



Potential DOC production from size-fractionated Arctic tundra soils

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ABSTRACT

Soil organic carbon (SOC) accumulated in the Arctic regions has been subject to impacts of climate warming, but the interactions of SOC with aquatic environments and their biogeochemical consequences remain poorly understood. Arctic tundra soil samples were collected from the upper permafrost of arctic Alaska and size-fractionated into the >2000 μm, 250–2000 μm, 53–250 μm and <53 μm fractions by dry sieving. Production potential of dissolved organic carbon (DOC) from bulk and size-fractionated soils were evaluated under different extraction time, temperature, soil/water ratio, and preservation conditions. The soil DOC (<0.7 μm) was further fractionated into high-molecular-weight (HMW, >3 kDa) and low-molecular-weight (LMW, <3 kDa) DOC fractions using ultrafiltration to examine the molecular weight distribution of soil DOC. Our results showed that, on average, the DOC yield was ~2.6% of total organic carbon (TOC) for moist acidic tundra (acidic) soils and ~1.8% of TOC for moist non-acidic tundra (non-acidic) soils. In general, soil extraction at higher temperature (22 °C vs. 2 °C) resulted in a 10–20% higher DOC. Degradation of soil DOC became noticeable after 24 h. Content of OC in different sized soil particles followed the order of 53–250 μm > 250–2000 μm > less than 53 μm. In both acidic and non-acidic soils, DOC yields increased with decreasing soil particle size, while TOC content increased with increasing particle size. Soil DOC released from bulk acidic soils contains 65% of HMW-DOC and 35% of LMW-DOC, but 44% and 56% respectively in non-acidic soil DOC. Acidic soils seemed to have higher potential of releasing DOC than non-acidic soils. On average, up to 2% of arctic SOC could be potentially released into aquatic systems during soil/water interactions. The fate of this newly released soil DOC and its biogeochemical impacts on aquatic systems needs further investigation.

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1. Introduction

Arctic tundra soils have long been recognized as an important player in the global carbon cycle because of the large stocks of organic carbon (Oechel et al., 1993; Hobbie et al., 2000). While the exact inventory of soil organic carbon (SOC) in the Arctic region is not known, Arctic tundra ecosystem alone could contain ~30% of the global SOC pool when the carbon stores in the deep active layer and upper permafrost are considered (Michaelson et al., 1996; Bockheim et al., 1998; Ping et al., 1998). Surface organic matter is often mixed by freeze–thaw and subsequent frost heave processes (cryoturbated) into the underlying mineral soil horizons, particularly in the lower active layer and upper permafrost. Thus, the cryoturbated organic matter could become encased in permafrost or reenter the biogeochemical cycles (Ping et al., 1997). It is important to examine characteristics of deep cryoturbated carbon and its fate once it enters the terrestrial and aquatic systems for a better understanding of impacts and biogeochemical consequences of climate and environmental changes in the Arctic region (Dou et al., 2008).

Mounting evidence has suggested a climate and environmental change in the Arctic during the past several decades (e.g., Serreze et al.,

2000; ACIA, 2005; Hinzman et al., 2005). Under a warming condition, carbon currently sequestered in arctic soils will likely be remobilized and available for biogeochemical cycling through coastal erosion (Rachold et al., 2000; Guo et al., 2004; Jorgenson and Brown, 2005), thawing of permafrost (Romanovsky and Osterkamp, 1997; Jorgenson et al., 2006), and releasing of SOC into the aquatic system (Frey and Smith, 2005; Guo and Macdonald, 2006; Guo et al., 2007) in addition to direct outgassing from soils to atmosphere (Davidson and Janssens, 2006). However, transport pathways and mechanisms of soil organic carbon across soil/water and land/ocean interfaces are poorly understood. Quantitative examination of potential DOC production from arctic soils, especially in the deep part, are urgently needed.

The impact of warming on arctic soils has been a major issue for climate change science. Indeed, the responses and feedback of soil organic carbon to climate change have received considerable attention but mostly on the decomposition of soil organic carbon and CO₂ fluxes across the soil/atmosphere interface (Davidson and Janssens, 2006 and references therein). The processes governing the conversion of soil organic matter to DOC are the central factor in understanding how soil warming and thus thawing of permafrost will affect arctic surface waters and the arctic environment as a whole (e.g., Michaelson et al., 1998; Neff and Hopper, 2002). However, little is known about the chemical characteristics of soil organic matter in arctic tundra soils and the potential of producing dissolved organic carbon (DOC) once the soils are eroded into the aquatic

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system. Particularly, the chemical characteristics and OC phase distribution of cryoturbated organic matter between size-fractionated soils and soil DOC have not been revealed. In addition, how experimental conditions affect carbon release has rarely been addressed.

In this study, arctic soils from both acidic and non-acidic tundra soils were collected and size-fractionated into different particle size fractions using dry sieving, including the $<53 \mu\text{m}$, $53\text{--}250 \mu\text{m}$ and $250\text{--}2000 \mu\text{m}$ fractions. Bulk and size-fractionated soils were further leached under different experimental conditions, such as soil/water ratio, temperature, extraction time, and preservation to evaluate SOC size partitioning, chemical characteristics and potential for releasing DOC into aquatic environments. The goal was to quantify the effect of experimental conditions on the production of soil DOC and to give a first order estimate on potential carbon release from permafrost during its interaction with hydrological cycle.

2. Materials and methods

2.1. Soil sampling

The ecosystem functions of the Arctic Foothills of northern Alaska could be roughly divided into two major areas with soils having different substrate reactions: acidic ($\text{pH} < 5.5$) ecosystems predomi-

nately at the southern part, and non-acid ($\text{pH} > 6.5$) ecosystems predominately at the northern parts (Fig. 1). The moist acidic tundra (acidic) and wet non-acidic tundra (non-acidic) soils represent the two major types of arctic tundra soils in previous studies (Michaelson et al., 1996; Ping et al., 1998; Walker et al., 1998). Different soil pH could be caused by the factors such as loess deposition, degree of cryoturbation, vegetation cover and parent material age. In turn, the difference in substrate reactions has been recognized to affect many aspects of ecosystem functions, such as vegetation community, soil properties, carbon dynamics and ecosystem energy and gas flux (Ping et al., 1998; Walker et al., 1998).

Soil samples were collected from the acidic and non-acidic tundra sites on Sagwon Hills in northern part of the Arctic Foothills (Fig. 1). The physical environments of the two sampling sites are presented in Table 1.

These sample sites represent the major land cover types: moist acidic tundra (MAT) and moist non-acidic tundra (MNT), defined by pH values of substrate reactions and moisture content (Walker et al., 1998). The dominant vegetation in the acidic tundra included *Salix* spp., *Betula nana*, *Ledum decumbens*, *Eriophorum vaginatum*, *Vaccinium vitis idaea*, *Vaccinium uliginosum*, *Arctostaphylos rubra*, *Cassiope tetragono*, and *Sphagnum* moss and lichens, while non-acidic tundra included *Carex bigelowii*, *Salix arctica*, *S. reticulata*, *Eriophorum triste*,

