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RESEARCH

Soil properties and molecular compositions of soil organic matter in four different Arctic regions

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Background: The Arctic permafrost stores enormous amount of carbon (C), about one third of global C stocks. However, drastically increasing temperature in the Arctic makes the stable frozen C stock vulnerable to microbial decomposition. The released carbon dioxide from permafrost can cause accelerating C feedback to the atmosphere. Soil organic matter (SOM) composition would be the basic information to project the trajectory of C under rapidly changing climate. However, not many studies on SOM characterization have been done compared to quantification of SOM stocks. Thus, the purpose of our study is to determine soil properties and molecular compositions of SOM in four different Arctic regions. We collected soils in different soil layers from 1) Cambridge Bay, Canada, 2) Council, Alaska, USA, 3) Svalbard, Norway, and 4) Zackenberg, Greenland. The basic soil properties were measured, and the molecular composition of SOM was analyzed through pyrolysis-gas chromatography/mass spectrometry (py-GC/MS).

Results: The Oi layer of soil in Council, Alaska showed the lowest soil pH and the highest electrical conductivity (EC) and SOM content. All soils in each site showed increasing pH and decreasing SOC and EC values with soil depth. Since the Council site was moist acidic tundra compared to other three dry tundra sites, soil properties were distinct from the others: high SOM and EC, and low pH. Through the py-GC/MS analysis, a total of 117 pyrolysis products were detected from 32 soil samples of four different Arctic soils. The first two-axis of the PCA explained 38% of sample variation. While short- and mid-hydrocarbons were associated with mineral layers, lignins and polysaccharides were linked to organic layers of Alaska and Cambridge Bay soil.

Conclusions: We conclude that the py-GC/MS results separated soil samples mainly based on the origin of SOM (plants- or microbially-derived). This molecular characteristics of SOM can play a role of controlling SOM degradation to warming. Thus, it should be further investigated how the SOM molecular characteristics have impacts on SOM dynamics through additional laboratory incubation studies and microbial decomposition measurements in the field.

Keywords: soil organic matter (SOM), Arctic soil, pyrolysis-GC/MS, soil physical and chemical properties, chemical characterization of SOM

Introduction

Soil emits carbon dioxide (CO_2) to the atmosphere, but on the other hand, it plays a role as a large carbon reservoir in terrestrial ecosystem. The soil organic matter (SOM) is the key component to control over these biogeochemical processes since it contains various types of organic substances such as carbohydrates, proteins, etc. (Tate 1992). The soil organic carbon (SOC) is one of the measurable parameters to represent SOM. Soil stores more than 1,500 Pg of organic carbon (C) (Jobbágy and Jackson 2000), and the C storage in tundra is about 6% of the global soil C stocks (Vancampenhout et al. 2009). The Arctic gains lots of attention from the scientific community due to sharply increasing temperature trends compared to the other regions. The high latitude terrestrial ecosystems preserve a large amount of SOC against from microbial decomposition owing to cold and sometimes wet soil environments (McGuire et al. 2009). Recently, permafrost is extensively thawing, and the emission of greenhouse gases from the thawed active layer is increasing due to global warming (Karhu et al. 2014; Schuur et al. 2008; Schuur et al. 2009).

Soil organic matter (SOM) is generally derived from plants, animals, and microorganisms, and it affects many soil physical, chemical, and biological parameters such as soil structure, erosion, available nutrients, and mineralization (Feller and Beare 1997). Particularly, C sequestration from terrestrial ecosystems and SOM decomposition depends on the characteristics of SOM due to its influence on microbial activities. The characteristic of SOM is determined by several factors such as climate, plants, microorganisms, and soil properties (Kögel-Knabner 2002; Piccolo 2001). Therefore, the understanding of the relationship among climate, vegetation, and SOM characteristics from various regions would help us predict the responses of SOM to climate change (Vancampenhout et al. 2009).

Complex SOM can be characterized by a pyrolysis-Gas Chromatography-Mass Spectrometry (py-GC/MS). Gaseous compounds produced through the pyrolysis of soil samples move in a mobile phase and are separated into several chemical compounds in the column. Based on the molecular weight, each compound is characterized through mass spectrometry. The greatest merit of the py-GC/MS is decomposition of samples into small molecules at the high temperature of 500°C–1,400°C. This allows us to analyze the liquid or solid types of macromolecules or polymers. Thus, this analytical method is widely used for the environmental samples such as natural organic matter or microplastics (Picó and Barceló 2020).

While the research area of permafrost C decomposition, SOM dynamics, etc. related to climate change is greatly getting attention, the study for SOM is not enough. Particularly, the quantitative approaches such as SOC contents, stocks in permafrost regions have been studied a lot, but qualitative ones like SOM characteristics is not well investigated (Vancampenhout et al. 2009). Therefore, our research goal is to understand basic properties of Arctic soil and SOM composition through py-GC/MS in the Arctic which is vulnerable to climate change.

