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Potential of Svalbard reindeer winter droppings for emission/absorption of methane and nitrous oxide during summer

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Abstract

Droppings of Svalbard reindeer (*Rangifer tarandus platyrhynchus*) could affect the carbon and nitrogen cycles in tundra ecosystems. The aim of this study was to evaluate the potential of reindeer droppings originating from the winter diet for emission and/or absorption of methane (CH_4) and nitrous oxide (N_2O) in summer. An incubation experiment was conducted over 14 days using reindeer droppings and mineral subsoil collected from a mound near Ny-Ålesund, Svalbard, to determine the potential exchanges of CH_4 and N_2O for combinations of two factors, reindeer droppings (presence or absence) and soil moisture (dry, moderate, or wet). A line transect survey was conducted to determine the distribution density of winter droppings at the study site. The incubation experiment showed a weak absorption of CH_4 and a weak emission of N_2O. Reindeer droppings originating from the winter diet had a negligible effect on the exchange fluxes of both CH_4 and N_2O. Although the presence of droppings resulted in a short-lasting increase in N_2O emissions on day 1 (24 h from the start) for moderate and wet conditions, the emission rates were still very small, up to 3 μg N_2O m^{-2} h^{-1}.

Keywords: Carbon cycle; Distribution density; Gas exchange; Nitrogen cycle; Pellet-shaped droppings

1. Introduction

In Svalbard in the European High Arctic, Svalbard reindeer (*Rangifer tarandus platyrhynchus*) are the only large grazing mammal (Aanes et al., 2002) and changes in the population structure and their behavior as a consequence of environmental perturbations such as climate change could affect the C and N cycling in the tundra ecosystems. Impacts of Svalbard reindeer on vegetation result from trampling disturbance, grazing pressure, and the excretion of waste (Cooper et al., 2001; Cooper and Wookey, 2001; van der Wal et al., 2001), where grazing is particularly detrimental for vascular plant reproduction (Cooper and Wookey, 2003; Cooper, 2006). The droppings of grazing

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animals are rich in organic matter, and are a possible source of CH_4 and N_2O as previously shown in a study of yaks grazing on the Tibetan Plateau (Lin et al., 2009).

Droppings of Svalbard reindeer, which might potentially affect the C and N cycles in the Arctic tundra ecosystem, have different physical forms and constituents during winter and summer. Svalbard reindeer droppings originating from the winter diet take the form of oval pellets and conditions in the inner part of these pellets can be partly anaerobic. As a result, it is possible that CH_4 and N_2O are formed inside winter droppings, and some of these gases are emitted to the atmosphere. A study of poultry manure found that pelletized manure occasionally produced N_2O emissions higher than raw manure (Hayakawa et al., 2009). The composition ratios of shrubs, bryophytes, and lichen in the diet increase in winter, although graminoids are the main diet (Bjørkvoll et al., 2009). Lichens are an important winter diet for reindeer (Cooper and Wookey, 2001); however, Svalbard reindeer seem rather independent of lichens perhaps due to the limited availability of macrolichens through the obliteration by trampling and selective grazing (van der Wal et al., 2001). In contrast to winter droppings, droppings originating from the summer diet, which consists mainly of graminoids, forbs, and shrubs (Bjørkvoll et al., 2009), generally have a clumpy shape.

The main purpose of the present study was to evaluate the potential contribution of Svalbard reindeer droppings originating from the winter diet to atmosphere–land exchanges of CH_4 and N_2O. An incubation experiment was conducted to investigate the potential CH_4 and N_2O exchange of winter droppings in summer. In addition, exchange fluxes of CH_4 and N_2O at a field site near Ny-Ålesund, Svalbard, were measured to compare with the exchanges determined by the incubation experiment. The distribution density of reindeer droppings at the study site was also investigated to evaluate the droppings as a pool of C and N per unit area.

2. Materials and methods

2.1. Study site

The study site was an area of mounds located on ice-free land at the base of the Brøgger glacier near Ny-Ålesund, Svalbard (78°56′N, 11°51′ E; Fig. 1). The annual mean air temperature and precipitation in this area in 2001–2008 were −4.2 °C and 433 mm, respectively (Yoshitake et al., 2010). Deglaciation around the study site is estimated to have occurred hundreds of years ago (Bekku et al., 2004a). The soil type at the study site was regosolic cryosols (Bekku et al., 2004b), and the vegetation was typical of the High Arctic *Dryas octopetala* zone (Adachi et al., 2006). However, the distribution of *D. octopetala* was limited to relatively dry locations, and the polar willow (*Salix polaris*), *Saxifraga oppositifolia*, grasses, and mosses were also common plants. The land surface at the study site was covered by thin black soil crusts with soil surface communities consisting of algae, cyanobacteria, and lichen (Yoshitake et al., 2010), or patches of mosses, grasses, and shrubs over mineral soils originating from physically weathered parent materials.

