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Contribution of the nongrowing season to annual N_2O emissions from the continuous permafrost region in Northeast China

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Abstract. Permafrost regions store large amounts of soil organic carbon and nitrogen, which are major sources of greenhouse gas. With climate warming, permafrost regions are thawing, releasing an abundance of greenhouse gases to the atmosphere and contributing to climate warming. Numerous studies have shown the mechanism of nitrous oxide (N_2O) emissions from the permafrost region during the growing season. However, little is known about the temporal pattern and drivers of nongrowing season N_2O emissions from the permafrost region. In this study, N_2O emissions from the permafrost region were investigated from June 2016 to June 2018 using the static opaque chamber method. Our aims were to quantify the seasonal dynamics of nongrowing season N_2O emissions and its contribution to the annual budget. The results showed that the N_2O emissions ranged from −35.75 to 74.16 $\mu g \cdot m^{-2} \cdot h^{-1}$ during the nongrowing season in the permafrost region. The mean N_2O emission from the growing season were 1.75–2.86 times greater than that of winter and 1.31–1.53 times greater than that of spring thaw period due to the mean soil temperature of the different specified periods. The nongrowing season N_2O emissions ranged from 0.89 to 1.44 kg ha^{-1}, which contributed to 41.96–53.73% of the annual budget, accounting for almost half of the annual emissions in the permafrost region. The driving factors of N_2O emissions were different among during the study period, growing season, and nongrowing season. The N_2O emissions from total two-year observation period and nongrowing season were mainly affected by soil temperature, while the N_2O emissions from growing season were controlled by soil temperature, water table level, and their interactions. In conclusion, nongrowing season N_2O

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emissions is an important component of annual emissions and cannot be ignored in the permafrost region.

1 Introduction

Permafrost regions cover approximately 25% of terrestrial land and store large amounts of nitrogen stocks (31–102 Pg) in soils (Harden et al., 2012). With climate warming, permafrost regions are thawing and degrading globally (IPCC, 2013). Large amounts of soil nitrogen have been released to the atmosphere from the permafrost region. Nitrous oxide (N_2O) is a major component of N exchanged between terrestrial ecosystems and atmosphere in the permafrost region and feedback to climate warming. N_2O is the third most important greenhouse gas with 265 times the global warming potential of CO_2 and 9 times that of CH_4, which contributes 6% to global climate warming (IPCC, 2013). Soil biological processes, which release approximately 60% of total natural N_2O emissions, are the largest source of N_2O emissions to the atmosphere (IPCC, 2013). Permafrost regions were considered to release negligible amounts of N_2O emission because of the limited mineral N content. Recently, “hot spots” for N_2O emissions from permafrost regions were found in the subarctic (Marushchak et al., 2011;Repo et al., 2009). The rates of N_2O emissions from bare peatland could reach 31–31.4 mg m^{-2} day^{-1}, which are as high as N_2O emissions from tropical soil (Marushchak et al., 2011;Repo et al., 2009;Castaldi et al., 2013). The cumulative N_2O emissions range from 0.9 to 1.4 g m^{-2} during the growing season, indicating that the permafrost region is also an important source of N_2O emissions

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(Repo et al., 2009). In the past, research on N_2O emissions from permafrost regions were mainly focused on the growing season (Repo et al., 2009;Gao et al., 2019b;Chen et al., 2017). However, in the permafrost region, N_2O emissions from the nongrowing season are unclear.

N_2O emissions have been widely researched during the nongrowing season in different ecosystems (Maljanen et al., 2010;Merbold et al., 2013;Furon et al., 2008). A significant release of N_2O emissions have been observed during the nongrowing season, particularly during the spring thaw period. During the nongrowing season, the rates of N_2O emission could be more than 230 g N ha^{-1} d^{-1} (Glenn et al., 2012;Flesch et al., 2018;Chantigny et al., 2017) and the cumulative N_2O emissions released can be as high as 40 kg ha^{-1} in agricultural soil (Dunmola et al., 2010). The importance of nongrowing season N_2O emissions to the annual budget, which contributed more than 50% of the annual values, have been shown in different ecosystems (Fu et al., 2018;Virkajärvi et al., 2010;Yanai et al., 2011). Scientists have focused primarily on N_2O emissions during the nongrowing season in the agricultural (Furon et al., 2008;Dietzel et al., 2011), grassland (Virkajärvi et al., 2010;Merbold et al., 2013), forest (Maljanen et al., 2010), wetland (Hao et al., 2006), and tundra ecosystems (Brooks et al., 1997). Nongrowing season N_2O emissions are an essential component of global N cycling. Permafrost regions, which are characterized by cold temperatures, are mainly distributed in high-latitude and high-altitude areas, and are extremely sensitive to climatic warming. The nongrowing season lasts for more than half of the year in the permafrost region. Determining nongrowing season N_2O emissions is important for accurately evaluating annual N_2O emission from permafrost regions. However, N_2O emissions from permafrost regions still remain uncertain during the nongrowing season.

Daxing'an Mountains, located in Heilongjiang province of Northeast China, are a unique high latitude and the second largest permafrost region in China. Under the threat of global warming, the permafrost region in the Daxing'an Mountains has been significantly degrading and thawing (Jin et al., 2007). The area of the permafrost region has decreased by 35%, leading to the deepening of the active layer, thinning of the permafrost layer, and increasing ground temperatures, which changes the N cycle (Jin et al., 2007). The previous in-situ N_2O measurements from permafrost region of the Daxing'an Mountains have primarily been reported during the growing season or the spring thaw period (Gao et al., 2019b;Cui et al., 2018;Gao et al., 2019a). In the context of global climate warming, N_2O emission during the nongrowing season are unclear in the permafrost region of the Daxing'an Mountains.

The typical vegetation in the permafrost region of the Daxing'an Mountains is cool-temperate coniferous forest dominated by *Larix gmelinii*, forming the southern boundary of the boreal forest. In this study, in-situ N_2O emission were measured from the permafrost region at three forest sites in the Daxing'an Mountains for two full years. The objectives of this study were to: (i) characterize the nongrowing season

N_2O emissions from continuous permafrost regions; (ii) evaluate the contributions from the nongrowing season, particularly the spring thaw period, to annual N_2O emissions; and (iii) investigations the key regulatory factors on N_2O emissions. Observation of the nongrowing season N_2O emissions from permafrost regions provides insight into regional climate warming and the impact of the permafrost region on global climate change.