Materials and Methods

Sampling site

The Council site (64.5°N, 163.4°W) is in Seward Peninsula of Northwest Alaska, USA (Fig. 1). Annual temperature and precipitation in Council is 2.8°C and 404.1 mm, respectively (Table 1) (Nam et al. 2021). Soil is classified as a Histic-Tubic Cryosol (Nam et al. 2021). Cambridge Bay, Nunavut in Canada is located in southeast coast in Victo-

Fig. 1 Research sites for studying soil properties and soil organic matter characterization in Circum-Arctic.

Table 1 Description of soil sampling sites

Environmental parameter	Council, Alaska, USA	Cambridge Bay, Nunavut, Canada	Svalbard, Norway	Zackenberg, Greenland
Latitude & longitude	64.5° N, 163.4° W	69.1° N, 105.0° W	78.9° N, 12.0° E	74.3° N, 21.0° W
Annual precipitation (mm)	404.1 (1971 to 2010)	141.8 (1981 to 2010)	37.4 (2004 to 2014)	200.0 (1996 to 2012)
Annual temperature (°C)	–2.8 (1971 to 2010)	–13.8 (1981 to 2010)	–3.7 (2004 to 2014)	–9.0 (1996 to 2012)
Vegetation composition	*Eriophorum vaginatum*, *Vaccinium uliginosum*, *Sphagnum* moss, lichen	*Dryas octopetala*, *Carex* spp.	*Saxifrage oppositifolia*, *Cetraria delisei*	*Cassiope tetragona*, *Salix arctica*

Each site information was referred from published articles: Council, Alaska, USA (Nam et al. 2021), Cambridge Bay, Canada (McLennan et al. 2015), Svalbard, Norway (Jung et al. 2014; Klokk and Rønning 1987; Norwegian Meteorological Institute 2014), and Zackenberg, Greenland (Jensen et al. 2013).

ria Island. Annual temperature and precipitation in Cambridge Bay are –13.8°C and 141.8 mm, respectively (Table 1), and soil type is a Turbic Cryosol (McLennan et al. 2015). Svalbard site (78.9°N, 12.0°E) (Fig. 1) is located in Norwegian archipelago, and annual temperature and precipitation is –3.7°C and 37.4 mm, respectively (Table 1) (Norwegian Meteorological Institute 2014). Zackenberg (74.3°N, 21.0°W) is in northeast Greenland (Fig. 1). Annual temperature and precipitation are –9.0°C and 200 mm, respectively (Table 1), and soil type is a Turbic Cryosol (Jensen et al. 2013).

Soil sampling

All soil samples (three replicates in each site) were acquired during July and August, Arctic summer. In Alaskan site, soil core samples were acquired from moist acidic tundra in July 2014. Major vegetation was cottongrass (*Eriophorum vaginatum)*, blueberry (*Vaccinium uliginosum)*, *Sphagnum* moss, and lichen (Table 1) (Nam et al. 2021). Sampled soil was sectioned into Oi, Oe, and A layer, and the mineral A layer was in more than 50 cm deep; while the Oi layer contains slightly decomposed organic matter, the Oe layer is composed of intermediately decomposed organic matter (Weil and Brady 2017). In Cambridge Bay, organic and mineral layers of soil were sampled from *Dryas integrifiloia and Carex* spp. (Table 1) dominated area in July 2015 (McLennan et al. 2015). The organic layer depth varied from 5 to 20 cm. The organic layer was not well developed in Svalbard and Zackenberg, and soil sampling was conducted from 0–5 and 5–10 cm depth. Svalbard soil was acquired from *Saxifrage oppositifolia* and *Cetraria delisei* (Table 1) dominated area in July 2014 (Jung et al. 2014; Klokk and Rønning 1987). Soil in Zackenberd was sampled from *Cassiope tetragona* and *Salix arctica* community in mid-August in 2011 and 2012, respectively (Table 1) (Jung et al. 2020).

Soil analyses

Soil was air-dried and passed through a 2-mm sieve. Soil pH and electrical conductivity (EC) were measured by a pH/EC meter (Thermo Scientific Orion Star A125 pH/Conductivity meter; Thermo Fisher Scientific, Waltham, MA, USA) after mixing soil with water (1:5 ratio) (Rhoades 1996; Thomas 1996). Soil texture was measured from mineral soil, so the Oi and Oe layers from Alaskan soil and organic layer from Cambridge Bay were excluded in this analysis. The organic matter was removed from soil by adding H_2O_2, and soil was horizontally shaken after adding 5% sodium hexametaphosphate for 18 hours. The weight of sand-size particles was calculated after wet-sieving through a 53-μm sieve, and that of clay-size particles was calculated from a pipette method. Finely pulverized soil was passed through a 250-μm sieve and then used for soil C and total nitrogen (TN) contents through an elemental analyzer (FlashEA 1112; Thermo Fisher Scientific). In case soil pH was greater than pH 5, total inorganic carbon was removed by adding 1M HCl solution to soil, and thus the analyzed C was considered as SOC.

