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Organic carbon accumulation in the glacier forelands with regard to variability of environmental conditions in different ecogenesis stages of High Arctic ecosystems

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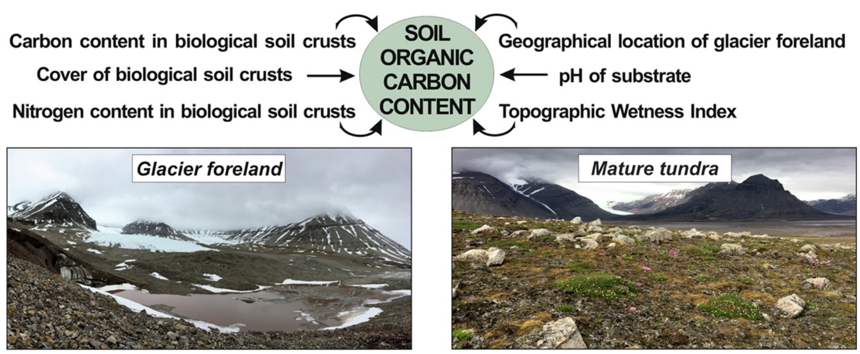
HIGHLIGHTS

- Biological soil crusts significantly affect soil formation in the Arctic forelands.
- Soil development was also associated with pH and wetness of substrate.
- Due to foreland individuality, soil development occurs differently in each foreland.
- Soil organic carbon content significantly differs between forelands and mature tundra.
- Site location and habitat types affect variation of biotic and abiotic variables.

GRAPHICAL ABSTRACT



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ABSTRACT

Recently deglaciated surfaces of glacier forelands are subjected to a variety of biotic and abiotic factors that lead to continuous soil formation. Until now, no attempt has been taken to analyse multiple factors that might affect soil development in the Arctic forelands. The main aim of this research was to determine the factors that influence soil development in the eight forelands of Svalbard. Moreover, the effects of both habitat type (glacier foreland and mature tundra) and geographical location on environmental variables treated as potential factors influencing soil formation were tested. In 2017, at each location a series of 1 m^2 plots was established; all 168 plots were investigated in terms of soil properties, spatial data, biological soil crusts (BSCs) properties, percent cover of BSCs and vascular plants. Stepwise multiple linear regression analysis using forward variable selection showed that soil development was significantly associated with six of fifteen analysed factors, i.e. BSC cover, carbon and nitrogen content in BSCs, soil pH, Topographic Wetness Index and foreland location. Two-way analysis of variance followed by Tukey's test revealed significant differences in studied environmental variables between habitat types and studied

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Soil development
Svalbard

locations, showing that foreland soils still retain particular initial characters to differentiate them from tundra soil.

1. Introduction

Soil development and vegetation succession are inseparably linked and influence each other. On the one hand the stage of soil development is one of the main factors responsible for local habitat diversity in the Arctic region and on the other transformation of vegetation over time greatly affects the soil properties (Ohtsuka et al. 2006). Currently, on-going climate warming in combination with variations of snow precipitation and glacier ablation, ''aging'' of glacier snow, and decreasing albedo, resulting in a progressive recession of glaciers and a rapid enlargement of ice-free areas within their marginal zones (Berger et al 1993; Zemp et al. 2008; Nuth et al. 2013), provide excellent conditions for extensive studies aiming to explain the nature of the above-mentioned complex processes. The marginal zones deglaciated by modern glaciers are called forelands, a term used to describe the land exposed from ice since the glacier maximum of the Little Ice Age (Matthews 1992). Currently, they are an important area for research on soil development due to restricted size, a harsh microclimate resulting in a relatively simple ecosystem, a short historical modification of substrate by environmental processes, and a specified period of ecosystem development (Matthews 1992). Thus, foreland might be considered to be spatial representation of temporal changes in terms of soil development and soil-forming process such as accumulation of soil organic matter, cryoturbation, pervection, stony or gravelly desert pavement formation, salinization and gleization (Matthews 1992; Bockheim et al. 2014; Szymański et al. 2019). Most of the research concerning soil formation in glacier foreland were conducted in the Alps (e.g. Egli et al. 2000, 2001; Burga et al. 2010 and references therein; Dümig et al. 2011; D'Amico et al. 2014), Alaska (e.g. Crocker and Major 1955; Crocker and Dickson 1957; Burt and Alexander 1996), Canada (Breen and Lévesque, 2006; Jacobson and Birks, 1980; Tisdale and Fosberg, 1966), continental Norway (Haugland 2004), Iceland (Vilmundardóttir et al., 2014, 2015a, 2015b), and the Antarctic (Frenot et al. 1995, 1998; Strauss et al. 2009, 2012). In Svalbard, pedological studies have only been conducted in the Werenskioldbreen foreland (Pirożnikow and Górniak 1992; Kabala and Zapart, 2009, 2012), northeastern coast of Sørkapp Land (Szymański et al. 2019), and in the neighbourhood of Ny-Ålesund (Kastovska et al. 2005; Nakatsubo et al. 2005). Spitsbergen (the largest island of the Svalbard Archipelago where the current study areas were located) is characterized by the greatest glacier cover within Svalbard, which has undergone gradual deglaciation since c. 1920 (Małecki 2013). Studies show mass losses of glaciers varying from -0.12 m w.eq. a^{-1} (Hagen et al. 2003) to -0.55 m w.eq. a^{-1} (Dowdeswell et al. 1997). Several decades of observation of selected Svalbard glaciers reveal a clear trend in their mass loss (e.g., Jania and Hagen 1996; Nuth et al. 2010; Małecki 2013; Sobota et al. 2016). Due to their retreat, new land is exposed, allowing one to track spatial and temporal changes of substrate properties. In previous studies in the glacier forelands of the High Arctic (Elberling et al. 2004; Nakatsubo et al. 2005; Kabala and Zapart, 2009), great attention was paid to carbon accumulation and its cycle. Very few studies refer to the relationship between carbon storage and vegetation (e.g. Nakatsubo et al. 2005; Yoshitake et al. 2011; Vilmundardóttir et al. 2015a), especially in terms of cryptogamic organisms (Wietrzyk et al. 2016, 2018). Harsh climatic conditions of Arctic terrestrial environments limit the distribution, cover and diversity of vascular plants and result in their low decomposition rate (Jung et al. 2018). In such habitats unfavourable to vascular plants, cryptogamic organisms are dominant, forming on the soil surface so-called biological soil crusts (BSCs, also known as cryptobiotic or cryptogamic crusts), which are well adapted to the severe conditions and able to persist in periodical desiccation, freezing, thawing, rehydration and continuous summer solar radiation (Elster 2002). BSCs perform many essential roles in various ecological processes, such as nitrogen fixation (Breen and Lévesque 2006; Pushkareva et al., 2017), organic matter accumulation (Yoshitake et al. 2010), sulphur, nitrogen and carbon cycles (Shively et al. 2001; Rippin et al. 2018), biostabilization processes against soil erosion and eolian deflation (Belnap and Lange 2001; Garcia-Pichel and Wojciechowski 2009), soil moisture retention (Belnap 2006), facilitation of plant establishment (Breen and Lévesque 2006; Yoshitake et al., 2010), that are essential on large, newly exposed soil surfaces after deglaciation (Wietrzyk et al. 2016). Here, BSCs can be the only primary producers and constitute the trophic base of the developing ecosystem on which vascular plants depend (Elster et al. 1999; Breen and Lévesque 2008). However, research on the relationship between BSC succession and soil development has not been conducted in glacier forelands. Until now, no attempt has been made to analyse multiple factors that might affect soil development in the glacier forelands. It is believed that the age of substrate, distance from the glacier forehead, and vegetation cover play major roles in soil development in glacier forelands (Stevens and Walker 1970; Darmody et al. 2005; D'Amico et al. 2014; Wietrzyk et al. 2018); furthermore Jenny (1994) has noted that parent material, topography and climate influence soil formation.

