Chronological changes in soil biogeochemical properties of the glacier foreland of Midtre Lovénbreen, Svalbard, attributed to soil-forming factors

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Abstract

Glacier forelands have provided great opportunities to study vegetation succession and soil development along the chronosequence. However, there are a few studies on soil biogeochemical changes caused by environmental factors apart from time. We aimed to study soil development and biogeochemical changes by considering various factors, including time, in the glacier foreland of Midtre Lovénbreen, Svalbard. Eighteen vegetation and soil variables were measured at 38 different sampling sites with varying soil ages, depths, and glacio-fluvial activity. In addition to the quantitative measurement of soil organic matter (SOM), the compositional changes in SOM were determined after size-density fractionation. In the topsoil, soil organic carbon (SOC) and total N contents increased along soil chronosequence and were highly correlated with vegetation-associated variables. Our findings suggest that plant-derived material was the main driver of the light fraction of SOM accumulated in the topsoil. Moreover, the heavy fractions of SOM were composed of microbially transformed organic compounds, eventually contributing to SOM stabilization within short 90-yr deglaciation under harsh climate conditions. Soil vertical profiles showed that other environmental parameters, besides time, also affected soil biogeochemical properties. The total P content and electrical conductivity (EC) increased in the top 5-cm soil by subglacial materials that remained immediately after the glacier receded. The high P and Mg contents in the subsoil were attributed to the parent materials, while the high Na and K contents in the surface soil were due to sea-salt deposition. We found that glacio-fluvial runoff could delay ecosystem development by inhibiting vegetation development and SOM accumulation. In conclusion, we emphasize the importance of considering various soil-forming factors, including parent/subglacial materials, aeolian deposition, and glacio-fluvial runoff, as well as soil age, to comprehensively understand the ecosystem development in glacier forelands.

Keywords: Glacier foreland, Soil-forming factors, Soil biogeochemical property, Chronosequence, Glacio-fluvial runoff, Svalbard

1. Introduction

Global warming has caused significant recession of glaciers since the mid-19th century, exposing the ice-free land surfaces (Yde et al., 2011). The newly exposed glacier forelands are regarded as the best place for studying spatial changes along chronosequence, as the distance from the glacier edge is a proxy for the age of the land surface (Hågvar, 2012; Schmidt et al., 2008). As a result, the glacier forelands in the Arctic and alpine regions are ideal for studying the chronological changes in terrestrial ecosystems, such as vegetation succession, microbial community development, and geochemical weathering (Bekku et al., 2004; Borin et al., 2010; Dong et al., 2016; Hågvar, 2012; Mateos-Rivera et al., 2016; Müller et al., 2012; Nakatsubo et al., 1998; Prach and Rachlewicz, 2012; Uchida et al., 2002; Yde et al., 2011).

Glacier forelands have received considerable attention from soil scientists studying early soil development and soil organic matter (SOM) accumulation, focusing on chronological changes in soil organic carbon (SOC) and total N contents (Heckmann et al., 2016; Kabala and Zapart, 2012; Nakatsubo et al., 2005; Tanner et al., 2013; Vilmundardóttir et al., 2014a, 2014b). The SOC content has gradually advanced within approximately 100-150 years, owing to the increased vegetation cover on the soil surface (Hodkinson et al., 2003; Wietrzyk et al., 2018; Yoshitake et al., 2011). The increase in total N content is mainly caused by cyanobacteria in the early stage of soil development and by plant-derived organic debris in later stages (Mapelli et al., 2011; Pessi et al., 2019; Schmidt et al., 2008). Contrary to the extensive research on the quantitative measurement of SOM, studies on SOM fractionation were relatively limited in deglaciated forelands (Gentsch et al., 2015; Herndon et al., 2017; Khedim et al., 2021; Startsev et al., 2020). For temperate and tropical soils, SOM fractionation based on both size and density is generally used to understand the qualitative properties of SOM, such as mean residence time, microbial accessibility, and carbon sequestration (Lavallee et al., 2020; Six et al., 2002). To date, few studies have investigated the spatial distribution of SOM fractions through size-density fractionation in the glacial forelands (Jílková et al., 2021; Prater et al., 2020), and only a handful of them have dealt with chronological changes in SOM fractions (Schweizer et al., 2018). The variability of each SOM fraction along the chronosequence is required to provide important information on SOM quality and stability in glacial forelands.

