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Citation	Eurasian Journal of Forest Research, 10(1), 79-84
Issue Date	2007-03
Doc URL	https://hdl.handle.net/2115/24499
Type	departmental bulletin paper
File Information	10(1)_P79-84.pdf



N₂O Flux in Alas Ecosystems Formed by Forest Disturbance Near Yakutsk, Eastern Siberia, Russia

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Abstract

An alas is a round area of grassland with a pond at the center, formed by subsidence associated with permafrost thawing in taiga forests in eastern Siberia. To characterize the relationship between the N₂O dynamics and soil properties of forest–alás ecosystems, we investigated soil N₂O fluxes in four thermokarst ecosystems composed of forest, grassland, and ponds near Yakutsk in July 2000. At all sites, pH, EC, and organic carbon (OC) content in soil were higher in the grasslands (pH 7.3–9.3, EC 22–63 mS m⁻¹, OC 1.4%–15.3%) than in the forests (5.6–6.3, 1.4–6.8 mS m⁻¹, 0.4%–1.7%), and C/N was lower in the grasslands (10–18) than in the forests (18–24). Both emission (positive values) and uptake (negative values) of N₂O occurred in the forests (–2.1 to 1.0 μg N m⁻² h⁻¹) and grasslands (–1.3 to 31 μg N m⁻² h⁻¹). N₂O emissions at the edge of ponds varied widely (0 to 140 μg N m⁻² h⁻¹). N₂O was taken up in the ponds (–2.2 to 0.0 μg N m⁻² h⁻¹). There were significant differences in N₂O fluxes among land cover types. N₂O flux was positively correlated with soil moisture, but N₂O fluxes were smallest in the ponds because of the biological denitrification there. Therefore, an increase in soil moisture increased N₂O flux.

Key words: alas, eastern Siberia, larch forest, N₂O flux, Yakutsk

Introduction

N₂O is an important greenhouse gas, contributing about 6% of the radiative forcing of the global climate (IPCC 2001). Total N₂O emission is estimated to be 17.7 Tg year⁻¹ (IPCC 2001). Major sources of atmospheric N₂O include agricultural soils, natural tropical soils, and the oceans. The major N₂O sink is considered to be the atmosphere, where an estimated 12.3 Tg year⁻¹ is consumed by photodissociation and reaction with electronically excited oxygen atoms.

The forest area in the Russian Federation is about 8.5 × 10⁶ km², the largest in the world, and accounts for 22% of the world total (FAO 2003). The forest area in eastern Siberia is about 3.5 × 10⁶ km², or 41% of the Russian total (Forest Management Department of Sakha Republic, unpublished data, 2000). This area is larger than the forest areas of Canada (2.4 × 10⁶ km²) and the USA (2.2 × 10⁶ km²) (FAO 2003). Eastern Siberia is characterized by low precipitation (209 mm) and low temperature (–10.4 °C) (Robert 1997), permafrost (Desyatkin 1993), and occasional wildfires (Goldammer and Furyaev 1996). During 1988 to 1994, an average of 3.61 × 10³ km² of forest was burned almost annually (Forest Management Department of Sakha Republic, unpublished data, 2000). Seventy to eighty percent of the fires were caused by human activities, and the rest by natural events such as lightning (Goldammer and Stocks 2000). After a severe forest fire, when the permafrost has thawed considerably, thermokarsts called alases can form (Desyatkin 1993). Water supplied from the thawing

permafrost flows laterally into the alás, forming ponds with diameters ranging from several tens to several hundreds of meters. From the center of the pond to the periphery of the basin, there is a succession of belts of excess, normal, and inadequate moisture (Averenskiy and Desyatkin 1996). Microbiological processes of nitrification and denitrification regulate the production and consumption of N₂O (Sahrawat and Keeny 1986). Letey et al. (1980) reported that increasing soil moisture increased N₂O emission from the soil. Aulakh et al. (1992) reported that pH and organic carbon (OC) content in soil were important regulators of denitrification. Therefore, alás formation processes will influence N₂O flux.

