농학석사학위논문

반복적인 동결-융해가 북극 툰드라 지역의 유기탄소에 미치는 영향

Effect of repeated freeze-thaw cycles on soil organic carbon in Arctic tundra soil

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Abstract

Effect of Repeated Freeze-Thaw Cycles on Soil Organic Carbon in Arctic Tundra Soil

The Arctic plays a key role in the global carbon cycles, because permafrost stores more than half of global soil organic matter. Although freeze-thaw cycle (FTC) over permafrost is important because they can have large impact on composition of microbial communities and control decomposition of Soil organic matter to greenhouse gas, it is controversial to what extent the effect of FTC on soils. Soil organic carbon (SOC) can be divided into three main pools; labile, stable and inert. Our research has focused on the labile fractions, as it is considered more readily decomposed than the stable fraction and important as a supply of energy for soil microorganisms. Extracellular enzyme activities such as phenol oxidase and peroxidase activities are critical to understanding potential response to repeated FTCs, because these enzyme activities reflect the microbial nutrient demands and decomposition activity of labile SOC fraction. Therefore, we hypothesized that changes in soil temperature regimes due to repeated FTCs would cause a difference in the response of SOC decomposition and the ensuing microbial activity. To test the hypothesis, we designed incubation experiment in which soil samples were exposed to three controls; kept unfrozen (12 °C, thaw control) and frozen (-15 °C, frozen control) and repeated freeze-thaw cycle (-15~12 °C, FTC). Bulk soil samples for the organic soil horizon (0~30 cm) were obtained with shovel in a tundra region, Alaska

(64° 51’ N, 163° 42’ W). We measured variations of labile SOM fraction by acid hydrolysis method and microbial response such as phenol oxidase and peroxidase activities to elucidate mechanisms induced differences in SOC composition by repeated freeze–thaw. Soil samples were analyzed for total C, N, and CO_2 and CH_4 gas was released each time the soils were thawed. Our results obviously showed that Repeated Freeze-Thaw patterns under ponded conditions would facilitate conversion of SOC compounds into DOC pools. It also suggested that changes in SOC composition would be of a valuable index to SOC decomposition potential in Arctic tundra soil.

Key Words: Repeated Freeze-Thaw Cycle (FTC), Soil Organic Carbon (SOC), Dissolved Organic Carbon (DOC), Soil Decomposition, Soil respiration, Acid Hydrolysis

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List of Abbreviations

DOC	Dissolved Organic Carbon
EEA	Extracellular Enzyme Activity
FTC	Repeated Freeze-Thaw Cycle
GC-FID	Gas Chromatography- Flame Ionization Detector
NDIR	Non-Dispersive Infrared Sensor
PC	Phenolic Compound
SOC	Soil Organic Carbon
SOM	Soil Organic Matter

Introduction

Arctic tundra in northern region is extremely vulnerable to current climate change proceeded faster during the last few decades (Anisimov et al., 2007; Schuur et al., 2013). It has led to a concerted effort to comprehensively understand the role of soil carbon pool and its dynamics. This region represents one of the largest carbon storage. Environmental condition such as cold temperature, wet and acidic soil environments led to low ecosystem productivity and low decomposition rate support as high soil organic matter (SOM) reservoir (Rydin and Jeglum, 2013). Also, they are the most efficient terrestrial ecosystem at storing carbon per unit area (Parish et al., 2008) containing about 30 % of all carbon stored on Earth's soil (Gorham, 1991; Tarnocai et al., 2009). The thawing of permafrost in the arctic region may exacerbate climate change as a consequence of feedback mechanisms by which considerable amount of carbon is released from the soil to the atmosphere as global temperature rises, resulting in increased the vulnerability of permafrost to degradation under continued warming environments (Grosse et al., 2011; Koven et al., 2011). It is indicating the importance to clarifying characteristics of soil organic carbon (SOC) and its dynamics across soil and atmosphere for a better understanding of impacts and environmental changes in the Arctic tundra region (Dou et al., 2008).

The greatest feature of arctic tundra region is the permafrost below the soil. Permafrost is frozen ground in which a temperature less than 0 °C has existed continuously for two or more years. Although the magnitude of thawing in permafrost region varies depending on regional thermal characteristics, thermal

degradation of permafrost soil and related geomorphic processes can contribute to alter the SOM decompositions (Jorgenson et al., 2006). Thermal alternations of the arctic land due to permafrost thawing may cause unfavorable geomorphic processes and landforms such as thermal erosion, land-surface subsidence, and slope instability in the relief (Rowland et al., 2010). Such geomorphic disturbances often led to affecting the soil thermal regimes by modifying the surface energy and water balances (Bishop et al., 2011), thus increasing vulnerability of previously frozen SOM to decomposition (Schuur et al., 2009). Almost no water generated by melting snow and ice in summer can penetrate because the upper surface of permafrost called the permafrost table act as a barrier to water movement. Therefore, soil is saturated or drained horizontally along the permafrost table and consequently SOM can be exposed to either aerobic or anaerobic condition. The SOM decomposition process depends on conditions of geochemical factors such as soil mineralogy, redox potential and electron acceptor availability that are controlled by water regimes. Because of substantially difference soil water environment, it leads to differences in the decomposition process of SOM. In this regard, patterns of decomposition and the fate of soil carbon pools would be different depending on whether soils are exposed to the aerobic or anaerobic conditions by water regimes.

Research on freeze-thaw events has increased in recent years because of climate change and it alter their frequency and intensity (Arnold et al., 1998; Dale et al., 2001; Groffman et al., 1999; Moore and Mckendry, 1996). Changes to the SOC pools of arctic tundra region is likely under global climate change, where elevated temperature and changes to the water balance drive altered decomposition process and carbon loss as CO_2, CH_4 and dissolved organic

carbon (DOC) (Roulet et al., 1992; Rouse et al., 1997). In general, the rate of SOM decomposition is expected to increase as temperature increases (Hobbie, 1996; Nadelhoffer et al., 1991; Weintraub and Schimel, 2003). However, under field conditions, it is difficult to assess the effects of environmental factors including seasonal freeze-thaw events and water balance on belowground carbon cycling because environments are highly heterogenous. Therefore, there have been few studies to evaluate ecosystem-scale controls on their effects on SOC decomposition processes. Indeed, the responses of SOC to environmental factor have received considerable effort, however mostly on the understanding the processes controlling the exchange of CO2 and CH4 between the soil and atmosphere (Davidson and Janssens, 2006). The slightly less effort has been committed to exploring the role of SOC decomposition and export in the carbon dynamics of arctic tundra soil.