Pyrolysis-gas chromatography/mass spectrometry

A py-GC/MS was used to characterize molecular compositions of SOM. Three replicates were used for the py-GC/MS analysis from all soil samples except the Oi layer in Alaska (n = 2). Soil was finely ground, and ca. 10 mg of soil sample was pyrolyzed in the furnace-type pyrolyzer (EGA/PY-3030D; Frontier Laboratories Ltd., Koriyama, Japan). The temperature was heated from 40°C to 600°C at a rate of 10°C min^{-1}. Pyrolyzed gas products were passed through a GC/MS system, an Agilent 7890B GC (Agilent Technologies, Santa Clara, CA, USA) equipped with a UA-5 capillary column (30 m × 250 μm internal diameter × 0.25 μm film thickness) and an Agilent 5977C MS as a detector. The gaseous sample was injected with a split ratio of 1:10 under a 10 mL min^{-1} helium flow. The flow rate of Helium, a carrier gas, was 1 mL min^{-1}. The injector temperature was set to 320°C. The initial temperature of the oven was set to 50°C for 5 minutes, and then gradually increased to 320°C with a rate of 10°C min^{-1}. The final temperature was continued for 10 minutes. Electron impact ionization (70 eV) was used.

We used AMDIS v. 2.66 for deconvolution and extraction, and then each compound was identified after comparing the spectra with a reference of the National Institute of Standards and Technology 2008 (NIST 08) mass library. The relative abundance of each pyrolysate was recalculated based on the sum of the peak components in each sample. We carefully and manually checked the identification and quantification of each peak. Based on previously published literature, we assigned a total of 117 pyrolysates into seven categories, according to their origins and chemical similarity: polysaccharides (Ps), lipids (Li), lignin (Lg), nitrogen compounds (N), phenols (Ph), and aromatics (Ar), and unidentified (Ud) (Buurman et al. 2007; Chefetz et al. 2002; Gleixner et al. 2002; González-Pérez et al. 2007; Grandy et al. 2009; Mambelli et al. 2011; Schellekens et al. 2017; Stewart 2012).

Statistical analyses

We used the one-way ANOVA model to test mean differences among soil samples. When significant differences were detected ($p < 0.05$), a post-hoc analysis (Tukey's HSD method) was used to separate mean differences. In addition, principal component analysis (PCA) was used to reduce dimensionality of all soil properties and SOM composition data. Statistical analyses were carried out using R Statistical Software (version 3.2.2; R Foundation for Statistical Computing, Vienna, Austria) and JMP® 16.2.0 (SAS Institute Inc., Cary, NC, USA).

Results

Soil properties

The Oi soil layer of Council, Alaska showed the lowest soil pH (3.9) and the highest EC (924 μS/cm) and SOC content (416 mg/g) (Table 2). The TN value was the highest in the organic layer of Cambridge Bay, Canada as 28.3 mg/g, and the organic soils in Council, Alaska followed as 9–10 mg/g. Therefore, the C/N ratio was the highest and the lowest in the Oi layer of Council, Alaska and the Cambridge Bay soils, respectively. All soils in each site showed increasing soil pH and decreasing SOC and EC values with soil depth. The textural analysis of mineral layers classified as the loam soil for Council, Alaska, loamy sand for Cambridge Bay, Canada, silt loam for Svalbard, Norway, sandy loam for *Cassiope* soil in Zackenberg, Greenland, and clay loam for *Salix* soil in Zackenberg, Greenland (Table 2).

Several soil physical and chemical properties were correlated to each other. Particularly, the soil C/N ratio was significantly correlated to soil pH and EC (Table 3). Soil texture was weakly correlated with SOC and TN contents, but not with any other chemical properties (Table 3). The PCA with all physical and chemical parameters showed that PC1 and PC2 explained more than 85% of variation (Fig. 2). The PC1 divided the samples according to the SOC content, and the PC2 split samples with a higher pH and more sand versus samples with a higher clay content.

Pyrolysis-GC/MS

A total of 117 pyrolysis products were detected from 32 soil samples acquired from four different Arctic soils (Table 4). We identified 101 compounds from GC/MS library, but the rest of 16 pyrolysates were not assigned as known compounds. The each compound was categorized into chemical groups based on their origin and chemical similarity (Table S1). The PCA showed that the PC1 and PC2 explained 23.16% and 14.92%, respectively (Fig. 3). Several short- and mid- hydrocarbon compounds were placed in the left side of PC1, and the mineral layer of Council, Alaska soil was scattered in this area (Fig. 3). In the upper right side, the organic layer of Council, Alaska and Cambridge bay soil was located, and this was associated with lignins and polysaccharides. The soils under *Cassiope* in Zackenberg, Greenland was related to some aromatic compounds. The rest of soils containing only a few number of compounds were situated in the lower right side.

