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Seasonal Variation of Emission Fluxes of CO_2, CH_4, and N_2O from Different Larch Forests in the Daxing'An Mountains of China

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Abstract: Using a static chamber-gas chromatography method, we investigate the characteristics of soil CO_2, CH_4, and N_2O fluxes and their relationships with environmental factors during the growing season in four typical *Larix gmelinii* forests (moss–*Larix gmelinii* forest, *Ledum palustre*–*Larix gmelinii* forest, herbage–*Larix gmelinii* forest, and *Rhododendron dauricum*–*Larix gmelinii* forest) in the Greater Khingan Mountains. Our results show that all four forest types are sources of CO_2 emissions, with similar average emission fluxes (146.71 mg·m^{-2} h^{-1}–211.81 mg·m^{-2} h^{-1}) and no significant differences. The soil in the moss–*Larix gmelinii* forest emitted CH_4 (43.78 µg·m^{-2} h^{-1}), while all other forest types acted as CH_4 sinks (−56.02 µg·m^{-2} h^{-1}–−28.07 µg·m^{-2} h^{-1}). Although all forest types showed N_2O uptake at the beginning of the growing season, the N_2O fluxes (4.03 µg·m^{-2} h^{-1}–5.74 µg·m^{-2} h^{-1}) did not differ significantly among the four forest types for the entire growing season, and all acted as sources of N_2O emissions. The fluxes of CO_2, CH_4, and N_2O were significantly correlated with soil temperature and soil pH for all four forest types. Multiple regression analysis shows that considering the interactive effects of soil temperature and moisture could better explain the changes in greenhouse gas emissions among different forest types. The average Q_{10} value (8.81) of the moss–*Larix gmelinii* forest is significantly higher than that of the other three forest types (3.16–3.54) ($p < 0.05$), indicating that the soil respiration in this forest type is more sensitive to temperature changes.

Keywords: greenhouse gases; *Larix gmelinii*; temperature sensitivity; Greater Khingan Mountains

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1. Introduction

Over the past century, global warming has become an incontrovertible phenomenon. The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report highlights that global warming has accelerated significantly in recent years. Significantly, CO_2, CH_4, and N_2O are the top three contributors to the enhanced greenhouse effect, occupying the first, second, and fourth positions, respectively. Scientific evidence indicates that the global concentration of CO_2 has risen from approximately 280 ppm before the Industrial Revolution to around 410 ppm in 2019, and the concentrations of CH_4 and N_2O (in 2012) have increased by 160% and 20% [1], respectively; therefore, these conditions have ultimately led to a rapid increase in global average temperature. Research shows that the temperature between 2001 and 2020 increased by 0.99 °C compared to the pre-industrial era [2]. The excessive warming amplitude and rapid warming rate is concerning [3]. Consequently, research on the source/sink effects and intensity of ecosystem carbon is receiving increasing attention. Notably, investigating the response mechanisms of CO_2, CH_4, and

N_2O to environmental factors and their contribution to the greenhouse effect is a crucial aspect of global climate change research.

Research on soil CO_2, CH_4, and N_2O emissions in recent decades has focused primarily on different land use types, such as croplands [4], grasslands [5], wetlands, and deserts [6,7]. However, studies on greenhouse gas emissions from pristine forest ecosystems in high-altitude regions are relatively uncommon [8]. Forest ecosystems, as a critical component of terrestrial ecosystems, not only maintain over 86% of the global vegetation carbon pool but also support 73% of the global soil carbon pool [9]. Therefore, even minor changes in forest soil can potentially affect global atmospheric greenhouse gas concentrations, which, in turn, can impact the structure and functions of terrestrial ecosystems [10].

The Daxing'anling forest region, the largest pristine forest area in China and the only bright coniferous forest area in the country, plays an irreplaceable role in carbon sequestration and emission reduction, soil conservation, climate regulation, air purification, biodiversity protection, and maintaining ecological balance [11]. Consequently, in the context of global warming, research on the levels of greenhouse gas emissions from natural forest soils and the effects of soil temperature and humidity on carbon emissions in high-altitude regions in China has become increasingly important.

This study aims to analyze the characteristics of CO_2, CH_4, and N_2O emissions from the soil of four typical *Larix gmelinii* forests in the Daxing'anling region during the growing season (May to September) and their relationship with environmental factors. The ultimate goal of this study is to provide a theoretical basis for the overall accounting of soil carbon emissions in this region.

2. Materials and Methods

2.1. Site Description

The study area is located within the Huzhong National Nature Reserve of the Daxing'anling Mountains (122°42′14″–123°18′05″ E; 51°17′42″–51°56′31″ N) and belongs to a cold temperate continental monsoon climate region. The region experiences distinct spring and autumn seasons, with a short summer period (generally not exceeding 30 days), large temperature differences between the four seasons and day and night, and an annual average temperature of −4.3 °C. The coldest month is January, with an average temperature of −35.8 °C, while the hottest month is July, with an average temperature of 24.5 °C. The frost-free period ranges from 80 to 100 days, and the plant growth period is relatively short (around 100 days). The study area is located at an elevation of 847 to 974 m, with a maximum elevation difference of 16.6 m.

The experimental site is a 25-hectare permanent monitoring plot (122°59′14″–123°00′03″ E; 51°49′01″–51°49′19″ N, altitude range 847 m–974 m) within the reserve. The vegetation in the plot is vertically distributed, and the main vegetation types include a moss–*Larix gmelinii* forest (XL) located in the valley, a *Ledum palustre*–*Larix gmelinii* forest (DX) located in the lower part of the mountain slope, an herbage–*Larix gmelinii* forest (CL) located in the middle and upper part of the mountain slope, and a *Rhododendron dauricum*–*Larix gmelinii* forest (DJ) located in the upper part of the mountain slope. All the forests are mature, with a slope ranging from 5° to 27°, and a canopy closure ranging from 0.3 to 0.7. The soil is mainly brown coniferous forest soil, with a thin soil layer containing a large number of gravel particles, and no clear differentiation is observed in the soil profile. It should be noted that the soil subtypes of the four forest types are different. Among them, XL belongs to the surface latent brown coniferous forest soil; due to its low-lying terrain, soil water supersaturation, and the existence of a seasonal frozen layer and permafrost layer, litterfall cannot be completely decomposed, resulting in the process of peatification and gleization, thus forming semi-peaty soil texture. The other three forest types of soil belong to the brown coniferous forest soil subclass.