The aim of this research was to determine the factors that influence the organic carbon content in soil, which in turn can be considered as an indicator of soil development in the glacier forelands. Moreover, we investigated and tested the effect of both habitat type (glacier foreland vs mature tundra) and geographical location (glacier) on abiotic and biotic variables of the studied habitats. The following hypotheses were postulated: (1) since BSCs are the major component of Arctic tundra ecosystems and plant communities of glacier forelands, they influence soil development in glacier forelands most significantly, and (2) habitat type is a more important determinant of environmental factors than the geographical location of a glacier.

2. Material and methods

2.1. Study area

The fieldwork was conducted during the summer of 2017 in the forelands of eight glaciers and in the mature tundra surrounding them in Svalbard. Study areas were located in two regions of Spitsbergen: (1) in Isfjorden area (central Spitsbergen) where the forelands of Rieperbreen, Svenbreen, and Ferdinandbreen are located, and (2) in Kongsfjorden area (NW Spitsbergen) where the forelands of Austre Brøggerbreen, Vestre Brøggerbreen, Austre Lovénbreen, Midtre Lovénbreen, and Vestre Lovénbreen are located (Fig. 1; supplementary file 1).

In the vicinity of Austre Brøggerbreen, Vestre Brøggerbreen, Austre Lovénbreen, Midtre Lovénbreen and Vestre Lovénbreen,

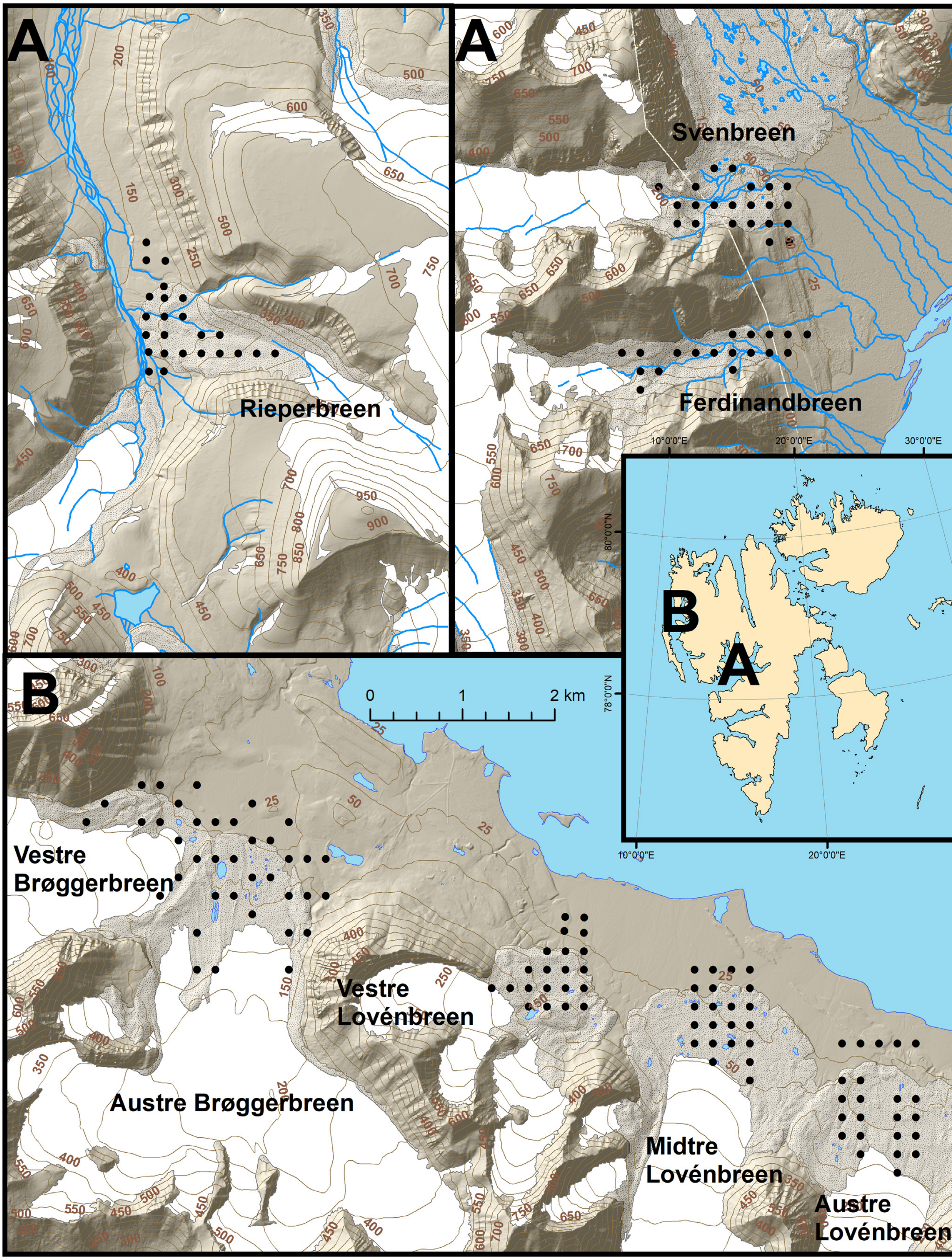

Fig. 1. Location of sampling plots (black dots) within study areas. Glaciers of Isfjorden area (A): Rieperbreen, Ferdinandbreen and Svenbreen; glaciers of Kongsfjorden area (B): Austre Brøggerbreen, Vestre Brøggerbreen, Austre Lovénbreen, Midtre Lovénbreen, and Vestre Lovénbreen (© Norwegian Polar Institute 2019; http://www.npolar.no).

metamorphic rocks from the Proterozoic prevail such as phyllite, quartzite and schist, as well as carboniferous rocks such as dolomite and limestone from Carboniferous and Permian. Additionally, siliceous clastic rocks such as sandstone, shale, and conglomerate from the Carboniferous period and from the Paleocene are present. Chert, shale, sandstone and limestone from Permian, as well as shale, siltstone and sandstone from early Triassic, also occur in the vicinity of Austre Brøggerbreen and Vestre Brøggerbreen (Saalmann and Thiedig 1998). The occurrence of siliceous clastic rocks, such as sandstone, siltstone, mudstone and shale from the Cretaceous, Paleocene and early Eocene periods, characterizes the vicinity of Rieperbreen (Dallmann et al. 2001). The geology of the neighbourhood areas of Svenbreen and Ferdinandbreen is more complex due to the presence of metamorphic rocks, such as granitic gneiss, migmatite, amphibolite, quartzite, mica schist and marble from the Proterozoic; the following rocks were also recorded: siliceous clastic rocks, such as sandstone, siltstone, shale and conglomerate from the late Devonian and clastic and carboniferous rocks from the Carboniferous period as well as carbonate rocks from Carboniferous and Permian periods (Dallmann 1999; Dallmann et al. 2004, 2009).