Discussion

Soil properties in four different Arctic regions

The four study sites belonged with major vegetation

Table 2 Physical and chemical properties of soils

Sample	pH	EC (μS/cm)	SOC (mg/g)	TN (mg/g)	C/N ratio	Sand (%)	Silt (%)	Clay (%)
AK Oi	3.9 ± 0.3^{g}	924.3 ± 663.9^{a}	416.0 ± 32.6^{a}	$9.0 \pm 2.2^{b,c}$	48.9 ± 11.1^{a}			
AK Oe	4.8 ± 0.1^{f}	148.3 ± 43.1^{b}	278.7 ± 131.5^{a}	10.3 ± 5.4^{b}	26.8 ± 1.8^{b}			
AK A	$5.2 \pm 0.1^{e,f}$	107.7 ± 29.5^{b}	22.7 ± 3.4^{b}	1.0 ± 0.0^{d}	$20.9 \pm 3.2^{b,c}$	$51.3 \pm 2.2^{a,b}$	$41.6 \pm 1.7^{a,b}$	7.1 ± 0.6^{b}
CB O	$7.4 \pm 0.1^{a,b}$	$396.2 \pm 102.3^{a,b}$	309.3 ± 44.7^{a}	28.3 ± 1.7^{a}	10.9 ± 1.2^{c}			
CB M	7.8 ± 0.1^{a}	69.6 ± 6.7^{b}	49.3 ± 10.08^{b}	$5.0 \pm 0.8^{b,c,d}$	10.3 ± 0.7^{c}	74.9 ± 2.5^{a}	20.8 ± 1.6^{b}	4.3 ± 1.1^{b}
SV D1	6.6 ± 0.1^{c}	80.4 ± 14.5^{b}	58.0 ± 12.4^{b}	$5.0 \pm 0.8^{b,c,d}$	12.2 ± 0.5^{c}	$39.3 \pm 0.0^{a,b}$	52.8 ± 0.0^{a}	7.8 ± 0.0^{b}
SV D2	$6.9 \pm 0.3^{b,c}$	45.4 ± 6.0^{b}	43.7 ± 2.6^{b}	$4.0 \pm 0.0^{b,c,d}$	11.2 ± 0.4^{c}	$41.2 \pm 0.0^{a,b}$	53.1 ± 0.0^{a}	5.7 ± 0.0^{b}
ZK C D1	5.0 ± 0.1^{f}	60.6 ± 0.5^{b}	39.7 ± 9.7^{b}	$2.3 \pm 0.9^{c,d}$	$16.2 \pm 1.3^{b,c}$	62.8 ± 10.9^{a}	$26.3 \pm 9.8^{a,b}$	10.9 ± 1.1^{b}
ZK C D2	5.0 ± 0.1^{f}	33.8 ± 8.3^{b}	34.3 ± 8.3^{b}	$2.3 \pm 0.5^{c,d}$	$16.0 \pm 0.6^{b,c}$	65.3 ± 5.5^{a}	$23.0 \pm 5.9^{a,b}$	11.7 ± 1.2^{b}
ZK S D1	$5.6 \pm 0.1^{d,e}$	95.3 ± 23.1^{b}	21.0 ± 6.5^{b}	1.3 ± 0.5^{d}	$15.6 \pm 0.7^{b,c}$	25.8 ± 10.5^{b}	$40.2 \pm 7.1^{a,b}$	34.1 ± 3.4^{a}
ZK S D2	5.8 ± 0.2^{d}	47.1 ± 6.5^{b}	17.7 ± 2.6^{b}	1.0 ± 0.0^{d}	$16.4 \pm 1.0^{b,c}$	24.1 ± 10.3^{b}	$42.1 \pm 6.4^{a,b}$	33.8 ± 4.2^{a}

AK (Council, Alaska, US), CB (Cambridge Bay, Canada), SV (Svalbard, Norway), ZK (Zackenberg, Greenland).
SOC: soil organic carbon; EC: electrical conductivity; TN: total nitrogen. Oi: fibric, relatively undecomposed organic layer; Oe: hemic, partially decomposed organic layer; A: A horizon; O: organic layer; M: mineral layer; D1: 0–5 cm; D2: 5–10 cm; C: *Cassiope tetragona*; S: *Salix arctica*.
Different small letters in each column denote significant differences among samples ($p < 0.05$).