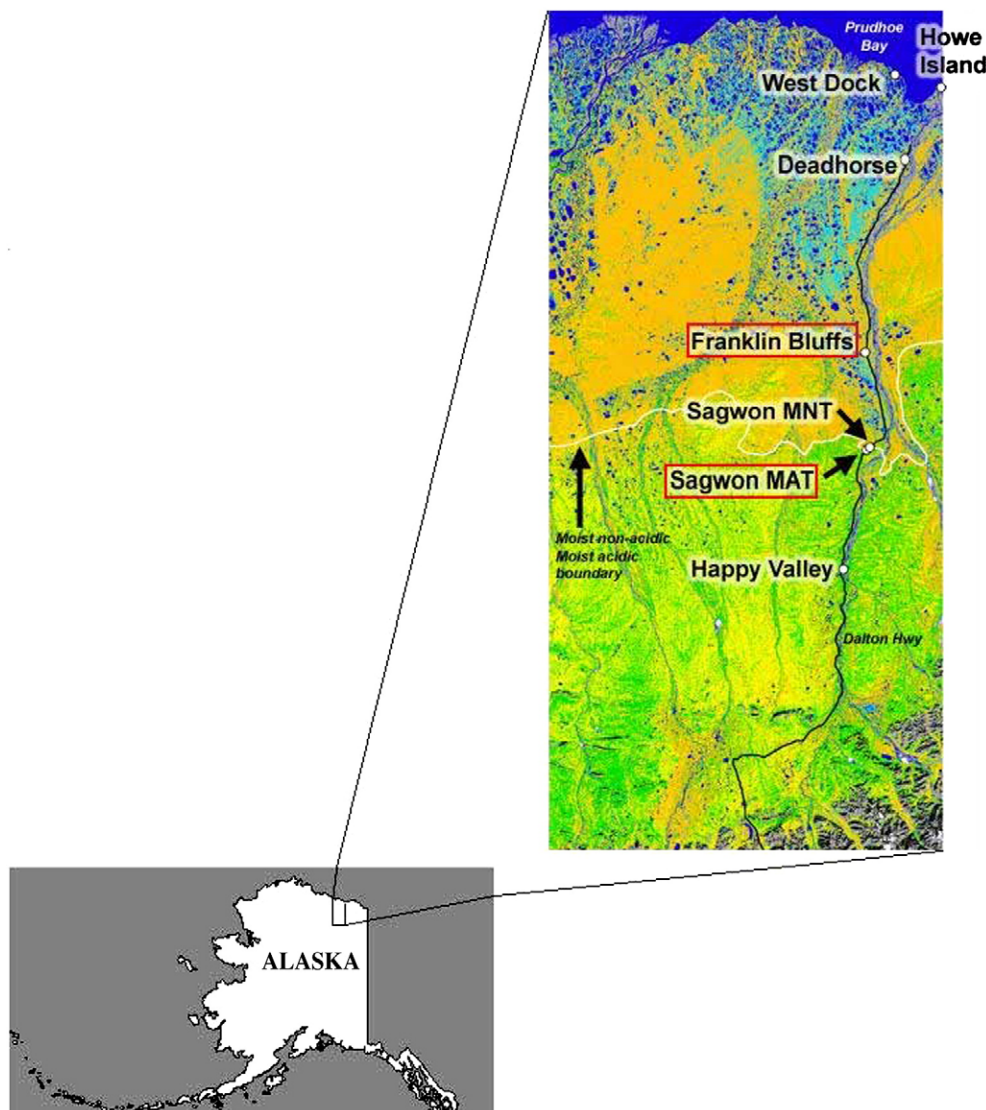


Fig. 1. Study area and sampling sites.

Table 1
Descriptions of study sites

Site	Lat. N. Long. W	Elevation (m)	Landform	Microrelief	Parent material	Vegetation community
MAT	69°23.708' N 148°44.165' W	261	Rolling hills (Arctic Foothills)	Frost boils	Loess/ moraine	Tussock sedge, shrub, moss
MNT	69°59.046' N 148°41.619' W	37	Rolling hills (Arctic Foothills)	Frost boils	Loess	Low shrubs, herbs

Dryas integrifolia, *A. rubra*, grasses and basiphilous forbs, and *Tomentypnum niten* moss (CAVM Team, 2003). The soils of the moist acidic tundra sites were poorly drained and has discontinuous surface organic horizons. They are classified as Ruptic Histoturbels (Soil Survey Staff, 2006) and Histic Gleyic Cryosols (WRB, 2006). The soils of the moist non-acidic tundra sites were somewhat poorly drained and had thin surface organic horizons in between the non-sorted circles. They are classified as Aquic Molliturbel (Soil Survey Staff, 2006) and ISSU Working Group WRB (2006).

Pits of approximately 1 m² were excavated to a 1 m depth at each site using shovel in active layers and a gasoline-powered chisel for the frozen layers. The excavations were made so that the vertical profile exposed a complete cycle of the surface microrelief patterns (<2 m) to include both the frost boil and the interboil areas. Soil profiles were described according to the Soil Survey Manual (Soil Survey Division Staff, 1993). Cryogenic morphological characteristics were described in Ping et al. (1998). Horizons selected herein for the potential DOC production experiments were upper permafrost organic/mineral-mixed horizons (i.e. O_{ajj}/C_f depth at 60–100 cm), which represented those commonly found in arctic tundra soils affected by cryoturbation (Michaelson et al., 1996). The depth of organic layer was 9 cm for the acidic tundra soil and 5 cm for the non-acidic tundra soil. Samples were collected from genetic horizons during August 2003, and kept frozen until analysis was performed.

All soil samples were freeze-dried. Duplicate soil samples were mixed for sieving and extraction experiments. For DOC extraction of

size-fractionated soils, dry sieving procedure was used to minimize possible destruction of aggregates and thus to avoid the biases of DOC yields among particle size fractions. The recovery rate of dry sieving is greater than 99% (data not shown). Detailed dry sieving, soil size fractionation and DOC extraction are given in Fig. 2.

2.2. Dissolved organic carbon extractions from bulk and size-fractionated soils

Extraction kinetics: Twelve soil sub-samples (2.25 g each) from the MNT site were dispersed into centrifuge tubes containing 45 ml of nano-pure water, resulting in a soil/water ratio of 1:20. The soil suspensions were then sterilized by 20 μ l saturated HgCl₂ solution, and agitated for 60 min using a lab rotator (Lab-Line Inc., Model 1346). After 2, 6, 12, 24, 48, 74 h, respectively, the soil suspensions were centrifuged at 3000 rpm (Hermle Z300), then filtered through glass fiber filters (0.7 μ m, GF/F Waterman) to separate dissolved organic matter from particulate organic matter and to quantify the yield of DOC in terms of normalized DOC concentrations (Fig. 2). The equilibrated extraction time was then determined by the time series samples. For comparison purposes, the same optimum extraction time was used for subsequent soil extraction experiments.

Effects of soil/water ratio on DOC yield: Different soil to water ratios, 1:5, 1:10, 1:20, and 1:40, were used in a series of soil extraction experiments to examine the extraction efficiency under different soil/water ratios. Other procedures for organic matter preservation, shaking time/intensity, solution temperature, centrifugation and filtration were the same for all treatments. Duplicate samples were used for each treatment.

DOC yields from sequential extraction: Soil DOC was extracted by four consecutive extractions from four treatments with soil/water ratios of 1:5, 1:10, 1:20 and 1:40, respectively. The same soil/water ratio was maintained throughout the continuous extraction process by carefully balancing water lost during each extraction.

Examination of microbial degradation during extraction processes: Eight soil solutions with a soil/water ratio of 1:20 were divided into

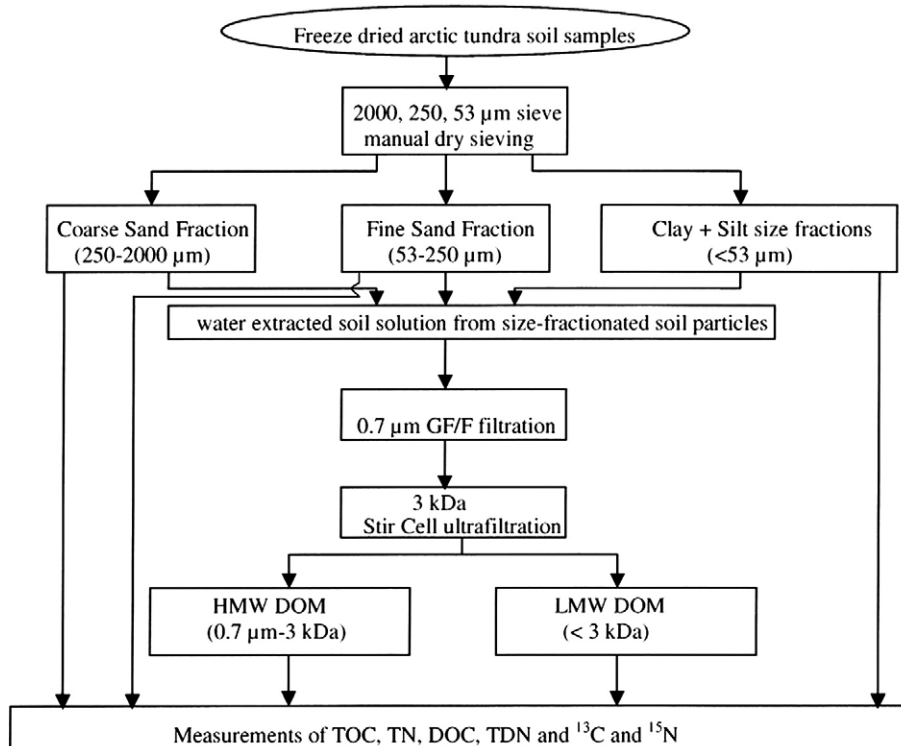


Fig. 2. Schematic diagram showing detailed procedures of soil size fractionation and soil DOC extraction.

two groups, one treated with HgCl₂ solution and the other without HgCl₂. The extraction experiments were carried out at 22 °C and extended to 24 h and 72 h to examine the extent of microbial degradation during extraction experiments.