2.2. Gas Sampling and Flux Measurement

Gas sampling and flux measurement: gas fluxes of CO_2, CH_4, and N_2O from the soil surface of the four *Larix gmelinii* forests (XL, DX, CL, and DJ) were measured using a static chamber-gas chromatography method from May to September 2019. The sampling chamber was made of stainless steel and covered with reflective paper. It was divided into a top chamber (50 cm × 50 cm × 50 cm) and a base (50 cm × 50 cm × 20 cm). During gas sampling, the top chamber was placed in the groove of the base, and water was added to ensure airtightness. The base of the sampling chamber remained stationary throughout the growing season to minimize interference with the internal vegetation and soil. A small fan was installed inside the chamber to avoid concentration differences. Three replicates were randomly set up for each forest type, and gas samples were collected on one clear day during the first, second, and third ten-day periods of each month between 9:00 and 12:00. Gas samples were collected using a 60 mL syringe, and one sample was taken every 10 min for 30 min (four gas samples were collected for each chamber) and stored in gas bags. CO_2 and CH_4 gas concentrations were analyzed using an HP4890 gas chromatograph. Gas fluxes were calculated using the following formula:

$$F = \frac{dc}{dt} \cdot \frac{M}{V_0} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \cdot H \quad (1)$$

where F is the gas flux (mg·m^{-2} h^{-1}), with positive values indicating emissions and negative values indicating uptake; dc/dt is the slope of the linear change in gas concentration over time during sampling; M is the molar mass of the gas being measured; P and T are the atmospheric pressure and temperature at the sampling site; H is the height of the sampling chamber; and V_0, P_0, and T_0 are the molar volume, standard atmospheric pressure, and absolute temperature of the gas at standard conditions, respectively.

2.3. Soil Sampling and Measurement

Measurement of soil physicochemical properties and environmental factors: during gas sampling, soil temperature at depths of 5, 10, and 15 cm was measured using a portable thermometer (JM624), and soil moisture content at depths of 5, 10, and 15 cm was determined using a time-domain reflectometer (TDR-100). Six points from each forest type were randomly selected, and soil drills were used to obtain 0–15 cm mixed soil samples for the determination of soil chemical properties. The SOC content was measured using the $K_2Cr_2O_7$ oxidation approach [12]. Total nitrogen (TN, g kg^{-1}) was monitored using a C/N analyzer (Elementar, Langenselbod, Germany) [13]. Soil pH value was calculated with a pH meter in the supernatant (1:5 soil:water) (Hach Company, Loveland, CO, USA).

2.4. Statistical Analyses

Analyze and visualize data using R (version 4.2.1). The least significant difference (LSD) test for one-way analysis of variance (ANOVA) was used to distinguish the difference and significance of the CO_2 flux, CH_4 flux, N_2O flux, and soil indicators under different forest types. Spearman correction analysis was used to determine the pairwise correlation between the greenhouse gas flux and soil indicators under different forest types. Multiple linear stepwise regression analysis was used to screen the influencing factors of greenhouse gas flux in different forest types. Akaike information criterion (AIC) [14] was used to measure the effect of soil temperature and humidity interaction on the goodness of equation fitting.

3. Results and Analysis

3.1. CO_2 Flux

During the growing season (May to September), the average soil CO_2 fluxes of four forest types were 146.71 (XL), 187.69 (DX), 211.81 (CL), and 194.4 mg·m^{-2} h^{-1} (DJ) (Figure 1), respectively; cumulative emissions (142 days from 5 May to 23 September) in descending order are 7218.48 (CL) > 6625.15 (DJ) > 6396.48 (DX) > 4999.88 kgCO_2 ha^{-1} (XL) (Table 1). There was no significant difference among them ($p > 0.05$), and all of them acted as sources of CO_2 emissions (Figure 1). Among them, CL had the highest CO_2 emission intensity, which was 1.09 (DJ), 1.13 (DX), and 1.44 times (XL) higher than the other forest types, respectively. The CO_2 flux from the soil of the four forest types showed a significant seasonal variation pattern, with higher emissions in summer than in autumn and spring. The four forest types have similar CO_2 emission intensity in spring, but XL has lower CO_2 emissions than the other three forest types in summer and autumn. The lowest CO_2 flux was observed in spring, and as the month advanced, the CO_2 emission intensity showed a characteristic of first increasing and then decreasing. However, there were some differences in the specific patterns: XL and DX had the highest average CO_2 flux in midsummer, and the former reached the peak emission (285.25 mg·m^{-2} h^{-1}) in mid-July, while the latter reached the peak emission (321.14 mg·m^{-2} h^{-1}) in late July. The CL and DJ had the highest average CO_2 flux in late summer, and both reached the peak emission (336.15 and 326.49 mg·m^{-2} h^{-1}, respectively) in early August. There was no significant difference in the CO_2 fluxes among the four forest types for the same month ($p > 0.05$) according to the variance analysis.

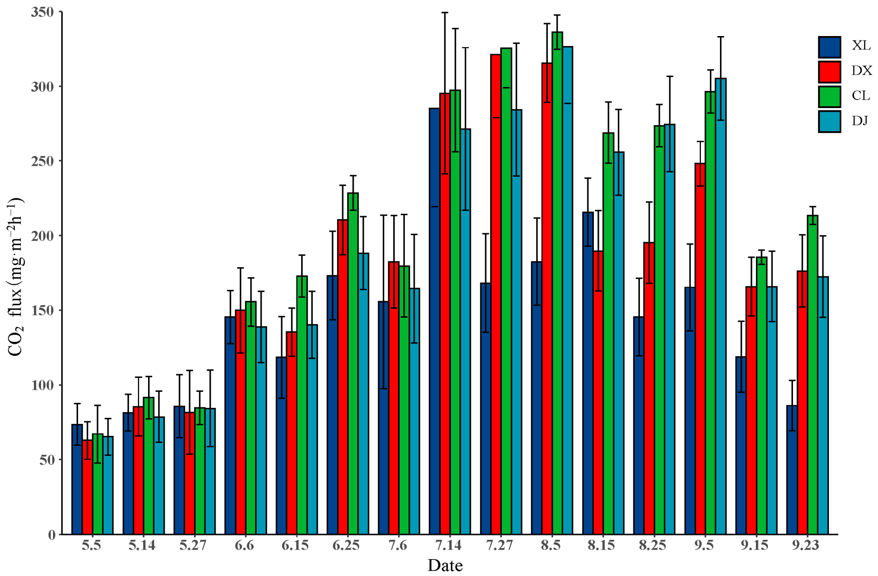

Figure 1. CO_2 flux of different forest types.