As global climate change is expected to be severe continuously on a global basis, SOM of arctic tundra region will evidently interacted with soil carbon dynamics and it will further modify the extent of its interaction with SOC pools. In addition, repeated freeze-thaw cycles are expected to accelerate their frequency and intensity because of climate change that may alter the melting of permafrost and the cumulative effect of successive freeze-thaw cycles can lead to considerable decomposition and modification of SOC pools (Grogan et al., 2004). However, few attempts have been made to investigate the effect of repeated fluctuations in soil temperature on the decomposition of SOC pools. Therefore, we hypothesized that repeated fluctuation in soil temperature would alter the response of decomposition of SOM and this response would be different depending on whether the soil is saturated with the water or not. In

this study, we tested the effects of repeated freeze-thaw cycle on SOC pool dynamics, especially DOC which is considered a quickly reactive indicator of soil productivity and is used by microorganisms as a source of energy and carbon skeletons for their structures, and evaluated CO_2 and CH_4 efflux from the results of incubation experiments. The objective of this study was to examine the effect of the two water conditions (ponded, unsaturated) and the three temperature conditions (constant thaw and freeze temperature and repeated freeze-thaw cycles) on the patterns of SOC pool dynamics especially focused on DOC and the ensuing CO_2 and CH_4 efflux for SOC decomposition from the results of incubation experiments. Furthermore, we conducted an experiment to apply acidic hydrolysis approach to characterize the changes in SOC quality such as changes in the proportion to SOC pools, mainly the proportion to hydrolyzable and unhydrolyzable pool during incubation.

Materials and Methods

Site and soil descriptions

The study site was located at Council, Seward Peninsula (Figure. 1) in northwest Alaska (64° 51′ N, 163° 42′ W), and the soils of this region are histic gelisols underlain by discontinuous permafrost where the process of thermal thawing is still in progress (Yoshikawa and Hinzman, 2003). The annual mean air temperature and precipitation were -3.1±1.4 ℃ and 258 mm, respectively, and the highest mean air temperatures of the year were 11±1.2 ℃ during July and lowest were -14.9 ℃ during January, which were obtained by the Alaska Climate Research Center. This site was representative of subarctic tundra vegetation where lichen, moss (*Sphagnum spp.*), blueberry (*Vaccinium uliginosum*) and water sedge (*Carex aquatilis*) were dominant (Park and Lee, 2014).

At sampling (August, 2015), the thaw depth measured using stainless steel cone penetrometer with an area of 1 cm^2 (Penetrograph, Eijkelkamp, Netherlands) was 36.5±1.3 cm, and the corresponding penetration resistance was 2.3±0.1 MPa (n=16). Three locations were randomly chosen as replicates, and were taken individually upper soil using a shovel and stored at -20 ℃ before starting the physicochemical analyses of soils and the incubation experiments. The soil was mainly made up of fibric types of organic materials (Table 1), while the lower mineral layer was texturally silt loam (USDA classification scheme: 133.1 g kg^{-1} for sand, 635.9 g kg^{-1} for silt, and 231.1 g kg^{-1} for clay) mixed with sapric organic materials (USDA Soil Taxonomy, 2014).

Figure 1. Map showing study location of subarctic tundra in Council, Alaska.

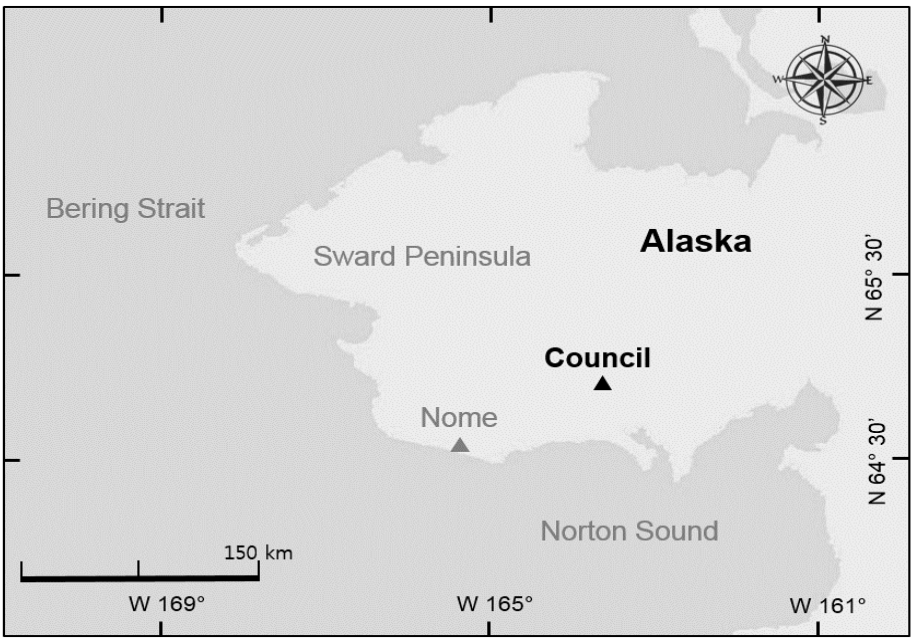

Bering Strait
Sward Peninsula
Alaska
Council
Nome
Norton Sound
150 km
W 169°
W 165°
W 161°
N 65° 30'
N 64° 30'

Table 1. Fundamental characteristics of soil used in this study.

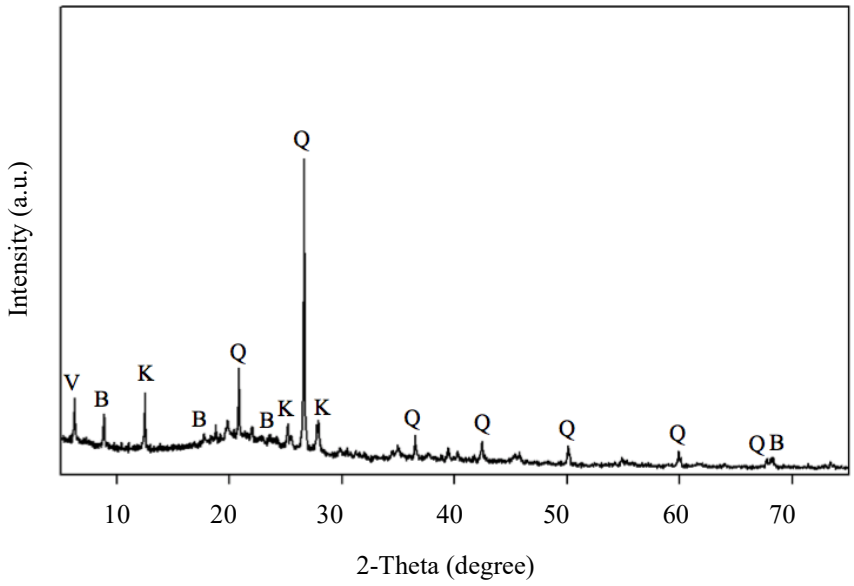
Fundamental characteristics						Major elements		
Organic Soil Materials	pH (1:5)	EC (dS m^{-1})	TC (g kg^{-1})	TN (g kg^{-1})	C/N ratio	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)
Fibric	4.53	0.17	326.30	13.40	24.36	23.10	7.43	2.84