Effect of temperature on DOC yield: DOC extraction experiments were carried out under two different temperatures, 2 °C and 22 °C. Soil/water ratio of 1:20 and other extraction conditions were the same as those described above. Replicate samples were used for all treatments.

DOC yields from size-fractionated soil particles: Freeze-dried soil samples from both MAT and MNT sites were dry sieved into three different size fractions: 250–2000 μm, 53–250 μm; and <53 μm (Fig. 2, and Gregorich et al., 2003; Xu, 2005). DOC yields from each size-fractionated soils were quantified according to the extraction procedures described above, under a soil/water ratio of 1:20, temperature of 2 °C, and 24 h of extraction time. Duplicate treatments and sampling were consistently employed.

2.3. Ultrafiltration of soil DOC

Soil DOC extracted from bulk and size-fractionated soil particles was ultrafiltered using a stirred cell ultrafiltration unit (Amicon 8050) and fractionated into high-molecular-weight (HMW) and low-molecular-weight (LMW) fractions (Fig. 2). A 3 kDa (kilo-Dalton) cutoff membrane (YM3, Millipore, USA) was used for the ultrafiltration. Therefore, the HMW-DOC is operationally defined here as the 3 kDa–0.7 μm fraction, while the LMW-DOC is the <3 kDa fraction. Technical data for nominal MW cutoff calibration of the membrane can be found at manufacture's website (www.millipore.com).

2.4. Measurements of DOC and total dissolved nitrogen

Concentrations of DOC were determined by the high temperature combustion method with a Shimadzu TOC-V analyzer (Guo et al., 1994). Immediately after sample collection, all DOC samples, including bulk DOC (<0.7 μm), HMW-DOC (3 kDa–0.7 μm), LMW-DOC (<3 kDa) fractions, were acidified with 12 M HCl to a pH of ≤2 (2 drops added into a 20 ml water sample). At least three injections were performed for each DOC sample analysis. Analytical precision, in terms of coefficient of variation, was within 1–4% depending on sample's concentrations. Concentrations of total dissolved nitrogen (TDN) were measured by a TNM-1 total nitrogen unit interfaced with the Shimadzu TOC analyzer (Guo and Macdonald, 2006). Potassium nitrate was used as a standard.

2.5. Measurements of elemental (C and N) and stable isotope ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) composition

Bulk and size-fractionated soil samples were pretreated with 1 M HCl to remove inorganic C and measured for C and N elemental composition (in terms of concentrations of total organic carbon, TOC, and total nitrogen, TN) and their stable isotope composition ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) using a continuous flow isotopic ratio mass spectrometer (Guo et al., 2003; Guo and Macdonald, 2006). Stable C and N isotope ratios were calculated in terms of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, by the formula $(R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$, where R is the ratio of $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$ in soil samples or standard (PDB for carbon and atmospheric N₂ for nitrogen). The precision and accuracy of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis were ±0.1‰ and ±0.2‰, respectively.

2.6. Statistic analysis

The data from replicate measurements were analyzed by one-way ANOVA tests and Student's *t*-test. One-way ANOVA tested the null hypothesis, to compare multiple samples with a single variable. Differences between means were tested with Student's *t*-test. Statistical significance was assessed at the 0.05 level.

3. Results

3.1. Effects of extraction time, microbial degradation, temperature, sequential extraction and soil/water ratio on the production of soil DOC

Experimental conditions can considerably affect the extent to which soil DOC is released. Thus, the effect of experimental conditions on soil extraction needs to be quantitatively examined for the prediction of carbon release during soil interactions with hydrological cycle. Variations of DOC concentrations extracted from arctic tundra soils against extraction time are shown in Fig. 3. The DOC yield can fit in an empirical equation " $y=20.87x^{0.1775}$ " ($R^2=0.935$). Linear regression analysis showed that the production of DOC increased significantly from 2 to 24 h (p -value=0.016), and changed little from 24 to 72 h (p -value=0.132). Using Student's *t*-test, our results show that, at 72 h extraction time, the DOC concentration of soil suspension treated with HgCl₂ was significantly higher than the one without HgCl₂ ($p=0.059$), while at 24 h, the difference was insignificant ($p=0.742$) between these two treatments (Fig. 4A). These results indicate that microbial decomposition of soil DOC can indeed be significant after 24 h. As shown by kinetic experimental results (Fig. 3), soil DOC yields could be close to maximum after 24 h of extraction, and long extraction time could result in microbial degradation of DOC and thus underestimation of soil DOC production. Therefore, a 24 h of extraction time was used to examine the potential DOC production from tundra soils. The effect of possible microbial degradation on soil DOC production was examined under experiments by adding HgCl₂ as an antimicrobial agent to one batch and comparing to a control batch without HgCl₂.

The release of CO₂ either directly from soils or through the decomposition of DOC could be significant under long term extraction. For example, Neff and Hooper (2002) found a much higher CO₂ flux from soils than DOC in a 365-day incubation experiment. Mayorga et al. (2005) reported considerably high CO₂ fluxes from young riverine DOC. The decomposition of organic matter and CO₂ fluxes are likely related to the quality of soil DOC (Dai et al., 2001; White et al., 2002). However, very little data are available for evaluating the decomposition of newly released soil DOC in arctic aquatic environments (Kling et al., 1991).

Soil DOC yields under two different temperatures (2 °C vs. 22 °C) are shown in Fig. 4. The DOC concentration extracted under lower temperature (2 °C) was 30.5 mg C/l, which was significantly lower than that under 22 °C (36.6 mg C/l), indicating that higher temperature gave rise to a higher soil DOC yield. Thus, under warming conditions, interactions of soil organic matter with aquatic systems could result in higher DOC export from tundra to streams, rivers, and the ocean. Since the arctic tundra soil samples were from cold upper permafrost and the interaction of SOC with aquatic environments will likely occur as soon as temperature is above freezing point, extraction

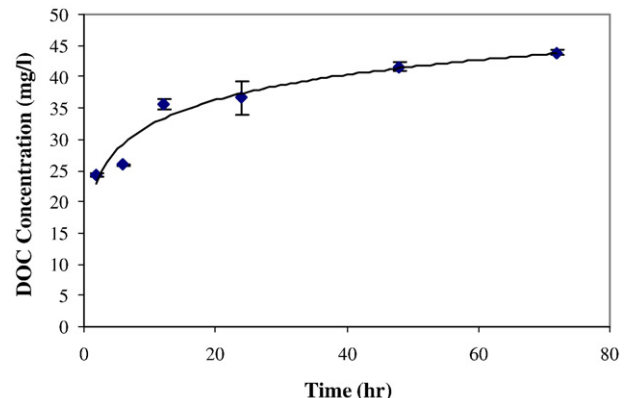


Fig. 3. Effects of extraction time on the production of soil DOC.