According to SoilGrids that involves WRB (Hengl et al. 2017), in the surrounding areas of Austre Brøggerbreen, Vestre Brøggerbreen, Austre Lovénbreen, Midtre Lovénbreen, and Vestre Lovénbreen soils are classified as Haplic Cryosols. In the vicinity of Rieperbreen, Svenbreen, and Ferdinandbreen Haplic Cambisols are observed as well (Hengl et al. 2017).

Data on climatic condition of the studied areas in the period of 1970–2000 are presented by Fick and Hijmans (2017). Mean annual air temperature (MAAT) in the foreland of Rieperbreen is c. − 8 °C and mean annual precipitation (MAP) is c. 400 mm. MAAT in the foreland of Svenbreen and Ferdinandbreen is also c. − 8 °C and MAP is c. 300 mm. MAAT and MAP in the foreland of Austre Lovénbreen, Midtre Lovénbreen, and Vestre Lovénbreen are c. − 6 °C and 420 mm, respectively, and in the forelands of Austre Brøggerbreen and Vestre Brøggerbreen are c. − 7 °C and 430 mm, respectively. The warmest month in all of the studied forelands is July with a mean monthly air temperature c. 6–7 °C. The coldest month in all of the studied forelands is January with a mean monthly air temperature ranging from − 15 °C to − 18 °C in the forelands of glaciers occurring in the Kongsfjorden area and c. − 19 °C in the forelands in the Isfjorden area (Fick and Hijmans 2017).

The mature tundra of Kongsfjorden and Isfjorden areas is represented by northern Arctic tundra (dwarf-shrub/herb tundra of subzone B) and middle Arctic tundra (prostrate/hemiprostrate dwarf-shrub tundra of subzone C), respectively (CAVM 2003; Jónsdóttir 2005). In both areas cryptogamic species are an important component of plant communities (CAVM, 2003).

2.2. Data sampling

In each glacier foreland (referred to as foreland hereafter) and surrounding mature tundra in front of the terminal moraine (referred to as tundra hereafter), a series of 1 m^2 plots was established (Fig. 1). Altogether, 168 plots were investigated: 104 in the Kongsfjorden area and 64 in the Isfjorden area; 127 of these plots were located in forelands and 41 in the tundra. At each plot data on overall percent cover of BSCs (BSC cover) and vascular plants (VPLANT cover) was collected. Corresponding fragments of BSCs and surface soil samples were collected in each plot.

2.3. Spatial analyses

GIS data were obtained from open-access databases (Fick and Hijmans 2017; Porter et al. 2018) and analysed with SAGA GIS 7.0.0 software (Conrad et al. 2015), which allowed one to obtain the following variables for each plot: time elapsed after glacier retreat (on the base of ranges of glacier in the past), distance to the current glacier forehead (m), slope (mean value for plot in radian), aspect (mean exposure value for plot in radian) and Topographic Wetness Index (TWI). To obtain these parameters, a 2 m resolution Digital Terrain Model (DTM) was used (Porter et al. 2018) with the application of Basic Terrain Analysis (Conrad et al. 2015). TWI is hydrologically based topographic index, which determines the tendency of area to accumulate water. It is defined as: $TWI = \ln(SCA/\tan \varphi)$, where SCA is the Specific Catchment Area and φ is the slope angle, and the assumption of uniform soil properties is set (Mattivi et al. 2019).

2.4. Soil sample analyses

Soil samples were oven-dried at 30 °C for 24 h in the laboratory before they were gently crushed and sieved using a 2 mm sieve to remove coarse material (fraction >2 mm). All laboratory analyses were conducted on fine earth material (fraction <2 mm) with the exception of soil particle-size distribution determination, which was conducted on fine earth material <1 mm. Soil texture was determined using laser diffraction (Malvern Mastersizer 3000) after a 3-min ultrasound dispersion of the sample. Total carbon content was determined in triplicate via gas chromatography using a CHN elemental analyser (Vario Micro Cube). The results of three replicates were averaged and treated as one observation in further analyses. Total carbon content in non-calcareous samples was treated as soil organic carbon (SOC). The content of carbonates ($CaCO_3$) was measured in five replicates using a volumetric calcimeter method (Loeppert and Suarez 1996). SOC content in calcareous samples was calculated by subtraction of the carbon content in carbonates from the total carbon content. The comparability test with direct measurement of SOC after carbonate removal has not been performed. Soil pH was measured in distilled water in a 1:2.5 soil/water ratio using a glass electrode (Thomas 1996).

BSC samples were gently cleaned from the soil material and crushed, and the absence of carbonates was checked in all samples. The organic carbon content in BSCs (BSCC) and total nitrogen in BSCs (BSCN) were determined by means of gas chromatography using a CHN elemental analyser (Vario Micro Cube); three replicates were used and the results were averaged and treated as one observation in further analyses.

2.5. Statistical analyses

Principal component analysis (PCA) performed on correlation matrix (without additional rotation procedure) was used to detect the closely associated variables and to visualise differences between plots located in forelands and tundra. The following biotic and abiotic variables were included in the analysis: aspect of the plot, BSCC content, BSC cover, BSCN content, $CaCO_3$ content, clay content, distance to the glacier forehead, sand content, silt content, slope of the plot, soil pH, SOC content, time elapsed after glacier retreat, TWI and VPLANT cover.

Stepwise multiple linear regression analysis using forward variable selection with a threshold of $p < 0.05$ to entry was applied to investigate the variables that influence the SOC content. Altogether 15 variables were included in the analysis (including above-mentioned variables as well as foreland location as categorical variable). Only plots located in the forelands were included into analyses. Prior to the analysis the linearity assumptions between variables were verified and the distribution normality of residuals was determined by means of the Kolmogorov-Smirnov test ($p < 0.05$). The potential collinearity of the predictors was checked by calculating the variance inflation factors (VIFs). A detailed residual analysis was performed in order to validate the regression model, obtain reliable regression coefficients and detect the outliers (extreme cases). The Durbin-Watson statistic was calculated to evaluate the potential presence of a serial correlation of residuals. Since VIFs for sand and silt were >10, only one variable (silt) was included in the model.