Svalbard reindeer in Ny-Ålesund are descended from animals introduced to the Brøgger Peninsula in 1978, since which time the population has fluctuated with densities upto 0.89 individuals km^{-2} (Aanes et al., 2002). Svalbard reindeer are non-migratory. Seasonal and temporal foraging patterns of the reindeer are highly constrained because of the landscape. This leads to fluctuations in the reindeer population and vegetation communities (Cooper and Wookey, 2001, 2003; Aanes et al., 2002). Svalbard reindeer eat the droppings of barnacle geese (*Branta leucopsis*) as part of the summer diet (van der Wal and Loonen, 1998).

2.2. Incubation experiment

Fresh soil for the incubation experiment was collected on 22 July 2009 (Fig. 1). An area with no plants was chosen and the upper 2–3 cm of the surface soil was removed to avoid effects of the black crust rich in organic matter (Yoshitake et al., 2010). The subsoil (mineral soil) down to a depth of 15 cm from the surface was then collected for the incubation experiment, mixed well, and passed through a 2 mm sieve. A portion of the sieved soil was immediately tested to determine the initial water content, and another portion was vacuum freeze-dried for chemical analysis.

Reindeer droppings were collected on 24 July 2009 at an area 600 m distant from the aforementioned area (Fig. 1), where relatively numerous reindeer droppings were observed. Droppings with an oval pellet shape and blackish color originating from winter diet were collected from six locations on gravel. The size and fresh weight of the collected droppings were measured, and droppings in their original form were used for the incubation experiment. Some of the droppings were

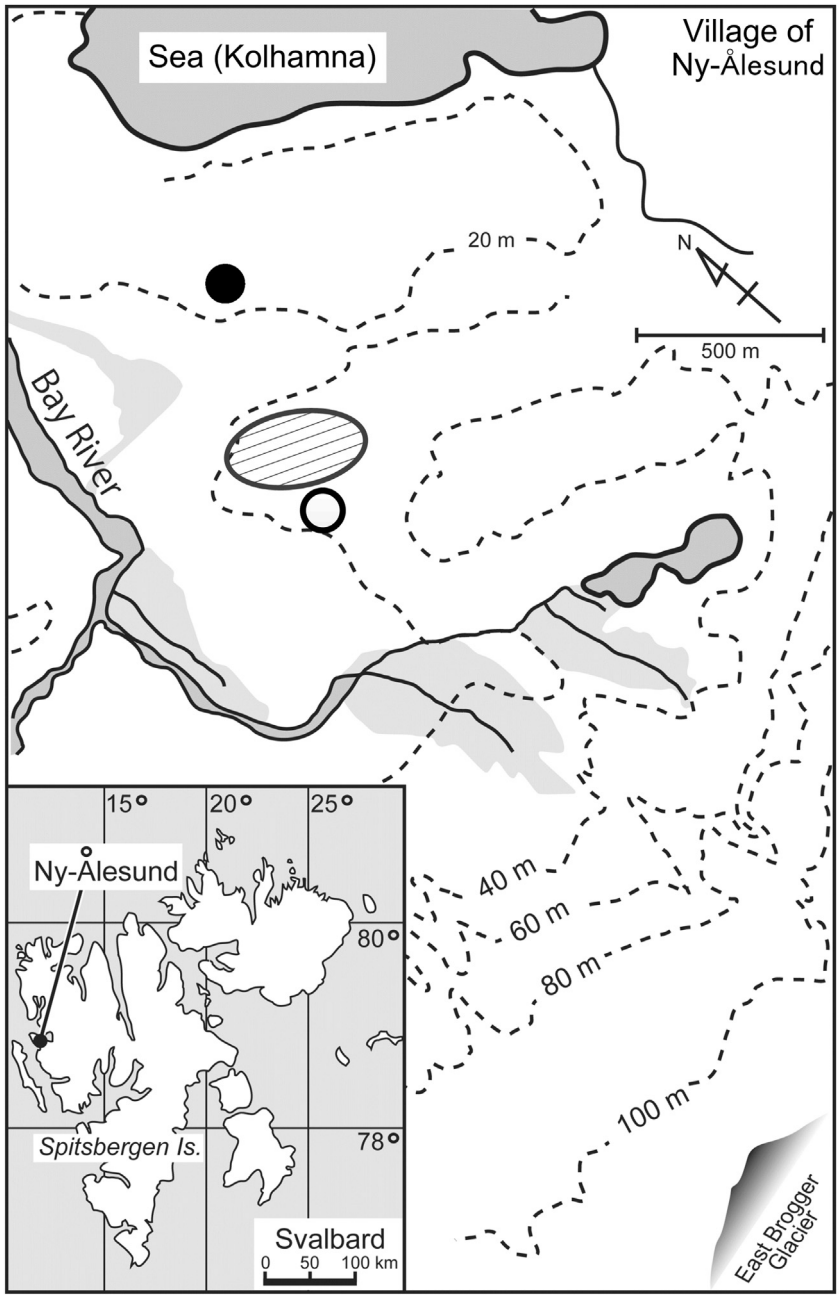

Fig. 1. Location of the study site (78°56′N, 11°51′ E) on Brøgger Peninsula, Svalbard. The black and white circles indicate the sites where subsoil and reindeer droppings for the incubation experiment were collected, respectively. The black circle also indicates the location where the field measurements were performed. The ellipse indicates the area where the line transect survey for the distribution of reindeer droppings was conducted.

used to determine the initial water content, and some were vacuum freeze-dried and then crushed for chemical analysis.