Table 3 Correlation between soil physical and chemical parameters in all soil samples

	pH	EC	SOC	TN	C/N ratio	Sand	Silt
EC	–0.338						
SOC	–0.261	0.612^{***}					
TN	0.298	0.311	0.733^{***}				
C/N ratio	$–0.741^{***}$	0.784^{***}	0.593^{***}	–0.019			
Sand	0.171	–0.106	0.464^{*}	0.440	–0.186		
Silt	–0.041	0.243	–0.161	–0.163	0.138	$–0.828^{***}$	
Clay	–0.242	–0.066	$–0.608^{**}$	$–0.566^{**}$	0.170	$–0.830^{***}$	0.374

SOC: soil organic carbon; EC: electrical conductivity; TN: total nitrogen.
Different symbols next to the correlation mean p-values: $^{*}p \le 0.05$; $^{**}p \le 0.01$; $^{***}p \le 0.001$.

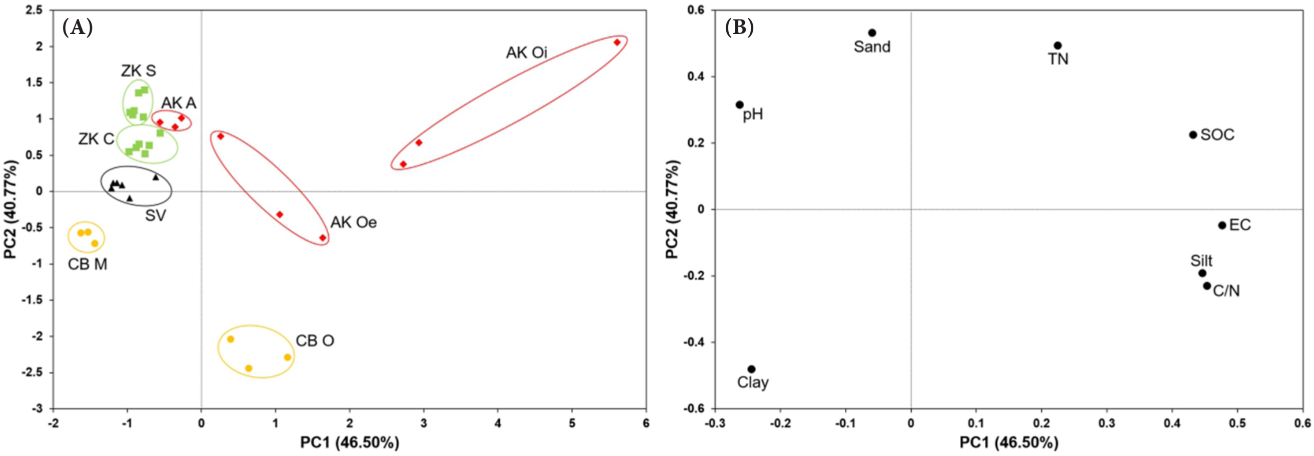

Fig. 2 Principal component analysis of soil physical and chemical parameters; score (**A**) and loading (**B**) on the first two ordination axes. AK (Council, Alaska, US), CB (Cambridge Bay, Canada), SV (Svalbard, Norway), ZK (Zackenberg, Greenland). SOC: soil organic carbon; EC: electrical conductivity; TN: total nitrogen. Oi: fibric, relatively undecomposed organic layer; Oe: hemic, partially decomposed organic layer; A: A horizon; O: organic layer; M: mineral layer; C: *Cassiope tetragona*; S: *Salix arctica*.

groups in Circumpolar Arctic vegetation Map (CAVM Team 2003). Soil pH slightly varied among sites, and the largest difference in pH were between Council, Alaska and Cambridge Bay, Canada (Table 2). The soil in Council, Alaska showed a low pH value of 3.9 to 5.2 (Table 2). Soil pH variation is related to the properties of soil solution, soil mineral chemistries, and biotic factors (Thomas 2019; Valentine and Binkley 1992). Acidification of Alaska soil could be attributed to 1) the elimination of free carbonates by enhancing soil drainage, 2) leaching of carbonates due to increased temperature and precipitation, and 3) strengthening of acidification by plants (Ping et al. 2005). The SOM would be one of the main factors for soil acidification (Ritchie and Dolling 1985; Ping et al. 2005). In addition, the study site in Alaska is characterized by moist acidic tussock tundra consisting of cotton-grass, moss, and bog blueberry compared to other sites in our study (Nam et al. 2021; Park and Lee 2014). Nam et al. (2021) reported that the main vegetation in Council, Alaska was *Sphagnum* moss. The *Sphagnum* moss acidifies the soil by maintaining high cation exchange capacity and a high soil moisture content (Gough et al. 2000). In contrast to Alaska, Cambridge Bay, Canada soil had a high pH of 7.4 to 7.8 (Table 2). This seems to be resulted by the effect of the parent rocks. Most areas of Victoria Island including Cambridge Bay is based on the carbonate rocks such as limestone and dolomite (McLennan et al. 2015). These base-rich bedrocks would result in high soil pH in Cambridge Bay, Canada (McLennan et al. 2015).