- Coefficient of variation was calculated as 95.8-107.3%; thus, standard deviation was not listed.
- Organic soil materials were determined by USDA Soil Taxonomy (USDA Soil Taxonomy, 2014).
- pH: 1:5 (soil:water).
- EC: electric conductivity
- TC: total carbon content
- TN: total nitrogen content
- C/N ratio: a ratio of carbon to nitrogen

The pH and EC were potentiometrically measured using Orion 5 star (Thermo, USA) in 1:5 (w/v). The soils were acidic (pH 4.53), and the EC of the soils was very low (0.17 dS m^{-1}). Contents of total C and N (Flash EA 1112, Thermo) were respectively 326.30 g kg^{-1} and 13.40 g kg^{-1}, resulting in the ratios of C to N (C/N ratios) was 24.36 (Table 1). Elemental composition was measured by X-ray fluorescence (XRF) using Axios^{MAX}-Mineral (PANalytical, Netherlands) and X-ray diffraction (XRD) using X'pert PRO multipurpose diffractometer (PANalytical, Netherlands), respectively. The quantitative mineralogical composition of sediments and capping agents was identified using the Hanawalt method (Hanawalt et al., 1938) and analyzed using MAUD software (Lutterotti et al., 1997) with The American Mineralogist Crystal Structure Database (Downs and Hall-Wallace, 2003). Quartz (40.8±1.18 %), Kaolinite (29.2±2.26 %), Biotite (28.65±2.32 %), and Vermiculite (1.2±0.14 %) were identified in the soil (Figure 2). Quartz is non-reactive primary mineral, and kaolinite is non-reactive 1:1 phyllosilicate secondary mineral consisting of 1 tetrahedral sheets and 1 octahedral sheet, cations and water molecules cannot be intercalated in the interlayer spacing. Biotite is common phyllosilicate mineral within the mica group. Biotite has a highly perfect basal cleavage, and consists of flexible sheets, or lamellae, which easily flake off. It has a monoclinic crystal system, with tabular to prismatic crystals with an obvious pinacoid termination. XRF result confirmed the elemental composition of the identified minerals by XRD unless iron oxide has not identified.

Figure 2. X-ray diffraction pattern of soil.

X-ray diffraction patterns of the soil with spectral reference of the minerals identified. Different codes indicate the minerals from the American mineralogist crystal structure database. (Q; quartz, K; kaolinite, B; biotite, V; vermiculite)


Intensity (a.u.)
V
B
K
B
Q
B
K
Q
K
Q
Q
Q
Q
Q B
10
20
30
40
50
60
70
2-Theta (degree)

Incubation experiment

Prior to incubation of subarctic tundra soils that are subject to repeated freeze-thaw cycles, the freezing and thawing temperatures were determined based on the highest mean air temperatures of the year were 11±1.2 °C during July and lowest were -14.9 °C during January. Two water regime and 3 temperature conditions were laid out in a completely randomized design in triplicate: Unsaturated and Ponded water conditions and constant thaw (T) and freeze (F) and repeated freeze-thaw (FTC) temperature conditions. Soils was packed into a 150 mL polyethylene bottle (6.3 cm in diameter) to a depth of 5 cm for unsaturated conditions, while each 1 cm deep of water layer was overlaid to the top of the soil layer. Each bottle was covered with a perforated cap to ensure gas exchange. Each freeze-thaw cycle consisted of thawing at 12±1 °C for 7 days, and freezing at -15±1 °C for 5 days (1 cycle is 12 days for repeated freeze thaw condition). In case of constant thaw and freeze conditions kept 12±1 °C and -15±1 °C respectively for 60 day. Soil water content of each bottle was adjusted to a level of field moisture capacity at a matric potential of -33 kPa: 0.5 m^3 m^{-3}. Every 12 days (1cycle for repeated freeze-thaw condition) after, soil sample was sampled and homogenized for soil chemical analyses.

For gas flux analysis, each 150 g (wet basis) of organic soil was packed into 500 mL jar and other conditions were established as mentioned above. Every 12 days after, we sampled 1 mL from the headspace to measure CH_4 flux in the jars using an air-tight syringe and analyzed on a gas chromatograph with flame ionization detector (GC-FID, hp 6890, Agilent) system described table 2. In case of CO_2 flux used small non-dispersive infrared (NDIR) CO_2 sensors (SH-300 DC, Soha Tech).

Table 2. The optimum operating conditions of GC-FID used.

Parameter	Conditions
Column	DB-5-SMS UI (0.25 mm i.d. x 30 m, 0.25 μm)
Column temperature	50 ℃ (0.5 min) → 80 ℃ (2.5 min) Ramp rate of 15 ℃ min^{-1}
Detector temperature	270 ℃
Inlets temperature	200 ℃
Injection mode / Split mode	Manual / Split ratio of 10:1
Injection volume	1 mL
Gas flow	H_2 (35 mL min^{-1}), N_2 (30 mL min^{-1})

Soil analysis

The DOC was measured spectroscopically with UV-vis spectrophotometer (Genesys 5, Milton Roy, USA), approximately 4 g of fresh soil was extracted with distilled water at a soil-to-solution ratio of 1:5 (w/v), and filtered through a Whatman No. 42 filter paper followed by a 0.45 µm nylon membrane. The filtrates were used to determine DOC with a total organic C using a UV-Visible spectrophotometer. The DOC concentration was expressed in mg C kg^{-1} dry soil.

The amount of phenolic compounds was determined by Folin-Ciocalteu colorimetric assay (Box, 1983; Folin and Ciocalteu, 1927) and expressed as mg C kg^{-1} dry soil. A portion of each soil sample was air-dried and ground to a fine powder using a ball mill (MM400, Retsch, Germany) to analyze for total C, N and contents. Total C and N contents were analyzed with an elemental analyzer (Flash EA 2000, Thermo Scientific, Cambridge, UK).

Phenol oxidase activity (PHO) and Peroxidase (PEO) as a surrogate of extracellular enzyme activity (EEA) involved in recalcitrant organic C decomposition, was estimated by calculating the specific substrate consumption rates (Carreiro et al., 2000; Pind et al 1994). To do so, about 0.4 g of fresh soil sample was homogenized with distilled water, and each suspension was mixed with 10mM of L-DOPA (L-3,4-dihydroxy phenylalanine) and for peroxidase received H_2O_2 (0.3%) and then immediately incubated at each treatment temperature for 1 hour. After incubation, the suspension was centrifuged at 3000 rpm to stop enzymatic reaction. The supernatant was filtered through a Whatman GF/C glass filter, and the absorbance was measured at 460 nm using a UV-Vis spectrophotometer (Orion

Aquamate 7000, Thermo, USA). Phenol oxidase and peroxidase activity was expressed as the amount of 2,3-dihydroindole-5,6-quinone-2-carboxylate (diqc) produced per unit time and per unit mass of dry soil using the Beer-Lambert law (Pind et al., 1994).