The purpose of this study was to characterize the relationship between the N₂O dynamics and soil properties in four forest–alás ecosystems near Yakutsk city, eastern Siberia.

Materials and Methods

Site description

This study was conducted in four alás ecosystems near Yakutsk city (62°05'N, 129°45'E), Russia. Locations of each study site are shown in Figure 1, and the area of each alás is shown in Table 1. The ground level within each alás ranged from 4 to 25 m lower than that in the surrounding forest. Each alás had a pond measuring from several tens to several hundreds of meters in diameter in its center. The water depth of the ponds was 10 cm.

The adjacent forest consists mainly of larch (*Larix*

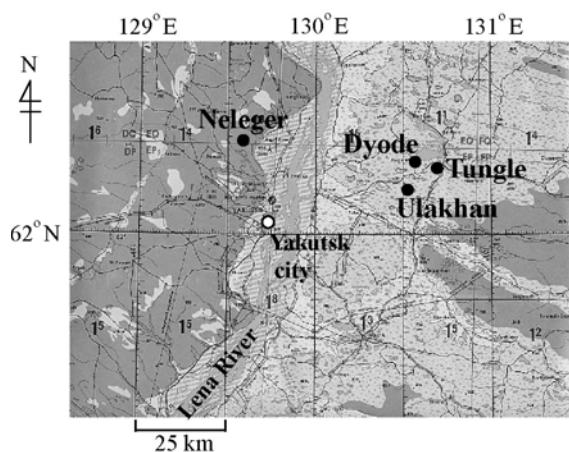


Fig. 1. The four study sites.

Table 1. Properties of forest and grassland soils.

Alas	area km ²	soil texture	pH	EC	OC	TN	C/N
				mS m ⁻¹	%	%	
Dyode	Forest	SL	5.9	2.0	0.68	0.03	23
	Grassland	SiCL	9.3	24.7	1.42	0.09	18
Neleger	Forest	SiC	6.3	6.8	1.71	0.07	24
	Grassland	LiC	7.3	34.3	12.17	0.94	13
Ulakhan	Forest	L	5.6	1.4	0.43	0.02	18
	Grassland	SiL	9.1	63.4	15.30	1.06	15
Tungle	Grassland	SiCL	9.3	21.9	3.53	0.37	10

SL, sandy loam; SiCL, silty clay loam; SiC, silty clay; LiC, light clay; L, loam; SiL, silty loam; TN, total nitrogen; EC electrical conductivity.

gmelinii) trees more than 200 years old, with *Vaccinium vitisidaea* predominant on the forest floor. The grassland of alases consists predominantly of *Elytrigia repens* and *Calamagrostis langsdorffii*.

Soil sampling and analysis

Soil samples were collected in the forests and grasslands with no replication in July 2000. Disturbed samples (~500 mL in a PVC bag) were collected from 0 to 20 cm below the O horizon. The samples were air-dried for more than 3 weeks in the laboratory, and then sieved through a 2-mm-mesh sieve for chemical analyses.

Soil pH was determined with a glass electrode pH meter in the supernatant suspension of 1:2.5 soil:deionized water. Electrical conductivity (EC) was determined with an EC meter in 1:5 soil:deionized water then multiplied by 5 to approximate that of a water-saturated soil paste. After the air-dried soil samples were ground, total carbon and nitrogen contents were determined by C/N analyzer (Vario-EL, Elementer). Carbonate-C content was analyzed by measuring the amount of CO₂ produced from 0.3 to 0.8 g of soil to which 15 mL of 2 M HCl was added in an Erlenmeyer flask. OC content was calculated by subtracting the carbonate-C content from the total C content (Loeppert and Suarez 1996; Sawamoto *et al.* 2000; Morishita *et al.* 2003).

N₂O flux

N₂O flux was measured by using a closed chamber technique in July 2000. Open-bottom stainless steel chambers 25 cm in height and 18.5 to 21.0 cm in diameter were used as described previously (Morishita *et al.* 2003). The day before the measurement, chambers were installed to 3 cm depth in the soil. The flux was measured in the forest (3–8 replications), in the grassland (6–8), at the edge of the ponds (2–4), and in the ponds (2–4). At 0, 10, 20, and 40 min after the chamber was closed, a 20-mL air sample was taken into a 10-mL glass bottle vacuum-sealed with a butyl rubber stopper and a plastic cap.