One of the key assumptions in space-for-time substitution studies is that there are no other influencing factors other than time on soil formation (Dümig et al., 2011; Heckmann et al., 2016; Schmidt et al., 2008). However, the biogeochemical properties of deglaciated soils are not only affected by time but also by parent materials, geographical features, and geomorphological disturbances (Anderson, 2007; Bardgett et al., 2005; Szymański et al., 2019; Wojcik et al., 2021; Yde et al., 2011). For example, total P, Ca, and Mg in glacier forelands are mainly affected by leaching or weathering of parent bedrock (Andy et al., 2008; D'Amico et al., 2014; Jun et al., 2013). Subglacial materials remaining after deglaciation and aeolian deposits of sea salts have proven to be sources for various biogeochemical components of foreland soils (ARCUS, 2000; Hallbeck, 2009; Ren et al., 2019; Wojcik et al., 2021; Zeng et al., 2013). Moreover, geomorphological-related processes, particularly glacio-fluvial runoff, can redistribute or remove topsoil materials (Wojcik et al., 2020, 2021). These various soil-forming factors over time have caused disturbance and heterogeneity in soil profile development in the glacial forelands (Wojcik et al., 2021). Therefore, the knowledge of vertical and horizontal distributions of soil biogeochemical properties are essential to understand the influential factors for soil development.

In this study, we performed field surveys and laboratory analyses to determine major soil-forming factors and their effects on soil biogeochemical properties in the Midtre Lovénbreen glacier foreland in Svalbard. Eighteen vegetation and soil variables were measured at 38 different sampling sites with varying soil ages, depths, and intensity of glacio-fluvial runoff. The objective of this study was to investigate the chronological changes in SOC and total N contents and their fractions during approximately 90-year deglaciation period. Moreover, we examined the horizontal and vertical distributions of soil biogeochemical properties influenced by bedrock, geographical features, and glacio-fluvial runoff. Our hypotheses were as follows: 1) the SOM accumulation in the topsoil of the glacier foreland would be mainly attributed to the plant-derived materials, which could be stabilized through the formation of heavy fractions within a short period, even in harsh climate conditions; 2) bedrock origin and surrounding abiotic environment have a great impact on the vertical variability of soil biogeochemical properties; and 3) the glacio-fluvial runoff delays soil chronological development.

2. Materials and methods

2.1. Study area

The study was conducted in the Midtre Lovénbreen glacier foreland (78.9 °N, 12.1 °E) on the Brøggerhalvøya Peninsula in northwestern Spitsbergen, Svalbard (Fig. 1). The bedrock in the Brøggerhalvøya Peninsula is dominated by quartzite, phyllite, red sandstone, and conglomerate, interlayered with marble, limestone, and dolomite (Nilsen et al., 1999; Shi et al., 2018). Those rocks consisted of quartz, mica, chlorite, feldspar, pyrite, and apatite with additional contributions of carbonate minerals, which was confirmed by the previous studies using the X-ray diffraction and SEM-EDS (Scanning Electron Microscopy-Energy Dispersive Spectroscopy) analyses (Borin et al., 2010; Koutsopoulou et al., 2010; Mapelli et al., 2011). The average annual temperature and precipitation for the past 30 yrs (1981-2020) are -6 ℃ and 400-420 mm, respectively (Agnelli et al., 2021; Wietrzyk-Pełka et al., 2021). Since the end of the Little Ice Age (1900-1920), the volume of the Midtre Lovénbreen glacier has decreased by approximately 25% (Hansen, 1999; King et al., 2008).