Table 1. Cumulative greenhouse gas emissions and global warming potential.

Forest Type	CO_2 Cumulative Emissions (kg ha^{-1})	CH_4 Cumulative Emissions (kg ha^{-1})	N_2O Cumulative Emissions (kg ha^{-1})	GWP (kg ha^{-1})
XL	4999.88	1.16	0.196	5087.29
DX	6396.48	−1.91	0.143	6391.34
CL	7218.48	−0.96	0.137	7259.31
DJ	6625.15	−1.26	0.141	6635.67

3.2. CH_4 Flux

During the growing season, there were significant differences ($p < 0.05$) in the average soil CH_4 fluxes among the four forest types, which were 43.78 (XL), −56.02 (DX), −28.07 (CL), and −37.06 µg·m^{-2} h^{-1} (DJ), respectively (Figure 2); XL cumulative emissions were 1.16 kgCH_4·ha^{-1}, while other forest types cumulatively absorbed 1.91 (DX), 0.96 (CL), and 1.26 KgCH_4 ha^{-1} (DJ) (Table 1). The soil of XL showed significant differences in CH_4 emissions from the other three forest types ($p < 0.05$) and exhibited a clear seasonal variation pattern, with a feature of first increasing and then decreasing. The lowest flux was observed in early May (−3.18 μg·m^{-2} h^{-1}), indicating CH_4 uptake, while the peak emission (118.86 μg·m^{-2} h^{-1}) was reached in mid-August. The soil of DX, CL, and DJ showed a trend of CH_4 uptake throughout the growing season, but all of them exhibited CH_4 emissions in early May. Among them, the absorption intensity of DX in summer is higher than that in spring and autumn, but the peak uptake (−101.9 μg·m^{-2} h^{-1}) occurred in spring (27 May), with no obvious seasonal variation pattern. CL and DJ showed the highest uptake intensity in early summer (6 June), with the former reaching the peak uptake (−49.54 μg·m^{-2} h^{-1}) in mid-June, but the latter reaching the peak uptake (−74.32 μg·m^{-2} h^{-1}) in autumn (5 September). Overall, the two forest types exhibited a trend of increasing, decreasing, and then increasing CH_4 uptake intensity.

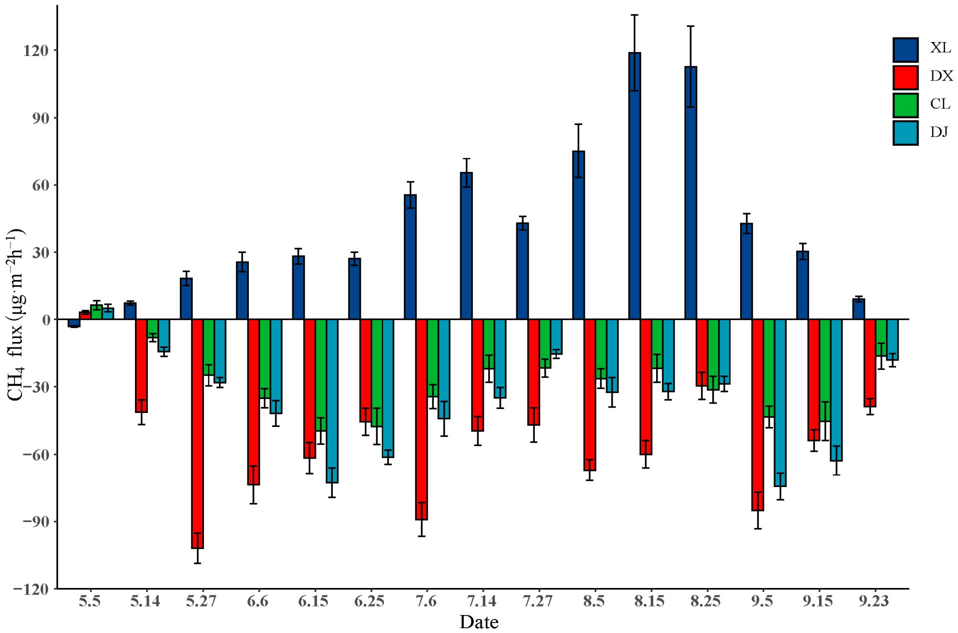

Figure 2. CH_4 flux of different forest types.

3.3. *N_2O Flux*

During the growing season, there were no significant differences ($p > 0.05$) in the average soil N_2O fluxes among the four forest types, which were 5.74 (XL), 4.2 (DX), 4.03 (CL), and 4.15 μg·m^{-2} h^{-1} (DJ) (Figure 3). Cumulative emissions in descending order were 0.196 (XL) > 0.143 (DX) > 0.141 (DJ) > 0.137 kgN_2O ha^{-1} (CL) (Table 1), all of which acted as sources of N_2O emissions, but in early spring, they showed absorption of N_2O, which then shifted to N_2O emissions with the advancement of the month (Figure 3). Among them, XL and DX exhibited the highest uptake peaks (−6.61 and −3.88 μg·m^{-2} h^{-1}, respectively) in mid-May, and the former exhibited the highest emission peak (13.14 μg·m^{-2} h^{-1}) in early September, while the latter exhibited the highest emission peak (10.71 μg·m^{-2} h^{-1}) in early August. The CL and DJ exhibited the highest uptake peaks (−1.19 μg·m^{-2} h^{-1} and −10.32 μg·m^{-2} h^{-1}, respectively) in early May, and the former exhibited the highest emission peak (13.99 μg·m^{-2} h^{-1}) in mid-August, while the latter exhibited the highest emission peak (16.61 μg·m^{-2} h^{-1}) in early August. The differences in soil N_2O fluxes among different forest types in the same season showed different patterns, with significant differences ($p < 0.05$) observed between CL and DJ in spring (May) and between CL and XL in autumn (September).