Soil EC is an indirect parameter to represent soil physical and chemical properties (Corwin and Yemoto 2020). Soil EC was the highest in the Oi layer of Alaska soil, and organic layer of Cambridge Bay and the Oe layer of Alaskan soil followed (Table 2). There were no significant differences among the rest of soil samples. The EC is determined by various factors such as soil salinity, proportion and mineralogy of clay, soil water content, cation exchange capacity (CEC), and soil structure (Sudduth et al. 2005). Comparing EC between layers, the organic layer was much higher than the mineral layer, and that in soil depth 0–5 cm was higher than 5–10 cm. The EC was positively correlated to C/N ratio ($r = 0.78$, $p < 0.0001$) and SOC ($r = 0.61$, $p = 0.0002$). All these results supported that this EC value would be attributed to the amount of SOM value. The SOM could provide CEC in soil, and thus resulted in higher EC from the samples with higher SOM contents (Corwin and Lesch 2005).

The SOC and TN contents were the highest in the Oi layer of Council, Alaska and organic layer in Cambridge Bay, Canada, respectively (Table 2). Compared to a higher SOC content in Oi and Oe layer in Council, Alaska, the TN content was low. This reflected that the C/N ratio in Council, Alaska site showed the highest value among four study sites; while the C/N ratio in Council, Alaska ranged from 20.9 to 48.9, that in other sites varied from 10.3 to 16.4. This characteristics of Alaska soil would be associated with vegetation composition of *Sphagnum* moss which has a very low TN content (Nam et al. 2021). In addition, the C/N ratio of Alaska soil decreased as the soil layer changed from Oi, Oe, to A layer. This indicated that soil C/N ratio decreased as soil decomposition degree increased.

The C/N ratio was one of the parameters correlated to many other measured soil parameters (Table 3). The C/N ratio of organic matter is often used for the parameter representing SOM decomposition degree (Malmer and Holm 1984) as more decomposition with a lower C/N ratio due to microbial consumption of C-rich organic materials. Our correlation and the PCA results showed that the C/N ratio was also related to soil pH and EC, and this led to the Council site, moist acidic tundra distinct from other field sites in the PCA score plot (Fig. 2). Although the other three sites are classified as same dry tundra, the samples

Table 4 A list of compounds identified from py-GC/MS analysis

Source	Compound name	Source	Compound name
Li1	n-Heptene (C7:1)	Li52	n-Hentriacontene (C31:1)
Li2	Heptane (C7:0)	Li53	Hentriacontane (C31:0)
Li3	n-Octene (C8:1)	Li54	Sitosterol
Li4	Octane (C8:0)	Li55	Lanosta-8,24-dien-3-ol, acetate
Li5	n-Nonene (C9:1)	Li56	Stigmasta-3,5-dien-7-one
Li6	Nonane (C9:0)	Li57	Stigmast-4-en-3-one
Li7	n-Decene (C10:1)	Ar1	Toluene
Li8	Decane (C10:0)	Ar2	Ethylbenzene
Li9	n-Undecene (C11:1)	Ar3	1,3-Dimethyl-benzene
Li10	Undecane (C11:0)	Ar4	Styrene
Li11	n-Dodecene (C12:1)	Ar5	p-Xylene
Li12	Dodecane (C12:0)	Ar6	1,2,4-Trimethyl-benzene
Li13	n-Tridecene (C13:1)	Ar7	1-Propynyl-benzene
Li14	Tridecane (C13:0)	Ar8	Indene
Li15	n-Tetradecene (C14:1)	Ar9	1-Ethynyl-4-methyl-benzene
Li16	Tectradecane (C14:0)	Ar10	1,2-Dihydro-napthalene
Li17	n-Pentadecene (C15:1)	Ar11	1-Methyl-1H-indene
Li18	Pentadecane (C15:0)	Ar12	1-Methyl-2-cyclopropen-1-yl-benzene
Li19	n-Hexadecene (C16:1)	Ar13	Naphthalene
Li20	Hexadecane (C16:0)	Ar14	1-Methyl-naphthalene
Li21	n-Heptadecene (C17:1)	Lg1	2-Methoxy-phenol
Li22	Heptadecane (C17:0)	Lg2	2-Methoxy-4-vinylphenol
Li23	n-Octadecene (C18:1)	Lg3	2,6-Dimethoxy-4-(2-propenyl)-phenol
Li24	Octadecane (C18:0)	N1	3-Methyl-butanenitrile
Li25	n-Hexadecanol	N2	1-Methyl-1H-pyrrole
Li26	n-Nonadecene (C19:1)	N3	Pyridine
Li27	Nonadecane (C19:0)	N4	Pyrrole
Li28	9,17-Octadecadienal	N5	2-Hydroxy-propanenitrile
Li29	n-Hexadecanoic acid	N6	C1-pyrrole 1
Li30	n-Eicosene (C20:1)	N7	C1-pyrrole 2
Li31	Eicosane (C20:0)	N8	Benzonitrile
Li32	n-Heneicosene (C21:1)	N9	Indole
Li33	Heneicosane (C21:0)	Ph1	Phenol
Li34	n-Docosene (C22:1)	Ph2	3-Methyl-phenol
Li35	Docosane (C22:0)	Ph3	2-Methyl-phenol
Li36	n-Tricosene (C23:1)	Ps1	Acetic acid
Li37	Tricosane (C23:0)	Ps2	1-Hydroxy-2-propanone
Li38	n-Tetracosene (C24:1)	Ps3	Furfural
Li39	Tetracosane (C24:0)	Ps4	2-Cyclopentene-1-one
Li40	n-Pentacosene (C25:1)	Ps5	2(5H)-Furanone
Li41	Pentacosane (C25:0)	Ps6	3-Furaldehyde
Li42	n-Hexacosene (C26:1)	Ps7	2-Methyl-2-cyclopentene-1-one
Li43	Hexacosane (C26:0)	Ps8	5-Methyl-2-furancarboxaldehyde
Li44	Heptacosane (C27:0)	Ps9	3-Methyl-2-cyclopentene-1-one
Li45	15-Tetracosenoic acid, methyl ester	Ps10	3-Methyl-1,2-cyclopentanedione
Li46	2-Methyl-hexadecane	Ps11	2,5-Dimethyl-4-hydroxy-3(2H)-furanone
Li47	Octacosane (C28:0)	Ps12	Levoglucosenone
Li48	2-Heptacosanone	Ps13	Maltol
Li49	Tocopherol	Ps14	1,4:3,6-Dianhydro-α-d-glucopyranose
Li50	Triacontane (C30:0)	Ps15	1,6-Anhydro-α-d-Glucopyranose
Li51	Stigmastan-3,5-diene	Ud	Ud1–16