Two-way analysis of variance (habitat type × location) followed by Tukey's (HSD) test, was performed to reveal significant differences in environmental variables between habitat type (foreland and tundra), as well as location (Rieperbreen, Ferdinandbreen, Svenbreen, Austre Brøggerbreen, Vestre Brøggerbreen, Austre Lovénbreen, Midtre Lovénbreen and Vestre Lovénbreen). Altogether, 15 abiotic and biotic variables were included in the analysis. Prior to the analysis, the normality of the distribution was verified using the Kolmogorov-Smirnov test and Levene's test was performed to assess the equality of variances. The data that did not meet the assumptions were Box-Cox-transformed. Due to the absence of $CaCO_3$ in the Rieperbreen foreland, this location was excluded from the two-way analysis of variance in $CaCO_3$ content (habitat type × location). Due to the lack of detailed data on the substrate age of plots located in the tundra (the age estimated as >120 years), as well as greater distance to glacier forehead of plots located in tundra, only one-way ANOVA followed by Tukey's (HSD) test was performed to reveal significant differences in the substrate age and distance from glacier forehead between locations. The statistical analyses were carried out using STATISTICA 13 (Statsoft, Tulsa, OK, USA), Statgraphics Centurion 18 software (Statpoint Technologies Inc, The Plains, Virginia), and PAST 3.26 (Hammer et al. 2001).

3. Results

3.1. Environmental variables in foreland and tundra at different locations

The first PC, explaining 29.54% of the dataset variability, was strongly connected to the time elapsed after glacier retreat, distance from the current glacier forehead, high content of BSCC and BSCN, and high cover of BSCs and vascular plants that resulted in a clear division of two datasets: first, representing the plots located in the forelands; and second, presenting the plots located in tundra (Fig. 2; supplementary file 2). The second PC, explaining 18.91% of the data set variability, was mainly associated with soil texture (Fig. 2; supplementary file 2).

Soils collected from the tundra were characterized by significantly higher values of TWI and higher BSC cover than those collected from the foreland (significant habitat type effect). This effect did not depend on location of the glacier (two-way ANOVA, $p < 0.05$; Table 1; Fig. 3A, B; Supplementary file 3, 4).

Both habitat type and geographical location had a significant effect on BSCC, clay and SOC content, as well as distance to the glacier forehead, slope and vascular plant cover. BSCC content was always significantly higher for tundra compared to forelands, but location also had a significant effect on this parameter. Soils from Austre Lovénbreen had a significantly higher BSCC content in comparison to Austre Brøggerbreen and Svenbreen; the other locations did not differ significantly in terms of BSCC content from these (Table 1; Fig. 3A). Clay content was significantly lower for tundra compared to forelands (Table 1; Fig. 3A). Soil from the Rieperbreen location contained the highest clay content (Fig. 3A). The slope proved to be significantly lower in tundra plots compared to forelands (Fig. 3B); Ferdinandbreen and Rieperbreen possessed the highest slope. SOC content was significantly higher at tundra plots, the highest value obtained from Ferdinandbreen and the lowest value from Austre Brøggerbreen, Austre Lovénbreen and Midtre Lovénbreen. Vascular plant cover was significantly higher for tundra, but depended also on location and was significantly higher in Midtre Lovénbreen and Vestre Lovénbreen than in Rieperbreen and Vestre Brøggerbreen (Table 1; Fig. 3B; Supplementary file 3, 4).

Two-way ANOVA revealed that location had a significant effect on aspect, as well as sand and silt contents in soil; however, significant interactions between location and habitat type were also recorded (Table 1; Fig. 3A, B). The lowest aspect was recorded in tundra occurring in the vicinity of the foreland of Ferdinandbreen, being significantly lower than at Austre Brøggerbreen and Rieperbreen forelands, as well as Austre Lovénbreen, Midtre Lovénbreen and Vestre Lovénbreen tundra. Austre Lovénbreen and Vestre Lovénbreen tundra soils were characterized by the highest sand content in soil, being significantly higher than at Rieperbreen and Vestre Brøggerbreen tundra. As regard silt content in soil, significant differences were only found between Austre Lovénbreen and Vestre Lovénbreen tundra and Vestre Brøggerbreen tundra.

Significant interactions between location and habitat type were also recorded in case of BSCN, $CaCO_3$ content and substrate pH (two-way ANOVA, $p < 0.05$). Decreased levels of BSCN content were observed at foreland plots of Austre Brøggerbreen, Ferdinandbreen, Svenbreen and Vestre Brøggerbreen (Table 1; Fig. 3A). These plots were characterized by significantly lower values of this parameter than tundra plots regardless of the location (significant habitat type × location interaction). The foreland of Vestre Brøggerbreen was characterized by significantly a higher $CaCO_3$ content than the remaining locations/habitat types (Table 1; Fig. 3A). As regard substrate pH, the most symptomatic was significantly the lowest values recorded at Rieperbreen foreland and tundra compared to the remaining locations and habitat types (Table 1; Fig. 3B; Supplementary file 3, 4).

Time elapsed after glacier retreat did not differ significantly between particular locations. Ferdinandbreen and Rieperbreen included plots located significantly further from the glacier forehead than those from Midtre Lovénbreen, Svenbreen, Vestre Brøggerbreen and Vestre Lovénbreen (one-way ANOVA, $p < 0.05$; Table 1; Fig. 3B; Supplementary file 3, 4).

3.2. Environmental variables influencing soil development in glacier forelands

Due to a clear division of plots into two habitat types and the dissimilarity of plots located in forelands and tundra (Fig. 2), only plots located in forelands were included in a stepwise multiple linear regression analysis aimed at determining the most influential factors affecting soil development.

The results of the multiple stepwise linear regression analysis are presented in Table 2. Forward stepwise procedure with 15 environmental variables as predictor factors and SOC content as the dependent variable revealed that only eight predictors were included in the model ($R = 0.692$, $R^2 = 47.93\%$, $F = 13.576$, $p < 0.001$). The analysis showed that SOC content was significantly associated with only six factors, i.e. BSC cover, BSCN content, BSCC content, substrate pH, TWI and foreland location. Three of these, i.e. BSCC content, TWI and foreland location, proved to have significant positive relation with SOC content, whereas three another factors, i.e. BSC cover, BSCN content, and substrate pH, were negatively associated with SOC content. SOC content was negatively related to $CaCO_3$ content and positively related to silt content; however, the effects of $CaCO_3$ and silt contents were not significant.