We also evaluated soil organic carbon fraction considering 3 pools (Labile Pool I and II and Recalcitrant Pool) from acid hydrolysis. we used the two-step acid hydrolysis method with H_2SO_4 (Oades and Wagner, 1970; Rovira and Vallejo, 2002). Briefly, 20 mL of 2.5 M H_2SO_4 was added to 300 mg soil, and the sample was hydrolyzed for 30 min at 105 °C, after which the hydrolysate was recovered by centrifugation and decantation. This hydrolysate was taken as labile pool I (LPI). The residue was hydrolyzed with 2 mL of 13 M H_2SO_4 overnight at room temperature. The concentration of the acid was then brought down to 2 N by dilution with water and the sample was hydrolyzed for 3 h at 105 °C. The hydrolysate was recovered in the same manner as for the LPI. The remaining residue dried at 60 °C, this fraction was taken as Recalcitrant Pool. The labile pool I and II were measured spectroscopically with UV-vis spectrophotometer (Genesys 5, Milton Roy, USA) and recalcitrant pool were analyzed for total C contents with an elemental analyzer (Flash EA 2000, Thermo Scientific, Cambridge, UK).

Statistical analysis

Data were statistically analyzed using the General Linear Models (GLM) procedures (SAS Institute, Version 24, Cary, USA). One-way analysis of variance (ANOVA) was used to evaluate the effect of environmental factor on DOC, Phenolic compounds, Phenol oxidase and Peroxidase activity, CO_2 and

CH_4 flux. The least significant difference (LSD) test at a confidence level of 95% was used to separate means.

Results and Discussion

Effect of water regime and repeated freeze-thaw cycle on the production of Dissolved Organic Carbon (DOC)

Experimental conditions containing water regimes, temperature and repeated freeze-thaw cycle can considerably affect the extent to which soil DOC is released. Thus, the effect of experimental conditions on soil SOC dynamics needs to be quantitatively examined for the prediction of DOC release during soil incubation. The variations of DOC concentrations during the incubation are presented in Figure 3. The DOC concentrations varied 529.69 - 1191.62 mg C kg^{-1} dry soil. Soil DOC concentration under three different temperatures conditions (Constant Thaw, Constant Freeze and repeated freeze-thaw) are shown Figure 3. The DOC concentration under constant thaw temperature (12 °C, Figure 3 (a)) was 829.02 mg C kg^{-1} dry soil, which was significantly higher than that under constant freeze temperature (-15 °C, Figure 3 (b)) (712.00 mg C kg^{-1} dry soil) and the variation also was minimal with a slight increase. Overall total DOC concentrations were positively and significantly higher under the ponded condition. These results imply that constant thaw condition increased microbial decomposition of SOC and resulted in simulating DOC productivity.

Extracellular enzyme activity (EEA) mediate the degradation, transformation and mineralization of SOM (Sinsabaugh et al., 1999; Sinsabaugh, 2010). Peroxidases are one of the EEA that use H_2O_2 as an electron acceptor and are known for their role in breakdown of weak carbon bonds between the polymers of lignin (Reid, 1995; Sinsabaugh, 2010). Therefore,

increases in the amount of peroxidase activity leads to increases in the amount of DOC and phenolic compounds. No significant difference in peroxidase activity in unsaturated conditions was found among the temperature conditions during the incubation (Figure 4). However, under the ponded condition, peroxidase activity was significantly higher than under the unsaturated condition after 12 days. These results imply that in ponded condition increased microbial decomposition of SOC and resulted in simulating DOC productivity. The larger difference of peroxidase activity under the repeated freeze-thaw cycle (Figure 4 (c)) would have made a bigger gap of DOC concentration between ponded and unsaturated conditions as the incubation time passed.

Figure 3. Changes in Dissolved Organic Carbon (DOC) concentration during incubation.

(a) Thaw, (b) Freeze and (c) Repeated Freeze Thaw Cycle (FTC). The vertical bars referred to the standard errors of the means of triplicate.