The incubation experiment was based on two conditions for reindeer droppings, the presence or absence of droppings, and three conditions for soil moisture, dry, moderate, or wet. Five samples were prepared for each combination of the above conditions. The soil moisture content was rated as follows: dry, with no water added and starting at 14% and falling to 6% soil

water content during the incubation period; moderate, with 15% soil water content; and wet, with 25% soil water content. Rectangular wide-mouth bottles with a volume of 500 mL (net volume of 571 mL determined using water) were used for the incubation experiment. On 23 July 2009, the sieved fresh soil with a weight of 90 g as dry soil (determined by the initial water content) was stuffed into the bottom of each bottle, and the surface was smoothed. The bottles were placed in a storage room with a mean temperature of 12.7 °C. On 24 July 2009, after one day of preincubation, reindeer droppings with a weight of around 4.5 g as dry matter (determined by the initial water content) were gently placed on the soil surface. The samples were then incubated until 7 August 2009 (14 days). Each bottle was weighed every morning during the incubation period to measure the evaporated water loss, and the lost water was replaced in all treatments except 'dry soil' by adding pure water.

Exchange fluxes of CH_4 and N_2O were measured daily until the fourth day of the incubation experiment, and then every second day until the end of the experiment (i.e., after 14 days). The bottles were open during the experiment, but a cap with a hole in the center fitted with a plug made of butyl rubber was used to close the bottle when measuring the exchange flux. A 25 mL sample of gas was collected using a syringe at 1 and 30 min after the bottles were capped. The collected gas was injected into a vacuum vial.

2.3. Field measurements

Exchange fluxes of CH_4 and N_2O were measured using a closed chamber method (see Adachi et al., 2006) at a field site in the study area. The chambers used in the present study consisted of a main body and a lid. The chambers were cylindrical with an inner diameter of 202 mm and a height of 150 mm, and the lids were circular in shape. The chambers were made of dark grey and opaque polyvinylchloride.

Three locations for flux measurement were selected near the site where the soil for the incubation experiment was collected (Fig. 1). The three locations differed in surface conditions as follows: 'Crust', soil crust with very few vascular plants; 'Crust + Plants', crust and plants including mosses and vascular plants dominated by *S. polaris* covering approximately half of the surface; and 'Plants', soil fully covered with mosses and vascular plants. One chamber was set up at each location. On 22 July 2009 the lower part of the main body of the chambers was gently hammered into the soil to a depth of approximately 50 mm. The internal height from the ground surface to the top of the chamber was measured to determine the inner volume.

Flux measurements were conducted between 14:00–16:00 on 24 and 29 July and 4 and 8 August 2009. The chambers were open except during measurements when the lids were used to seal the chambers. A 30 mL sample of gas was collected using a syringe at 1, 15, 30, and 45 min after the chambers were closed to determine the average change rate of the mixing ratio. The collected gas was injected into a vacuum vial. The air temperature and the volumetric water content of the soil inside each chamber were measured using a thermometer (TC-850, Line Seiki, Japan) and an amplitude domain reflectometry (ADR) probe (ML2x, Delta-T, U.S.A.) with a data logger (HH2, Delta-T).

2.4. Distribution of winter droppings

To determine the average weight per pat (a mound of droppings), reindeer droppings originating from winter diet were collected on 25 July 2009 from five pats near the location where the reindeer droppings for the incubation experiment were collected (Fig. 1). We then counted the number of pats of winter droppings on a nearby mound (Fig. 1). A line transect survey (e.g., van der Wal et al., 2001) with a length of 530 m and a width of 2 m was conducted to count the number of pats. The findings were expressed as the number of pats and the dry matter per unit area.

2.5. Chemical analyses

Three samples of mineral soil used for the incubation experiment were analyzed to determine the texture, soil pH (H_2O), total C and N, microbial biomass C and N, water-extractable C and N, ammonium N (NH_4–N), and nitrate N (NO_3–N). The total C and N were determined using an NC analyzer for solid samples (SUMIGRAPH NC-22F, Sumika Chemical Analysis Service, Japan). The microbial biomass C and N and water-extractable C and N were determined using the chloroform fumigation method (Brookes et al., 1985; Vance et al., 1987). The samples without fumigation correspond to water-extractable C and N, which approximate the substrate C and N. The NH_4–N and NO_3–N were determined using an auto analyzer (TRAACS2000, Bran + Luebbe, Germany) for extractions with a solution of 10% potassium chloride (w/v) as the extractant. The mixing ratios of CH_4 and N_2O in the gas samples were determined by gas chromatography, where a flame ionization detector and an

electron capture detector were used for CH_4 and N_2O, respectively.