2.2. Sampling strategy and environmental surveys

A total of 35 sampling points were selected from 300 vegetation survey sites by Moreau et al. (2005) with a stratified sampling strategy, to obtain the best-representing samples among the previous-studied sites. Five factors, the spatial distribution of research points (X-Y coordinates), soil ages, glacio-fluvial activities, slope and wind, were considered to select sampling points. Three additional sites from newly deglaciated areas since the survey by Moreau et al. (2005) were also chosen. The soil ages were calculated from high-resolution aerial photographs obtained in 1936, 1966, 1985, 1986, 1999, 2000, and 2013 supplied by the Norwegian Polar Institute. We classified the soil age groups into the following five intervals: <20, 20-40, 40-60, 60-80, and 80-90 yrs (Fig. 1). The information about glacio-fluvial characteristics followed the classification by Moreau et al. (2005): active, inactive, and no-runoff areas. The active sites had high-intensity and continuous runoff during the melting season in the glacial foreland. The inactive sites showed little glacio-fluvial runoff compared to the active sites, but glacial meltwater still formed the residual flow. The no-runoff sites were not affected by any glacio-fluvial runoff. In order to investigate the effect of glacio-fluvial activities on the glacier foreland, we selected three sites for each active, inactive, and no-runoff sites among the 40-60 yr sites (Fig. 1). To acquire a high-resolution topography of the study area and deriving vegetation indices like the normalized difference vegetation index (NDVI) data, over 1,000 ordinary color images (RGB) and near-infrared images were collected from Canon S100 camera. The camera was fitted with a near infrared-green-blue (NGB) filter onboard the rotary-wing drone over our study area in July, 2016 while flying at a speed of approximately 7 m/s from an altitude of roughly 100 m. Both along and across track overlaps were set to approximately 70-75%. Pix4D was employed to generate a digital elevation model (DEM) and orthorectified images. The corresponding mosaic results were obtained with a ground pixel resolution of approximately 5 cm. Several environmental variables, such as slope and aspect of topography, were extracted from the DEM. The elevation, slope, and aspect did not significantly differ according to the soil age and glacio-fluvial activities ($p>0.05$). This indicates that our sampling strategy can show the changes in vegetation and soil variables by soil age and glacio-fluvial runoff excluding the effects from microtopography.

2.3. Vegetation survey

Vegetation observations at each sampling site were conducted in July 2014. The vegetation coverage and frequency of lichen, bryophytes, and vascular plants were measured using a 4 m^2 quadrat (2 m×2 m) divided into 400 grids (10 cm×10 cm). The vegetation coverage was estimated visually by recording the ground covered by each plant species within the quadrat. The frequency was determined by calculating the proportion of the grid where the plant species was found among the total quadrat. In particular, the coverage and frequency of *Saxifraga oppositifolia* and *Salix Polaris*, the most dominant species among vascular plants, were measured separately, which are the most dominant species among vascular plants (Moreau et al., 2008). We analyzed the NDVI, which is obtained by taking the ratio of the difference between reflectance in the near-infrared and red regions of the spectrum and their sum. The NDVI has often been utilized to represent proxy data of the relative greenness of vegetation (Johansen and Tømmervik, 2014). While leaves strongly absorb wavelengths of visible light, they strongly reflect the wavelengths of near-infrared light. NDVI can be calculated as follows:

$\mathrm{NDVI} = \frac{R_{\mathrm{NIR}} - R_{\mathrm{red}}}{R_{\mathrm{NIR}} + R_{\mathrm{red}}}$, where R_{NIR} and R_{red} are the reflectance values of the near-infrared and red bands, respectively. NDVI has a range of -1 to +1 (e.g. dense and vital vegetation is close to +1, while low and scattered vegetation is close to 0).

2.4. Soil analysis

Soil samples were collected at soil depths of 0-5, 5-10, 10-20, and 20-30 cm during the same period of vegetation observation. The soil samples were air-dried, passed through a 2 mm sieve, and used for further soil analyses.