4. Discussion

4.1. Environmental variables in foreland and tundra at different locations

The melting of glaciers results in environmentally important effects which uncover new substrate. Thus, forelands serve as

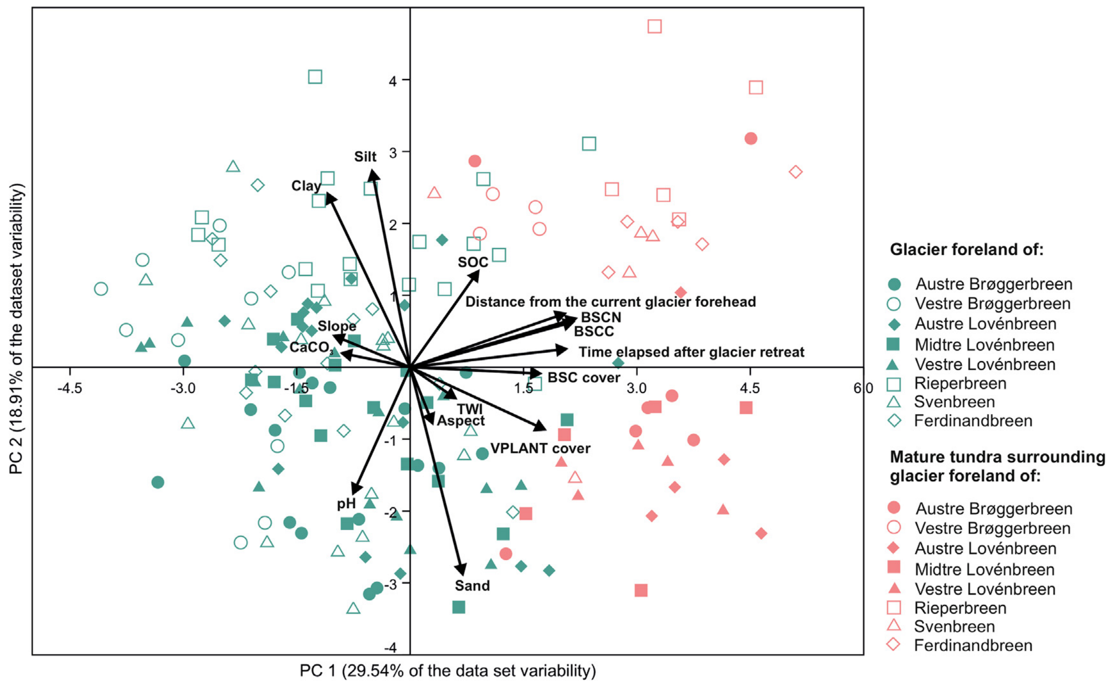

Fig. 2. PCA of the data set presenting the space defined by PCs 1 (29.54% explained variance) and 2 (18.91% explained variance). Plot located in each geographical location were presented by different symbols, while habitat types were presented by different colours.

Table 1
The results of two-way ANOVA for the effects of habitat type (foreland vs tundra) and geographical location (glacier) on environmental variables, with the exception of time elapsed after glacier retreat for which the results of one-way ANOVA for the effects of location (glacier) are presented. Significant effects ($p < 0.05$) are shown in bold.

Variable	Location		Habitat type		Location × Habitat type	
	F	p	F	p	F	p
Aspect (rad)	**7.53**	**<0.001**	0.236	0.628	**2.33**	**0.027**
Carbon content in biological soil crusts – BSCC (%)	**3.47**	**0.002**	**226.04**	**<0.001**	0.94	0.478
Biological soil crusts cover – BSC cover (%)	1.93	0.069	**60.58**	**<0.001**	1.42	0.201
Nitrogen content in biological soil crusts – BSCN (%)	**2.93**	**0.007**	**212.46**	**<0.001**	**2.5**	**0.019**
$CaCO_3$ (mg/g)	**4.63**	**<0.001**	**4.54**	**0.035**	**2.8**	**0.014**
Clay (%)	**13.35**	**<0.001**	**21.73**	**<0.001**	1.66	0.122
Distance to the glacier forehead (m)	**8.11**	**<0.001**	**–**	**–**	–	–
pH	**33.42**	**<0.001**	**66.95**	**<0.001**	**2.99**	**0.006**
Sand (%)	**5.65**	**<0.001**	0.031	0.861	**2.71**	**0.011**
Silt (%)	**3.91**	**<0.001**	0.770	0.382	**3.28**	**0.003**
Slope (rad)	**3.14**	**0.004**	**27.59**	**<0.001**	0.77	0.617
Organic carbon content in soil – SOC (%)	**16.72**	**<0.001**	**63.43**	**<0.001**	1.11	0.36
Time elapsed after glacier retreat (years)	1.36	0.226	–	–	–	–
Vascular plant cover – VPLANT cover (%)	**7.97**	**<0.001**	**83.76**	**<0.001**	0.74	0.639
Topographic Wetness Index – TWI	0.48	0.846	**7.34**	**0.007**	0.69	0.681

essential areas to study the changes in abiotic and biotic variables along areas where slow transformation of substrate into soil occurs (Kabała and Zapart 2012). According to our results (Table 1; Fig. 3A, B), the studied forelands are characterised by similar times of deglaciation that are in line with historical data on Little Ice Age ending (ending c. 1920) when recession of glaciers began (Hagen et al. 2003), but they presented differences in length of forelands and aspects. This is in accordance with studies conducted by Lyså and Lønne (2001), Rachlewicz et al. (2007), and Rasmussen and Kohler (2007).

Our results showed a clear division of plots located in forelands and tundra based on various biotic and abiotic factors, demonstrating that even at the marginal part of forelands, the soil is still not fully developed (Fig. 2). This was also confirmed by significant differences in SOC content between forelands and tundra (Table 1; Fig. 3B). The variation in other environmental variables resulted from difference between mature and initial habitats, geographical location of studied areas, as well as interaction between those two factors (Table 1; Fig. 3A, B). Furthermore, TWI and BSC cover clearly differed between habitat types (Table 1; Fig. 3A, B). The significantly higher TWI values in the tundra might be associated with lower terrain slope (Sörensen et al. 2006). In general, forelands present high variability in landform and greater differences in slopes due to on-going geomorphological processes (Laffly and Mercier 2002). A significantly lower slope in tundra compared to foreland regardless of glacier location was also confirmed by our results (Table 1; Fig. 3B). Vegetation cover also varied between habitat types (Table 1; Fig. 3B). A higher percent cover of BSCs and vascular plants in tundra than in forelands suggested that plant communities in the forelands do not reach a climax stage (Walker and Del Moral 2003), and confirmed that cryptogams are an important component of tundra communities in the Arctic (Wietrzyk et al. 2018). Tundra BSCs presented higher carbon and nitrogen contents in comparison to those growing on forelands,