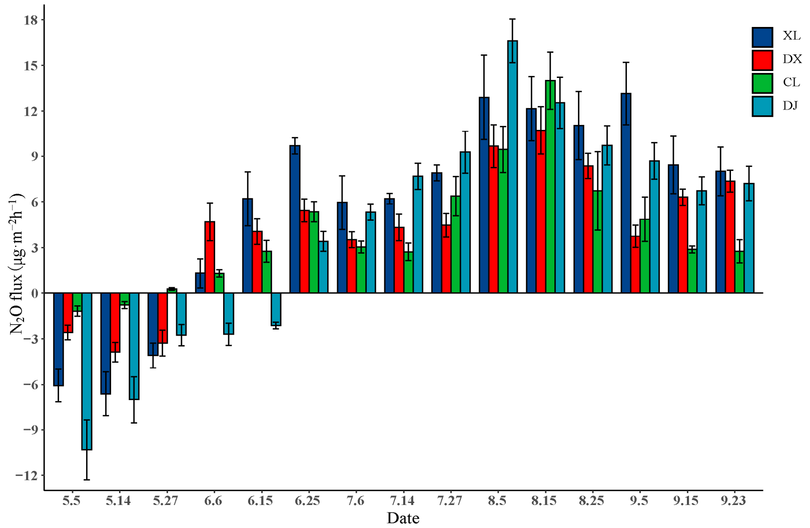

Figure 3. N_2O flux of different forest types.

3.4. Soil Indicators

During the growing season, the average soil temperatures of the four forest types were 2.3 °C (XL), 6.71 °C (DX), 7.7 °C (CL), and 6.43 °C (DJ). The soil temperatures at the depths of 5 (Figure 4A), 10 (Figure 4B), and 15 cm (Figure 4C) showed the same seasonal pattern as the average soil temperature, with higher temperatures in summer, followed by autumn and winter. XL had the lowest average temperature, which was significantly different from the other forest types ($p < 0.05$). Analysis of soil temperature in different months showed that the lowest temperatures for all four forest types occurred in May, while XL had the highest temperature in July, and the other three forest types had the highest temperature in August.

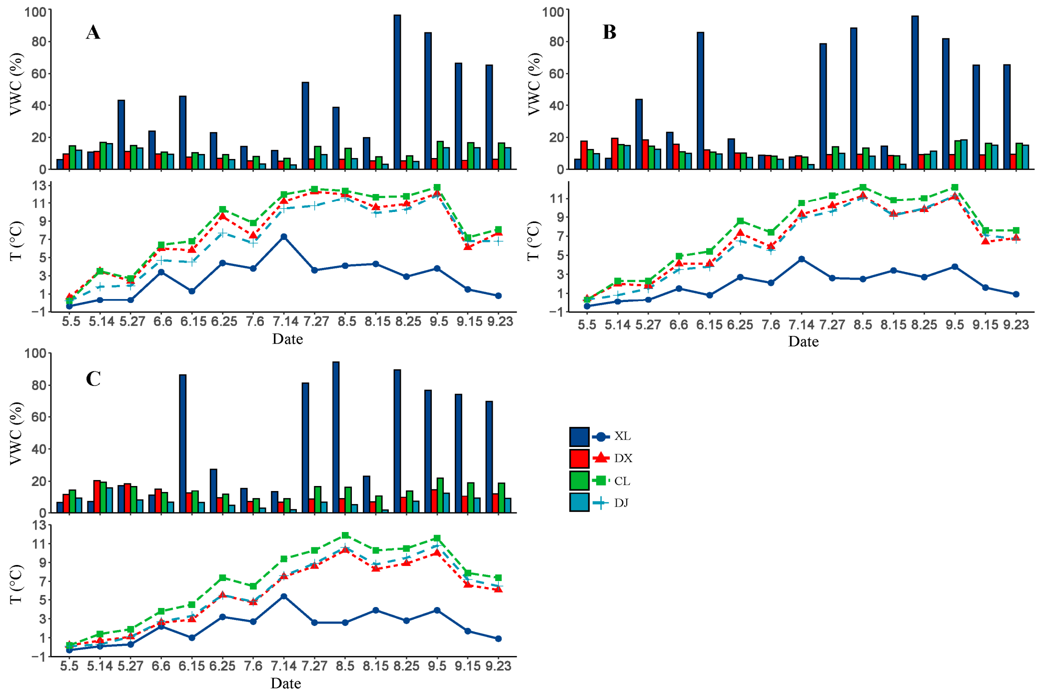

Figure 4. Soil temperature and humidity of different forest types. (**A**–**C**) represent the temperature and humidity of 5 cm, 10 cm, and 15 cm soil depth, respectively, in sequence.

The soil moisture content of the four forest types were 44.22% (XL), 10.12% (DX), 13.23% (CL), and 8.87% (DJ), with XL having the highest moisture content, which was significantly different from the other forest types ($p < 0.05$). The soil moisture content at a depth of 5 cm ranked as XL > CL > DJ > DX (Figure 4A), while the order of soil moisture content at other depths was consistent with the average soil moisture content.

The average soil organic carbon and total nitrogen content during the growing season and the highest monthly content were all highest in XL, which was significantly different from the other forest types ($p < 0.05$) (Figure 5A,C). The pH of the soil in all four forest types showed an acidic trend, and there were significant differences ($p < 0.05$) in the soil pH between XL, DX, and CL (Figure 5B). The differences in soil organic carbon, pH, and total nitrogen among the four forest types varied with the months, as shown in the figure.