The SOC and total N contents were determined by a combustion method (950 ℃) using an elemental analyzer (FlashEA 1112; Thermo Fisher Scientific, Waltham, MA, USA) for soil samples. The soil samples for SOC analysis were acid washed in prior to the EA analysis. The contents of total P, K, Ca, Na, and Mg were determined using an inductively coupled plasma optical mass spectrometer (OPTIMA 5300DV, PerkinElmer, Shelton, CT, USA) after digestion with perchloric acid (Kuo, 1996). Soil texture was analyzed by wet-sieving through a 53 μm sieve after removing SOM with H_2O_2 (34.5%), and silt and clay fractions were calculated using a pipette method. Soil pH and electrical conductivity (EC) were measured using an Orion Star$^{\mathrm{TM}}$ A215 (Thermo Fisher Scientific) at 1:2 (w/v) and 1:5 (w/v) ratio of soil to deionized water, respectively. To determine SOM quality, size-density fractionation was performed using sodium polytungstate solution (density 1.55 g cm^{-3}) and the wet-sieving method (Paré and Bedard-Haughn, 2011; Six et al., 2001; Yoo et al., 2017). A 10 g sample of air-dried soil was mixed with 30 mL of sodium polytungstate solution, and the free-light fraction (FLFs) was collected using pre-combusted

GF/A filters. The FLF was washed with deionized water several times until the EC dropped to less than 5 μS cm^{-1} (Mueller et al., 2015). The heavy fractions were immersed in water, horizontally shaken for 18 hr, and wet-sieved through a 53 μm sieve. The fraction remaining on the sieve consisted of sand-sized particulate organic matter (SF), while the fraction passing through the sieve were silt/clay-associated SOM (SCF). To determine the chemical composition of SOM, we analyzed SOM fractions (FLF, SF, and SCF) at 3-, 8-, 36-, 57-, 70-, 77-yr old sites using a double-shot analytical pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) method (Lee et al., 2020; Mattonai et al., 2020). The SF and SCF were treated with 10% hydrofluoric acid before the Py-GC/MS. This analysis was carried out using a furnace-type pyrolyzer (EGA/PY-3030D, Frontier Laboratories Ltd., Koriyama, Japan) connected to a gas chromatography-mass spectrometry (7890B/5977A, Agilent, Santa Clara, CA, USA). The detailed Py-GC/MS operational conditions are listed in Table S1. The pyrolysis products were identified based on the mass spectra of the NIST 08 libraries.

2.5. Statistical analysis

Statistical analyses were performed using the general linear model (GLM), Pearson correlation analysis, and linear regression model with SAS 9.4 (SAS Institute, 2013). Owing to the non-normal distribution of our data, we performed ANOVA using the GLM procedure, which can be applied to both balanced and unbalanced data. The fixed variables were soil age, depth, or glacio-fluvial activity. Least-square means were used to test for significant differences in the effects of fixed variables on vegetation and soil data. Only for the data with significant differences identified by ANOVA, we performed the Least Significant Difference (LSD) post-hoc test to determine the differences between specific sites with different soil age, depth, or glacio-fluvial activity. To determine the relationship between vegetation and soil variables, Pearson's correlation analysis was conducted using SAS 9.4. Linear regression models were created using the regression (REG) procedure to examine the relationship between SOC/total N content and chemical composition in SOM fractions with soil age. A statistical significance level of $p<0.05$ was generally applied, but statistical tendencies ($p<0.10$) are also reported.

3. Results

3.1. Vegetation and soil changes by soil age

Vegetation and soil biogeochemical properties varied significantly by soil age (Table 1). The vegetation frequency of *S. oppositifolia* continued to increase until 40-60 yr of deglaciation and then decreased thereafter (Fig. 2a). Despite an insignificant increase at the younger sites (<60 yr), the frequency of *S. polaris* increased significantly and marginally at the 60-80 yr ($p<0.05$) and 80-90 yr sites ($p<0.10$), respectively (Fig. 2b). The NDVI, a proxy for total vegetation cover (Johansen and Tømmervik, 2014), increased significantly with increasing soil age (Fig. 2c). Consistently, the contents of SOC and total N in the upper 5 cm soil showed an increase within 90-yr deglaciation (Fig. 2d-e). Soil EC was significantly higher at the youngest (<20 yr) and oldest (80-90 yr) sites compared to that at the medium-age sites (Fig. 2f). To determine the correlation between those six variables with significant chronological changes, we found that the SOC and total N contents had high correlation coefficients with the frequency of *S. oppositifolia* and *S. polaris* and NDVI (Table 2).

