be explained by the local effect of excreta of birds nesting on the ground including Arctic terns (*Sterna paradisaea*) and Arctic skuas (*Stercorarius parasiticus*).

The content of SOC and N_{tot} in the studied surface soil horizons is strongly and positively correlated ($r = 0.98$, $p < 0.001$), indicating a strong relationship between these two factors (Table 3). In general, the content of SOC and N_{tot} decreases with increasing distance from the seabird colony, indicating an impact of the birds' guano on the content of SOC and N_{tot} in the studied surface soil horizons due to soil fertilization, which leads to the encroachment of vegetation (Table 3, Figs 2 and 3).

The C/N ratio in the surface horizons of the studied soils and its spatial distribution are shown in Table 2 and Fig. 4, respectively. Surprisingly, most of the surface soil horizons studied show a relatively low C/N ratio (from 7 to 17) (Table 2), which may indicate a quite high decomposition rate for organic matter despite severe climate conditions. However, most likely, such a C/N ratio is related to SOM

Table 3

Spearman's rank correlation coefficients between soil organic carbon, total nitrogen, total phosphorus, C/N ratio, and distance from the center of the seabirds colony.

	Total nitrogen	Total phosphorus	C/N ratio	Distance from seabirds colony
Soil organic carbon	0.98***	0.67***	0.68***	-0.78***
Total nitrogen		0.70***	0.57***	-0.78***
Total phosphorus			0.32*	-0.50***
C/N ratio				-0.49***

* statistically significant at $p < 0.05$, *** statistically significant at $p < 0.001$.

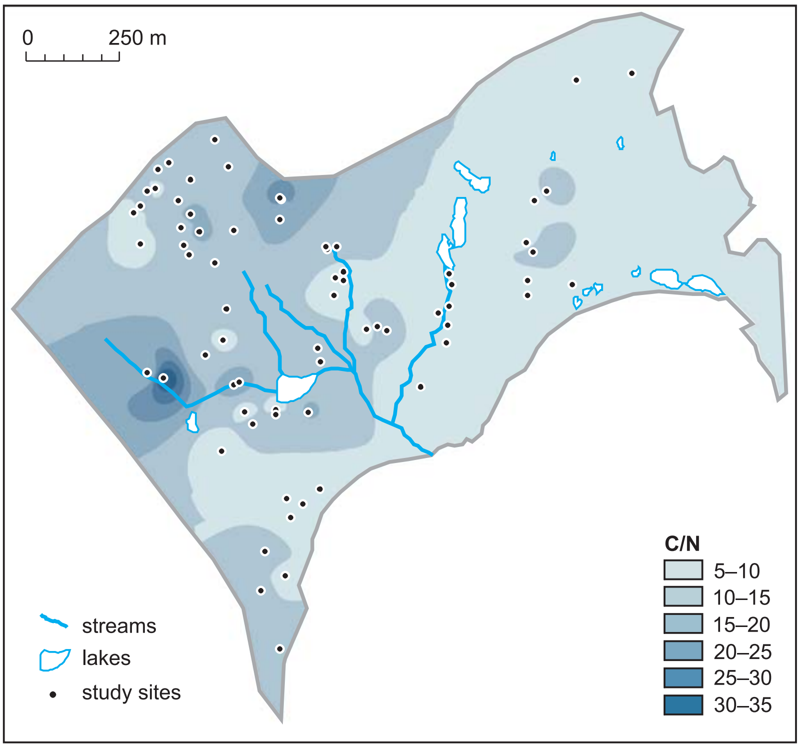

Fig. 4. C/N ratio and its spatial distribution in the soil surface horizons of the lower part of the Fuglebekken catchment.

with its high content of protein, polysaccharides, and chitin containing nitrogen (Beyer and Bölter 2000). Similar C/N ratios calculated for soils sampled in Spitsbergen were reported by Dziadowiec *et al.* (1994) and Świtoniak *et al.* (2014). The C/N ratio in the studied soils is strongly and positively correlated with SOC ($r = 0.68$, $p < 0.001$) and N_{tot} ($r = 0.57$, $p < 0.001$) (Table 3). Higher correlation coefficient between C/N ratio and SOC indicates that SOC content has stronger impact on C/N ratio than N_{tot} content in the studied soils. Lower correlation coefficient between C/N ratio and P_{tot} ($r = 0.32$, $p < 0.05$) indicates lower impact of P_{tot} on C/N ratio in comparison with SOC and N_{tot} (Table 3).

Content and spatial distribution of total phosphorus. — The content and spatial distribution of P_{tot} in the surface horizons of soils from the Fuglebekken catchment are shown in Table 2 and Fig. 5, respectively.