2 Materials and Methods

2.1 Site description

The experimental site was located on the continuous permafrost region in the Heilongjiang Mohe Forest Ecosystem Research Station at the Daxing'an Mountains, Northeast China (122°06′–122°27′E, 53°17′–53°30′N; 290–740 m elevation). The study region has a typical cold temperate continental climate with a long cold winter and short hot summer. Air temperature ranges from −52.3 to 36.6 °C with a mean annual temperature of −4.9 °C. Mean annual precipitation is 430–550 mm, 60% of which falls as rain primarily in the summer. Snow accumulation is 20–40 cm and covers the land for more than half of the year (from October to April). The soil at the study site is primarily brown forest soil, interspersed with meadow soil and marsh soil.

The typical vegetation in this permafrost region is a temperate coniferous forest with *L. gmelinii* as the dominant species. Other overstory species include *Betula*

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platyphylla, *Pinus sylvestris* var. *mongolica*. Shrub species include *Ledum palustre* var. *dilatatum*, *B. fruticose*, *Vaccinium uliginosum*, *V. vitis-idaea*, *Rhododendron dauricum*， and *Alnus sibirica*. Herbaceous species include *Carex appendiculata*, *C. schmidtii*, *Eriophorum vaginatum*, *Rubus clivicola*, and *Sanguisorba officinalis*. According the water table level from low to high, three types of typical swamp forests located in the permafrost region were studied: *L. gmelinii* - *Ledum palustre* var. *dilatatum* swamp forest (*LL*), *L. gmelinii* - *Carex appendiculata* swamp forest (*LC*), and *Betula fruticose* swamp forest (*B*). The soil physicochemical properties at the three swamp forests are shown in table 1.

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Table 1.

Soil properties at the three swamp forest sites in the permafrost region of Daxing'an Mountains, Northeast China (mean ± SD).

Environmental factor	*LL* site	*LC* site	*B* site
WTL	−13.19 ± 9.73b	−4.51 ± .51a	0.26 ± 5.67a
$SM_{0–10}$	117.30 ± 14.92c	174.20 ± 14.58a	162.31 ± 16.14b
$SM_{10–20}$	49.54 ± 8.28b	115.86 ± 10.98a	115.91 ± 9.13a
$pH_{0–10}$	4.77 ± 0.16c	4.99 ± 0.08a	4.89 ± 0.11b
$pH_{10–20}$	4.93 ± 0.18c	5.09 ± 0.07a	4.99 ± 0.11b
NH_4^+-$N_{0–10}$	5.49 ± 2.15a	5.98 ± 3.03a	4.92 ± 2.65a
NH_4^+-$N_{10–20}$	3.05 ± 1.57a	3.87 ± 1.94a	3.43 ± 1.88a
NO_3^--$N_{0–10}$	1.71 ± 0.73a	1.81 ± 1.02a	1.58 ± 0.63a
NO_3^--$N_{10–20}$	1.29 ± 0.57ab	1.44 ± 1.02a	1.02 ± 0.42b
$TOC_{0–10}$	39.95 ± 6.91a	42.01 ± 4.43a	35.57 ± 5.22b
$TOC_{10–20}$	15.62 ± 3.95b	18.25 ± 2.71a	16.62 ± 2.1ab
$TN_{0–10}$	2.19 ± 0.37b	3.78 ± 0.51a	1.97 ± 0.69b
$TN_{10–20}$	0.83 ± 0.15b	1.03 ± 0.21a	0.91 ± 0.13b
$C/N_{0–10}$	17.94 ± 4.17a	11.27 ± 144b	17.08 ± 3.55a
$C/N_{10–20}$	19.26 ± 5.65a	18.29 ± 4.24a	18.57 ± 3.82a

WTL, water table level; $SM_{0–10}$, soil moisture at 0–10 cm; $SM_{10–20}$, soil moisture at 10–20 cm; $pH_{0–10}$, pH at 0–10 cm; $pH_{10–20}$, pH at 10–20 cm; NH_4^+-$N_{0–10}$, ammonium nitrogen at 0–10 cm; NH_4^+-$N_{10–20}$, ammonium nitrogen at 10–20 cm;

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NO_3^--$N_{0–10}$, nitrate nitrogen at 0–10 cm; NO_3^--$N_{10–20}$, nitrate nitrogen at 10–20 cm; $TOC_{0–10}$, total organic carbon at 0–10 cm; $TOC_{10–20}$, total organic carbon at 10–20 cm; $TN_{0–10}$, total nitrogen at 0–10 cm; $TN_{10–20}$, total nitrogen at 10–20 cm; $C/N_{0–10}$, carbon-to-nitrogen ratio at 0–10 cm; $C/N_{10–20}$, carbon-to-nitrogen ratio at 10–20 cm.

2.2 N_2O emission measurements

The field experiment was conducted from June 2016 to June 2018. Three 20 × 20 m plots were permanently established at each *LL*, *LC*, and *B* site, respectively. N_2O emissions were measured with the static opaque chamber technique (Hutchinson et al., 2000). The polypropylene chamber collar with a water-filled channel (50 cm × 50 cm × 20 cm height) was randomly inserted 20 cm into the soil. Gas samples were measured from 9:00 am to 11:00 am, the hours that were most representative of the daily mean N_2O emissions (Alves et al., 2012). During each N_2O measurement period, chambers (50 cm × 50 cm × 50 cm height) were sealed by filling the collars with water and used to collect N_2O from the soil. Four-chamber headspace air samples were taken using a 50-mL plastic syringe at 0, 15, 30, and 45 min after chamber closure (Liu et al., 2019). Samples were injected into pre-evacuated 100 mL gas sampling bags (Delin Gas Packing Co., Dalian, China) for subsequent laboratory analysis. The air temperature inside the chamber was recorded when gas samples were being retrieved. Gas samples were taken twice per month during the growing season from June to September, monthly during the winter from October to December, and every three to ten days during the spring thaw period from March to May (45 sampling events in total).