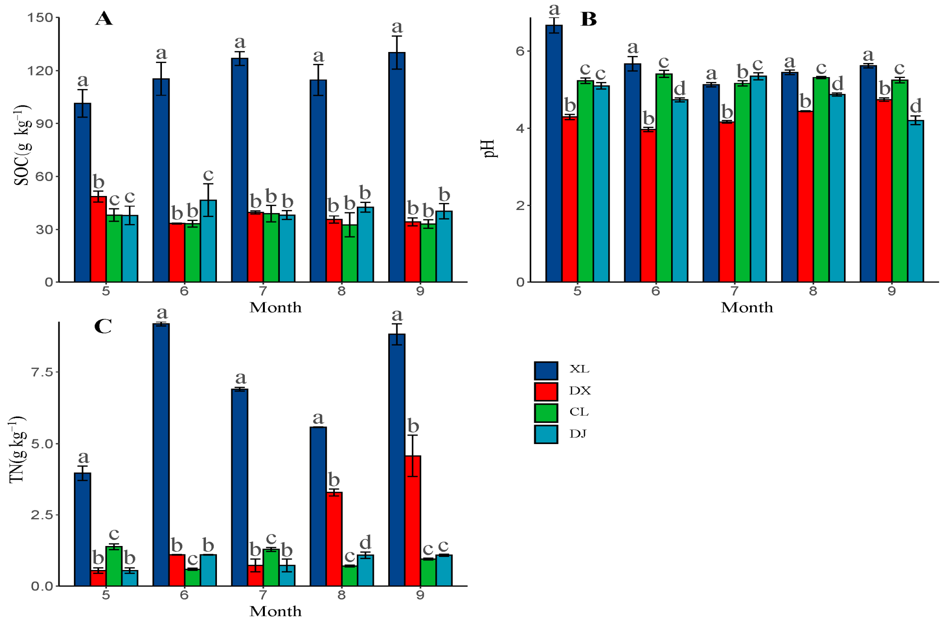

Figure 5. Soil organic carbon (SOC), pH, and total nitrogen (TN) of different forest types. Different lower-case letters indicate significant differences between different forest types in the same month ($p < 0.05$).

3.5. Relationship between Greenhouse Gas Flux and Environmental Factors

The correlation analysis between CO_2, CH_4, and N_2O and measured environmental factors showed that the soil CO_2 flux of the four forest types was significantly positively correlated with soil temperature at depths of 5, 10, and 15 cm ($p < 0.001$), and the correlation was close ($R > 0.9$), indicating that soil temperature is an important factor affecting CO_2 emissions (Figure 6). The correlation between CO_2 flux and pH varied among the forest types, with significant positive correlation between DX and pH ($p < 0.001$), and significant negative correlation between the other three forest types and pH ($p < 0.001$). Only in XL was the correlation between soil CO_2 flux and pH close ($R = 0.91$), while in the other three forest types, the degree of correlation was moderate ($R < 0.1$). There was no significant correlation between soil CO_2 flux and soil moisture, soil organic carbon, or soil total nitrogen in the four forest types.

The soil CH_4 flux of the four forest types was significantly correlated with soil temperature at depths of 5, 10, and 15 cm ($p < 0.01$), with significant positive correlation between XL and soil temperature, and significant negative correlation between the other forest types and soil temperature (Figure 6). The soil CH_4 flux of XL and CL was significantly negatively correlated with pH ($p < 0.05$), while the other forest types were significantly positively correlated with pH ($p < 0.05$). There was no significant correlation between soil CH_4 flux and soil moisture at a depth of 5 cm or 10 cm, soil organic carbon, or soil total nitrogen.

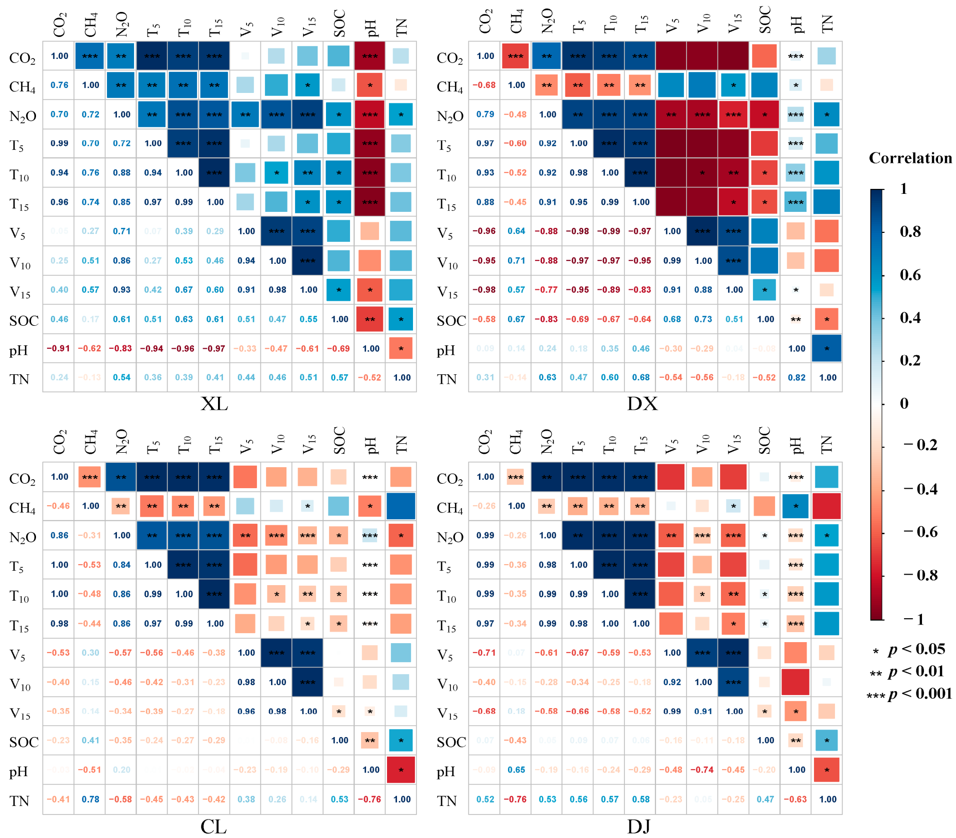

Figure 6. Correlation analysis between greenhouse gas flux and environmental factors.