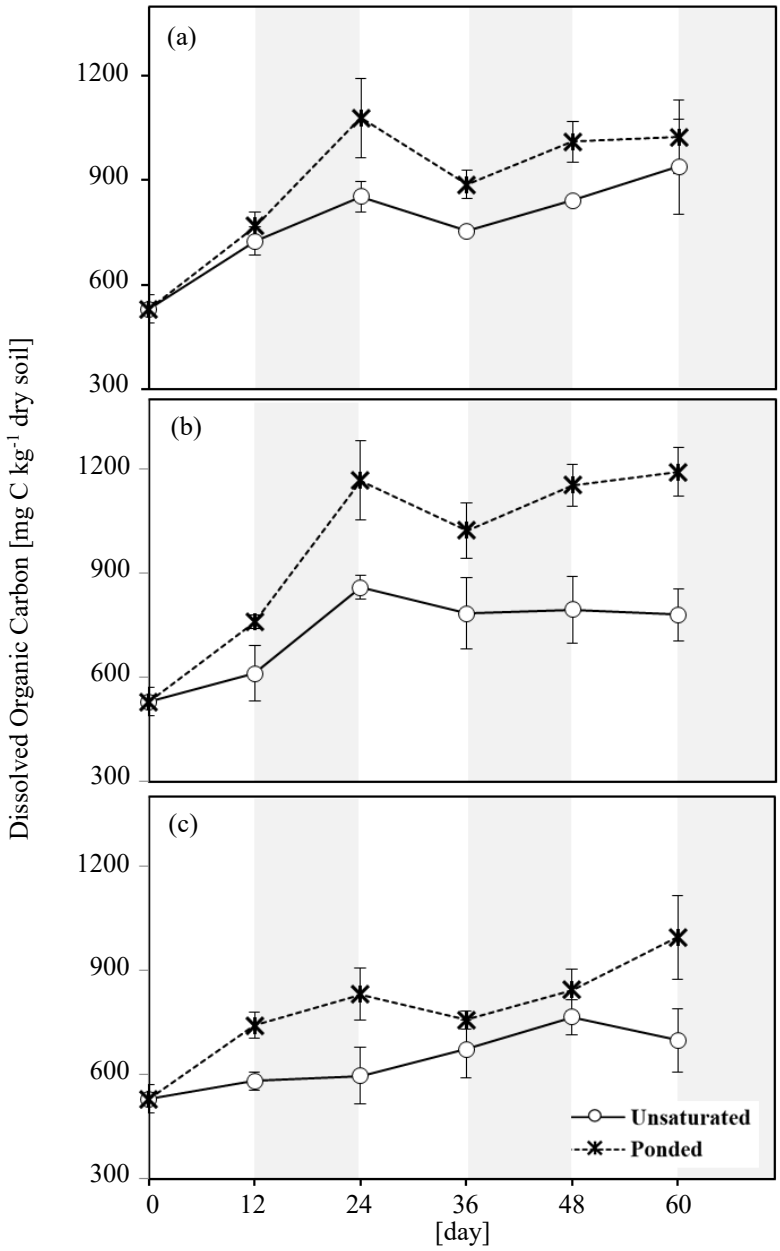
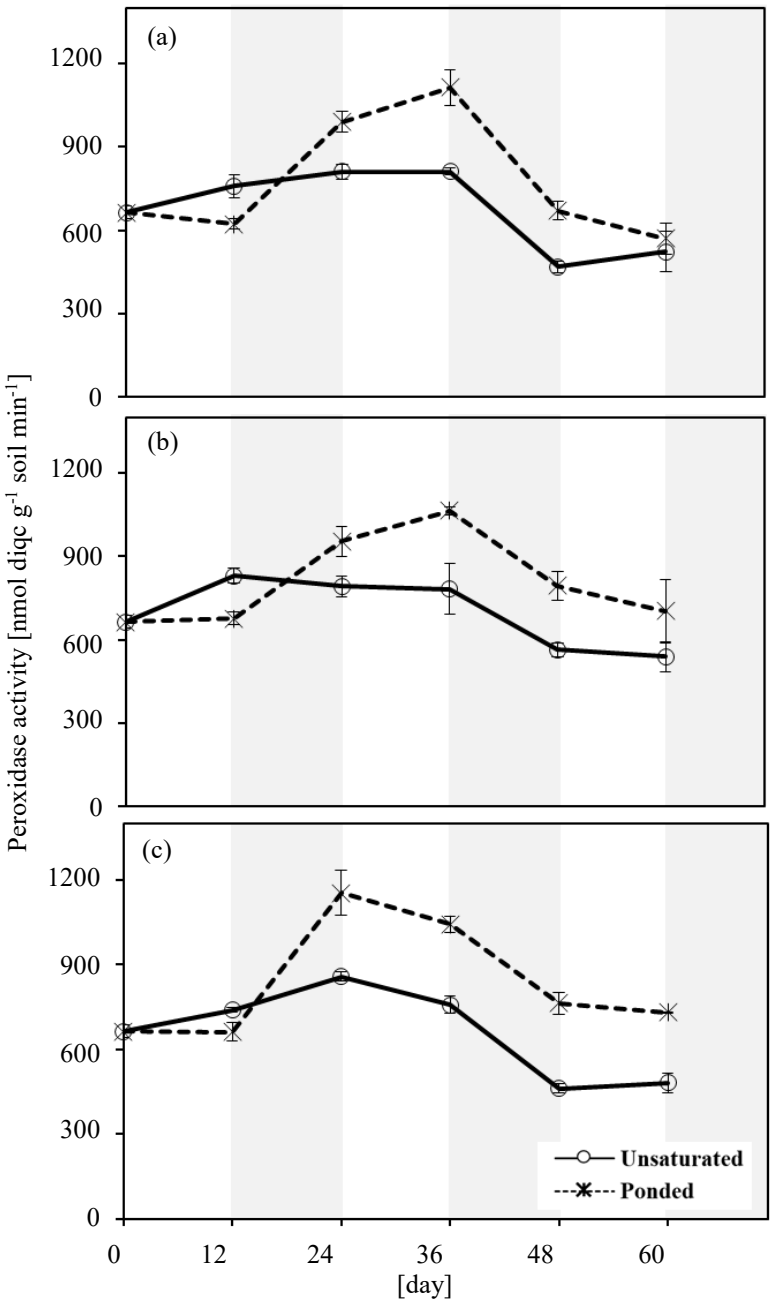

(a)
(b)
(c)
1200
900
600
300
0
12
24
36
48
60
[day]
Dissolved Organic Carbon [mg C kg-1 dry soil]
Unsaturated
Ponded

Figure 4. Changes in Extracellular Enzyme Activity (EEA) ; Peroxidase

(a) Thaw, (b) Freeze and (c) Repeated Freeze Thaw Cycle (FTC). The vertical bars referred to the standard errors of the means of triplicate.


(a)
(b)
(c)
1200
900
600
300
0
Peroxidase activity [nmol diqc g-1 soil min-1]
0
12
24
36
48
60
[day]
Unsaturated
Ponded

Effect of water regime and repeated freeze-thaw cycle on the production of Phenolic Compounds (PC)

Phenolic compound (PC) is one of the difficult material to decompose in DOC due to the resonance energy that stabilizes the carbon–carbon bonds of aromatic rings (Harwood and Parales, 1996). The variation of PC concentrations during the incubation were 10.7 – 21.91 mg C kg^{-1} dry soil (Figure 5). Generally, when decomposition of SOM in wetlands slows down due to lack of O2, and it led to reduces phenol oxidase activity and accumulates phenolic compounds (Davidson and Janssens, 2006). In fact, the PC concentration was higher in the ponded condition, which was similar to the previous DOC concentration results. However, the difference among the temperature conditions was not statistically significant, except the repeated freeze-thaw cycles under ponded conditions was increased during the incubations. Under the repeated freeze-thaw cycle, the bigger difference of PC concentration between ponded and unsaturated condition.

Phenol oxidases are one of the EEA mediated the degradation of recalcitrant compounds, phenolic compounds as oxidizing phenol and consuming O_2 as an electron acceptor (Sinsabaugh et al., 1999; Sinsabaugh 2010). The activity of phenol oxidase under ponded condition was expected to be lower than unsaturated condition, however in our result, the phenol oxidase activity under ponded condition was significantly higher than that under unsaturated condition. Recent studies indicate that temperature, moisture content, and nutrient availability can control the strength of enzyme latches which illustrates a slow decomposition due to the inhibition of hydrolase enzymes by complex macromolecular phenolic compounds (Hall et al., 2014) and PC degradation

reactions can be more complex than originally assumed (Mann et al., 2014; Pinsonneault et al., 2016; Pinsonneault et al., 2016). Therefore, PC decomposition is most likely to be limited by other factor such as the absence of suitable electron acceptors and nutrients and low pH. Overall, phenol oxidase activity was low (12.68 – 24.15 nmol diqc g^{-1} soil min^{-1}) and phenol compound content was kept constant in contrast to the increased DOC concentration result (Figure 3).