The gas N_2O concentration was analyzed with a gas chromatograph coupled with an electron capture detector (ECD) (Shimadzu GC2010, Shimadzu Analytical and Measuring Instruments Division, Kyoto, Japan). Compressed air containing 0.378 ppm N_2O was used for calibration. N_2 was used as the carrier gas with a flow rate of 20 mL min^{-1}. The N_2O was separated using a 1-m stainless steel column with an inner diameter of 2 mm from Porapak Q (80/100 mesh), and was detected by an ECD. The temperature for gas separation was maintained at 70 °C and the detector was set at 250 °C.

2.3 Measurements of meteorological and soil physiochemical properties

Soil temperature (ST) at 5, 10, and 15 cm deep was monitored at each collar using a portable digital thermometer with a thermocouple probe (JM-624, Jinming Corp., Tianjin, China). During the growing season, the water table level (WTL) was measured near the chamber in each plot using a ruler (Dobbie and Smith, 2006). In the nongrowing season, soil moisture was determined by the oven-drying mothed.

Using a 3.8 cm diameter stainless-steel sampling probe, soil samples were taken from the upper 0–10 cm and lower 10–20 cm soil layers close to each collar. Fine roots and visible organic debris were removed by passing the soil samples through a 2-mm sieve. Then, samples were stored in an insulated box (Esky) and stored at 4 °C

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for subsequent chemical analysis.

Soil moisture contents were determined by drying at 105 °C for 48 h followed by calculating the weight loss. Soil samples were air dried and sieved to <2 mm aggregate size and used to measure the soil pH. Soil pH was measured in a 2:5 air-dried soil: deionized water mixture using an InoLab pH meter (WTW InoLab pH 730, Weilheim, Germany). Soil mineral N, ammonium (NH_4^+-N), and nitrate (NO_3^--N) content were determined on 10 g samples of fresh soil based on a 1 mol/L KCl solution extraction procedure. The extracts were filtered through a 0.45 µm pore-diameter syringe filter, and then soil mineral N was analyzed using a Lachat flow-injection auto-analyzer (Seal Analytical AA3, Norderstedt, Germany). For the analyses of total N and C, sub-samples were further ground to a fine powder (<0.15 mm). Total N concentration was measured on aliquots of 1.0 g of soil using semi-micro-Kjeldahl method. The TOC content was determined by oxidation at 170 °C, with potassium dichromate in the presence of sulfuric acid. The excess potassium dichromate was titrated with a solution of Mohr's salt.

2.4 Statistical analysis

The N_2O emissions were calculated as reported by (Hou et al., 2012). A positive regression indicates the emission from soil to the atmosphere. A negative regression indicates a net uptake by the soil from the atmosphere. Cumulative N_2O emissions were linearly and sequentially accumulated from the emissions between every two adjacent intervals of the measurements following the procedure described by Ding et al. (2007).

The calendar year was divided into three seasons: winter, spring thaw period, and growing season. The winter was defined as the period during which the daily mean air temperature remained below 0 °C for at least five consecutive days. The spring thaw period was defined as the period when the daily maximum air temperature exceeded 0 °C and ended at soil thawing to a depth of 20 cm. The growing season was defined as the period that lasts from the end of the spring thaw period to the beginning of winter. We designated the winter and spring thaw period as the nongrowing season.

A one-way analysis of variance was used to test the difference of N_2O emissions and environment factors in the three swamp forest sites. A T-test was used to identify the differences in N_2O emissions between 2016/2017 and 2017/2018. The correlations between the N_2O emissions and environmental factors were tested using Pearson's correlation analysis. A linear correlation analysis and multivariate regression analysis were conducted to create explanatory models using the same variables as those used for describing the temporal variation of N_2O emissions. R software (Version 3.4.1, https://www.r-project.org/) was used for the statistical analyses. Significance was analyzed using Fisher's least significant difference (LSD) test at a probability level of 95% ($P < 0.05$). All figures were drawn using OriginPro 2018 software (OriginLab Corp., Northampton, MA, U.S.A.).

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3 Results

3.1 Temporal variation of N_2O emissions

During the two-year observation period, there was significant temporal variation in N_2O emissions in the permafrost region of the Daxing'an Mountains (Fig. 1a). However, the temporal pattern of N_2O emissions were different in the three swamp forests. The N_2O emissions ranged from −17.40 to 74.16, −35.75 to 64.73, and −26.47 to 79.25 $\mu g \cdot m^{-2} \cdot h^{-1}$ in the *LL*, *LC*, and *B* sites, respectively (Fig. 1a). The highest N_2O emissions occurred in different periods in three swamp forests, namely, they occurred in the beginning of the spring thaw period in the *LL* site and at the end of growing season in the *LC* and *B* sites. The lowest N_2O emissions from the three swamp forest sites were all observed in the spring thaw period. Negative emissions mainly occurred during the winter and spring thaw period. The N_2O emissions during the nongrowing season mainly ranged from −17.40 to 74.16, −35.75 to 60.76, and −26.47 to 71.82 $\mu g \cdot m^{-2} \cdot h^{-1}$ in the *LL*, *LC*, and *B* sites, respectively.

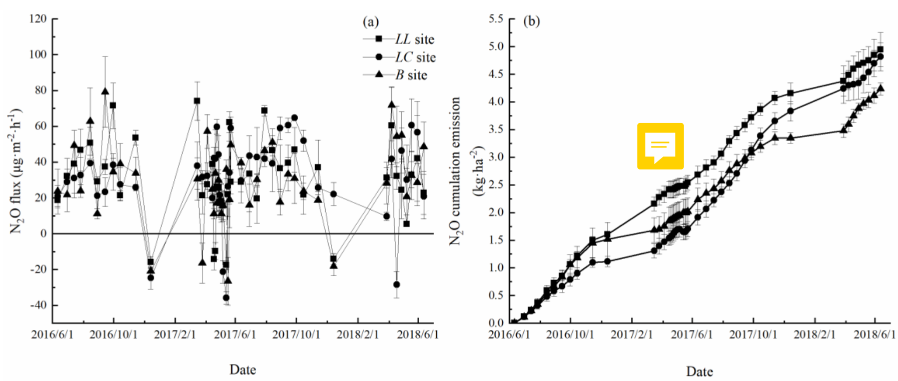

Figure 1. N_2O emissions (A) and cumulative N_2O emissions (B) from three types of

swamp forests in the permafrost region of the Daxing'an Mountains, Northeast China