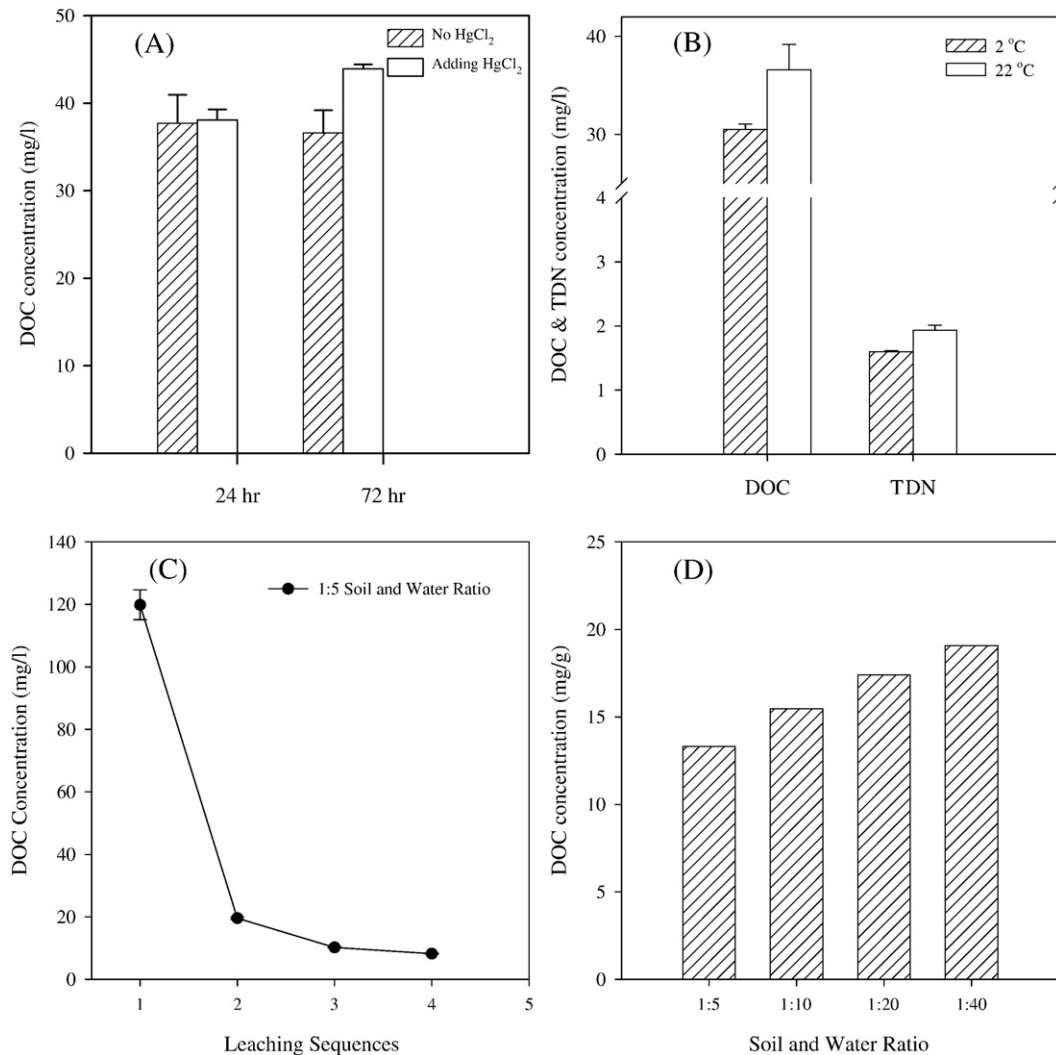


Fig. 4. DOC extraction experiments under different extraction condition: (A) effects of microbial processes (preservation with HgCl₂ vs. non-preservation); (B) effects of temperature (2 °C vs. 22 °C); (C) sequential extraction (4 times over a period of 24 h); (D) effects of soil/water ratio (normalized by soil mass).

of soil DOC at 2 °C is probably more realistic and best reflects tundra *in situ* conditions. Nevertheless, results from this type of extraction may provide, at the first approximation, the direction of potential DOC production from arctic soils under a warming scenario.

Results of sequential extraction (Fig. 4C.) showed that the DOC concentration from the first 24 h extraction was considerably ($p < 0.05$) higher than any subsequent three extractions regardless of soil/water ratios used. Therefore, most of soil DOC can be effectively extracted during the first 24 h. These results were consistent with those from extraction kinetic experiments shown in Fig. 3. One time extraction probably mimics better field conditions during soil–water interactions. For comparison purposes, one time extraction was consistently employed to evaluate DOC yield from arctic tundra soils.

The effect of soil/water ratios on DOC yields is shown in Fig. 4D. When normalized to soil mass, the DOC concentration (in terms of DOC per g of soils) increased with decreasing soil/water ratio (Fig. 4D). In other words, soil DOC yields increased with decreasing soil/water ratio. A soil/water ratio of 1:10 was commonly used in soil studies (e.g., Neff and Hooper, 2002; Maclauchlan and Hobbie, 2004). High soil/water ratios could be met in soil slurry solutions during initial soil thawing/melting. However, the concentration of total suspended particulate matter in arctic river waters is normally much less than 1 g/L (Cai et al., 2008) corresponding to a particulate–matter/water ratio of 1:1000. Here, an intermediate soil/water ratio of 1:20 was used for comparisons between treatments, although the soil/water

ratio may vary considerably in natural environments depending on soil and hydrological conditions.

3.2. DOC production from size-fractionated soils

Potential DOC production has been studied mostly on bulk soils. However, natural organic matter is highly heterogeneous not only in terms of elemental composition and isotope signatures (e.g., Megens et al., 2002; Guo et al., 2003) but also between sampling sites with different vegetation and hydrology (e.g., Judd and Kling, 2002; Lopez et al., 2007). Furthermore, DOC yields from bulk soil samples may not necessarily be applied to all soil size fractions. As shown in Fig. 5, organic carbon content (OC%) and stable isotope signatures ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of bulk soils were significantly different from those of size-fractionated soil fractions. For example, the 250–2000 μm size fraction had the highest OC content, whereas the 53–250 μm size fraction had the highest total nitrogen content compared to other size fractions (Table 2, Fig. 5).

Results in Fig. 5 also show the variations in OC content and stable isotope signature between soils with wet or dry sieving. The OC content of particle size fractions did not show a significant difference between dry and wet sieving although different size fractions had considerably different OC contents with the highest OC content measured for the larger size fraction (the 250–2000 μm , Fig. 5). Previous studies have shown that wet sieving generally results in

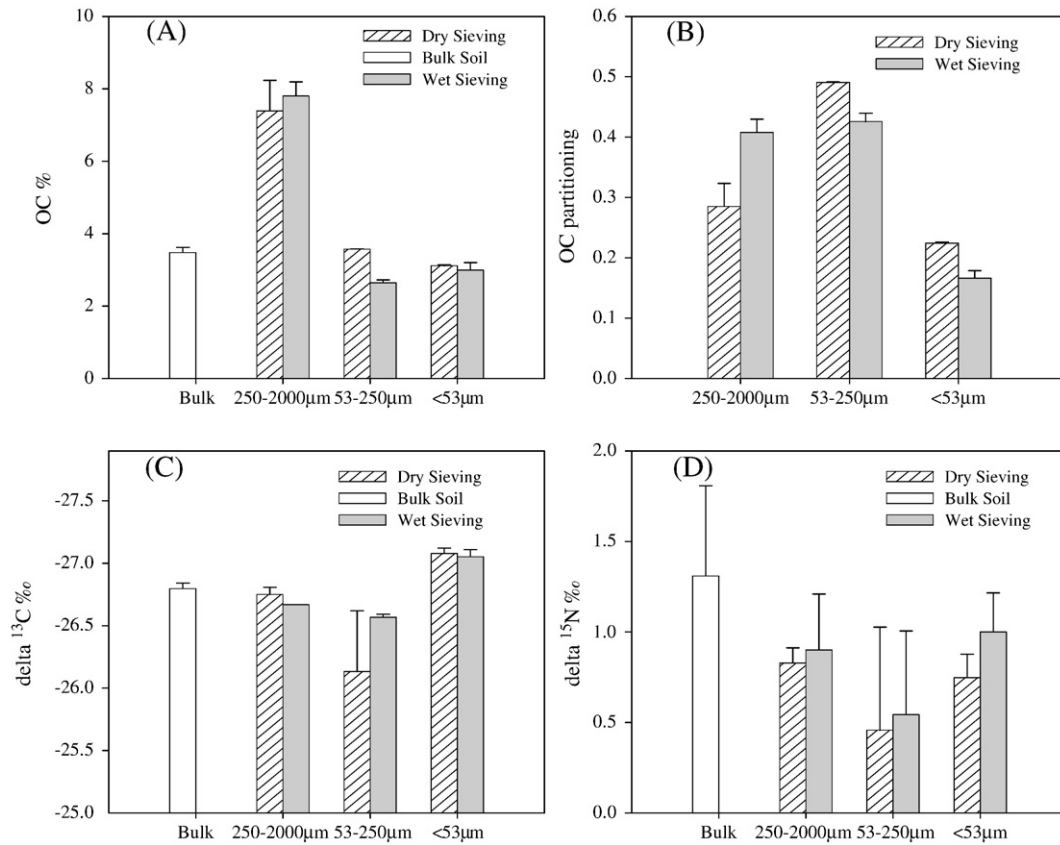


Fig. 5. Effects of dry and wet sieving on chemical characteristics of particle size fractions: (A) organic carbon (OC) content; (B) OC partitioning between particle size fractions in the bulk soil; (C) $\delta^{13}\text{C}$ values of bulk and size-fractionated fractions; (D) $\delta^{15}\text{N}$ values of bulk and size-fractionated fractions.

adding more organic matter to the smaller size fractions during particle size fractionation for temperate and tropical soils (Christensen, 1992). Our results show that arctic tundra soils had a slightly different trend compared to those of temperate and tropical soils. Arctic tundra soils contained a high content of fresh plant residues which were usually light and with less density than 1 g/cm^3 (Ping et al., 1997). Hence, wet sieving could lead to an enrichment of plant residues in the coarse size fraction, causing a partitioning slightly different from soils in temperate and tropic regions. The $\delta^{13}\text{C}$ values of bulk and size-fractionated soil samples ranged from -27.2% to -26.2% (Fig. 5). These values are similar to those reported for high latitude C3 plants and soils in arctic regions (Guo et al., 2007). In addition, the $\delta^{13}\text{C}$ values of bulk and size-fractionated soils from both dry and wet sieving didn't show a significant difference (Fig. 5), indicating little isotopic fractionation during sieving and a consistent

organic source tracer of $\delta^{13}\text{C}$. As shown in Fig. 5, both smaller and larger size fractions of soil seem to have a relatively lower $\delta^{13}\text{C}$ value although the $\delta^{13}\text{C}$ values are within a small range. Like $\delta^{13}\text{C}$, the $\delta^{15}\text{N}$ values had a similar distribution pattern between different soil size fractions. However, the $\delta^{15}\text{N}$ values had a large standard deviation, likely due to its relatively low N content and heterogeneous properties of soil samples. Overall, size-fractionated soils had significantly different chemical and isotope compositions, but dry and wet sieving did not result in a significant difference in chemical and stable isotope compositions. For the determination of soil DOC yields, dry sieving was used for soil size fractionation to avoid potential DOC redistribution between different soil size fractions during wet sieving.