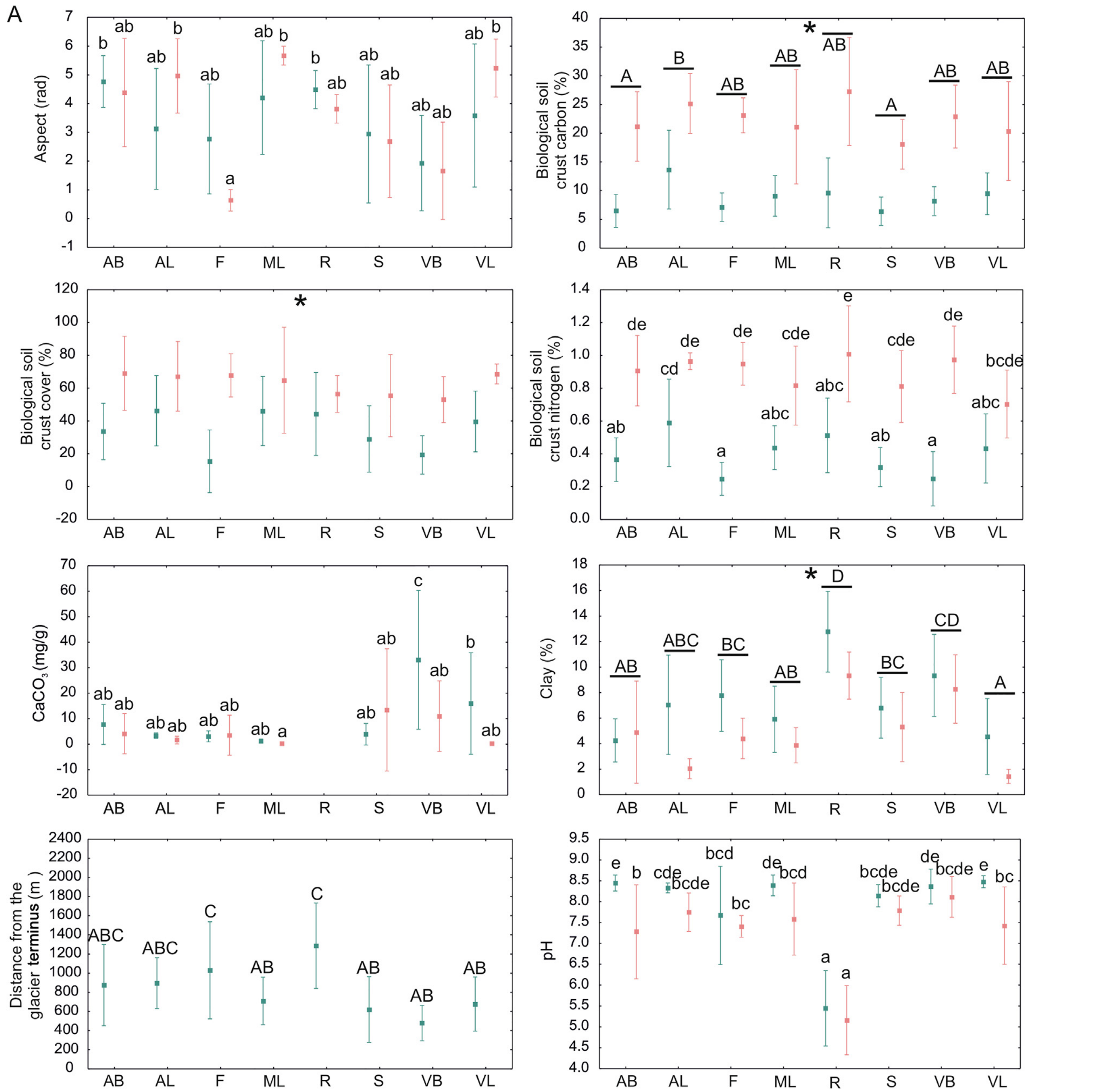

Fig. 3. A-B. Mean ± SD of studied environmental variables including habitat type (foreland vs tundra) and location (glaciers). The results of ANOVA ($p < 0.05$) are presented graphically. The different letters above the bars indicate statistically significant differences: the capital letters show the significant main effect of the location; the lowercase letters indicate the statistically significant interaction between habitat type and location; the asterisks (*) indicate the significant main effect of habitat type (see Table 1 for details on the main effects and interactions).

but the differences were also revealed between locations, and in the case of nitrogen, they were determined by the interaction between locations and habitat type. This might be connected with various forms of BSCs that might developed as a result of the domination of one or more particular organisms, such as cyanobacteria, green algae, mosses and lichens. The species composition (e.g. presence of cyanobacteria or cyanolichens with an ability for N-fixation) and stage of development of BSCs seems to influence their content of carbon and nitrogen. The following successional pattern was presented by Belnap and Eldridge (2001): large filamentous cyanobacteria, small cyanobacteria and green algae, very early successional lichens, early successional lichens/mosses, midsuccessional lichens/mosses and late successional lichens/mosses. Fischer and Subbotina (2014) showed that cyanobacteria and green algae forming early stages of crusts, occurred on coarse textured soils, and with an increasing content of fine material, the abundances of mosses and lichens increased. In our study area, this early stage of crusts in the form of thin mats were common in the recently uncovered foreland substrate, while the well-developed, thick BSCs, consisted mainly of mosses and lichens, dominated in the terminal moraine and tundra. Moreover, as BSCs depend on geomorphic characteristics and climate (Kidron et al. 2010; Fischer and Subbotina 2014), this might be the cause of variations in BSCs properties between studied locations (Table 1; Fig. 3A, B).

Differences in soil texture, $CaCO_3$ content and pH were observed between habitat type and locations, but interactions between those two factors were also revealed (Table 1; Fig. 3A, B). This