The SOM fractionation showed that the SOC and total N contents in the FLF, SCF and SF increased significantly with increasing soil age (Fig. 3a-b). In addition, we found by Py-GC/MS analysis that the relative proportion of lignin-derived aromatic compounds significantly increased in FLF with increasing soil age (Table S2). At the same time, lipid and fatty acid derivatives showed a higher abundance in the SCF and SF over the soil age (Table S2).

3.2. Vertical distribution of soil properties

In the Midtre Lovénbreen glacier foreland, soil biogeochemical properties varied vertically (Table 3). The results obtained by the post-hoc test were summarized in Table 4. The SOC and total N contents were significantly higher in the topsoil (0-5 cm) than in the deeper layers (5-30 cm). Higher SOM contents at upper soil depth were significant after 20 yrs of glacial retreat, and total N contents increased significantly from the early stage of deglaciation (<20 yr). Total P content at the youngest sites (<20 yr) was significantly higher in the topsoil (0-5 cm) than in the subsoils (5-30 cm); however, at the 40-60 yr sites, higher P content was found in the subsoils than in the topsoil. The clay contents were significantly lower in the surface layer (0-5 cm) relative to the deeper layers at <20 and 20-40 yr sites. Soil pH was higher than 8.0 at the overall sites of the glacier foreland but significantly lower in the soil surface (<5 cm) than in the deeper layers. As the result of elemental analysis, total K and Na contents were higher on the surface than in the deeper soils. In contrast, total Mg content tended to increase as the soil depth became deeper.

3.3. Vegetation and soil changes by glacio-fluvial runoff

Glacio-fluvial runoff had significant influence on vegetation and soil biogeochemical properties (Table 5). Vegetation frequencies of bryophytes, vascular plants, and *S. oppositifolia* in the active sites were significantly reduced by 83-89% compared to those in the no-runoff sites, and lichen frequency also showed a 93% decrease despite no significant difference (Fig. 4a). In the inactive sites, vegetation frequencies also decreased by 79% compared to those in the no-runoff sites. The SOC and total N contents were significantly lower in the active (by 76%) and inactive (by 57%) sites than those in the no-runoff sites (Fig. 4b-c). We found a decrease in SOC and total N contents for all SOM fractions in the runoff affected sites. In addition, the clay content and soil EC were significantly lower in the active and inactive sites compared to those in the no-runoff sites (Fig. 4d-e).

4. Discussion

4.1. Vegetation and soil development along the chronosequence

Vegetation succession along the soil chronosequence was observed in the Midtre Lovénbreen glacier foreland, which has been reported by the previous studies (Hodkinson et al., 2003; Moreau et al., 2008; Yoshitake et al., 2011; Müller et al., 2012). As a pioneer species in vegetation succession, *S. oppositifolia* is predominantly distributed in the early stage of deglaciation (Moreau et al., 2008; Müller et al., 2012). Meanwhile, *S. polaris*, the prostrate dwarf shrub, showed an increase in vegetation frequency at the relatively older sites (>60 yrs) of the glacier foreland. This result is consistent with that of Moreau et al. (2008), who found that the frequency of *S. polaris* increased remarkably after 70 yrs of deglaciation. Moreover, the increase in total vegetation cover with increasing soil age, confirmed by the NDVI, is consistent with the result reported previously for other glacier forelands in Svalbard (Hodkinson et al., 2003; Yoshitake et al., 2011).

The SOC and total N contents in the glacier foreland increased as soil age increased (Fig. 2d-e). The SOC and total N contents in the upper 5 cm soil were 1.63 g C kg^{-1} and 0.09 g N kg^{-1} at the youngest site (<20 yr), and 5.15 g C kg^{-1} and 0.31 g N kg^{-1} at the oldest site (80-90 yr). Our findings are consistent with those of the previous study on the Midtre Lovénbreen glacier foreland (Dong et al., 2016), which reported that SOC and total N contents in the upper 10 cm soil increased from 0.3 to 6.9 g C kg^{-1} and from 0.04 to 0.55 g N kg^{-1} after 80-yr deglaciation. Contrastingly, the SOC and total N contents of the Midtre Lovénbreen glacier foreland were significantly lower than those of the other glacier forelands in Svalbard, such as Werenskioldbreen and Irenebreen, where the average SOC and total N contents in the upper 5 cm soil were 4.5~22.2 g C kg^{-1} and 0.2~1.7 g N kg^{-1}, respectively (Kabala and Zapart, 2012; Wietrzyk et al., 2018). Hodkinson et al. (2003) attributed the slow SOM accumulation in the Midtre Lovénbreen glacier foreland to the nutrient-poor condition associated with low temperature and dry conditions. Although the climate-derived factors would not only affect the Midtre Lovénbreen but also other glacier forelands around it (Austre Brøggerbreen, Vestre Lovénbreen and Austre Lovénbreen), the slowest SOC accumulation in the Midtre Lovénbreen foreland was reported compared to that in the other glacier forelands (Wietrzyk-Pełka et al., 2020)