The soil N_2O flux of the four forest types was significantly positively correlated with soil temperature at a depth of 5 cm ($p < 0.01$) and extremely significantly positively correlated with soil temperature at depths of 10 and 15 cm ($p < 0.001$) (Figure 6). It was also significantly correlated with soil moisture at a depth of 5 cm ($p < 0.01$) and extremely significantly correlated with soil moisture at depths of 10 and 15 cm ($p < 0.001$). The correlation between soil N_2O flux and environmental factors varied among the forest types. XL was significantly positively correlated with soil moisture, while the other forest types were significantly negatively correlated with soil moisture. XL and DJ were significantly positively correlated with soil organic carbon ($p < 0.05$), while the other forest types were significantly negatively correlated with soil organic carbon ($p < 0.05$), with a smaller correlation coefficient in DJ ($R = 0.07$) and a moderate degree of correlation. XL and DJ were significantly negatively correlated with pH ($p < 0.001$), while the other forest types were significantly positively correlated with pH ($p < 0.001$). Among the four *Larix gmelinii* forests, the soil N_2O flux of the grassland was significantly negatively correlated with soil total nitrogen ($p < 0.05$), while the other three forest types were significantly positively correlated with soil total nitrogen ($p < 0.05$).

Multiple linear regression analysis was conducted to examine the relationship between measured environmental factors and soil CO_2, CH_4, and N_2O fluxes in different forest types. To eliminate the influence of multicollinearity on the fitting model, the mean values of soil temperature and moisture at depths of 5 cm, 10 cm, and 15 cm were used for analysis. The stepwise regression method was employed to select environmental factors with a variance inflation factor (VIF) less than 10 to establish a multiple linear regression model. The interaction effect of soil temperature and moisture was also considered by adding an interaction term to the model. The fit of different models was compared by analyzing the adjusted R^2, equation significance (p), and Akaike information criterion (AIC). The results showed that the environmental factors affecting greenhouse gas emissions varied among different forest types. For example, in XL and DJ, soil temperature and moisture were the main factors affecting CO_2 flux, and the addition of the interaction effect between soil temperature and moisture improved the fit of the model and reduced the AIC value compared to the model without the interaction term (Table 2). Soil moisture and soil total nitrogen were better predictors of CO_2 emissions in DX, while the interaction effect of soil temperature and moisture did not significantly affect CO_2 flux in CL (Table 2).

Table 2. Fitting the relationship between soil greenhouse gas flux and environmental factors.

Forest Type	Gas	Equation	Adj R^2	p	AIC
XL	CO_2	CO_2 = 36.27T − 0.28V − 2.02TN + 113.72	0.995	<0.001	83.15
		CO_2 = 23.48T − 1.29V + 0.4T × V + 97.37	0.998	<0.01	72.17
	CH_4	CH_4 = 23.25T + 0.84V − 0.87SOC − 9.37TN + 120.06	0.912	<0.001	117.97
		CH_4 = −30.1T − 3.37V + 2.48TN + 1.69 T × V + 51.89	0.998	<0.001	52.85
	N_2O	N_2O = 2.71T + 0.19V − 0.05SOC − 4.55	0.987	<0.001	38
		N_2O = −0.09V + 0.99TN + 0.11 T × V − 9.07	0.998	<0.001	5.72
DX	CO_2	CO_2 = 24.33T − 16.84TN + 8.43	0.948	<0.001	130.43
		CO_2 = −24.38V − 6.18TN + 384.45 (T × V Insignificant)	0.997	<0.001	89.91
	CH_4	CH_4 = 0.68SOC − 81.98	0.413	<0.01	92.7
		CH_4 = 1.34V − 69.68 (T × V Insignificant)	0.387	<0.01	92.99
	N_2O	N_2O = − 0.79V + 1.6TN + 39.37	0.892	<0.001	59.53
		N_2O = 0.9T − 6pH + 1.22 TN − 26.11 (T × V Insignificant)	0.939	<0.001	50.51
CL	CO_2	CO_2 = 21.4T − 2.26V + 9.67TN + 68.72	0.99	<0.001	38.78
		CO_2 = 22.27T − 1.7V + 8.7TN + 63.55 (T × V Insignificant)	0.99	<0.001	35.88
	CH_4	CH_4 = −0.53T − 0.25V − 0.12SOC + 30.31TN + 10.07pH − 99.61	0.44	>0.05	114.9
		CH_4 = 20.31T + 13.34V + 6.99TN − 1.5 T × V − 223.53	0.998	<0.001	26.07
	N_2O	N_2O = 0.71T − 1.7	0.715	<0.01	67.99
		N_2O = 4.98T + 2.95V − 6.57 TN − 0.31T × V − 27.04	0.984	<0.001	24.76
DJ	CO_2	CO_2 = 21.18T + 5.49	0.994	<0.001	101.09
		CO_2 = 27.76T + 1.9V − 0.73T × V + 51.64	0.999	<0.001	35.16
	CH_4	CH_4 = 3.07T + 6.32V + 55.37pH − 370.62	0.757	<0.01	112.69
		CH_4 = 12.25T + 11.22V + 15.18pH − 1.37 T × V − 205.64	0.991	<0.001	64.33
	N_2O	N_2O = 2.22T − 21.45	0.984	<0.001	45.83
		N_2O = 3.26T + 0.79V − 0.82pH − 0.12T × V − 14.16	0.999	<0.001	−14.49

The addition of the interaction effect between soil temperature and moisture improved the fit of the model for soil CH_4 flux in XL, CL, and DJ. For DX, soil organic carbon and soil moisture could separately explain soil CH_4 flux, while the fit of the two equations was not high (Table 2).

Except for DX, the addition of the interaction effect between soil temperature and moisture improved the fit of the model for soil N_2O flux in all other forest types and reduced the AIC value.

3.6. Temperature Sensitivity of Soil Respiration and Global Warming Potential

Soil temperature is one of the most important factors affecting soil respiration, and it affects almost every aspect of the soil respiration process. There are many empirical models that describe the relationship between soil temperature and soil respiration, among which the exponential model proposed by Van't Hoff that is widely applicable for ecosystems within a certain temperature range [15]. In this study, the exponential model $R_s = ae^{bt}$ (where R_s is soil CO_2 flux, t is soil temperature, and a and b are parameters to be estimated) was chosen to fit the relationship between soil CO_2 flux and temperature at different soil depths in the four forest types. The parameter b in the exponential relationship model was used to calculate the temperature sensitivity of soil respiration (Q_{10}): $Q_{10} = e^{10b}$. The results showed that there was a good fit between soil CO_2 flux and temperature in all four forest types ($p < 0.001$), and changes in soil temperature could explain the variation in soil respiration rate.