The annual mean N_2O emissions ranged from 27.80 to 32.51, 26.10 to 37.89, and 25.86 to 33.16 μg·m^{-2}·h^{-1} in the *LL*, *LC*, and *B* sites, respectively (Table 2). The mean N_2O emissions from the growing season typically higher than that of winter and the spring thaw period in the three swamp forest sites. In 2016/2017, the mean N_2O emissions were all highest in the growing season and lowest in the winter. In contrast, during 2017/2018, the mean N_2O emissions were lowest during the spring thaw period in the *LC* site and highest during the spring thaw period in the *B* site. For the different types of swamp forests, the mean N_2O emissions from the *LC* site were significantly higher than the mean N_2O emissions in the *B* site in the 2017/2018 growing season. There was no significant difference in N_2O emissions during the winter, spring thaw period, and annually in the three swamp forests. The N_2O emissions from different periods were generally not significantly different between the two years. Differences in N_2O emissions were found during the growing season and spring thaw period. The mean N_2O emissions during the growing season from the *LC* site and the N_2O emissions during the spring thaw period from the *B* site were both significantly higher in 2017/2018 than 2016/2017.

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Table 2.

Summary of N_2O emissions during specified periods from the three swamp forest sites in the permafrost region of the Daxing'an Mountains, Northeast China

Specified period	Duration (Days)		Mean N_2O emissions ($\mu g \cdot m^{-2} \cdot h^{-1}$)					
			2016/2017			2017/2018		
	2016/2017	2017/2018	*LL* site	*LC* site	*B* site	*LL* site	*LC* site	*B* site
Growing season	134	129	40.42 ± 15.97Aa	29.54 ± 7.30Ab	38.35 ± 23.42Aa	40.09 ± 14.68ABa	47.73 ± 12.27Aa	33.17 ± 12.48Ba
Nongrowing season								
Winter	155	161	19.80 ± 34.74Aa	9.62 ± 29.69Aa	17.41 ± 33.14Aa	14.95 ± 26.23Aa	33.31 ± 16.25Aa	8.13 ± 22.89Aa
Spring thaw period	77	75	22.49 ± 24.90Aa	27.56 ± 26.06Aa	20.89 ± 21.73Ab	32.74 ± 16.69Aa	31.04 ± 31.31Aa	41.66 ± 18.78Aa
Annual	366	365	27.80 ± 24.36Aa	26.10 ± 22.44Aa	25.86 ± 24.06Aa	32.51 ± 18.31Aa	37.89 ± 22.26Aa	33.16 ± 19.55Aa

The different capital letters indicate that the N_2O emissions were significantly different among the types of swamp forest; different lowercase letters indicate that the N_2O emissions were significantly different between the two years.

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3.2 Seasonal contribution of N_2O emissions to the annual budget

Cumulative N_2O emissions primarily increased during the study period (Fig. 1b). The annual N_2O emissions ranged from 2.27 to 2.68, 1.92 to 2.90, and 2.00 to 2.24 kg ha^{-1} yr^{-1} in the *LL*, *LC*, and *B* sites, respectively (Table 3). The cumulative N_2O emissions during the growing season ranged from 1.02 to 1.46 kg ha^{-1}, which contributed to 46.27 to 58.04% to the annual emissions. The cumulative N_2O emissions from the growing season were higher than the cumulative N_2O emissions during the winter and spring thaw periods, and were 1.2 to 3.2 times greater than that of the winter and 1.5 to 3.7 times greater than that of the spring thaw period. The cumulative N_2O emissions during the nongrowing season were mainly lower than during the growing season, which contributed to 41.96–53.73% to annual emissions. The cumulative N_2O emissions during the spring thaw period ranged from 0.35 to 0.66 kg ha^{-1}, contributing to 15.63 to 33.00% to the annual emissions.

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Table 3.

The cumulative N_2O emissions and its contribution to annual N_2O emissions from the three swamp forest sites in the permafrost region of Daxing'an Mountains, Northeast China.

Forest types	Year	Cumulative N_2O emissions (kg ha^{-1})					Contribution to annual N_2O emissions (%)			
		Annual	GS	NGS	Winter	STP	GS	NGS	Winter	STP
LL site	2016/2017	2.68 ± 0.15	1.24 ± 0.06	1.44 ± 0.21	1.00 ± 0.20	0.44 ± 0.04	46.27	53.73	37.31	16.42
	2017/2018	2.27 ± 0.16	1.21 ± 0.07	1.06 ± 0.18	0.56 ± 0.16	0.50 ± 0.03	53.30	46.70	24.67	22.03
LC site	2016/2017	1.92 ± 0.14	1.03 ± 0.13	0.89 ± 0.13	0.48 ± 0.11	0.41 ± 0.02	53.65	46.35	25.00	21.35
	2017/2018	2.90 ± 0.11	1.46 ± 0.03	1.44 ± 0.10	0.93 ± 0.12	0.51 ± 0.03	50.34	49.66	32.07	17.59
B site	2016/2017	2.24 ± 0.21	1.30 ± 0.15	0.94 ± 0.08	0.58 ± 0.07	0.35 ± 0.01	58.04	41.96	25.89	15.63
	2017/2018	2.00 ± 0.22	1.02 ± 0.11	0.98 ± 0.22	0.32 ± 0.20	0.66 ± 0.08	51.00	49.00	16.00	33.00

GS: growing season; NGS: nongrowing season; STP: spring thaw period.

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3.3 Temporal control of soil N_2O emissions