Soil EC was higher at the youngest and oldest sites than other-age soils, respectively (Fig. 2f). The slightly high EC at the youngest sites (<20 yr) was probably due to inorganic materials remaining on the soil surface after glacier retreat, such as sulfates, bicarbonates, and dissolved ions in subglacial meltwater (Hallbeck, 2009; Ren et al., 2019). Over time, these inorganic material content might be decreased in the soil by erosion, leaching, or plant uptake, leading to lower soil EC (Fig. 2f) (Hallbeck, 2009). However, the EC of the top soil increased significantly in the oldest sites (80-90 yr) with the highest SOM accumulation (Fig. 2f). The could be explained by the fact that sea salts containing soluble/exchangeable ions could be deposited at the oldest sites exposed longer and closer to the ocean

(Ansari et al., 2013; Zeng et al., 2013). The other possible reason for the higher EC at the 80-90 yr sites than others could be the SOM accumulation with increasing soil age. The SOM with various functional groups can enhance the exchange of ionic substances, eventually increasing soil EC (Adviento-Borbe et al., 2006; Newcomb et al., 2017).

4.2. Compositional changes in soil organic matter

The data presented in Table 2 indicate that surface SOM accumulation along the chronosequence is highly affected by increasing vegetation coverage on the soil surface (Wietrzyk et al., 2018; Yoshitake et al., 2011). Our finding is supported by the results of SOM fractionation and Py-GC/MS analysis. The SOC and total N contents in the FLF increased significantly with increasing soil age (Fig. 3a-b). The FLF, typically composed of plant leaves and debris, is more susceptible to microbial degradation than SCF and SF fractions, owing to its inherently labile properties or non-protected portions by soil minerals/aggregates (Six et al., 2001; von Lützow et al., 2007; Yang et al., 2012; Zhao et al., 2016). In addition, the relative proportion of lignin-derived aromatic compounds significantly increased in FLF with increasing soil age (Table S2). These results confirmed that plant-derived FLF is an essential source of SOM input, resulting in surface SOC and total N accumulation in the deglaciated foreland.

Moreover, the SOC and total N contents in the other SOM fractions, SCF and SF, also increased significantly with increasing soil age (Fig. 3a-b). Arctic cryogenic conditions inhibit plant growth and microbial degradation (Schulz et al., 2013; Wietrzyk et al., 2018; Yoshitake et al., 2011), restricting SOM accumulation. Nevertheless, the increased SOC and total N contents in the SCF and SF reflect the association of microbial metabolites with soil mineral particles along the soil chronosequence (Bernasconi et al., 2011; Dümig et al., 2012; Thomazini et al., 2015). Our Py-GC/MS analysis results (Table S2) showed a high abundance of organic compounds microbially transformed, such as lipid and fatty acid derivatives (Yang et al., 2020), in the SCF and SF of old sites (57, 70 and 77 yr). Therefore, SOM can be stabilized as a mineral-associated form within a short deglaciation period, even in the harsh climatic conditions of the High Arctic (Khedim et al., 2021; Schulz et al., 2013; Thomazini et al., 2015).