Among the four forest types, the average Q_{10} value in XL was significantly higher than that in the other forest types ($p < 0.05$), with the highest value at a soil depth of

10 cm (11.82) and the lowest at a soil depth of 5 cm (5.31) (Table 3). There was no significant difference in the average Q_{10} values between the DX, CL, and DJ, and the highest Q_{10} value was at a soil depth of 5 cm for all three forest types, with values of 3.32, 3.25, and 3.6, respectively. The lowest Q_{10} value was at a soil depth of 15 cm, with values of 3.03, 3.06, and 3.46, respectively.

Table 3. Temperature sensitivity of soil respiration.

Forest Type	Soil Depth	Equation	R^2	p	b	Q_{10}
XL	5 cm	$CO_2 = 87.7e^{0.167t}$	0.947	<0.001	0.167	5.31
	10 cm	$CO_2 = 85.5e^{0.247t}$	0.868	<0.001	0.247	11.82
	15 cm	$CO_2 = 84.7e^{0.223t}$	0.921	<0.001	0.223	9.3
DX	5 cm	$CO_2 = 62.7e^{0.12t}$	0.876	<0.001	0.12	3.32
	10 cm	$CO_2 = 81.3e^{0.115t}$	0.814	<0.001	0.115	3.16
	15 cm	$CO_2 = 95.1e^{0.111t}$	0.73	<0.001	0.111	3.03
CL	5 cm	$CO_2 = 71.3e^{0.118t}$	0.959	<0.001	0.118	3.25
	10 cm	$CO_2 = 80.9e^{0.115t}$	0.952	<0.001	0.115	3.16
	15 cm	$CO_2 = 90e^{0.112t}$	0.917	<0.001	0.112	3.06
DJ	5 cm	$CO_2 = 71.2e^{0.128t}$	0.988	<0.001	0.128	3.6
	10 cm	$CO_2 = 78.7e^{0.127t}$	0.965	<0.001	0.127	3.56
	15 cm	$CO_2 = 86.5e^{0.124t}$	0.926	<0.001	0.124	3.46

The global warming potential (GWP) is jointly determined by CO_2, CH_4, and N_2O. In a 100-year time frame, the greenhouse effect of CH_4 and N_2O is 25 times and 298 times of CO_2 [16], respectively. The results show that the GWP of the four forest types are 5087.29 (XL), 6391.34 (DX), 7259.31 (CL), and 6635.67 kg ha^{-1} (DJ) (Table 1). Among them, CL is the highest, which is 1.09 times, 1.13 times and 1.42 times of DJ, DX, and XL, respectively.

4. Discussion

4.1. Differences in Greenhouse Gas Flux between Different Forest Types during the Growing Season

The results of this study showed that all four forest types were sources of CO_2 emissions, with similar emission intensities and no significant differences. Although XL had a higher soil organic carbon content, its CO_2 emission intensity was the lowest among the four forest types. The reason may be that the forest type is located in low-lying terrain, and there is long-term ponding during the growth season. When exposed to the same solar radiation heat, the warming amplitude is smaller than that of the other three forest types. Although the soil contains rich substrate carbon sources, the lower temperature weakens the activity of microorganisms involved in soil respiration, and ultimately limits the soil CO_2 flux of this forest type. Therefore, the soil carbon storage does not significantly affect CO_2 emissions [17]. This also indirectly indicates that temperature is the main controlling factor of soil respiration in this region. The soil CO_2 flux in all four forest types showed a clear seasonal pattern, with higher fluxes in summer and lower fluxes in spring and autumn, which is consistent with previous studies on the seasonal variation of soil respiration in the Daxing'An Mountains [11].

It has been reported that different factors such as tree species composition, understory plant species, and vegetation cover can affect the types and numbers of rhizosphere and soil microorganisms, thereby affecting soil respiration [18]. Although the four forest types in this study had differences in shrub and herbaceous plant species, the dominant tree species in all four forest types were *Larix gmelinii*, and the forest canopy closure was above 0.7 in three forest types except for XL (0.2–0.3). DX, CL, and DJ have the same tree species and greater density, and the effect of soil temperature on XL's CO_2 flux may be the main reasons for the lack of significant differences in soil CO_2 flux among the four forest types [19]. To explore the differences and mechanisms of soil CO_2 flux among different forest types, in addition to measuring soil microorganisms, improvements in measurement methods such as long-term and continuous monitoring of soil CO_2 flux are needed to more accurately reflect the differences among different forest types.

The production and oxidation of CH_4 in soil occur simultaneously, and whether the soil emits or absorbs CH_4 depends on which process dominates. It is generally believed that methane-oxidizing bacteria are more active in well-ventilated soil environments, which is more conducive to CH_4 oxidation, while methane-producing bacteria are more active in poorly ventilated, humid and anaerobic environments, which is more conducive to CH_4 production [20]. In this study, XL was often flooded during the growing season, which is more similar to wetland soil. Long-term soil waterlogging is beneficial for the production of anaerobic environments, with stronger activity of methane-producing bacteria. The overall soil environment is more conducive to the production and emission of CH_4. During the growing season, as the temperature increases, the permafrost of this forest type begins to melt; as the temperature continues to rise, the melted soil layer becomes deeper, and the larger anaerobic environment and stronger soil microbial activity are more conducive to the production of CH_4. This also explains the significant seasonal variation in CH_4 emissions from the soil of XL.

It has been reported that only about 10% to 24% [21,22] of the CH_4 produced in the soil of wetland ecosystems is emitted into the atmosphere, and the rest is oxidized as it diffuses from the soil–atmosphere interface upwards. In this study, the soil of DX, CL, and DJ had good ventilation, and this oxygen-rich environment was more conducive to CH_4 oxidation by methanotroph, making the CH_4 concentration in the soil lower than that in the atmosphere. The existence of concentration differences leads to the diffusion of CH_4 from the atmosphere into the soil, so these three types of forest soils exhibit absorption of CH_4. The CH_4 absorption by CL and DJ showed an increasing-decreasing-increasing trend, which may be due to the increased microbial activity with rising temperature during the growing season [23,24], leading to a gradual increase in CH_4 absorption. The rainy season favors the formation of anaerobic environments in the soil, which is conducive to CH_4 production, resulting in an overall decreasing trend in CH_4 absorption. In the autumn, with the decrease in rainfall and the influx of water into the lower-altitude DX and XL, there is CH_4 absorption by the soil in the DJ and CL.