Back at the laboratory at Hokkaido University, Sapporo, Japan, N₂O concentrations in the gas samples were analyzed with a Shimadzu GC-14B gas chromatograph (GC). Analysis was performed within 3 months after the sampling. The GC was equipped with an electron capture detector and a 1-m Porapak N column. A 1-mL subsample was injected into the GC. The injection, detection, and column oven temperatures were 250, 340, and 60 °C, respectively. Pure Ar incorporated with 4% CH₄ was used as the carrier gas, with a flow pressure of 63 kPa. Standard N₂O of 0.296, 0.592, and 0.888 ppmv were used for calibration.

N₂O fluxes were calculated from the changes in the N₂O concentration in the chamber with time, by using a linear regression relation:

$$\text{N}_2\text{O flux } (\mu\text{g N m}^{-2} \text{ h}^{-1}) = \rho \times V/A \times \Delta c/\Delta t \times 273/T,$$

where ρ is the density of N₂O-N ($1.25 \times 10^9 \mu\text{g m}^{-3}$) under standard conditions; V (m³) and A (m²) are the volume and bottom area of the chamber; $\Delta c/\Delta t$ ($10^{-6} \text{ m}^{-3} \text{ m}^{-3} \text{ h}^{-1}$) is the rate of N₂O concentration change in the chamber during a given period; and T is the absolute temperature (K).

The minimum detectable N₂O concentration was 0.003 $\mu\text{L L}^{-1}$, which corresponds to a minimum detectable N₂O flux of $\pm 0.6 \mu\text{g N m}^{-2} \text{ h}^{-1}$. Non-detectable N₂O fluxes were treated as 0 $\mu\text{g N m}^{-2} \text{ h}^{-1}$.

Soil temperature and moisture

Soil temperature and moisture were measured when N₂O flux was measured. Soil temperature was measured with a digital thermometer at a depth of 4 cm. Soil moisture was measured as volumetric water content by FDR (ML2 Theta Probe, Delta-T Devices) at a depth of 0 to 7 cm. All measurements were taken with 5 replications.

Statistical analysis

Nonparametric rank-sum tests were conducted for comparisons of N₂O fluxes among different forest–alasecosystems, and for comparisons of N₂O flux, soil temperature, and soil moisture among land cover types: we used the Wilcoxon test for two-group comparison and the Kruskal–Wallis test for multiple-group comparison. When there was a significant difference, we used the Steel–Dwass test to compare the means by Excel Statistics (Esumi Ltd., Tokyo, Japan).

Result

Soil properties

Soil properties at each site are shown in Table 1. The pH, EC, and OC content were generally much higher in the grasslands, and C/N was lower in the grasslands.

There was a significant difference among the values of both soil temperature and moisture among the land cover types (Table 3). Forest had the lowest soil temperatures, owing to shading by canopy, and the lowest soil moisture, owing to water uptake by trees.

N₂O flux

N₂O flux at each site is shown in Table 2. Both uptake and emission were observed in the forest sites (−2.1 to 1.0 μg N m^{−2} h^{−1}) and in the grassland sites (−1.3 to 31 μg N m^{−2} h^{−1}). At the edge of the ponds, N₂O emission varied widely (0 to 140 μg N m^{−2} h^{−1}). In the ponds, only N₂O uptake was observed (−2.2 to 0 μg N m^{−2} h^{−1}). The median values of N₂O fluxes in each land cover type except grassland were not significantly different among the alases (Table 2). There were significant differences in the mean values of N₂O flux among land cover types (Table 3), in the order of edge of pond ≥ grassland ≥ forest = pond.

Relationship between N₂O flux and soil temperature and moisture

Figure 2 shows the relationship between N₂O flux and soil moisture. N₂O flux increased as soil moisture increased ($P < 0.01$), but the ponds showed N₂O uptake, and some fluxes at the edge of the ponds were small or not detected. The N₂O flux was not significantly correlated with the soil temperature ($P > 0.05$).