Figure 5. Changes in Phenolic Compounds (PC) concentration during incubation.

(a) Thaw, (b) Freeze and (c) Repeated Freeze Thaw Cycle (FTC). The vertical bars referred to the standard errors of the means of triplicate.

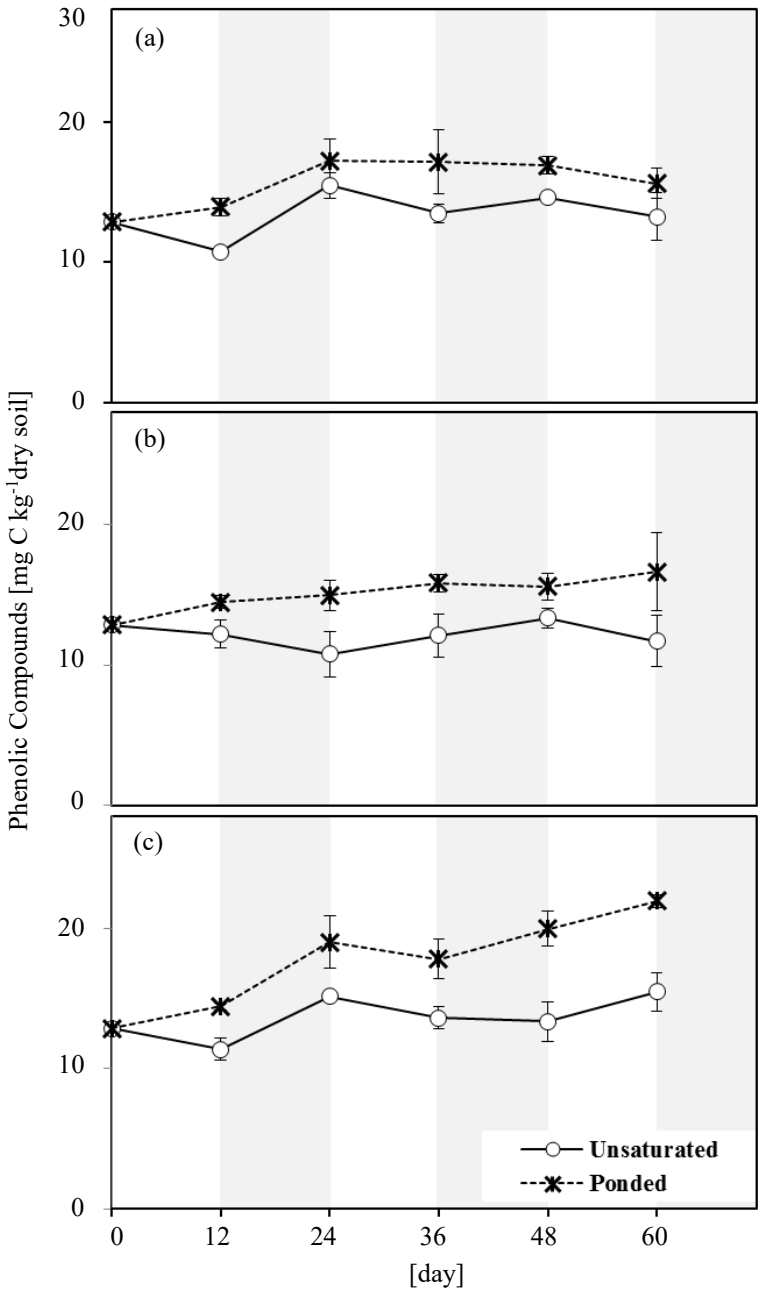
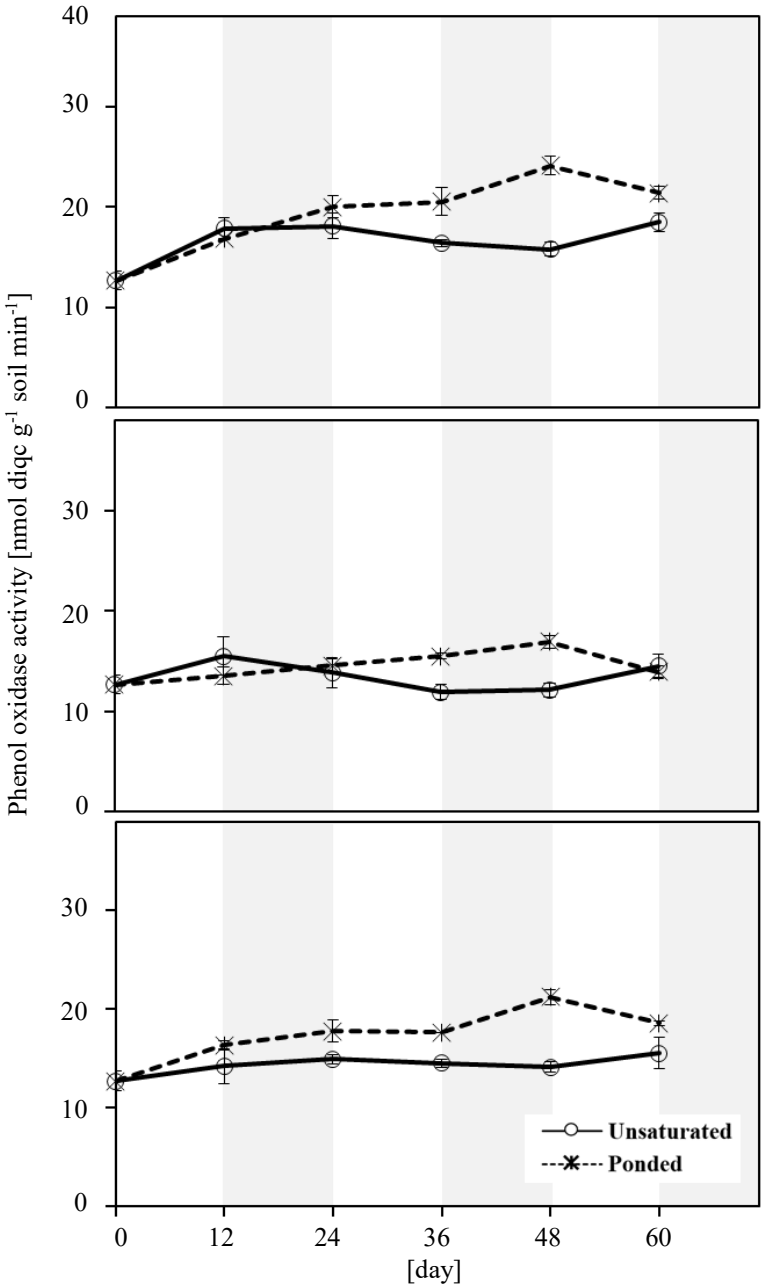

(a)
(b)
(c)
30
20
10
0
Phenolic Compounds [mg C kg-1dry soil]
0
12
24
36
48
60
[day]
Unsaturated
Ponded

Figure 6. Changes in Extracellular Enzyme Activity (EEA) ; Phenol oxidase

(a) Thaw, (b) Freeze and (c) Repeated Freeze Thaw Cycle (FTC). The vertical bars referred to the standard errors of the means of triplicate.