4.3. Soil biogeochemical changes by the vertical profiles

The SOC and total N mainly derived from vegetation showed higher contents in the topsoil (0-5 cm) than in the subsoil (5-30 cm) (Table 4). In the Arctic, most vegetation has a shallow and widespread root system in the top soil (Wang et al., 2016), leading to the enrichment of SOC and total N contents in the soil surface. In addition, as nitrogen fixation is an aerobic process, available nitrogen for plants and microbes is especially higher in the topsoil layer than in the deeper layer (Augusto et al., 2017; Tanner et al., 2013). Interestingly, at the young sites (<20 yr), there was no significant difference in SOC content with soil depth, but there was a significant difference in total N content (Table 4). This is probably because cyanobacteria emerged within 4-5 years of glacier retreat before vegetation establishment, resulting in earlier development of soil N fixation than SOC accumulation in the topsoil of glacier forelands (Khedim et al., 2021; Mapelli et al., 2011; Pessi et al., 2019; Schmidt et al., 2008; Vries et al., 2021).

Total P content was higher in the soil surface than in the deeper layers within the early stage of deglaciation, whereas this vertical gradient reversed gradually after 40 yrs of the glacier retreated (Table 4). Our results are consistent with the findings in the Hailuogou glacier foreland (Gongga Mountain, Southwest China), where total P contents were higher in the topsoil (0-10 cm) of younger sites (30 yr) and the subsoil (20-50 cm) of older sites (80 and 120 yr), respectively (Jun et al., 2013). At the younger sites, the higher total P content in the topsoil relative to the subsoil is probably due to the subglacial materials remaining on the soil surface after the glacier retreated (Ren et al., 2019; Wojcik et al., 2020). In comparison, at the older sites (>40 yr), the lower P content in the topsoil than in the subsoil is likely to be utilized by plants/microbes for growth or precipitated down to the subsoil after the glacial retreat (Jun et al., 2013). An additional reason for the higher subsoil P content in comparison with the topsoil with increasing soil age is that soil P is mainly derived from the underlying parent rock materials (Andy et al., 2008; Augusto et al., 2017). Previous studies conducted in the Midtre Lovénbreen glacier foreland reported the occurrence of apatite, containing P element, which results obtained by X-ray diffraction and SEM-EDS (Scanning Electron Microscopy-Energy Dispersive Spectroscopy) analyses (Borin et al., 2010; Mapelli et al., 2011). Despite no significant chronological effects, the vertical distribution of total

P content in the glacier foreland could be explained by subglacial deposits and parent materials.

The clay content tended to decrease in the surface layer (0-5 cm) relative to the deeper layers (Table 4). Water/wind erosion and vertical translocation can cause the removal of fine earth fractions from the surfaces of glacier forelands (Vilmundardóttir et al., 2014b). Kabala and Zapart (2012) reported that snow/glacier melting every spring in the Werenskioldbreen glacier foreland of Svalbard might be a possible reason for the clay loss in the uppermost soil layer (0-3 cm).

At all sampling sites, soil pH higher than 8.0 is probably due to marble schist, one of the bedrocks in the Midtre Lovénbreen glacier foreland (Shi et al., 2018; Wietrzyk et al., 2018). However, a lower soil pH in the topsoil compared to the subsoil layers might be attributed to the weakly-acidic compounds released from the decomposition procedure of plant-derived FLF (Bernasconi et al., 2011; Vilmundardóttir et al., 2014a; Wietrzyk-Pełka et al., 2020). In addition, meltwater can cause carbonate leaching every spring, eventually resulting in lower soil pH in the topsoil than in the subsoil (Kabala and Zapart, 2012).

Higher K and Na contents at the upper than deeper layers might be explained by the landscape feature of the glacier foreland. Owing to the fjord landscape of Svalbard, the glacier forelands are continuously exposed to oceanic influences, accordingly susceptible to the wind deposition of the sea salts (ARCUS, 2000; Ansari et al., 2013; Zeng et al., 2013). Conversely, total Mg content was significantly higher with increasing soil depth (Table 4). According to the petrographic analysis, parent bedrocks in the Brøggerhalvøya Peninsula, where the Midtre Lovénbreen glacier belongs, contained primarily quartz, mica, chlorite, feldspar, pyrite and apatite (Nilsen et al., 1999; Shi et al., 2018). In particular, Mg was confirmed by the SEM-EDX analysis as the main element contained in chlorite minerals (Koutsopoulou et al., 2010), which could explain the higher total Mg content in the deeper layers. Therefore, we showed that the vertical distribution of soil biogeochemical properties could be influenced not only by vegetation development but also by parent materials and the surrounding abiotic environment.