The relationship between N_2O emissions and environmental factors during the different specified periods are shown in Table 4. During the entire two-year observation period, the N_2O emission were all significantly positively correlated with soil temperature at 5, 10, and 15 cm in the three swamp forest sites. Except for the soil temperature, the N_2O emissions from the *LL* site were also positively correlated with air temperature (P<0.05) and C/$N_{0–10}$ (P<0.05) and negatively correlated with $pH_{0–10}$ (P<0.01), $pH_{10–20}$ (P<0.05), NO_3^--$N_{0–10}$ (P<0.05), NO_3^--$N_{10–20}$ (P<0.05), and $TN_{0–10}$ (P<0.05). The N_2O emissions from the *LC* site were significantly positively correlated with $TOC_{0–10}$ (P<0.01) and $TN_{10–20}$ (P<0.01). The N_2O emissions from the *B* site were significantly positively correlated with air temperature (P<0.001), NH_4^+-$N_{0–10}$ (P<0.05), and NH_4^+-$N_{10–20}$ (P<0.05). Similar to the entire period, the N_2O emissions from the nongrowing season were mainly significantly positively correlated with soil temperature in the *LC* and *B* sites and weakly positively correlated with soil temperature in the *LL* sites. The N_2O emissions from the *LL* site were also significantly negatively correlated with $pH_{0–10}$ (P<0.05) and $TN_{0–10}$ (P<0.001); the N_2O emissions from the *LC* site were significantly positively correlated with $TN_{0–10}$ (P<0.05). The N_2O emissions from the *B* site were significantly positively correlated with air temperature (P<0.05), NH_4^+-$N_{0–10}$ (P<0.01), NH_4^+-$N_{10–20}$ (P<0.01), and NO_3^--$N_{0–10}$ (P<0.05). For the growing season, the impact of environmental factors on N_2O emissions were complicated. The N_2O emissions were significantly positively correlated with T_{15} (P<0.05) and negatively correlated with NO_3^--$N_{0–10}$ (P<0.05) and

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NO_3^--$N_{10\text{–}20}$ ($P<0.01$) in the *LL* site. The N_2O emissions from *LC* site were significantly influenced by air temperature, water table level, NO_3^--N, TOC, TN, and C/N ratio. The N_2O emissions from the *B* site were only significantly positively correlated with water table level ($P<0.05$).

Table 4.

The relationship between N_2O emissions and environmental factors from three swamp forest sites in the permafrost region of the Daxing'an Mountains, Northeast China.

Environmental factor	Two full-year			Growing season			Nongrowing season		
	LL site	*LC* site	*B* site	*LL* site	*LC* site	*B* site	*LL* site	*LC* site	*B* site
*T*a	0.17*	0.14	0.30***	−0.26^{+}	−0.50***	0.15	0.11	0.16	0.26*
T_5	0.33***	0.26**	0.35***	0.07	−0.13	0.19	0.17	0.25*	0.29**
T_{10}	0.37***	0.28**	0.36***	0.20	−0.03	0.21	0.20^{+}	0.26*	0.31**
T_{15}	0.39***	0.30***	0.34***	0.30*	0.06	0.14	0.21^{+}	0.32**	0.32**
WTL				−0.13	−0.29*	0.29*			
$SM_{0–10}$							−0.08	−0.02	0.03
$SM_{10–20}$							−0.10	0.08	−0.03
$pH_{0–10}$	−0.24**	0.07	−0.18^{+}	−0.01	0.08	−0.20	−0.25*	0.08	−0.15

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pH_{10-20}	−0.21*	0.15	−0.12	−0.05	0.14	0.05	−0.17	0.22^{+}	−0.19
NH_4^+-N_{0-10}	0.08	0.05	0.20*	0.21	0.19	−0.06	0.07	−0.11	0.32**
NH_4^+-N_{10-20}	0.05	0.01	0.24*	−0.08	−0.23	0.14	0.21^{+}	0.15	0.34**
NO_3^--N_{0-10}	−0.24*	0.05	0.01	−0.32*	0.28*	−0.16	−0.08	0.09	0.29*
NO_3^--N_{10-20}	−0.22*	0.09	−0.11	−0.36**	0.36*	−0.02	0.01	0.11	0.03
TOC_{0-10}	0.13	0.26**	−0.14	0.23	0.48***	−0.15	−0.16	0.01	−0.05
TOC_{10-20}	0.08	0.10	−0.06	0.03	−0.02	−0.01	−0.14	0.11	−0.09
TN_{0-10}	−0.21*	0.06	−0.03	0.08	−0.35*	−0.04	−0.43***	0.14	0.03
TN_{10-20}	0.01	0.26**	−0.16^{+}	0.19	0.65***	−0.16	−0.06	0.26*	−0.15
C/N_{0-10}	0.21*	0.15	−0.08	0.13	0.53***	−0.05	0.10	−0.17	−0.14
C/N_{10-20}	0.06	−0.14	0.04	−0.18	−0.54***	0.04	−0.13	−0.13	0.05

$^{+}$: indicates significant effects at $P < 0.1$; *: indicates significant effects at $P < 0.05$; **: indicates significant effects at $P < 0.01$; ***: indicates significant effects at $P < 0.001$.

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The Pearson correlation analysis showed that the soil temperature was the key environmental factor controlling the N_2O emissions during the entire observation period and the nongrowing season. During the entire observation period, soil temperature at 5, 10, and 15 cm could explain 10.39 to 14.48, 6.07 to 8.34, and 10.66 to 12.02% of the temporal variation of N_2O emissions in the *LL*, *LC*, and *B* sites, respectively. During the nongrowing season, N_2O emissions from the *LL* site were weakly positively correlated with soil temperature, explaining 1.73 to 3.27% of N_2O emissions. The soil temperature could explain 5.02 to 9.54% and 7.51 to 9.36% of the N_2O fluctuation in the *LC* and *BC* sites, which were lower than the entire observation period.