2.6. Flux calculation

The exchange fluxes of CH_4 and N_2O in the incubation experiment were calculated on a mass balance basis. It was assumed that the initial air pressure was 1013 hPa. The molar number of the gas in the bottle just before the first sampling (M_1, nmol) is expressed by

$$M_1 = \frac{273.15\, C_1 V_{bot}}{22.4(273.15 + T_{air})} \times 10^3, \quad (1)$$

where C_1, V_{bot}, and T_{air} are the mixing ratio of the gas at the first sampling (ppm), the air space of the bottle (0.532 L; excluding the solid volume of soil), and the air temperature (°C), respectively. The molar number of the gas taken from the bottle at the first sampling (M_2, nmol) is expressed by

$$M_2 = \frac{273.15\, C_1 V_{syr}}{22.4(273.15 + T_{air})} \times 10^3, \quad (2)$$

where V_{syr} is the volume of sampled gas (25 mL). The molar number of the gas in the bottle just before the second sampling (M_3, nmol) is expressed by

$$M_3 = \frac{273.15\, C_2 (V_{bot} - V_{syr})}{22.4(273.15 + T_{air})} \times 10^3, \quad (3)$$

where C_2 is the mixing ratio of the gas at the second sampling (ppm). Therefore, the change in the molar number of the gas during the sampling interval (Q, nmol) is

$$Q = M_3 + M_2 - M_1. \quad (4)$$

The exchange flux (F_{inc}, nmol m^{-2} h^{-1}) is derived from

$$F_{inc} = \frac{60\, Q}{A_{bot} t}, \quad (5)$$

where A_{bot} and t are the area of the soil surface inside the bottle (0.00497 m^2) and the sampling interval (29 min in principle), respectively. F_{inc} was then converted into a mass unit (μg CH_4 m^{-2} h^{-1} or μg N_2O m^{-2} h^{-1}; 0°C, 1013 hPa). 1 nmol of CH_4 and 1 nmol of N_2O correspond to 0.016 μg CH_4 and 0.044 μg N_2O.

The exchange fluxes of $CH_4$and N_2O in the field measurements (F_{fie}, nmol m^{-2} h^{-1}) were calculated using the average change rate of mixing ratio inside the chamber (ΔC, ppm min^{-1}) without a correction for air pressure.

$$F_{fie} = \frac{60 \times 273.15 \Delta C V_{cha}}{22.4 A_{cha}(273.15 + T_{air})} \times 10^3, \quad (6)$$

where V_{cha} and A_{cha} are the chamber volume (2.9–3.1 L, specific to each chamber) and the area of the soil surface inside the chamber (0.0320 m^2), respectively. F_{fie} was also converted into a weight unit (μg CH_4 m^{-2} h^{-1} or μg N_2O m^{-2} h^{-1}).

Analysis of variance (ANOVA) was conducted on the fluxes derived from the incubation experiment (OriginPro 8.5, OriginLab). A two-way ANOVA with the two factors of reindeer droppings and soil moisture was applied to the exchange fluxes from the incubation experiment. A one-way ANOVA with the factor of surface conditions was applied to the exchange fluxes from the field measurements. Tukey's test was also conducted to evaluate the significance of the difference among levels within the factors.

3. Results

3.1. Soil and dropping properties

The subsoil used for the incubation experiment had C and N contents of 17.2 ± 1.3 SD mg C g^{-1}dry soil (ds) and 0.97 ± 0.04 mg N g^{-1} ds (Table 1). These

Table 1
Main properties of soil used in the incubation experiment, means and standard deviations ($n = 3$).

Classification		Regosolic cryosols
Texture		Sandy loam
Sand	(% ds)	68.6 ± 0.0
Silt	(% ds)	20.4 ± 0.9
Clay	(% ds)	11.0 ± 0.9
Soil pH (H_2O)		7.6 ± 0.0
Total C	(mg C g^{-1} ds)	17.2 ± 1.3
Total N	(mg N g^{-1} ds)	0.97 ± 0.04
C:N ratio		17.8 ± 0.8
Microbial biomass C	(μg C g^{-1} ds)	68.2 ± 2.5
Microbial biomass N	(μg N g^{-1} ds)	7.73 ± 0.45
Microbial biomass C:N ratio		8.8 ± 0.6
Water-extractable (substrate) C	(μg C g^{-1} ds)	28.4 ± 0.8
Water-extractable (substrate) N	(μg N g^{-1} ds)	3.73 ± 0.19
Water-extractable C:N ratio		7.6 ± 0.4
Ammonium N	(μg N g^{-1} ds)	0.52 ± 0.02
Nitrate N	(μg N g^{-1} ds)	0.08 ± 0.01

ds, dry soil. Water-extractable C and N approximate the C and N as a substrate for microbes.

Table 2
Main properties of reindeer winter droppings used in the incubation experiment, means and standard deviations ($n = 50$ for length and width; $n = 3$ for others).