4.4. Soil biogeochemical changes by glacio-fluvial runoff

Glacio-fluvial runoff considerably increased the horizontal heterogeneity in soil-ecosystem development in glacier forelands, but relevant studies are lacking (Wojcik et al., 2021). From previous studies, limited results were obtained, such as focusing only on the changes in plant colonization by various glacio-fluvial runoff (Moreau et al., 2008) or not isolating its effects from topographical factors (Wojcik et al., 2020). Therefore, our study conducted under the controlled conditions of soil age and topography is valuable for acquiring empirical data on soil biogeochemical changes caused by glacio-fluvial runoff.

Vegetation development in the glacier foreland was inhibited by active glacio-fluvial runoff (Fig. 4a), consistent with the previous study on the Midtre Lovénbreen glacier foreland (Moreau et al., 2008). Meanwhile, in the inactive sites, we found the contradictory result with Moreau et al. (2008), who reported a minor impact of the inactive glacio-fluvial runoff on the vegetation frequencies. This result might be because we selected the sampling points with no difference in soil age and topographical features among the sites of the previous study (Moreau et al., 2008). The glacio-fluvial runoff disturbed the surface SOC and total N accumulation as well as vegetation development (Fig. 4b-c). Among the SOM fractions, a remarkable change was observed in the SOC and total N contents of the plant-derived FLF, which was lower in the active (by 87%) and inactive (by 78%) sites than in the no-runoff sites. We suppose that runoff can directly restrict soil chronological development by sweeping the accumulated SOC and total N from the soil surface. In particular, plant-derived FLF is easily swept away by glacio-fluvial runoff owing to its low density (Lavallee et al., 2020; Six et al., 2001). In addition, the lack of vegetation development in the active and inactive sites could not protect the soil surface from glacio-fluvial runoff, probably further increasing soil erosion (Church and Ryder, 1972; Gurnell et al., 2000). Moreover, the SOC and total N contents of SCF and/or SF were lower in the active and inactive sites than in the no-runoff sites (Fig. 4b-c), negatively affecting SOM stabilization. This probably due to the lower clay contents affected by glacio-fluvial runoff (Fig. 4d), inhibiting the adsorptive interaction between soil particles and SOM (Lavallee et al., 2020; Six et al., 2002). The soil EC, related to the amount of soil inorganic nutrients, was lower in the active and inactive sites than in the no-runoff sites (Fig. 3f). Our results are contrasted with the findings by Wojcik et al. (2020), who reported that the deposition of SOC and clay particles was enhanced by glacio-fluvial runoff. However, we confirmed empirically that glacio-fluvial runoff retarded the SOM accumulation and stabilization by removing cover plants, clay particles and soil nutrients, eventually inhibiting the ecosystem development in the glacier foreland.

4. Conclusions

In this study, early soil development in the glacial foreland of Midtre Lovénbreen was investigated by considering various environmental factors as well as time. Our data obtained by SOM fractionation and Py-GC/MS analysis revealed that the surface accumulation of FLF along the chronosequence was mainly due to the plant-derived material, including lignin-derived aromatic compounds. The increases of heavy fractions (SCF and SF), the association of soil mineral particles to organic compounds microbially transformed, shwed the SOM stabilization within a short period of deglaciation under harsh climatic conditions of the High Arctic. Meanwhile, the vertical soil profile showed that subglacial materials, parent bedrock, and aeolian deposition played important roles as soil-forming factors for determining soil biogeochemical properties in this region. Lastly, we made a pioneering attempt to clarify the changes in both vegetation and soil development caused by glacio-fluvial runoff by isolating the effects of time and topography. As a result, the active and inactive sites of glacio-fluvial runoff significantly delayed ecosystem development by inhibiting vegetation establishment and SOM accumulation. Our findings strengthened the interpretation of ecosystem development in glacial forelands by focusing on various soil-forming factors from soil age to abiotic factors including glacio-fluvial runoff. Lastly, we suggest that additional experiments in various glacial forelands are required to verify and consolidate the diverse effects of soil-forming factors on vegetation and soil development.

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