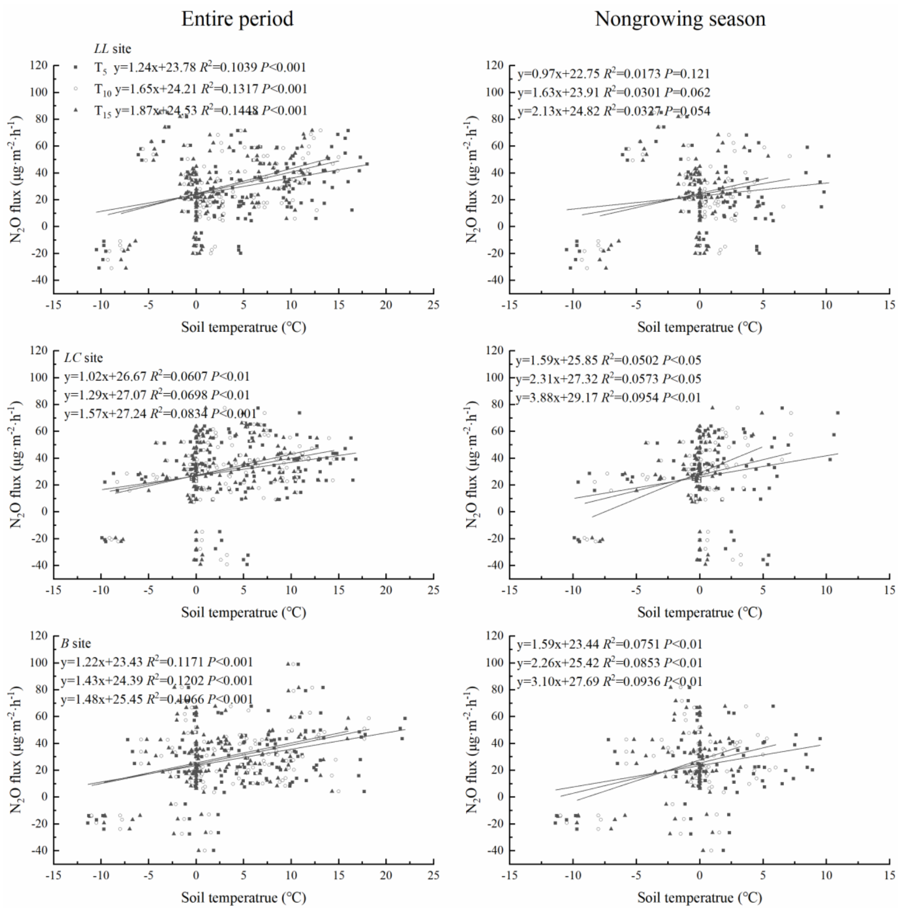

Figure 2. The linear models between N_2O emissions and soil temperature during the entire observation period and nongrowing season in the three swamp forest sites in the permafrost region of the Daxing'an Mountains, Northeast China.

During the growing season, multivariate regression analyses showed that the N_2O emissions were affected by soil temperature, water table level, and their interactions (Table 5). Soil temperature, water table level, and their interactions could explain 26.35, 19.46, and 12.36% of the temporal variation of N_2O emissions in the three swamp forest sites, respectively.

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Table 5.

Models of N_2O emissions during the growing season against soil temperature and water table level for the three swamp forest sites in the permafrost region of the Daxing'an Mountains, northeast China.

Forest type	a	b	c	d	R^2	P
LL site	−11.55	4.03	−3.19	0.25	0.2635	<0.001
LC site	22.44	0.94	−3.99	0.28	0.1946	<0.01
B site	27.57	0.77	−1.50	0.21	0.1236	<0.05

The regression models are: $y= a + b\times T_5 + c\times WTL + d\times T_5\times WTL$, where a, b, c, and d are the regression coefficients.

4 Discussion

4.1 Soil temperature controls the mean N_2O emissions from the different periods

In previous studies, the N_2O emissions from the permafrost region primarily focused on emissions during the growing season (Gil et al., 2017;Lamb et al., 2011;Voigt et al., 2017). Permafrost regions are mainly distributed in high-altitude and high-latitude zones. It was difficult to measure N_2O emissions during the nongrowing season in the cold climate conditions of the permafrost region. Publications on nongrowing season N_2O emissions are scarce and the difference of mean N_2O emissions among the winter, spring thaw period, and growing season are unknown in the permafrost region.

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The nongrowing season N_2O emission ranged from −35.75 to 74.16 μg·m^{-2}·h^{-1} in the permafrost region of the Daxing'an Mountains, northeast China. The results were similar to the rate of annual N_2O emission (−35.75 to 79.25 μg·m^{-2}·h^{-1}) in the permafrost region of the Daxing'an Mountains and within the range of N_2O emissions reported in permafrost ecosystems (−35.75 to 2662 μg·m^{-2}·h^{-1}) (Gao et al., 2019a;Mu et al., 2017). The N_2O emissions confirmed our previous findings that the N_2O emissions from the Daxing'an Mountains ranged within the intermediate range for permafrost ecosystems (Gao et al., 2019b).

The annual N_2O emissions showed significant temporal variations in grasslands (Du et al., 2006). There were significant differences in the mean N_2O emissions in the spring, summer, autumn, and winter in grasslands, whereas the temporal pattern over the course of the five-year study (Du et al., 2006). The N_2O was taken up during the freezing period and emitted during the thawing period and growing season in marshes, indicating that the emissions were different among the three specified periods (Hao et al., 2006). These trends were also observed in the permafrost region. In the "hot spots" of N_2O emission from permafrost region, high N_2O emissions were observed during the nongrowing season in the bare peatland, which contributed 20–69% to the annual emissions from the bare peatland (Marushchak et al., 2011). In the vegetated permafrost ecosystem, the N_2O emissions during the nongrowing season, growing season, and annually were mainly negligible (Marushchak et al., 2011). The N_2O

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emissions from the spring thaw period and nongrowing season were lower than that of growing season in the permafrost region of the Daxing'an Mountains (Chen et al., 2017;Gao et al., 2019a;Wu et al., 2019). However, the drivers of N_2O emissions between the nongrowing season and growing season were not clear in the permafrost region. Our results showed that the N_2O emissions were the highest during the growing season and lowest during the nongrowing season. The mean N_2O emissions from the growing season were significantly higher than the emissions from the winter in the *LL* and *B* sites, whereas the N_2O emissions during the spring thaw period was not significantly different from growing season and winter in the three swamp forests (Fig. 3). The N_2O emissions from the growing season were 1.75–2.86 times greater than the winter emissions and 1.31–1.53 times greater than during the spring thaw period in the three forest types.

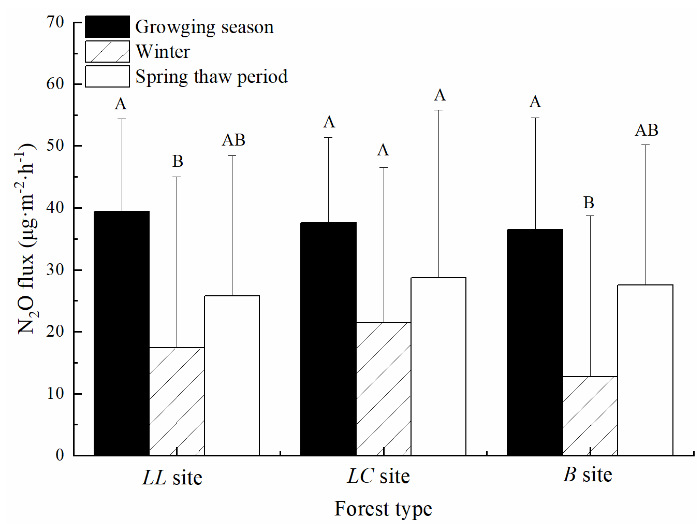

Figure 3. The difference of N_2O emissions among the growing season, winter, and spring thaw period in the permafrost region of the Daxing'an Mountains, Northeast

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China.