py-GC/MS: pyrolysis-gas chromatography/mass spectrometry; Ps: polysaccharides; N: N-containing compounds; Lg: lignins; Ph: phenols; Ar: aromatics; Li: lipids (Cx: y in parentheses means the number of carbon [x] and that of double bond [y] in hydrocarbon); Ud: unidentified.

were clustered among same sampling sites.

Molecular compositions of SOM

The soil in Council, Alaska was widely distributed along the PC1 and located in the upper part along the PC2 (Fig. 3A). The chemical composition of organic soil horizons (Oi and Oe) were not distinct, but the soils in the A layer were placed in the left part along the PC1 where lipids were

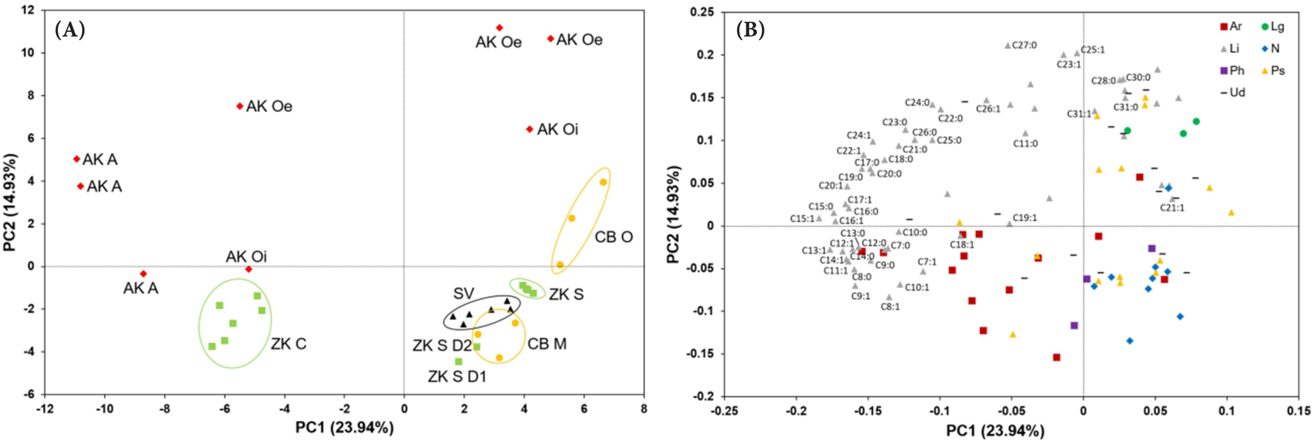

Fig. 3 Principal component analysis using relative abundances of pyrolysis products; score (**A**) and loading (**B**) on the first two ordination axes.
AK (Council, Alaska, US), CB (Cambridge Bay, Canada), SV (Svalbard, Norway), ZK (Zackenberg, Greenland). Oi: fibric, relatively undecomposed organic layer; Oe: hemic, partially decomposed organic layer; A: A horizon; O: organic layer; M: mineral layer; C: *Cassiope tetragona*; S: *Salix arctica*; Ps: polysaccharides; N: N-containing compounds; Lg: lignins; Ph: phenols; Ar: aromatics; Li: lipids; Ud: unidentified.