The soil surface horizons from the Fuglebekken catchment exhibit a fairly variable content of P_{tot}, *i.e.* ranging from 0.4 to 6.2 g kg^{-1} (Table 2, Fig. 5). The lowest content of P_{tot} occurs in the eastern part, occupied by the lateral moraine of the Hansbreen glacier, and southern part, along the Hornsund coast, of the studied area, and ranges from 0.4 to 1.0 g kg^{-1}. Locally, the content of P_{tot} is slightly higher, *i.e.* up

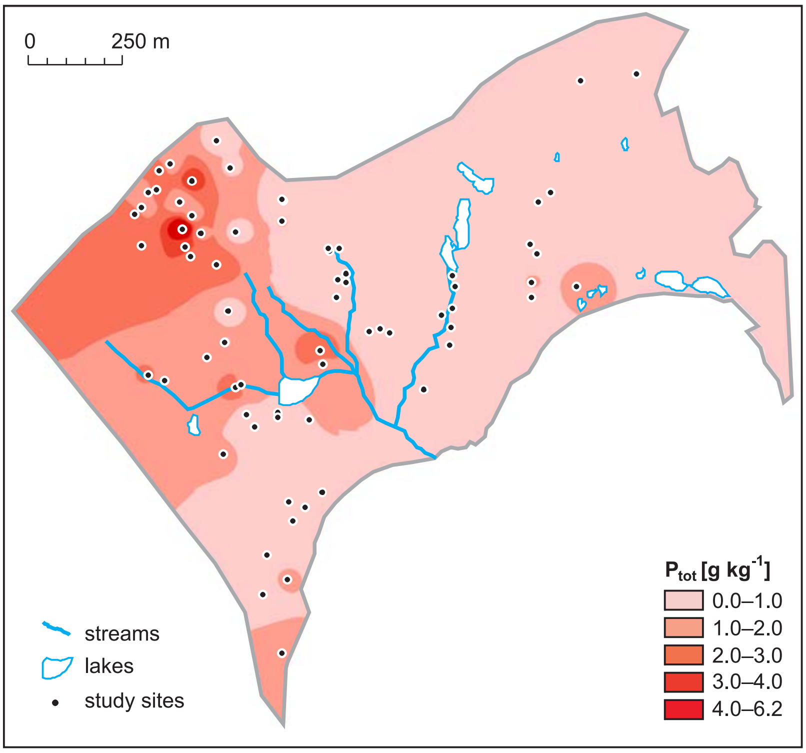

Fig. 5. Content and spatial distribution of total phosphorus (P_{tot}) in the soil surface horizons of the lower part of the Fuglebekken catchment.

to 1.1 g kg^{-1}, in these parts of the studied catchment. This is most likely related to the local effect of the excreta of reindeer and/or seabirds such as Arctic terns (*Sterna paradisaea*) and Arctic skuas (*Stercorarius parasiticus*), which nest on the ground, and were observed at some sites in the studied catchment. The highest content of P_{tot} is found in soils occurring in the northwestern part of the catchment – in close proximity to a large seabird colony and along streams flowing from the direction of the colony (Fig. 5). This shows an impact of the guano of seabirds (little auks) on the content of P_{tot} in the soils studied. In addition, the content of P_{tot} is strongly and positively correlated with SOC ($r = 0.67$, $p < 0.001$) and N_{tot} ($r = 0.70$, $p < 0.001$) (Table 3), indicating strong indirect influence of seabird guano on the accumulation of soil organic matter. In other words, seabird colonies are specific hotspots of organic matter in a fairly – organically – poor tundra environment. Hotspots of organic matter dot areas near streams flowing from the direction of the seabird colony.

The obtained P_{tot} data clearly indicate that the guano of seabirds strongly fertilizes the soil cover of the colony and its close vicinity, and the influence of birds clearly weakens with increasing distance from the colony ($r = -0.50$, $p < 0.001$) (Table 3, Fig. 5). This is in agreement with data previously presented by Zwolicki *et al.* (2013) and Ziółek and Melke (2014). Furthermore, the studied bird colony is located