We found that the mean N_2O emissions of the three specified periods were significantly positively correlated with soil temperature at 5, 10, and 15 cm, which could explain 91.36–94.07, 91.97–95.92, and 81.71–92.85% of the temporal variation of mean N_2O emissions in the *LL*, *LC*, and *B* sites, respectively (Fig. 4). In a laboratory experiment, the N_2O emissions were strongly dependent on soil temperatures above zero (Oquist et al., 2004). The net N_2O production rates at −4 °C equaled those observed at +10 to +15 °C in the boreal forest soil (Oquist et al., 2004). However, the field soil temperature in the winter in the Daxing'an Mountains was significantly lower than the simulated cold temperature in the laboratory, meaning that the winter N_2O emissions may be lower than N_2O emissions during the growing season (Oquist et al., 2004). In the nongrowing season, soil moisture was consistently saturated in the 0–10 cm soil layer of three swamp forests, which implies that N_2O production occurred predominantly due to denitrification. The denitrification rates showed similar temporal variations of N_2O emissions in agricultural soil in the winter (Tatti et al., 2014). The copy numbers of denitrifier genes (*nirS* and *nirK*) remained stable from November to January and increased in March and April, indicating that N_2O emissions during the spring thaw period were higher than during the winter (Tatti et al., 2014). During the growing season, N_2O emissions were significantly positively correlated with soil temperature in the permafrost region (Marushchak et al., 2011;Cui et al., 2018;Chen et al., 2017). Thus, the soil temperature controlled the mean N_2O

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emissions during the winter, spring thaw period, and growing season. Soil temperature was the key environmental factor determining the temporal variation of N_2O emissions in the permafrost region of the Daxing'an Mountains.

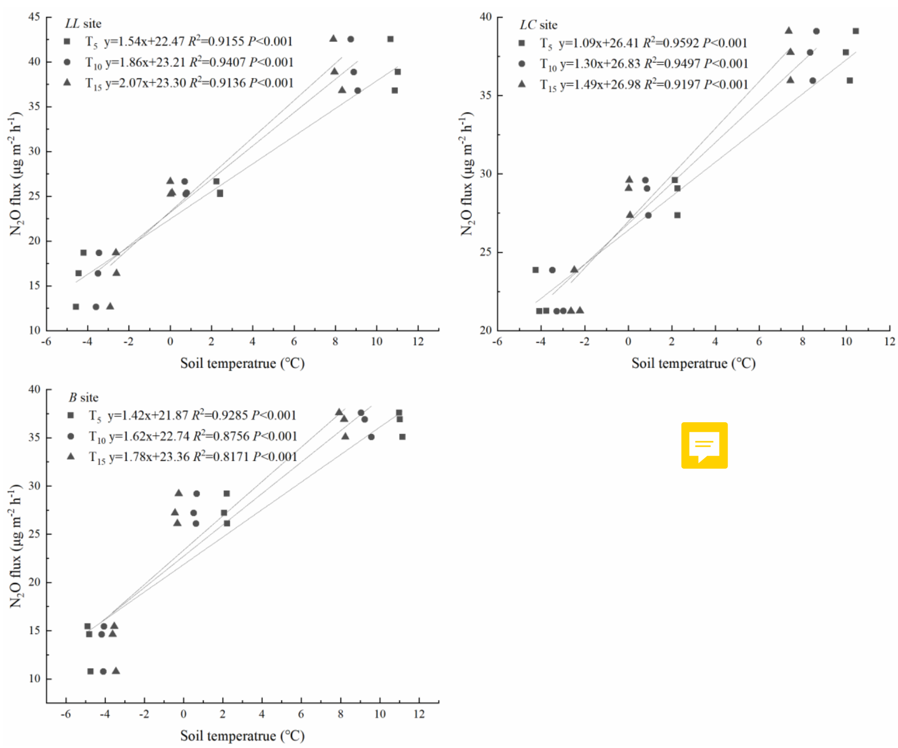

Figure 4. The relationship between mean N_2O emission from different specified periods and soil temperature in the permafrost region of the Daxing'an Mountains, Northeast China.

4.2 Contribution of nongrowing season to annual N_2O budget

The cumulative N_2O emissions from the permafrost region was mainly evaluated during the growing season (Repo et al., 2009;Takakai et al., 2008;Gao et al., 2019b).

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The N_2O emissions from the permafrost region were as high as 14 kg ha^{-1} and released approximately 0.1 Tg yr^{-1} N_2O emissions to the atmosphere in the bare peat region of the Arctic, accounting for up to 0.6% of the global annual N_2O emissions (Repo et al., 2009). A few studies have indicated that the nongrowing season contributed greatly to the annual N_2O emissions from the frigid terrestrial ecosystems (Li et al., 2012;Zhang et al., 2018;Fu et al., 2018). However, the contribution of the nongrowing season to the annual N_2O budget is uncertain in the permafrost region.

The cumulative N_2O emissions during the nongrowing season ranged from 0.89 to 1.44 kg ha^{-1}, which contributed to 41.96–53.73% of the annual budget in the permafrost region of the Daxing'an Mountains. In frigid terrestrial ecosystems, the N_2O emissions of the nongrowing season contributed to 20–74% of the annual emissions; therefore, our results were within the range of previous studies (Li et al., 2012;Zhang et al., 2018;Fu et al., 2018;Marushchak et al., 2011). During the spring thaw period, the soil temperature and soil moisture dramatically changed, which significantly affected the release of N_2O emissions. A pulse or burst of N_2O emissions have been observed in agriculture (Flesch et al., 2018), grassland (Virkajärvi et al., 2010), forest (Wu et al., 2010), marsh (Song et al., 2008), and peat ecosystems (Flesch et al., 2018). The pulse N_2O emissions during the spring thaw period had enormous influence on the contribution of the nongrowing season to the annual budget in the frigid terrestrial ecosystems (Li et al., 2012;Fu et al., 2018). When the pulse of N_2O emissions occurred during the spring thaw period, emissions from the non-growing

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seasons dominated (67–74%) the annual total emissions (Fu et al., 2018). When no pulse of N_2O emissions were found during the spring thaw period, the contribution of the spring thaw period to the total annual N_2O budget was very small and accounted for only 6.6% of the annual emissions (Li et al., 2012). In the present study, there was no significant large burst of N_2O emissions during the spring thaw period. The cumulative N_2O emissions during the spring thaw period ranged from 0.35 to 0.66 kg ha^{-1} and contributed 15.61 to 33.00% of the annual budget in the permafrost region of the Daxing'an Mountains, and these ranges were generally lower than the emissions during the winter and growing season.