Results of DOC yields from each soil size fraction are given in Table 2. On average, 2.6% of the bulk soil TOC can be released into the DOC pool from the acidic soils during soil–water interaction, whereas about 1.8% of TOC could be partitioned into the DOC pool from the non-acidic soils. These results are similar to those reported previously for high latitude soils (e.g., Neff and Hooper, 2002; Dou et al., 2008). Interestingly, for both acidic and non-acidic soils, size-fractionated soil fractions with higher TOC content seemed to contribute least to DOC yields, such as the 250–2000 μm fraction, while the soil fractions with lower TOC content gave rise to higher DOC yield (Table 2). This indicates that the fresh plant residues in the larger size soil fraction although high in TOC content are less decomposed and release less DOC (in terms of DOC/TOC ratio), whereas the more humified organic components in the smaller size fractions release more DOC during the soil–water interaction. Overall, DOC yields in acidic soils are higher than those in non-acidic soils (Table 2), indicating that acidic soils have higher potential to release soil DOC during soil–water interaction. Moreover, size-fractionated soil fractions can indeed have different DOC yields depending on their decomposition status and TOC contents. In acidic tundra soils, DOC from the coarse soil fraction

Table 2

Distribution of SOC species in bulk and size-fractionated soils from the upper permafrost of moist acidic tundra (MAT) and moist non-acidic tundra (MNT)

Sample	C/N	Size fraction	TOC	POC/TOC	DOC/TOC	LMW/DOC	HMW/DOC
MAT soil							
Bulk	21	-	7.9	97.4	2.6	35	65
>2000 μm	-	-	-	-	-	-	-
250–2000 μm	28	6.9	11.8	98.1	1.9	45	55
53–250 μm	20	77.3	8.0	97.3	2.7	38	62
<53 μm	20	15.8	5.6	96.9	3.1	42	58
MNT soil							
Bulk	20	-	3.5	98.2	1.8	56	44
>2000 μm	-	-	-	-	-	-	-
250–2000 μm	26	15.6	7.4	99.1	0.9	59	41
53–250 μm	21	55.4	3.6	98.5	1.5	41	59
<53 μm	16	29.1	3.1	98.1	1.9	45	55

(250–2000 μm) accounted for 1.9% of total organic carbon in that fraction. In the finest soil fraction (<53 μm), the extracted DOC accounted for ~3% of the TOC, which was slightly larger than the yield of bulk soils (2.6%), whereas the DOC yield from the 53–250 μm soil fraction was 2.7%, very close to that of bulk soils (Table 2). Since the 53–250 μm size fraction comprised 79% of the bulk soil TOC, normalized DOC yield from all the size-fractionated soils would give rise to a similar DOC yield to bulk soils. The highest DOC yield from the finest fraction (<53 μm) likely resulted from its high microbially transformed organic matter (Ping et al., 1997). Similar trends were also observed in the non-acidic soil although TOC contents and DOC yields are both lower in the non-acidic soil (Table 2). For example, the TOC content in non-acidic soils increased with increasing soil particle size while DOC yields decreased with increasing size, similar to those observed for acidic soils.

Previous studies indicated that large amounts of relatively fresh soil organic matter is stored in the upper permafrost in arctic tundra soils (Michaelson et al., 1996). Presumably, after humification, fresh, less decomposed organic matter could produce higher amount of DOC. In addition, the finest fraction (<53 μm) also had higher potential of releasing DOC than bulk soils, likely aided by microbial activities or other factors such as DOM redistribution among particle size fractions during cryoturbation. Although the overall percentage of SOC released into aquatic environments was low (~2% of TOC), the total quantity of DOC released can be extremely large (up to 2% of SOC stock) should permafrost thaw completely. In addition, loss of organic carbon through respiration could be significant after soil DOC release into the aquatic environment and during their transport (Michaelson et al., 1998; Neff and Hopper, 2002; Mayorga et al., 2005). Further studies are needed to investigate the fate of soil DOC released from both bulk and size-fractionated soils.

3.3. Partitioning of soil DOC between high-molecular-weight and low-molecular-weight fractions

Soil DOC was further fractionated into LMW- and HMW-DOC fractions to examine the molecular weight distribution of soil DOC. As shown in Table 2, about 1.8–2.6% of soil TOC can be released into the DOC pool. Within this soil DOC pool, about 35% was in the <3 kDa LMW-DOC fraction and 65% was in the >3 kDa HMW-DOC fraction in the acidic tundra soils, while 56% was in the LMW-DOC fraction and 44% was in the HMW-DOC fraction in non-acidic tundra soils (Table 2). Higher percentages of HMW-DOC were observed in the acidic tundra soils than in the non-acidic tundra soils, likely due to non-acidic tundra soils contained more highly decomposed organic matter compared to acidic soils (Dai, 2001; Dai et al., 2001). It seems that acidic soils could preserve more organic matter and at the same time contain a higher fraction of HMW-DOC compared to non-acidic soils.

Similar to the results of bulk soils, higher percentage of HMW-DOC in the bulk soil DOC was also found in all size-fractionated acidic soil fractions, ranging from 55% to 62% (Table 2). For example, 55% of soil DOC was in the HMW-DOC fraction from the 250–2000 μm soil size fraction, 62% was in the HMW-DOC fraction from the 53–250 μm soil size fraction, and 58% was in the HMW DOC fraction from the <53 μm soil fraction. However, this was not always the case for all size-fractionated non-acidic soil fractions. 41% of soil DOC was in the HMW DOC fraction from the 250–2000 μm soil size fraction, 59% from the 53–250 μm soil size fraction, and 55% from the <53 μm soil size fraction in non-acidic soils. Overall, the HMW-DOC was the predominated fraction in bulk soil DOC, similar to those found for Alaska river waters (Guo et al., 2003; Guo and Macdonald, 2006) although the ultrafilter cutoffs used are slightly different (3 kDa in this work vs. 1 kDa used in river water studies). The HMW-DOC percentages in our arctic tundra soils were generally lower than those reported in other soil studies (e.g., van Hees et al., 2005), likely related to different membrane cutoffs and/or concentration factors used during ultrafiltration (Guo and Santschi, 2007) in addition to the climate factor (Dai, 2001).

Interestingly, soil size fraction with lower DOC yields contained higher percentages of LMW-DOC in that specific soil size fraction (Table 2). In the acidic soils, DOC yields followed the order of (<53 μm)>(53–250 μm)>(250–2000 μm) with a corresponding LMW-DOC percentage of 42%, 38% and 45%, respectively. In the non-acidic soils, similar trends were observed. The 53–250 μm soil size fraction had the median DOC yield (1.5%), but contained the lowest LMW-DOC fraction (41% of DOC). These results indicate that SOC bound to the 53–250 μm size soil particles contained relatively higher HMW-DOC and could be considered highly degradable or more labile in terms of photo-degradation and microbial degradation after entering aquatic environments (Michaelson et al., 1998; Dai, 2001).

Our results here agreed well with previous studies (Ping et al., 1997; White et al., 2004) that the components of SOM associated with coarse particles in arctic tundra soils were less humified plant residue. Cold soil environment retarded the humification process leading to the large amount of SOM preserved in these deep horizons. Ping et al. (1997) found that the arctic tundra soils had high proportions of hemicellulose. Hence, the results from physical size fractionation indicated that a relatively low degree of decomposition occurred in arctic tundra soils due to cryoturbation and subsequent sequestration at below freezing temperature.