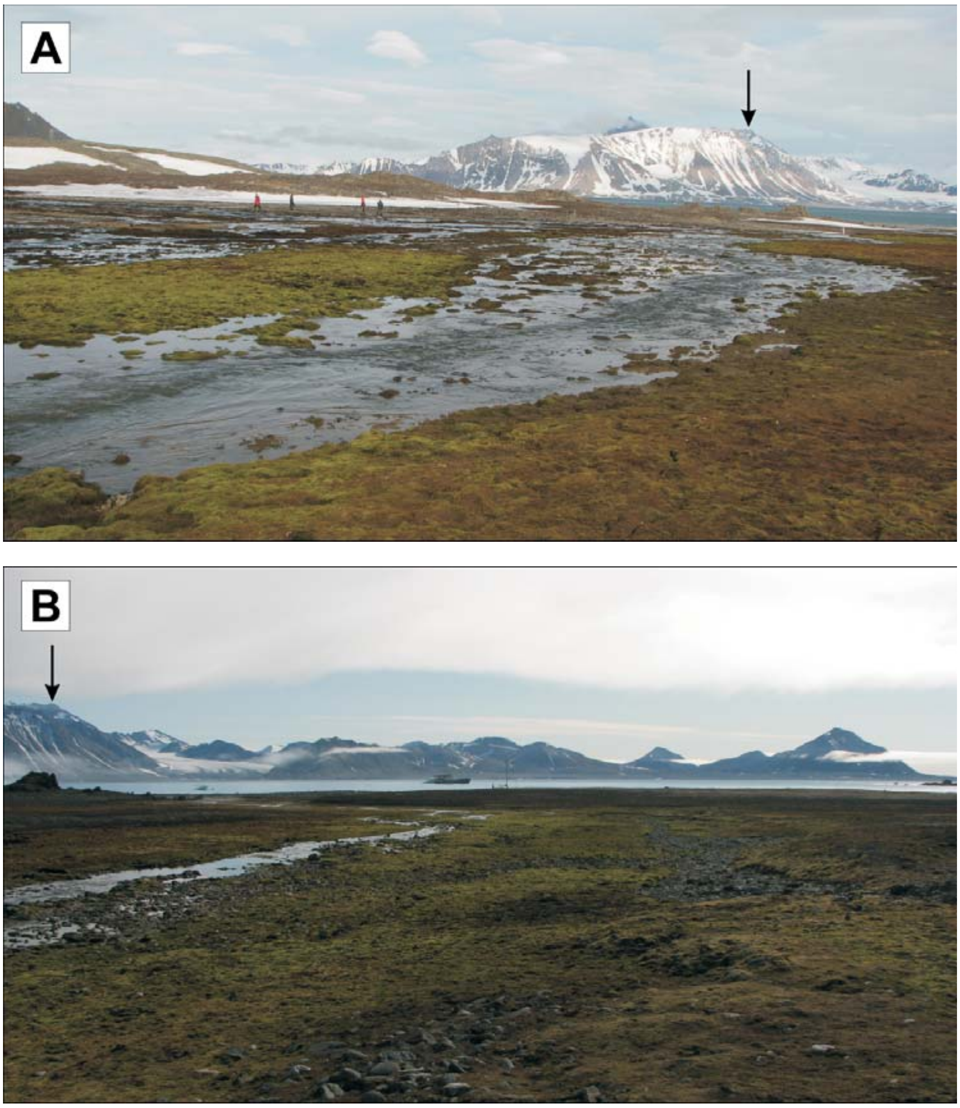

Fig. 6. Fuglebekken stream in late June (**A**) and in early August (**B**); arrows show the same peak for better orientation.

on the slope of the Ariekammen mountain, which is the main contributing area of the Fuglebekken stream and its tributaries, and this also affects the P_{tot} concentration in soils along the streams. The enrichment in P of soils along streams occurs mainly during the melting of the snow cover (June and early July). At this time, streams contain a large amount of water, which flows outside their main channels (Fig. 6).

As shown by Opaliński (1991) and Madan *et al.* (2007), the fertilization of soils with nitrogen and phosphorus in polar areas considerably increases the number of plants and primary production. In the case of the studied catchment, and most likely also in many other catchments in Spitsbergen and located on uplifted marine terraces, seabirds play a crucial role in the fertilization of nutrient-poor Arctic soils, and are responsible for large variances in SOC, N_{tot}, and P_{tot} content in the surface horizons of the studied soils (Opaliński 1991; Szymański *et al.* 2013). The obtained results of concentrations of SOC, N_{tot}, and P_{tot} in the surface horizons of Arctic soils from the Fuglebekken catchment indicate the presence of a considerable mosaic of microecosystems even within a very small area. This mosaic is related to large differences in soil type, local hydrology, vegetation type and quantity, and especially the location of seabird nesting colonies (Paré and Bedard-Haughn 2012; Szymański *et al.* 2013; Wojtuń *et al.* 2013; Migała *et al.* 2014).

Conclusions

- Surface soil horizons in the Fuglebekken catchment show considerable differences in content of soil organic carbon, total nitrogen, and total phosphorus. This mosaic is related to high variability of soil type, hydrology, vegetation type and quantity, and especially location of seabird nesting colony.
- The highest content of soil organic carbon, total nitrogen, and total phosphorus occurs in soil surface horizons from sites fertilized by seabird guano and also along streams with their contributing area in close proximity to the seabird colony. The content of soil organic carbon, total nitrogen, and total phosphorus is highly negatively correlated with distance from the seabird colony, indicating strong influence of the birds on the fertility of the soils and indirectly on the accumulation of soil organic matter.
- The lowest content of soil organic carbon, total nitrogen, and total phosphorus occurs in soil surface horizons from the lateral moraine of the Hansbreen glacier and from sites in close proximity to the lateral moraine.
- The content of nutrients (N, P) and soil organic carbon in soil surface horizons are strongly and positively correlated with each other, *i.e.* the higher the content of nutrients, the higher the content of soil organic carbon.

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