The mean N_2O emissions were the lowest in the winter and highest in the growing season, which were not the same as the cumulative N_2O emissions in the three swamp forests. The permafrost region of the Daxing'an Mountains was located at a high latitude, which had a longer nongrowing season than growing season. In the permafrost region of the subarctic, the nongrowing season lasts for more than 9 mouths (283 days) (Marushchak et al., 2011). The length of winter was more than twice of spring thaw spring in the Daxing'an mountains. Although the mean N_2O emissions in winter were lower than during spring thaw period, the cumulative N_2O emissions in winter were higher than the emissions from the spring thaw period. The cumulative N_2O emissions during winter were as important as the spring thaw period. Only one study reported the cumulative N_2O emissions during nongrowing seasons in the permafrost region. Marushchak et al. (2011) found that the N_2O emissions from the nongrowing season contributed 20–69% to the annual emissions in the bare peat zone of the permafrost region. Our results confirmed that half of the N_2O emissions were released during the nongrowing season, indicating that the N_2O emissions during the nongrowing season cannot be ignored in the permafrost regions. In the future, the N_2O emissions of the nongrowing season should be emphasized in the permafrost region, especially in the context of global climate change.

4.3 Drivers of N_2O emissions on different temporal scales

Most previous studies on the permafrost region have focused exclusively on the growing season (Gao et al., 2019b;Repo et al., 2009;Cui et al., 2018). The N_2O emissions during the growing season were mainly influencing by air temperature, soil temperature, water table level, soil moisture, precipitation, pH, NH_4^+-N, NO_3^--N, TOC, gross N mineralization, N content, and C/N ratio in the permafrost region (Ma et al., 2007;Gil et al., 2017;Marushchak et al., 2011;Chen et al., 2017;Cui et al., 2018;Paré and Bedard-Haughn, 2012). However, the drivers of nongrowing season N_2O emission remain unknown in the permafrost region.

N_2O production processes are very complex and can be produced by nitrification, nitrifier denitrification, and denitrification in the permafrost region (Ma et al., 2007;Gil et al., 2017;Siljanen et al., 2019). Soil water content controls the redox conditions in the soil, which determines the pathway of N_2O emissions. The soil water content showed significant temporal variation in the permafrost region of the

Daxing'an Mountains. Thus, the pathway of N_2O emissions may be different in the nongrowing season and growing season. During the growing season, the water table level ranged from −31.6 to 10.27 cm in the three swamp forests. N_2O emission may have come from simultaneous nitrification and denitrification in the *LL* site and denitrification in the *LC* and *BC* sites (Gao et al., 2019b). In the 2016 growing season, the N_2O emissions mainly controlled multiple environmental factors (Gao et al., 2019b). Our results show that the N_2O emissions were driven by soil temperature and water table level and their interactions, explaining 12.36–26.35% of temporal variation of N_2O emissions during the two growing seasons. As the permafrost ecosystem is strongly temperature limited, the N_2O emissions were mainly significantly positively correlated with soil temperature in the permafrost region (Marushchak et al., 2011;Cui et al., 2018;Chen et al., 2017). Soil temperature could increase nitrification and denitrification, thus promoting the release of N_2O flux. Wu et al. (2019) found that the N_2O emissions were significantly negatively correlated with soil moisture in the three forests of the Daxing'an Mountains. Our results confirm that the decrease of the water table level was beneficial to the release of N_2O emissions. Soil temperature and water table level were key factors controlling the emission of N_2O during the growing season. In contrast, the nongrowing season N_2O emissions were mainly controlled by soil temperature in the permafrost region of the Daxing'an Mountains.

During the nongrowing season, the soil moisture was consistently exceeded 60%

in the three swamp forests. The N_2O emissions were major produced by denitrification in the permafrost region. The nongrowing season N_2O emissions were positively correlated with soil temperature in the three swamp forests. The denitrifier genes were stable during the winter and increased during the spring thaw period (Tatti et al., 2014). Wertz et al. (2013) found that the community structures of denitrifiers were different between below-zero and above-zero temperatures. During the nongrowing season, the soil temperature affected the abundance and community structures of denitrifiers and thus the release of N_2O emissions in the permafrost region of the Daxing'an Mountains. In the field, environmental factors are always changing; therefore, any factor can be a limiting factor for a long period. The N_2O emissions from the two-year study period were controlled by soil temperature in the permafrost region of the Daxing'an Mountains. Soil temperature was the major limiting factor related to annual N_2O emissions in the permafrost region. Except for soil temperature, the N_2O emissions from the permafrost region were also affected by pH, NO_3^--N, TN, and C/N ratio.

5 Conclusions

The N_2O emissions from the nongrowing season were quantified in the permafrost region. The N_2O emissions ranged from −35.75 to 74.16 $\mu g \cdot m^{-2} \cdot h^{-1}$ during the nongrowing season. The mean N_2O emissions were lowest in the winter and highest in the growing season, and were controlled by soil temperature. The cumulative N_2O emissions during the nongrowing season greatly contributed to the annual budget, which cannot be ignored. In the different periods studied, N_2O emissions had different key limiting factors in the permafrost region. The nongrowing season and the annual N_2O emissions were driven by soil temperature, whereas the growing season N_2O emissions were affected by soil temperature, water table level, and their interaction.

Data availability. The data used in the present study are available in the Supplement.

Supplement. The supplement related to this article is available online at: https://doi.org/

Author contributions. Dawen Gao and Hong Liang designed and guided the experiment, provided supervision, and contributed to revise of the manuscript. Tijiu Cai and Houcai Sheng provided and set up field experimental sites. Liquan Song conducted laboratory analysis. Weifeng Gao conducted the field sampling, analyzed the data and wrote the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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