mainly scattered (Fig. 3B). It was very particular that the A layers of the Council, Alaska soil contained 77% of lipids in average compared to other samples in this study. In the loading plot, mid/short length of alkane and alkene (C8–C24) was distributed in the right side of the PC1. It is known that these compounds were produced by microbial decomposition (Buurman et al. 2007; Kuhn et al. 2010). Some organic layer soils in Alaska were placed in the right side of PC1, and this was characterized as relatively lower lipids contents (54.4% in average) and higher polysaccharides contents (19.1%) compared to the other Alaskan samples in the left side. Moreover, the long-chain alkane and alkene (C28–C31), lignin, and polysaccharides compounds were distributed in the right side of PC1 (Fig. 3B). In general, long-chain lipids and lignins are derived from plants (Gagosian et al. 1987; Matsumoto et al. 1990). Thus, we could indicate that the Alaskan upper organic and lower mineral layers were mainly composed of vascular plant-derived and microbially-processed compounds, respectively.

Soils in Cambridge Bay, Canada were located in the right side of PC1, but the organic and mineral layer of soils were separated along the PC2. The organic layer of Cambridge Bay soils was located in the same quadrant. Samples in the quadrant 1 which contained long-chain alkanes and alkenes and lignins, and this meant SOM in these samples were mainly derived from plants (Gagosian et al. 1987; Matsumoto et al. 1990). The mineral layer of Cambridge Bay soils was placed in the same quadrant of Svalbard soils and soils under *Salix* in Zackenberg. This was associated with N-containing compounds and some polysaccharides. The origin of N-containing compounds could vary, but microbial necromass was relatively more enriched with N-containing compounds (Gunina and Kuzyakov 2022). Since the upper layer of Cambridge Bay soils were associated with the plant-derived materials, this could be quite compatible that the lower layer soils were associated with microbial-processed compounds inferred from the distribution of N-containing compounds.

Relatively short-alkane and -alkene and aromatic compounds derived from naphthalene-containing compounds were abundant in soils under *Cassiope* in Zackenberg (Fig. 3). We found that the py-GC/MS of *Cassiope* plant leaves resulted in a high proportion of lipids and particularly a higher proportion of naphthalene-containing compounds among aromatic compounds in Adventdalen, Svalbard (data not shown). Jung et al. (2020) also reported higher aliphatic compounds in *Cassiope* than *Salix* site. Thus, we presumed that the SOM characteristics of *Cassiope* soil was largely reflected by plant characteristics. On the other hand, there were very few compounds were detected from the soils under *Salix* in Greenland and Svalbard soils. They were associated with the mineral layer of Cambridge Bay soil. We inferred that samples with more microbially-processed compounds, lower SOM contents, and a smaller number of detected compounds distributed in this quadrant.

Conclusions

We analyzed soil physical and chemical properties and SOM characteristics from four different Arctic soils. Council, moist acidic tundra, showed a low soil pH and a high C/N ratio and contained acidic tundra vegetation such as *Eriophorum vaginatum*, *Vaccinium uliginosum*, *Sphagnum* moss. On the contrary, Cambridge Bay, Svalbard, and Zackenberg showed similar soil properties representing dry tundra with low annual precipitation. However, soil traits such as soil texture or pH could differentiate the dry tundra sites and clustered among sampling sites. The moist and dry tundra sites were very apparent in py-GC/MS analysis as well. However, The the py-GC/MS could also divide soil samples according to the origin of SOM among samples with low SOC contents. The different ecosystem structure would be the most important factor to distinguish SOM characteristics, but the decomposition degree could be the other parameter to classify soil samples. These different soil and SOM characteristics could control the response of soil, i.e., SOM dynamics to external disturbances. The SOM is a key component for understanding the direction of climate change. Our results of soil properties and SOM composition in various Arctic regions would be employed as basic information to understand changes in soil biogeochemical processes in the Arctic tundra in response to future climate change. Thus, it is the next step that understanding how soil and SOM features have impact on SOM decomposition and turnover in the Arctic.

Supplementary Information

Supplementary information accompanies this paper at https://doi.org/10.5141/jee.22.069.

Table S1. The relative abundance of source categories in each sample.

Abbreviations

C: Carbon
SOM: Soil organic matter
CO_2: Carbon dioxide
py-GC/MS: pyrolysis-Gas Chromatography-Mass Spectrometry
SOC: Soil organic carbon
EC: Electrical conductivity
TN: Total nitrogen
PCA: Principal component analysis
CEC: Cation exchange capacity
AK: Council, Alaska, US
CB: Cambridge Bay, Canada
SV: Svalbard, Norway
ZK: Zackenberg, Greenland

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Not applicable.

Authors' contributions

SJ and SN did investigation, methodology, data curation, writing - original draft preparation. JYJ did conceptualization, writing - original draft preparation, review & editing.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable

Competing interest

The authors declare that they have no competing interests.

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