Comparison with previous studies

Owing to the lack of N₂O flux data from Siberia, we compared our data with values measured in northern Europe and in temperate and tropical regions. Our study forests acted as both sinks and sources of N₂O (−2.1 to 1.0 μg N m^{−2} h^{−1}) (Table 2). These values were similar to those previously reported in forests on mineral soil, but were smaller than those in forests on peat soil in northern Europe (Table 4). All of those values were smaller than those previously reported in tropical and temperate forests (Table 4). The N₂O fluxes in grasslands, at the edge of ponds, and in the ponds were similar to those previously reported in grasslands in the temperate region, in marsh in the temperate region, and in wetland in Finland (Table 4).

Table 2. N₂O flux at each site.

Cover	Alas	N ₂ O flux			Soil temperature °C	Soil moisture m ³ m ^{−3}
		median	min	max		
Forest	Dyode	0.0 a	−1.0	0.9	20.3	0.03
	Neleger	0.0 a	−1.5	0.0	15.2	0.01
	Ulakhan	0.0 a	−2.1	1.0	17.7	0.05
Grassland	Neleger	3.5 a	2.1	31.0	18.7	0.24
	Ulakhan	0.0 b	−1.3	0.0	28.4	0.02
	Tungle	2.6 ab	0.0	12.4	27.2	0.17
Edge of pond	Dyode	35.6 a	0.0	113.3	25.5	0.43
	Neleger	120.8 a	54.2	139.7	18.1	0.60
	Ulakhan	2.8 a	0.0	4.1	23.2	0.46
	Tungle	90.5 a	53.2	127.7	31.3	0.42
Pond	Neleger	−0.3 a	−0.8	0.0	19.4	−
	Ulakhan	−1.6 a	−2.2	−1.6	27.5	−

Values followed by different letters are significantly different by Steel–Dwass test ($P < 0.05$) among alases within each land type.

Table 3. Summary of N₂O flux, soil temperature, and soil moisture by cover type.

Cover	N ₂ O flux	Soil temp.	Soil
	μg N m ^{−2} h ^{−1}	at 4 cm °C	moisture m ³ m ^{−3}
Forest	0.0 bc	17 b	0.02 b
Grassland	2.1 ab	23 a	0.20 b
Edge of pond	53.7 a	24 ab	0.46 a
Pond	−0.8 c	21 ab	−

Values followed by different letters are significantly different by Steel–Dwass test ($P < 0.05$).

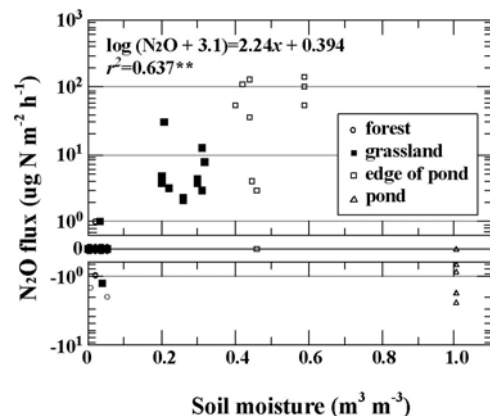


Fig. 2. Relationship between N₂O flux and soil moisture content (m³ m^{−3}). The regression equation excludes plots of ponds.

Table 4. N₂O flux from natural ecosystems.