Shape		Oval pellet
Length	(mm)	12.9 ± 1.5
Width	(mm)	7.0 ± 0.6
Total C	(mg C g^{-1}dm)	420.6 ± 3.4
Total N	(mg N g^{-1}dm)	12.4 ± 0.2
C:N ratio		33.8 ± 0.5
NH_4–N	(μg C g^{-1}dm)	30.3 ± 1.4
NO_3–N	(μg N g^{-1}dm)	0.05 ± 0.06

dm, dry matter.

values were similar in total C and richer in total N compared to the values of 14.3 mg C g^{-1} ds and 0.12 mg N g^{-1} ds of soil from a newly deglaciated moraine near the tip of East Brøgger Glacier (Yoshitake et al., 2007). The subsoil in the present study had one quarter of the total C and one third of the total N compared to mineral soil with a similar age of formation sampled near the study site, i.e., 66.1 mg C g^{-1} ds and 2.82 mg N g^{-1} ds (Yoshitake et al., 2007).

The C:N ratio of the microbial biomass of the subsoil used for the incubation experiment was rich in N compared to the subsoil itself, while the ratio of water-extractable C and N was richer in N than the microbial biomass (Table 1). The microbial biomass C of the subsoil used for the incubation experiment was 68.2 ± 2.5 μg C g^{-1} ds. This was less than one-tenth of that in soil sampled from a location near the study site, 724 μg C g^{-1} ds, and similar to that sampled from a newly deglaciated moraine near the tip of East Brøgger Glacier, i.e., 55 μg C g^{-1} ds (Bekku et al., 2004b).

Table 2 shows the properties of winter droppings used for the incubation experiment. The droppings were dry with initial water content of 10.9%. The reindeer droppings had a mean length of 12.9 ± 1.5 SD mm and width of 7.0 ± 0.6 mm ($n = 50$). The C:N ratio of the reindeer droppings, 33.8 ± 0.5, was higher than that of the subsoil for the incubation experiment, 17.8 ± 0.8 (Table 1). However, the NH_4–N content of the reindeer droppings, 30.3 ± 1.4 μg N g^{-1}dm (dry matter), was 58 times higher than that of the subsoil on a mass basis. The NO_3–N content of the reindeer droppings was very low, i.e., 0.05 ± 0.06 μg N g^{-1} dm.

Table 3
Spatial distribution of winter droppings, means and standard deviations ($n = 5$ for dry matter).

Type of droppings		Pellet-shaped
Numbers in transect	(pat)	137
Numbers per area	(pat m^{-2})	0.129
Dry matter per pat	(g pat^{-1})	27.3 ± 6.6
Dry matter per area	(g m^{-2})	3.52 ± 0.85
Total C per area[a]	(g m^{-2})	1.48 ± 0.36
Total N per area[a]	(g m^{-2})	0.044 ± 0.011

Location, hilly area near Ny-Ålesund; Date, 4 August 2009; Length of line transect, 530 m; Width of line transect, 2 m.

[a] These values were calculated using the total C and N contents ($n = 3$) shown in Table 2 and the dry matter ($n = 5$).

Table 3 shows the distribution density of winter droppings estimated from the line transect survey. The pat density of winter droppings was 0.129 pat m^{-2}. The mean dry matter per pat of winter droppings was 27.3 ± 6.6 SD g dm pat^{-1} ($n = 5$). The mean dry matter of the winter droppings per area was therefore estimated to be 3.52 ± 0.85 g dm m^{-2}.

3.2. Fluxes in the incubation experiment

The CH_4 fluxes in the incubation experiment generally showed an absorption tendency for dry and moderate soil moisture conditions. For wet conditions there was an absorption tendency until day 4 of the incubation, then a weak emission (Fig. 2). The mean flux ± SD with reindeer droppings and dry, moderate, or wet conditions was −1.0 ± 1.8, −1.4 ± 2.6, and 0.2 ± 2.1 μg CH_4 m^{-2} h^{-1}, respectively, and without reindeer droppings and dry, moderate, or wet conditions was −1.1 ± 3.3, −1.9 ± 3.3, and −0.2 ± 2.9 μg CH_4 m^{-2} h^{-1}, respectively. A positive or a negative value for fluxes denotes emission or absorption, respectively. The reindeer droppings did not affect the CH_4 fluxes but the soil moisture significantly affected the CH_4 fluxes ($P < 0.001$). There was a difference between wet conditions and the other two conditions, with the wet condition resulting in a near zero flux of CH_4, where as the dry and moderate conditions showed an absorption tendency for CH_4 (Fig. 2).

The N_2O fluxes in the incubation experiment were near zero except in days 1 and 2 (24 and 48 h from the start) (Fig. 3). The mean flux ± SD with reindeer droppings and dry, moderate, or wet conditions was 0.2 ± 1.4, 0.4 ± 1.7, and 0.6 ± 1.8 μg N_2O m^{-2} h^{-1}, respectively, and without reindeer droppings and dry, moderate, or wet conditions was 0.4 ± 1.4, 0.1 ± 1.6, and 0.4 ± 1.6 μg N_2O m^{-2} h^{-1}, respectively. Neither the reindeer droppings nor the soil moisture affected the exchange fluxes of N_2O. However, the presence of reindeer droppings enhanced emissions of N_2O at day