4. Discussion

4.1. Phase partitioning of soil organic carbon in arctic tundra soils

The OC partitioning between particle size fractions are shown in Table 3 for acidic and non-acidic soils from the upper permafrost. Soil OC was mostly partitioned in the 53–250 μm fine sand size fraction, followed by the <53 μm silt and clay fraction and the 250–2000 μm coarse sand fraction. In the acidic soils, ~79% of total OC store was in the 53–250 μm fraction, 11% in the <53 μm and 10% in the 250–2000 μm fraction (Table 3). In the non-acidic soils, 49% of the total OC store was in the 53–250 μm fraction, 29% in the 250–2000 μm fraction and 22% in the <53 μm fraction. Higher percentage of large size SOM in acidic soil relative to non-acidic soils is consistent with its characteristics in SOM stabilization and preservation.

The upper permafrost generally contributed the highest carbon density materials within the whole pedon in tundra soils. Compared to the low-bulk density surface organic horizons, the relatively high bulk density deeper horizons with greater thickness had more weight in sequestering OC (Michaelson et al., 1996). Preferential stabilization of SOM in fine sand fraction in tundra soils was presumably caused by: (i) inherent soil-type characteristics, such as inputs from parent material (e.g. loess); (ii) the inclusions of macro-OM causing a high SOM content in sand fraction; (iii) preferential loss of SOM associated with fine sand fractions being retarded by the low decomposition rates of organic matter in tundra soils as occurred in other regions (Amelung et al., 1998); (iv) the different energy input to disperse soil particles during size fractionation procedures, for example, increased carbon content in finer fractions caused by sonication (Christensen, 1992).

Within each soil size fractions (dry sieving followed by extraction), HMW- and LMW-DOC comprised ~1–2% of total organic carbon (Table 2).

Table 3

Phase partitioning of organic carbon (%) between particulate organic carbon (POC), high-molecular-weight (HMW), and low-molecular-weight (LMW) organic carbon fractions in upper permafrost soils from acidic and non-acidic tundra

Size fraction	250–2000 μm			53–250 μm			<53 μm		
	POC	HMW	LMW	POC	HMW	LMW	POC	HMW	LMW
Acidic tundra	7.1	1.5	1.3	76.1	1.7	1.1	9.1	1.3	0.9
Non-acidic tundra	26.9	0.7	0.9	47.7	0.8	0.6	20.9	0.8	0.7

The summation of all HWM- and LMW-DOC from each size-fractionated soils seemed higher than the total DOC pool from bulk acid and non-acidic soils, indicating the heterogeneous nature of soil samples. For realistic prediction of soil DOC release, more investigations on different soils with different topography, vegetation community, and hydrological conditions are needed. Overall, our data were within the ranges reported for the soil DOC production, e.g., 1–10% of the total soil OC store (Christensen, 1992). These results indicated that soils preserved in the upper permafrost could release up to 1–3% TOC into aquatic ecosystems during soil–water interactions. Thus, organic matters stored in deep horizons in the upper permafrost could contribute significant amount of soluble organics when permafrost is degraded. With the projected climate warming in the Arctic and thus warming soil temperature and changing hydrological conditions, the deep organic carbon sequestered in permafrost could be released and contribute significant amount of bioavailable DOC to arctic food webs (Judd and Kling, 2002) and play an important role in the carbon cycle (Hobbie et al., 2000).

4.2. Chemical characterization of soil DOC and the effects of different soil types on DOC production

Normally, highly degraded or older soil organic matter has a lower C/N ratio due to the escape of CO₂ but not nitrogen during organic matter degradation (Ping et al., 1998). In addition, organic matter with higher C/N ratio such as lignin could have a lower degradation compared to other organic components although fresher and coarse plant materials may have a higher C/N ratio. The C/N ratios of bulk and size-fractionated soil fractions are listed in Table 2. In general, soil C/N ratio seems to decrease with decreasing soil particle size for both acidic and non-acidic soils (Table 2) although bulk soils had similar C/N ratio between acidic (21) and non-acidic soils (20). Lower C/N ratios in finer soils indicate that SOM alteration was higher in the finer fractions than in coarser fractions (Christensen, 1992; Solomon et al., 2002). In other words, finer sized soil organic matter contains more degraded materials with a relatively lower C/N ratio in both acidic and non-acidic soils (Table 2).

Variations of C/N ratio in soil DOC extracted from size-fractionated soils are depicted in Fig. 6. Similar to trends in size-fractionated soils, the C/N ratio of soil DOC also shows a general increase with increasing soil particle size (Fig. 6). For example, DOC from the 250–2000 μm soil fraction had the highest C/N ratio, with 14 and 23 in acidic and non-acidic soils, respectively (Fig. 6). Although the C/N ratios of soil DOC from bulk and size-fractionated soils were similar, the DOC from the <53 μm soil fraction had the lowest C/N ratio in both soils (Fig. 6). The higher C/N ratio in the 250–2000 μm fraction suggested that it was mainly derived from poorly decomposed plant materials. In samples from the non-acidic upper permafrost, the C/N ratio of DOC ranged from 18 to 23. These suggested that organic matter stored in deep

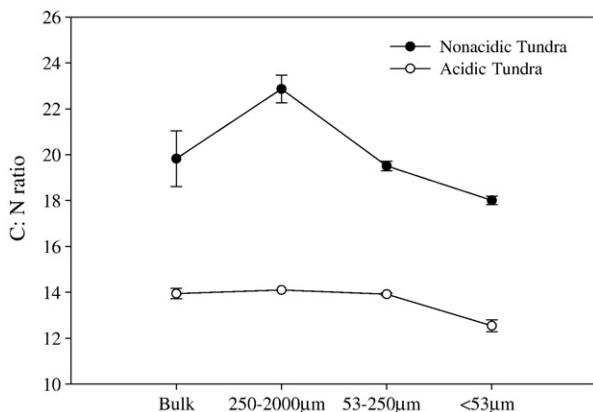


Fig. 6. C/N ratios of DOC from bulk and size-fractionated soils from the upper permafrost of acidic and non-acidic tundra.

horizons including DOC was significantly less humified, in agreement with earlier observations (Ping et al., 1997, 1998). Furthermore, the C/N ratio of DOC in non-acidic soils was higher than that of acidic soils, indicating different chemical characteristics of DOC between these two types of tundra soils (Fig. 6). However, it is not clear if the difference in C/N ratio between acidic and non-acidic soils is mainly the result of vegetation type or soil degradation and preservation between different environments (acidic vs. non-acidic). Since vegetation cover types in acidic and non-acidic tundra could be different (Walker et al., 1998), the results here indicated that patterns of DOC production were affected by the input from different vegetation cover. Judd and Kling (2002) and Neff and Hooper (2002) also found that vegetation cover type could have a control on DOC production and export in arctic tundra. In addition to vegetation cover, nutrient cycling and hydrological conditions are also important in affecting soil C/N ratio. For example, nutrient retention and mineralization play an important role in controlling decomposition rate and respiration pattern (Manzoni et al., 2008), and could affect the C/N ratio in degraded organic materials.

As shown in Table 2, acidic tundra soils produced more DOC than non-acidic soils. This difference in DOC production between acidic and non-acidic soil is again in agreement with that acidic soils preserve more less-degraded soil organic matter than non-acidic soils. For example, TOC content in bulk soils was 7.9% for the acidic soil compared to 3.5% for the non-acidic soil (Table 2), with a decrease in soil DOC yield with increasing soil size. Higher HMW-DOC fraction was also observed in the acidic soil DOC compared to non-acidic soil DOC, regardless of bulk soil or size-fractionated soil (Table 2). Stable isotope composition of SOM in bulk and size-fractionated soils varied little and are all within the range reported for C3 plants. However, both bulk and size-fractionated soil fractions exhibited different $\delta^{13}\text{C}$ values between acidic and non-acidic soils (Fig. 7) although $\delta^{13}\text{C}$ values varied within a narrow range between -27% and -26% . As shown in Fig. 7, organic matter in non-acidic soils tended to have a lower $\delta^{13}\text{C}$ than in acidic soils. Lighter $\delta^{13}\text{C}$ values in non-acidic soil likely resulted from the accumulation of lighter C in microbial body due to higher microbial activity in the soil. For $\delta^{15}\text{N}$ composition, organic matter in non-acidic soils contained higher $\delta^{15}\text{N}$ values, suggesting that more altered organic materials in non-acidic soil. This seems consistent with the different characteristics of organic matter degradation/preservation between these two types of soils. Presumably, the differences in soil environment, nutrient cycling, landscape and hydrological cycle of these two major tundra soils could significantly affect the quantity and quality of organic matter and therefore DOC yields.