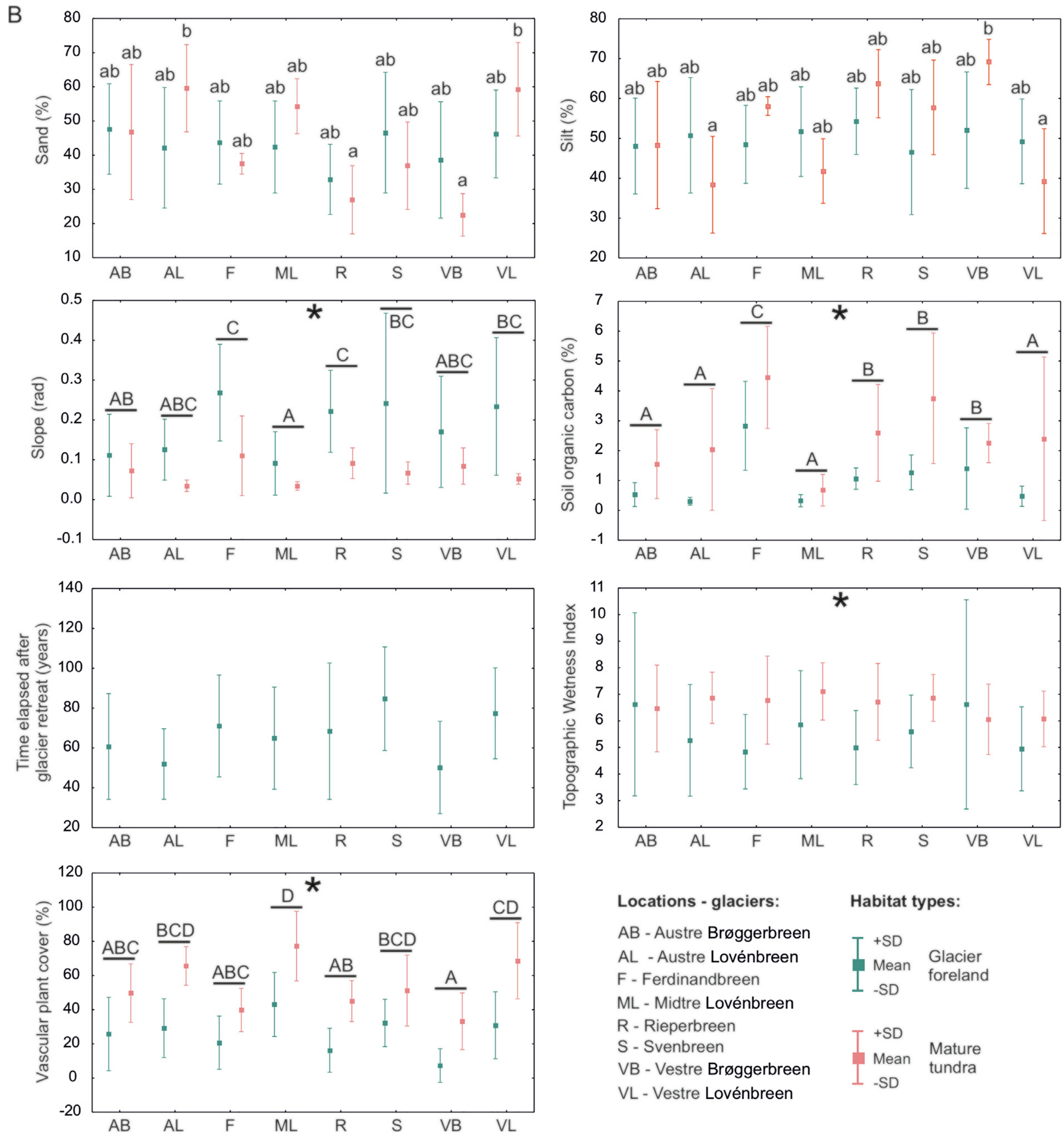

Fig. 3 (*continued*)

Table 2
Result of stepwise multiple regression analysis (R = 0.692, R^2 = 47.93%, F = 13.576, $p < 0.001$) for the effect of environmental variables on SOC content. Variables with significant effect ($p < 0.05$) are provided in bold.

N = 127	Standardized β coefficient	SE	t	p
Constant			2.316	0.022
Foreland location	0.337	0.077	4.358	0.000
Percent cover of biological soil crust (BSC cover)	−0.250	0.074	−3.365	0.001
Nitrogen content in biological soil crust (BSCN)	−0.786	0.158	−4.986	<0.001
Carbon content in biological soil crust (BSCC)	0.615	0.144	4.265	<0.001
pH	−0.199	0.076	−2.633	0.010
Topographic Wetness Index (TWI)	0.158	0.073	2.179	0.031
$CaCO_3$ content	−0.173	0.089	−1.946	0.054
Silt content	0.077	0.070	1.098	0.274

means that the effect of habitat type depends on location, and it was shown that the differences in sand, silt and $CaCO_3$ content between foreland and tundra depend on location. Consequently, their content was once greater on the tundra and once on the foreland depending on the location. This might be connected with differences in parent material (Harradine and Jenny 1958) as studied areas differ in terms of geology (Saalmann and Thiedig 1998; Dallmann 1999, 2001, 2004, 2009), as well as different climate features (Harradine and Jenny 1958; Fick and Hijmans 2017). Two kind of parent material might be found in foreland: moraines (formed of glacial till and connected with glacier activity; characterised by higher content of fine-grained particles and lower content of sand) and outwash plains (formed of glaciofluvial deposits and resulted from glacial river activity; characterised by higher content of sand and lower content of silt and clay) that are also linked with different particle-size (Matthews 1992; Moreau et al. 2008; Kabała and Zapart 2012; Szymański et al. 2019). Moreover, the soil properties changed along foreland due to substrate weathering and soil development and aeolian processes, as well as cryoturbation (Matthews 1992; Darmody et al. 2005; Ugolini et al. 2006), but foreland soil compared to tundra soil still represents an initial character which results in differences between those habitats.

4.2. Environmental variables influencing soil development in glacier forelands

Recently deglaciated surfaces of foreland, initially unvegetated, are subjected to a variety of environmental factors and changing conditions that lead to a continuous soil formation (Darmody et al. 2005). The majority of pedologic research in the forelands has involved chronosequence methodology (focusing on undisturbed sites) (e.g. Hodkinson et al. 2003; Yoshitake et al. 2011; Kabała and Zapart 2012; Wietrzyk et al. 2018). However, according to previous works (e.g. Moreau et al. 2008; Kabała and Zapart 2012; Wietrzyk et al. 2018), the forelands studied also consisted of disturbed areas and were characterized by high environmental variability, which resulted in differences in physical and chemical properties of soils, and in terms of the accumulation of SOC (Szymański et al. 2019). Thus, the chronosequence method does not provide representative characteristics of foreland ecosystem. Therefore, for our study of eight forelands in Svalbard, a grid method with random location of plots (covering also disturbed areas) was applied in order to determine the factors affecting SOC accumulation, which can be treated as an indicator of soil development. From 15 analysed variables, six (location of foreland, BSC cover, content of nitrogen and carbon in BSCs, substrate pH, and TWI) showed a significant relationship with soil development (Table 2). Although, two other variables connected with properties of substratum ($CaCO_3$ and silt) were included in the model, their effect was not significant.