Phenol oxidase activity [nmol diqc g-1 soil min-1]
40
30
20
10
0
30
20
10
0
30
20
10
0
Unsaturated
Ponded
0
12
24
36
48
60
[day]

Gas flux

We examined gas flux as the final product of SOC decomposition. Production of soil gases is important in nutrient and carbon cycling, particularly in peatlands due to their large atmospheric emissions of several greenhouse gases such as CO_2 and CH_4.

Environmental factor affected potential CO_2 production rates in the soil samples at figure 7. The highest CO_2 flux rate was observed in the unsaturated condition and it was about 5 times greater under unsaturated conditions (about 381.45 μg CO_2-C g soil C^{-1} day^{-1}) than ponded conditions (about 77.06 μg CO_2-C g soil C^{-1} day^{-1}) over incubation period at constant thaw condition. This result indicates that the moisture condition is important for CO_2 production. It demonstrates that lower DOC (Figure 3) and PC concentration (Figure 5) under unsaturated condition are due to microbial decomposition by aerobic respiration. The level of CO_2 flux was similar under the repeated freeze-thaw cycle and constant thaw condition.

In case of CH_4 flux (figure 8), The highest CH_4 flux rate was observed under constant thaw temperature at the ponded condition (about 10.45 μg CH_4-C g soil C^{-1} day^{-1}) due to anaerobic soil respiration of microorganisms. The availability of O_2 under unsaturated conditions will enhance decomposition and aerobic CH_4 oxidation, possibly resulting in an overall reduction of CH4 emissions. Interestingly, unlike CO_2 flux results which were no significant difference from the condition of repeated freeze-thaw cycle and constant thaw condition, CH_4 flux showed a low release rate at repeated freeze-thaw conditions. This result suggests that the microorganisms involved in methanogenesis may be slow to recover their activity under the repeated freeze-

thaw cycle and theses microorganisms are vulnerable to temperature changes.

In both ponded and unsaturated conditions, CO_2 and CH_4 was released below the detection limit under freeze condition.

The availability of O_2 by water regime causes a difference in microbial respiration process and the temperature condition will affect the microbial activity and determine the rate of soil carbon release as CO_2 and CH_4. This will ultimately impact the overall effect of these emitted greenhouses gases on ecosystem including positive feedback of global climate change.

Figure 7. Changes in CO_2 emission during incubation.

(a) Unsaturated condition and (b) Ponded condition. The vertical bars referred to the standard errors of the means of triplicate. Asterisk (∗) means below the detection limit.

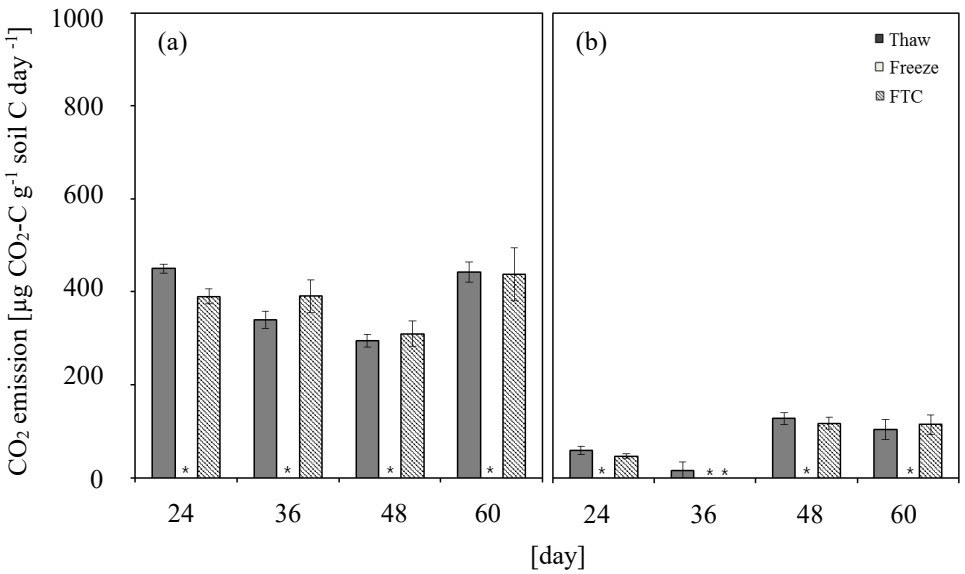
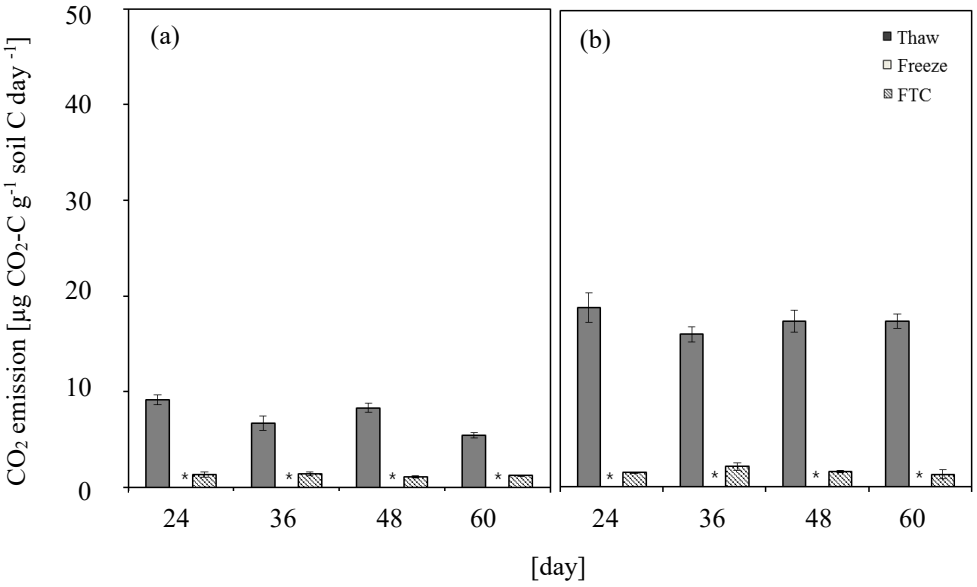

(a)
(b)
Thaw
Freeze
FTC
1000
800
600
400
200
0
CO_2 emission [μg CO_2-C g^{-1} soil C day^{-1}]
24
36
48
60
[day]

Figure 8. Changes in CH_4 emission during incubation.