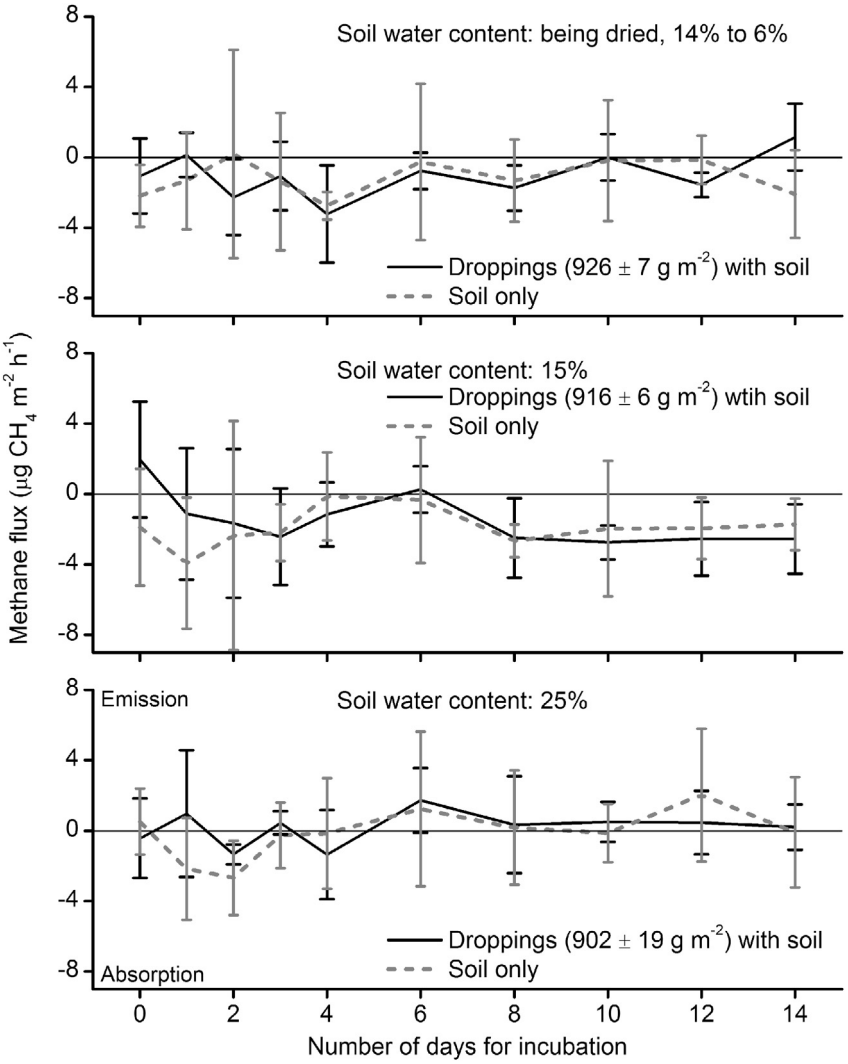

Fig. 2. Fluxes of CH_4 in the incubation experiment with mineral soil of three levels of soil water content and with or without reindeer droppings. Numbers in parentheses denote the applied amount of droppings. Bars denote the standard deviation ($n = 5$).

1 (24 h from the start) for the moderate and wet conditions ($P < 0.05$).

3.3. Fluxes in the field measurements

The exchange fluxes of CH_4 and N_2O for the field measurements are shown in Fig. 4. The study site was a weak sink of atmospheric CH_4. The mean flux ± SD of CH_4 was -28.2 ± 15.7 μg CH_4 m^{-2} h^{-1}. The difference in the CH_4 fluxes among the plots was significant ($P < 0.01$). The absolute values of N_2O fluxes were small and near zero. The mean N_2O flux was -0.3 ± 0.9 μg N_2O m^{-2} h^{-1}. The difference in the N_2O fluxes among the plots was not significant ($P = 0.05$).

4. Discussion

The present study used the subsoil in combination with the winter droppings for the incubation experiment. This was to simulate a situation that droppings existed on the ground surface contacting with soils. The effects of winter droppings on the CH_4 and N_2O exchanges were therefore evaluated by comparing the difference in exchange fluxes between the two conditions, i.e., the subsoil only and the subsoil with droppings. The leaching of substrates from the droppings to the soil might occur for the condition of subsoil with droppings. It is noted that this characteristic might affect the CH_4 and N_2O exchange fluxes, though not quantified in the present study.