Mizuno (2005) noted that different forelands represent different substrate quality exposure to species colonization. Our results confirmed this, and even expanded it in terms of soil development. Each foreland due to its environmental individuality and specificity, should be treated as a separate ecosystem. The significant differences might be already visible in the content of SOC in the particular forelands (Table 1; Fig. 3B). Therefore, foreland location was significantly associated with soil formation (Table 2) and our results showed that the process occurs differently on different forelands, even if they are adjacent to each other. Several studies conducted in Svalbard presented a difference in SOC accumulation across forelands, which was manifested by a different function of changes of SOC content over time after deglaciation or distance from the glacier forehead (Strauss et al. 2009; Kabała and Zapart 2012; Dong et al. 2016; Wietrzyk et al. 2018). According to soil-formation theory, time is considered as one of the major factors of soil formation (Jenny 1994; Huggett 1998). Burga et al. (2010) showed that the longer a surface is exposed to weathering after deglaciation, the soils are usually more developed. Both increasing time elapsed glacier retreat and connected with its distance from the glacier forehead positively affect development of vegetation cover and plant productivity (Burga et al. 2010; Wietrzyk et al. 2018); hence, increasingly more organic carbon is transferred from vegetation debris into the substrate (Burga et al. (2010)). Therefore, the older the substrate age the greater is the soil organic matter content (Burga et al. 2010). These processes influence other substrate properties, such as $CaCO_3$ content, substrate stabilization, soil pH, and soil texture (Frenot et al. 1995; Burga et al. 2010; Kabała and Zapart 2012). Nevertheless, in our results, neither time elapsed after glacier retreat, nor distance to the glacier forehead showed significant relationship with accumulation of SOC (Table 2). As suggested by Rydgren et al. (2014) the substrate age might have a fading effect on primary succession when evaluating it without additional environmental data, and furthermore, this effect may have been strengthened by the sampling methods used. This statement seems to be also valid in case of SOC accumulation in studied forelands. Our plots were designated in grid without avoiding disturbed sites and taking into account variability resulted from substantial habitat differences in small scale. Because of that we might draw the conclusion that in case of studied forelands, the local environmental conditions have a stronger effect on SOC accumulation than age of terrain (Table 2). However, regarding the difference between forelands and tundra, substrate age seems to be of greater importance (Table 1). It is widely known that weathering processes and soil development are influenced by environmental conditions and vegetation succession (Velde and Meunier 2008). It was observed that development of soil in the forelands significantly accelerates under continuous vegetation cover (Alexander and Burt 1996; He and Tang 2008; Mavris et al. 2010). Numerous studies have proved the influence of vegetation on soil formation, but the majority of them concerned only the vascular plants (e.g. Pirożnikow and Górniak 1992; Nakatsubo et al. 2010; Prach and Rachlewicz 2012), without taking into account the presence of cryptogamic species. However, as suggested by Bernasconi (2008), both plants and microorganisms can significantly increase the rate of weathering of minerals and soil formation. Our results showed substantial relevance of BSCs in the process of soil development in the forelands of Svalbard glaciers. Thus, we confirmed our hypothesis that BSCs, as the major component of Arctic tundra ecosystems and plant communities of forelands, significantly influence soil development. BSCs are complex associations between soil particles and typically pioneering spore-bearing organisms, such as algae, bacteria, cyanobacteria, microfungi, lichens, liverworts and mosses (Belnap and Lange 2001; Fischer and Subbotina 2014; Williams et al. 2017). Their development and formation of organic matrix on the surface and within the first few millimetres of soil is possible thanks to cyanobacterial secretion of extracellular polysaccharides that combine cells and soil particles, and additionally stabilize the previously barren soil (Belnap 2003; Garcia-Pichel et al. 2003; Breen and Lévesque 2008; Jung et al 2018). The regression model showed strong association between SOC content and content of carbon in BSCs. SOC content in soil increased with increasing content of carbon in BSCs demonstrating that BSCs are important source of organic carbon in soil (Table 2). The function of BSCs in carbon fixation and storage is essential; for instance, Belnap (2003) suggested that the BSCs can increase the carbon content in surface part of soil by up to 300%, while Evans and Lange (2001) and Housman et al. (2006) showed that BSCs are the main source of soil organic carbon in semi-arid ecosystems. It is believed that BSCs are particularly essential as a CO_2 reservoir. In north-western Svalbard, where some of studied areas were located, BSCs cover c. 90% of the soil (Williams et al. 2017), the first cubic centimetre of soil consisting of 7–17% organic carbon (Jung et al. 2018). Yoshitake et al. (2010) noted that in the succession process in the High Arctic foreland, BSC productivity might play an important role in the carbon cycle, and thus soil formation. This is in line with our results since, together with the content of carbon in BSCs, the nitrogen content in BSCs and BSC cover was significantly connected with soil formation. However, SOC content in soil was negatively related to nitrogen content in BSCs. This seems to be connected with the important role playing by BSCs in nitrogen fixation (Breen and Lévesque 2006; Pushkareva et al. 2017). BSCs, thanks to cyanobacterial and cyanolichen components are major sources of nitrogen in the barren glacier forelands where it is a limiting factor for vascular plant growth (Sancho et al. 2011; Pushkareva et al. 2017). With the development of vascular plant cover along the forelands, more and more nitrogen is bound by them, which decreases its content in BSCs; however, the BSCN content still positively influence soil formation. Furthermore, the development of vascular plant cover increases the competition between vascular plants and cryptogams resulting in a decrease in BSC cover. This is consistent with the studies by Breen and Lévesque (2006) showing that BSCs facilitate the establishment and maintenance of vascular plants during succession.

The TWI was also factor significantly related to soil development according to our regression model (Table 2). As showed by Sörensen et al. (2006), the spatial distribution of groundwater levels affects the properties of the soil. Most Arctic glacier forelands are characterized by changing water availability from a melting glacier leading to alternating periods of drought and flood (Breen and Lévesque 2008). The water limitation, together with low precipitation typical for the High Arctic forelands, restrict the development of vegetation cover, carbonate dissolution and leaching, as well as stabilizing substrate pH and inhibiting mineral weathering (Kabała and Zapart 2012).

The contents of $CaCO_3$ and silt were insignificant variables included in the model (Table 2). The soil development was connected with decreasing $CaCO_3$ content in soil that was also observed in other forelands, e.g. Werenskioldbreen (Kabała and Zapart 2012). Simultaneously with soil formation, the substrate loses its initial carbonates and becomes enriched in organic carbon that result in a progressively decreasing pH, intensified weathering of minerals, and formation of Al and Fe oxyhydroxides (Prietzel et al. 2013). Together with the processes of substrate weathering and soil development, the texture of soil changes. As the silt content in soil was negatively correlated with sand content, we may assume that coarse-grained material is replaced by a fine-grained one as soil developed. Darmody et al. (2005) noted that soil at older sites of Storbreen foreland was richer in silt and clay in comparison with soil occurring at more recently deglaciated sites. Increase of fine particles content in soil along the glacier foreland was also observed by Righi et al. (1999) and Andreis et al. (2001). Our results showed that soil formation was positively associated with the increase in silt content which is in line with literature data (Darmody et al. 2005). Nevertheless, as suggested by Szymański et al. (2019), the differences in the particle-size along the foreland might have resulted not only from soil weathering and soil-forming processes, but also from combination of different parent material and aeolian processes.

5. Conclusions

In the presented research eight forelands were studied to determine environmental factors affecting soil development. This was the first attempt to analyse multiple factors potentially influencing accumulation of organic carbon in soil along forelands of Arctic glaciers. The soil development was significantly associated with six of fifteen analysed factors, i.e. BSC cover, carbon and nitrogen content in BSCs, soil pH, Topographic Wetness Index and foreland location. $CaCO_3$ and silt contents were also included in the model, but their effect was not significant. Moreover, our results showed significant importance of BSCs in the process of soil development in the forelands of Svalbard glaciers. Due to the processes of weathering and continuous soil development, substrate features change along forelands, nevertheless, their soils still retain particular initial characters to differentiate them from tundra soil. If climate warming in the Arctic progresses as the current climatic models indicate, further primary vegetation succession and soil development in the glacier forelands in the Arctic will also proceed. With the further development of vegetation cover along forelands more carbon in the form of carbon dioxide (CO_2) will be uptaken and sequestrated in the foreland soils. This will play important role in decreasing CO_2 concentration in the atmosphere. This fact should be taken into consideration during development of new climatic models.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.135151.

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