The quality and characteristics of SOM in acidic and non-acidic tundra soils are still in debate. Because of more favorable pH for microbial activity and relatively easily degradable organic matter inputs in non-acidic tundra soils, the non-acidic tundra soils were generally hypothesized to have faster rates of soil C and N cycling than acidic tundra soils (Hobbie et al., 2002). This hypothesis would agree with the fact that less decomposed SOM appeared to be preserved in the acidic tundra soils than non-acidic tundra soils (e.g., Hobbie et al., 2002; White et al., 2004), although little is known about the chemical characteristics of DOC in arctic tundra soils. However, our data did not show that C/N ratio alone is a straightforward quality indicator when comparing different soils, and point to the limitation in using C/N ratio to determine the degradation status between soils. Studies combining detailed organic molecular composition and C/N ratio in both bulk soil and DOC are needed to provide insights into a better understanding of soil quality between acidic and non-acidic soils.

With the deepening active layer accompanied by thawing of permafrost (Romanovsky and Osterkamp, 1997; Jorgenson et al., 2006), the SOM preserved in upper permafrost could reenter biogeochemical cycles in arctic region (Guo et al., 2007). The result here could aid in the prediction and evaluation of biogeochemical

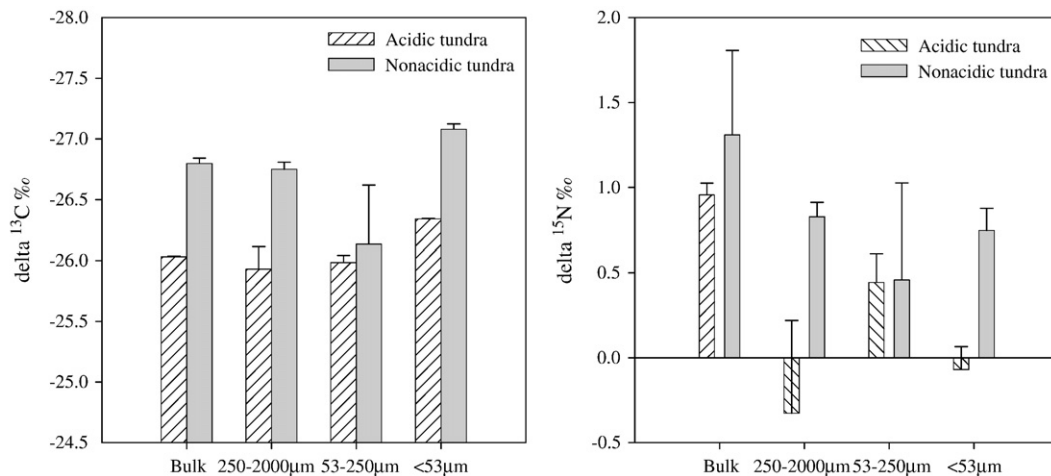


Fig. 7. Stable isotope (^{13}C , and ^{15}N) composition in bulk and size-fractionated soil organic matter from acidic and non-acidic tundra.

consequence of releasing deep SOC in arctic tundra in a changing climate. At the first approximation, up to 2% of arctic soil organic carbon stock could be potentially leached out into aquatic systems should permafrost be thawed and soils flushed into aquatic environments. This soil DOC flux will be large and may considerably affect carbon budget and biogeochemical cycling in the arctic aquatic environment although our estimation here could be the upper limit. Clearly, any scale up requires significant extension of a limited data set. More studies combining field investigation, controlled laboratory experiments and modeling with interdisciplinary approaches are needed for realistic prediction and to account for topographical and hydrological differences when it is scaled up to the arctic region.

5. Summary

Both acidic and non-acidic tundra soils were collected from northern Alaska for size fractionation into the 250–2000 μm , 53–250 μm and <53 μm soil fractions. Size fractionation of freeze-dried soils was carried out by dry sieving, followed by extraction of bulk and size-fractionated soils to examine the DOC production potential during soil–water interaction under a warming climate. Soil DOC was further fractionated into the low-molecular-weight and high-molecular-weight DOC fractions to examine the molecular weight distribution of DOC produced from bulk and size-fractionated soils.

The 53–250 μm size fraction stored the largest soil OC pool in both soil types. In the acidic tundra soils, ~79% of total OC was in the 53–250 μm size fraction, 11% in the <53 μm size and 10% in the 250–2000 μm size fraction. In the non-acidic soils, 49% of the total OC was in the 53–250 μm size fraction, 29% in the 250–2000 μm size fraction and 22% in the <53 μm size fraction.

Experimental conditions seem to significantly affect the extraction of soil DOC and thus the quantitative prediction of soil DOC yield during its interactions with hydrological cycle in a warming climate. Soil DOC yields, in general, increased with decreasing soil/water ratio. In addition, higher temperature gave rise to a higher soil DOC yield although the release of soil DOC could start as soon as the frozen soils are thawed or the temperature is above freezing point. Results of sequential extraction indicated that most of soil DOC could be effectively leached out during the first 24 h of extraction. Significant loss of DOC through microbial decomposition was observed after 48 h of extraction. Long-term extraction would likely underestimate the soil DOC yield.

Bulk tundra soils are indeed heterogeneous. On average, 2.6% of the bulk soil TOC can be released into the DOC pool from the bulk acidic tundra soils, whereas about 1.8% of TOC could be partitioned into the DOC pool from the bulk non-acidic soils. In both acidic and

non-acidic soils, DOC yields exhibited a consistent decrease with increasing soil size fraction, with the highest DOC yield in the <53 μm fraction and the lowest DOC yield in the 250–2000 μm soil fraction. The C/N ratio appeared to decrease with decreasing soil particle size, while stable C and N isotope composition had small variation between different soil size fractions although there is a significant difference between acidic and non-acidic soils. Soil heterogeneity including chemical composition within the same soil profile and hydrological/topographical between sampling sites would likely give rise to variable DOC yields.

Within the soil DOC pool, about 35% was in the <3 kDa LMW fraction and 65% was in the >3 kDa HMW fraction in the acidic soils, while 56% was in the LMW fraction and 34% was in the HMW fraction in non-acidic soils. The relative partitioning of DOC between HMW and LMW may be used as an index of DOC quality or lability although DOC size or MW cutoffs are highly operationally defined.

Interactions of soil organic matter with aquatic environments may be intensified under amplified warming conditions. Although the overall soil DOC yield was relatively low, the total quantity of DOC released can be extremely large (i.e., up to 2% of arctic SOC stock) should permafrost thaw and soils be flushed into aquatic environments. Further studies are needed to investigate the fate of soil DOC released from size-fractionated and bulk tundra soils and the impacts of soil DOC on aquatic systems as a whole.

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References

- Arctic Climate Impacts Assessment (ACIA). 2005. Impacts of a warming Arctic. Arctic Climate Impacts Assessment. Cambridge University Press, Cambridge.
- Amelung, W., Zech, W., Zhang, X., Follett, R.F., Tiessen, H., Knox, E., Flach, K.W., 1998. Carbon, nitrogen and sulfur pools in particle-size fractions as influenced by climate. *Soil Sci. Soc. Am. J.* 62 (1), 172–181.
- Bockheim, J.G., Walker, D.A., Everett, L.R., Nelson, F.E., Shiklomanov, N.I., 1998. Soils and cryoturbation in moist nonacidic and acidic tundra in the Kuparuk River basin. *Arctic Alaska USA. Arc. Alp. Res.* 30 (2), 166–174.
- Cai, Y., Guo, L., Douglas, T., 2008. Temporary variations in organic carbon species and fluxes from the Chena River Alaska. *Limnol. Oceanogr.* 53, 1408–1419.
- CAVM Team, 2003. Circumpolar Arctic Vegetation Map. Scale 1:7,500,000 Conservation of Arctic Flora and Fauna (CAFF) Map, vol. 1. U.S. Fish & Wildlife Service, Anchorage, AK.