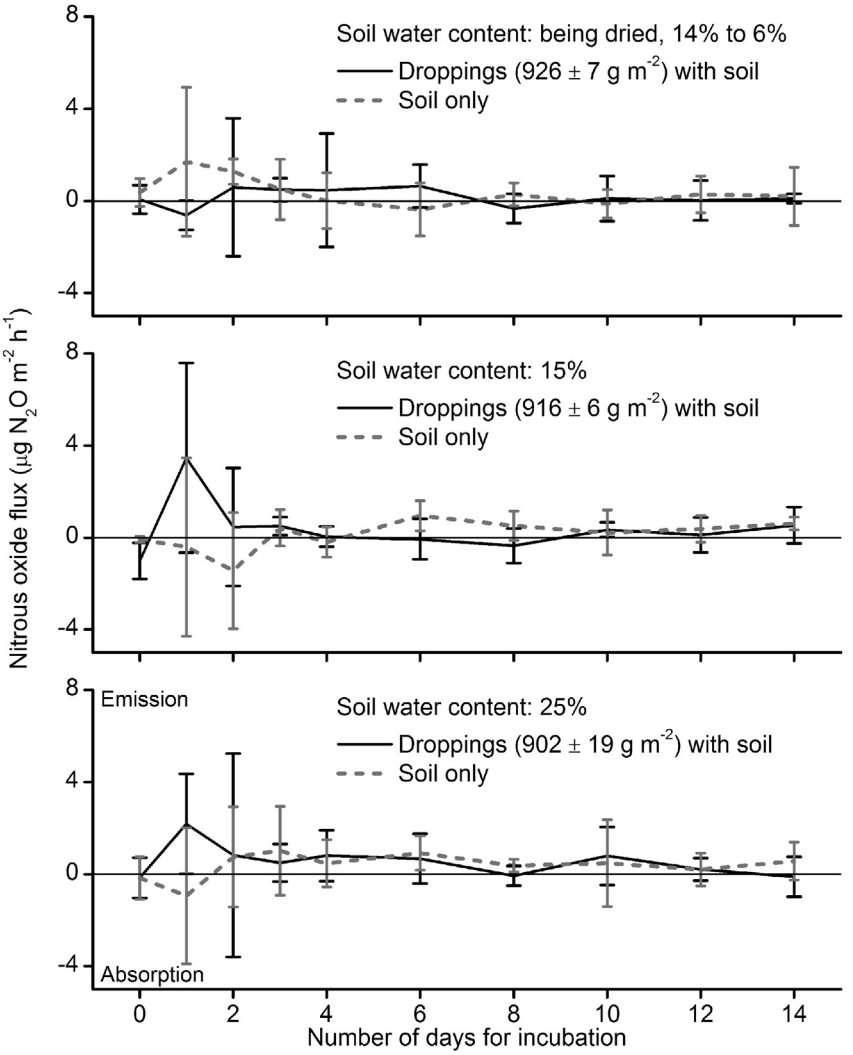

Fig. 3. Fluxes of N_2O in the incubation experiment with mineral soil of three levels of soil water content and with or without reindeer droppings. Numbers in parentheses denote the applied amount of droppings. Bars denote the standard deviation ($n = 5$).

The presence or absence of reindeer droppings did not affect the CH_4 fluxes (Section 3.2). In the present study, the reindeer droppings were placed on the soil surface. Reindeer droppings could be a source of CH_4 when buried into the soil by local disturbances, and exposed to anaerobic conditions in the presence of water. Reindeer droppings are composed of 40% C on a mass basis, and are therefore a good source of C (Table 2). However, the ability of reindeer droppings to supply degradable organic matter as a substrate for CH_4 production needs to be evaluated.

The presence or absence of reindeer droppings also did not affect the N_2O fluxes overall (Section 3.2). However, the presence of droppings did result in an increase in N_2O emissions at day 1 (24 h from the start) for the moderate and wet conditions (Fig. 3). This result suggests that the reindeer droppings absorbed water from the soil and net N_2O production inside the droppings occurred. This event lasted only a short time, and the quantitative contributions of nitrification and denitrification to the N_2O emissions were not investigated. However, the N_2O emission at day 1 for the dry condition without reindeer droppings (Fig. 3) suggested the possibility of short-lasting emission of N_2O in the process of soil drying. The initial water content of the reindeer droppings, 11%, was lower than that of the mineral soil, 14%. Therefore, the reindeer droppings could absorb water from the soil to a certain extent even in the dry condition. The lack of emissions of N_2O for the dry condition with reindeer droppings

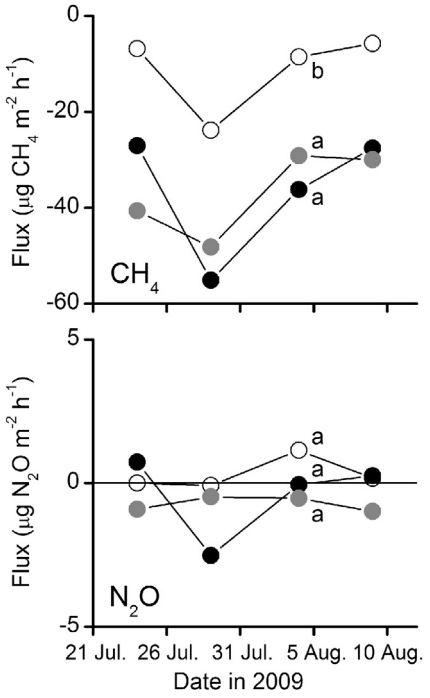

Fig. 4. Fluxes of CH_4 and N_2O during the field measurements. ○ 'Crust', ● 'Crust + Plants', and ● 'Plants' denote the surface conditions, covered by soil crust, covered by soil crust and plants (mosses and dwarf vascular plants) in approximately equal proportions, and fully covered by plants, respectively. The letters a and b indicate a significant difference ($P < 0.05$; Tukey's test).