(a) Unsaturated condition and (b) Ponded condition. The vertical bars referred to the standard errors of the means of triplicate. Asterisk (∗) means below the detection limit.


(a)
(b)
Thaw
Freeze
FTC
50
40
30
20
10
0
24
36
48
60
[day]
CO_2 emission [μg CO_2-C g^{-1} soil C day^{-1}]

Soil Organic Carbon (SOC) fraction by Acid hydrolysis method

Soil organic carbon (SOC) can be divided into labile and stable carbon. SOC fractionation mainly includes physical, chemical, and biological fractionations (Strosser, 2010) and among which we performed the acid hydrolysis method. This method divides SOC into 3 pools (Labile Pool I and II and Recalcitrant Pool). The labile pool I is known to predominantly contain polysaccharides which are of both plant origin (such as hemi-cellulose and starch) and microbial origin (mostly microbial cell walls) whereas the labile pool II is largely cellulose in composition (Oades and Wagner, 1970; Rovira and Vallejo, 2002). Through the acid hydrolysis method with H_2SO_4, we tried to divide the SOC into fractions which are easy (labile pool I and II) to decompose and difficult fractions (Recalcitrant pool) and want to confirm how they changed according to different environmental condition during incubation period. However, no significant differences were found within the temperature condition moisture conditions during the entire incubation period. It is presumed that the incubation period was short in order to confirm the change of high molecular weight substances such as hemicellulose (3720 - 54300 g mol^{-1}), lignin (800 - 1000 g mol^{-1}) and cellulose (10,000 - 14,000 g mol^{-1}).

Table 3. Soil Organic Carbon (SOC) fractionation with acid hydrolysis method

[mg C g^{-1} Soil C]

Fraction	Initial	Unsaturated			Ponded		
		Thaw	Freeze	FTC	Thaw	Freeze	FTC
LP I	22.9 (±0.5)	22.6 (±3.2)	19.4 (±1.4)	22.2 (±2.9)	22.4 (±4.7)	20.0 (±3.3)	21.7 (±4.0)
LP II	7.5 (±0.2)	7.1 (±0.4)	7.9 (±0.5)	7.0 (±0.3)	7.4 (±0.6)	8.8 (±1.8)	8.0 (±1.0)
RP	69.6 (±3.0)	70.3 (±0.1)	72.7 (±5.9)	70.8 (±1.1)	70.2 (±1.3)	71.2 (±1.2)	70.2 (±4.6)

- LPI: Labile pool I, Polysaccharides (hemicellulose, starch)
- LP II : Labile pool II, largely cellulose, lignin
- RP: Recalcitrant pool
- Values were the means (± standard errors (n=3))

Conclusion

Although freeze-thaw cycles and water regimes can alter soil chemical and physical properties and microbial activity, their overall impact on soil functioning remains unclear. We examined the effect of repeated freeze-thaw event and water regimes on soil organic carbon (SOC) dynamics in Arctic tundra soils. We found that dissolved organic carbon (DOC) production and the decomposition rates of SOC (gas emission) increased in continued thaw conditions during incubation. Particularly, the rates of DOC production and gas emission (CO_2 and CH_4) were higher under ponded conditions than under unsaturated soil conditions, with highest DOC and phenolic compounds concentration was observed in repeated freeze-thaw patterns under ponded conditions. our results suggest that repeated freeze-thaw patterns under ponded conditions would facilitate conversion of SOC compounds into DOC pools and that this conversion would be affected more by biotic factors that are dependent on the former. Therefore, this situation warrants further investigation on the role of other biotic factors, soil mineralogical characteristics, redox potential and electron acceptor availability.

Recent observations suggest that as the temperature increases due to the global climate change in arctic region, permafrost thaw may create thermokarst which is typical features formed from thermal erosion process (Jorgenson et al., 2006; Rowland et al., 2010; Wadhams and Davis, 2001). Because of thaw effects on surface hydrology, SOM emerging from permafrost can be exposed to either two completely different soil environments: aerobic in well drained region (unsaturated condition) or anaerobic conditions in poorly drained region (saturated condition). The frequency and intensity of freeze-thaw event also

will be stimulated because of climate change (Arnold et al., 1998; Groffman et al., 1999; Moore and McKendry, 1996; Wadhams and Davis, 2001). Therefore, more research is needed on changes in organic carbon depending on the various environmental factors. And the effect of freeze-thaw should be considered in the laboratory and simulation study for carbon dynamics.

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Abstract in Korean

반복적인 동결-융해가 북극 툰드라 지역의 유기탄소에 미치는 영향

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지윤미

북극 툰드라는 육상생태계 유기물의 1/3이상을 저장하는 곳으로 지구 탄소 순환에서 중요한 역할을 하는 지역이다. 기후 변화로 인한 온도 및 강수량의 변화는 이 지역의 동결-융해 기간 및 정도를 변화시키고, 미생물의 활성을 변화시켜 결과적으로 토양 탄소의 토양 호흡에 의한 대기로의 방출을 조절한다. 따라서 온도 와 수분과 같은 환경 요인에 의한 변화가 북극 툰드라 지역의 유기탄소에 미치는 영향을 조사하고자, 수분 조건을 달리한 배양 실험을 진행하였다. 이때, 토양수분은 담수와 불포화 조건으로, 온도는 융해와 동결이 각각 지속되는 항온 조건과, 융해와 동결이 반복되는 조건으로 설정하였다. 이들 환경 조건에 의해 토양의 유기탄소 중 용존 유기탄소와 같은 labile fraction이 어떻게 변하는지 살펴보았다. 토양시료를 분석한 결과, 용존 유기탄소와 페놀화합물 함량은 담수조건에서 더 높음을 확인했으며, 이는 담수조건에서 높은 체외효소와 낮은 미생물활성 때문으로 판단된다. 또한 동결-융해가 반복되는 경우 불포화 조건에 비해 담수 조건에서 더 많은 용존 유기탄소가 발생하는 것을 확인할 수 있었다. 토양

유기물 분해의 최종 산물로서 CO_2와 CH_4의 발생은 항상 융해 조건일 때 높았으며, CO_2의 경우 불포화 조건에서 CH_4의 경우 담수 조건에서 발생량이 많았다. 토양의 환경 조건에 따른 유기탄소의 변화는 미래 기후변화에 따른 북극 툰드라지역의 토양 유기탄소 변화의 민감도를 판단하는 지표가 될 것이다.

주요어: 반복적 동결-융해, 토양 유기탄소, 용존 유기탄소, 토양 유기물 분해, 토양 호흡, 산 분해 법

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