- Christensen, B.T., 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. *Adv. Soil Sci.* 20, 1–90.
- Dai, X.Y., 2001. Bioavailability and chemical characterization of soil organic matter in arctic soils. Ph.D. dissertation. University of Alaska Fairbanks, Fairbanks, AK.
- Dai, X.Y., Ping, C.L., Candler, R., Haumaier, L., Zech, W., 2001. Characterization of soil organic matter fractions of tundra soils in arctic Alaska by carbon-13 nuclear magnetic resonance spectroscopy. *Soil Sci. Soc. Am. J.* 65 (1), 87–93.
- Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedback to climate change. *Nature* 440, 165–173.
- Dou, F., Ping, C.L., Guo, L., Jorgenson, M.T., 2008. Estimating the impact of seawater on the production of soil water-extractable organic carbon during coastal erosion. *Journal of Environmental Quality* 37, 1–7. doi:10.2134/jeq2007.0403.
- Frey, K.E., Smith, L.C., 2005. Amplified carbon release from vast West Siberian peatlands by 2100. *Geophys. Res. Lett.* 32, 109401. doi:10.2929/2004GL022025.
- Gregorich, E.G., Beare, M.H., Stoklas, U., St-Georges, P., 2003. Biodegradability of soluble organic matter in maize-cropped soils. *Geoderma* 113 (3–4), 237–252.
- Guo, L., Coleman, C.H., Santschi, P.H., 1994. The distribution of colloidal and dissolved organic carbon in the Gulf of Mexico. *Mar. Chem.* 45, 105–119.
- Guo, L., Macdonald, R.W., 2006. Sources and transport of terrigenous organic matter in the upper Yukon River: evidence from isotope (^{13}C , ^{14}C and ^{15}N) composition of dissolved, colloidal and particulate phases. *Global Biogeochem. Cy.* 20, GB2011. doi:10.1029/2005GB002593.
- Guo, L., Santschi, P.H., 2007. Ultrafiltration and its applications to sampling and characterization of aquatic colloids. In: Wilkinson, K., Lead, J. (Eds.), *Environmental Colloids and Particles*. Chapter 4, IUPAC Series on Analytical and Physical Chemistry of Environmental Systems. John Wiley, pp. 159–221.
- Guo, L., Lehner, J.K., White, D.M., Garland, D.S., 2003. Heterogeneity of natural organic matter from the Chena River, Alaska. *Water Res.* 37 (5), 1015–1022.
- Guo, L., Semiletov, I., Gustafsson, O., Ingri, J., Andersson, P., Dudarev, O., Whie, D.M., 2004. Characterization of Siberian Arctic estuarine sediments: implications for terrestrial organic carbon export. *Global Biogeochem. Cy.* 18, GB1036. doi:10.1029/2003GB002087.
- Guo, L., Ping, C.L., Macdonald, R.W., 2007. Mobilization pathways of organic carbon from permafrost to arctic rivers in a changing climate. *Geophys. Res. Lett.* 34, L13603. doi:10.1029/2007GL030689.
- Hinzman, L.D., Bettex, N.D., Bolton, W.R., 2005. Evidence and implications of recent climate change in northern Alaska and arctic regions. *Climatic Change* 72 (3), 251–298.
- Hobbie, S.E., Schimel, J.P., Trumbore, S.E., Randerson, J.R., 2000. Controls over carbon storage and turnover in high-latitude soils. *Global Change Biol.* 6, 96–210 Suppl.1.
- Hobbie, S.E., Miley, T.A., Weiss, M.S., 2002. Carbon and nitrogen cycling in soils from acidic and nonacidic tundra with different glacial histories in Northern Alaska. *Ecosystems* 5 (8), 761–774.
- IUSS Working Group WRB, 2006. World Reference Base for Soil Resources. World Soil Resources Reports No. 103, FAO, Rome.
- Jorgenson, M.T., Brown, J., 2005. Classification of the Alaskan Beaufort Sea Coast and estimation of carbon and sediment inputs from coastal erosion. *Geo-Marine Letters* 25, 69–80.
- Jorgenson, M.T., Shur, Y.L., Pullman, E.R., 2006. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophys. Res. Lett.* 33, L02503.
- Judd, K.E., Kling, G.W., 2002. Production and export of dissolved C in arctic tundra mesocosms: the roles of vegetation and water flow. *Biogeochemistry* 60 (3), 213–234.
- Kling, G.W., Kipphut, G.W., Miller, M.C., 1991. Arctic lakes and streams as gas conduits to the atmosphere: implications for tundra carbon budgets. *Science* 251, 298–301.
- Lopez, C.M.L., Brouchkov, A., Nakayama, H., Tanaka, F., Fedorov, A.N., Fukuda, M., 2007. Epigenetic salt accumulation and water movement in the active layer of central Yakutia in eastern Siberia. *Hydrological Processes* 21, 103–109.
- Manzoni, S., Jackson, R.B., Trofymow, J.A., Porporato, A., 2008. The global stoichiometry of litter nitrogen mineralization. *Science* 321, 684–686.
- Mayorga, E., Aufdenkampe, A.K., Masiello, C.A., Krusche, A.V., Hedges, J.I., Quay, P.D., Richey, J.E., Brown, T.A., 2005. Young organic matter as a source of carbon dioxide outgassing from Amazonian rivers. *Nature* 436, 538–541.
- McLaughlan, K.K., Hobbie, S.E., 2004. Comparison of labile soil organic matter fractionation techniques. *Soil Sci. Soc. Am. J.* 68 (5), 1616–1625.
- Megens, L., van der Plicht, J., de Leeuw, J.W., Smedes, F., 2002. Stable carbon and radiocarbon isotope compositions of particle size fractions to determine origins of sedimentary organic matter in an estuary. *Org. Geochem.* 33, 945–952.
- Michaelson, G.J., Ping, C.L., Kimble, J.M., 1996. Carbon storage and distribution in tundra soils of Arctic Alaska. *USA. Arc. Alp. Res.* 28 (4), 414–424.
- Michaelson, G.J., Ping, C.L., Kling, G.W., Hobbie, J.E., 1998. The character and bioactivity of dissolved organic matter at thaw and in the spring runoff waters of the arctic tundra north slope, Alaska. *J. Geophys. Res.-Atmos.* 103 (D22), 28939–28946.
- Neff, J.C., Hooper, D.U., 2002. Vegetation and climate controls on potential CO_2 , DOC and DON production in northern latitude soils. *Global Change Biol.* 9, 872–884.
- Oechel, W.C., Hastings, S.J., Bourlitis, G., Jenkins, M., Riechers, G., Grulke, N., 1993. Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. *Nature* 361, 520–523.
- Ping, C.L., Michaelson, G.J., Loya, W.M., Candle, R.J., Malcolm, R.J., 1997. Characteristics of soil organic matter in arctic ecosystem of Alaska. In: Lal, R., Kimble, J.M., Stewart, R.A. (Eds.), *Carbon Sequestration—Advances in Soil Science*. CRC Press, Boca Raton, Florida, pp. 157–169.
- Ping, C.L., Bockheim, J.G., Kimble, J.M., Michaelson, G.J., Walker, D.A., 1998. Characteristics of cryogenic soils along a latitudinal transect in Arctic Alaska. *J. Geophys. Res.-Atmos.* 103 (D22), 28917–28928.
- Rachold, V., Grigoriev, M.N., Are, F.E., Solomon, S., Reimnitz, E., Kassens, H., Antonow, M., 2000. Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas. *Int'l. J. Earth Sci.* 89, 1437–3254.
- Romanovsky, V.E., Osterkamp, T.E., 1997. Thawing of the active layer on the coastal plain of the Alaskan Arctic. *Permafrost Periglac.* 8 (1), 1–22.
- Serreze, M.C., Walsh, J.E., Chapin, F.S., Osterkamp, T., Dyurgerov, M., et al., 2000. Observational evidence of recent change in the northern high-latitude environment. *Clim. Change* 46, 159–207.
- Soil Survey Division Staff, 1993. Soil survey manual. USDA Agric. Handbook, vol. 18. U.S. Government, Print. Office, Washington, DC.
- Soil Survey Staff, 2006. Keys to soil taxonomy, Tenth Edition. USDA Natural Resources Conservation Service, Washington, D.C.
- van Hees, P.A.W., Jones, D.L., Finlay, R., Godbold, D.L., Lundstom, U.S., 2005. The carbon we do not see – the impact of low molecular weight compounds on carbon dynamics and respiration in forest soils: a review. *Soil Biol. Biochem.* 37 (1), 1–13.
- White, D.M., Garland, D.S., Dai, X.Y., 2002. Fingerprinting soil organic matter in the arctic to help predict CO_2 flux. *Cold Regions Sci. Technol.* 35, 185–194.
- White, D.M., Garland, D.S., Ping, P.L., Michaelson, G.J., 2004. Characterizing soil organic matter quality in arctic soil by cover type and depth. *Cold Reg. Sci. Technol.* 38 (1), 63–73.
- Walker, D.A., Auerbach, N.A., Bockheim, J.G., Chapin, F.S., Eugster, W., King, J.Y., McFadden, J.P., Michaelson, G.J., Nelson, F.E., Oechel, W.C., Ping, C.L., Reeburg, W.S., Regli, S., Shiklomanov, N.I., Vourlitis, G.L., 1998. Energy and trace-gas fluxes across a soil pH boundary in the Arctic. *Nature* 394, 469–472.
- Xu, C., 2005. Size-fractionation and characterization of cryoturbated soil organic matter in Arctic tundra, Alaska. M.S. thesis, University of Alaska Fairbanks, Alaska, USA.