(Fig. 3) could be ascribed to two factors, insufficient water absorption of the reindeer droppings, and/or the occurrence of N_2O emissions from the reindeer droppings and/or the drying soil surface within 24 h of the start of the experiment.

The incubation experiment demonstrated that reindeer droppings originating from the winter diet did not emit N_2O in summer, despite the short-lasting emissions observed after water absorption in the first 24 h. The N mobility of the reindeer droppings was unexpectedly low in contrast to the hypothesis that N_2O production occurs inside the pellet-shaped droppings. This could be partly ascribed to the fact that the C:N ratio of the winter droppings was higher than that of the subsoil (Tables 1 and 2). However, the short-lasting emissions of N_2O observed just after water absorption suggests that the reindeer droppings could have already undergone emissions of N_2O with snow and ice melt and following rain events. It is therefore possible that the reindeer droppings collected in late July in the present study had already been exhausted for the potential of N_2O emission.

Fluxes from the incubation experiment were smaller for CH_4, and similar for N_2O, compared to the fluxes obtained by the field measurements (Section 3.3, Fig. 4). The use of the subsoil for the incubation experiment was to reduce the fluxes of the soil itself and to contrast the fluxes induced by the presence of reindeer droppings. The low fluxes derived from the incubation experiment only with the soil were as expected. Adachi et al. (2006) reported that CH_4 fluxes at 28 plots in the same area as the present study varied considerably with a range of approximately 900 μg CH_4 m^{-2} h^{-1} of emission to 300 μg CH_4 m^{-2} h^{-1} of absorption. The CH_4 fluxes by the field measurements in the present study, i.e., 28.2 ± 15.7 SD μg CH_4 m^{-2} h^{-1} of absorption, fell within this range; however, the absolute values were small compared to the results reported by Adachi et al. (2006). Christensen et al. (1999) reported that CH_4 and N_2O fluxes at plots covered by mosses and dwarf shrubs in a mountainous area near Abisko, Sweden, ranged from approximately 20–40 μg CH_4 m^{-2} h^{-1} of absorption and were near zero flux, respectively, for control plots without manipulations, findings were similar to the present study. The absolute values of SD in the incubation experiment were small, although those seemed large compared to the mean fluxes (Figs. 2 and 3). The SD in the incubation experiment ranged 1.8–3.3 μg CH_4 m^{-2} h^{-1} and 1.4–1.8 μg N_2O m^{-2} h^{-1} for CH_4 and N_2O, respectively. The SD of CH_4 fluxes in the incubation experiment corresponded to only several percent of the abovementioned CH_4 fluxes (Adachi et al., 2006). Meanwhile, Lin et al. (2009) reported that N_2O fluxes at an alpine meadow in Tibetan Plateau, without excreta of yak, showed 54–383 μg N_2O m^{-2} h^{-1} of emission. The SD of N_2O fluxes in the incubation experiment also corresponded to several percent of these fluxes.

The pool sizes for C and N in the winter droppings, 1.48 ± 0.36 SD g C m^{-2} and 0.044 ± 0.011 g N m^{-2} (Table 3), were very small compared to the pool sizes of C and N for the High Arctic soils. For example, Nakatsubo et al. (2005) reported that the soil organic matter content at a plot near the study site was 3200 g C m^{-2}. Bardgett et al. (2007) reported that the N pools of soils in Adventdalen, 10 km east of Longyearbyen, Svalbard, were 372.7 g N m^{-2} on dry ridges and 463.1 g N m^{-2} in moist meadows. It is noted that the pool sizes of C and N from the reindeer droppings increased when clumpy-shaped droppings from summer diets were included. Reindeer droppings form pats, and this could affect the C and N transfer to the soil beneath the pats. In addition, it might take several

years for the complete decomposition of reindeer droppings.

Winter droppings of Svalbard reindeer showed a very small effect on the emission and/or absorption of CH_4or N_2O in summer. However, the contribution of winter droppings to the atmosphere–land exchange of CH_4 and N_2O in spring has not been elucidated yet. We can hypothesize that fresh winter droppings are escaped from their decomposition in winter due to the isolation from the soil and the freeze in snow and ice, meanwhile the labile fraction of the winter droppings is rapidly decomposed when they melt in spring. This hypothesis is supported by the field evidence at arctic semi-desert in Ny-Ålesund, i.e., the increases in dissolved organic carbon, organic nitrogen, and inorganic nitrogen at the active snowmelt front (Glanville et al., 2012). They also found that the vegetation and belowground microbial communities responded rapidly with peaks in nutrient availability and soil respiration observed within 72 h of snowmelt. These results imply that the decomposition of the labile fraction of winter droppings in early spring also ends in a short term. In conclusion, a continuous research on the CH_4 and N_2O exchanges of winter droppings from the start of spring to the end of summer is needed to evaluate the total contribution of winter droppings to the CH_4 and N_2O emission/absorption. Furthermore, summer droppings of Svalbard reindeer are also involved in the C and N cycling in tundra ecosystems. It is expected that research on the CH_4 and N_2O exchanges of both the winter and summer droppings promote an understanding of the contributions of reindeer droppings to the C and N cycling in the tundra ecosystems from excretion to complete decomposition.

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