Lat.	Location	Soil	Vegetation	Study period	N ₂ O flux range μg N m ⁻² h ⁻¹	Reference
Forest						
	tropical forest				10 - 30	Bowman, 1990
	temperate forest				1.0 - 75	Bowman, 1990
N 53	Saskatchewan, Canada	sandy, clay loam	Aspen	annual	0.22	Corre <i>et al.</i> , 1999
N 58	Gardsjon, Sweden	orthic podzol	Norway spruce	annual	0.81 - 1.3	Klemedtsson <i>et al.</i> , 1997
N 61	Hameenlinna, Finland	carvic podzol	Scot pine	May - Oct.	0 - 7.5	Paavolaianen <i>et al.</i> , 1998
N 61	Ruotsinkyla, Finland	peat	<i>Picea abies</i>	Jun. - Oct.	3.6	Huttunen <i>et al.</i> , 2003
N 61	Vesijako, Finland	peat	<i>Picea abies</i>	Jun. - Oct.	12	Huttunen <i>et al.</i> , 2003
N 62	Finland	organic	Birch	Jun. - Dec.	28 ± 8.2	Maljanen <i>et al.</i> , 2003
N 62	Yakutia, Russia		Larch	Jul.	-2.1 - 1.0	this study
Grassland						
	temperate grassland				0.50 - 104	Bowman, 1990
N 53	Saskatchewan, Canada	sandy, clay loam		annual	0.44	Corre <i>et al.</i> , 1999
N 62	Yakutia, Russia		grassland	Jul.	-1.3 - 31	this study
Wetland						
	temperate wetland				1.0 - 149	Bowman, 1990
N 62	Finland (wetland)			Apr. - Dec.	-1.2 - 0	Regina <i>et al.</i> , 1996
N 62	Yakutia, Russia		edge of pond	Jul.	0 - 140	this study
N 62	Yakutia, Russia		pond surface	Jul.	-2.2 - 0	this study

Discussion

N₂O flux increased as soil moisture increased, but ponds took up N₂O (Table 2). Letey *et al.* (1980) reported that when soil is wetted, N₂O is produced more rapidly than it is consumed. Bowman (1990) reported that N₂O production increased owing to the dominance of denitrification at very high soil moisture content. Terry *et al.* (1981) reported that the major gaseous product before flooding was N₂O, and that after flooding was N₂. Aulakh *et al.* (1992) observed the largest N₂O flux at 60% of water-filled pore space. These findings support our result that N₂O emission increased as soil moisture increased, and show that N₂O flux is largest when the water table is near the soil surface, but the soil is not completely saturated, and is due to biological processes of denitrification.

There was no significant difference among the mean N₂O fluxes at the edge of the ponds of different alases (Table 2), but flux varied widely. Although the reason was not clear, both pH and OC content might have an influence. pH is an important factor affecting denitrification (Bandibas *et al.* 1994; Dalal 2003), with an optimum value (Valera and Alexander 1961; Stevens *et al.* 1998; Simek and Hopkins 1999; Simek *et al.* 2002), and a change in pH produces a change in the N₂O/N₂ ratio during denitrification (Cady and Bartholomew 1960; Firestone *et al.* 1980; Letey *et al.* 1980; Koskinen and Keeny 1982; Scholefield 1997; Simek *et al.* 2002; Rochester 2003). Carbon content is another important factor in denitrification (Beauchamp *et al.* 1989). An increase of soil carbon content will increase denitrification to N₂ (Stanford *et al.* 1975; Weiter *et al.* 1993; Pu *et al.* 1999; Davidsson and Stahl 2000; Simek *et al.* 2000; Cosandey *et al.* 2003; Freibauer and Kaltschmitt 2003). Therefore, the wide range of N₂O flux at the edge of the ponds might be due to the wide ranges of soil pH and soil carbon contents.

Conclusion

The mean values of N₂O flux were significantly different among the land cover type, and highest at the edge of the ponds. N₂O fluxes increased as soil moisture increased, but fluxes were smallest in the ponds due to biological process of denitrification.

Acknowledgement

We thank Prof. M. Fukuda, Hokkaido University, leader of the CREST program of the Japan Science and Technology Corporation (JST), for supporting this study and for his valuable comments. We also thank Prof. K. Takahashi and Drs. M. Shibuya, H. Saito, K. Kushida, Y. Kobayashi, and G. Iwahana, Hokkaido University; Drs. T. C. Maximov and A.P. Isaev and the staff of the Institute of Biological Problems of the Cryolithozone, Russian Academy of Sciences; and Dr. A. N. Fedrov and the staff of the Permafrost Institute, Siberian Branch, Russian Academy of Science, for their assistance in the fieldwork in Yakutsk. This study was supported by the CREST program of the Japan Science Technology Corporation (JST).

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