N_2O in soil is mainly produced through nitrification and denitrification [25]. In this study, although the four forest types are emission sources of N_2O, they showed a small absorption of N_2O at the beginning of the growing season. The reason may be that the temperature in the area in early spring is low, which is not conducive to the production of N_2O. Studies have indicated that the temperature range suitable for the activity of microorganisms such as nitrifying bacteria is 15 °C–35 °C [16], and when the temperature is less than 5 °C or more than 40 °C, the occurrence of nitrification will be inhibited, with the lower temperature and weaker microbial activity resulting in lower nitrogen mineralization and utilization rates in the soil. Additionally, since the concentration of N_2O in the atmosphere is higher than that in the soil [26,27], the soil in this region acts as a sink for N_2O at the beginning of the growing season. Over the course of the whole growing season, XL's emission of N_2O is stronger than that of the other three forest types, and the higher soil water content may be one of the important reasons, because some scholars have pointed out that when the soil water content is 45%–75% of the saturated water content, it is more conducive to the production of soil N_2O [28].

The production and emission of N_2O is a complex biochemical process. In this study, there were no significant differences in N_2O emissions among the four forest types; the reason may be that DX, CL, and DJ are of the same soil type and have similar nitrogen cycle processes, and the types and abundance of microorganisms involved in nitrification and denitrification processes are similar, resulting in similar N_2O emission intensity. XL may have higher total nitrogen and organic carbon content, but the low temperature may limit the biochemical process in its soil, although the emission of N_2O is greater than that of the other three forest types, but not significantly. Due to differences in understory vegetation, the content, storage form, and utilization process of nitrogen in the soil were not the same [29]. To explore the conversion process of nitrogen in the soil and its cycling process among the soil–plant–atmosphere, it is necessary to measure and analyze factors such as soil microorganisms, rhizobia, nitrate nitrogen, and ammonium nitrogen.

4.2. Selection of Factors Influencing Greenhouse Gas Fluxes

Correlation and regression analyses both indicated that temperature is an important factor influencing greenhouse gas fluxes in the study area, which is consistent with previous research results [30]. However, this study also observed differences between environmental factors significantly correlated with greenhouse gas fluxes and those with significant regression coefficients in the regression analysis. For example, in XL and CL, temperature and pH were significantly correlated with soil CO_2 flux, but in the regression analysis, temperature, moisture, and total nitrogen were significant factors. For soil CH_4 flux, temperature, moisture, and pH were significant environmental factors in correlation analysis, but in regression analysis, soil total nitrogen and organic carbon also had a significant impact. The N_2O flux in the four forest types was significantly correlated with measured environmental factors, but the significant environmental factors in the regression analysis varied depending on the forest type.

Normally, factors that are not significantly correlated are not suitable for regression analysis. However, based on previous experience and research results, the regression analysis results in this study were more reasonable. Adding the interaction effect of soil temperature and moisture significantly improved the goodness of fit of the equation. This result not only indicates that the effects of soil moisture and temperature on gas flux are not the same under different soil temperature/moisture conditions, but also partially confirms the inference that the regression analysis results are more reasonable. There may be two reasons for the above phenomenon: firstly, there may be inhibitory variables in environmental factors; due to the addition of inhibitory variables, environmental factors that were not originally related to gas flux show significant correlation with gas flux in regression analysis results. Secondly, there is a certain degree of collinearity between certain environmental factors. Due to the fact that multiple regression analysis controls other explanatory variables to analyze the impact of a certain explanatory variable on the response variable [31], some environmental factors with collinearity in the results may be covered, resulting in fewer environmental factors in the regression analysis results than in the correlation analysis results. However, further exploration is needed to determine which environmental variables are used as inhibitory factors or which environmental factors are removed to completely eliminate collinearity effects. The appearance of this phenomenon also provides directions for future research. For example, research on the main controlling factors of greenhouse gas fluxes should focus on factors directly related to gas production mechanisms, such as soil microorganisms, active organic carbon, nitrate nitrogen, and ammonium nitrogen. The reasons for the appearance of this phenomenon may be due to the occurrence of inhibition effects between environmental factors, and further exploration is needed to identify which environmental variables act as inhibitory factors.

4.3. Temperature Sensitivity of Soil Respiration and Global Warming Potential in Different Forest Types

In this study, among the four forest types, XL's CO_2 emission flux accounted for the smallest proportion in GWP, but it was still as high as 98.28%. DX, CL, and DX even appeared as a sink of CH_4. In general, CH_4 and N_2O contributed very little to GWP, while the CO_2 flux directly affected and even determined the GWP in this region.

Soil temperature is considered the primary limiting factor of soil respiration, typically explaining 60–80% of the variation in soil respiration rates [32]. Soil respiration temperature sensitivity coefficient (Q_{10}) is generally used to represent the effect of temperature on soil respiration rates. In this study, the Q_{10} values for XL ranged from 5.31 to 11.82, which is higher than the conclusion that the global Q_{10} value ranges from 1.3 to 3.3 [33] summarized by relevant scholars. The reason may be that the soil of this forest type is peat soil with a high organic matter content. Additionally, the influence of the permafrost layer results in lower soil temperatures throughout the growing season. If low-temperature stress is reduced, the higher organic matter content can provide sufficient substrate for microorganisms. Soil respiration intensity will increase sharply as the temperature rises. This is similar to the conclusion that Q_{10} values are higher in environments with lower soil temperatures, as found in relevant studies [34,35].

The Q_{10} values for DX, CL, and DJ ranged from 3.03 to 3.56, consistent with the conclusion of Chen et al. [36] that the Q_{10} value range measured in the northeastern region of China is 3.0 to 5.0. Zheng et al. [37] summarized and analyzed the temperature sensitivity of soil respiration in Chinese forest ecosystems and found that 72% of the Q_{10} values were concentrated between 1.5 and 3.0. However, the Q_{10} values of the four forest types in this study were all greater than 3.0, possibly because the temperature sensitivity of soil respiration has a certain spatial heterogeneity, which may increase with the increase of latitude and altitude. This is because researchers have analyzed 647 sets of global flux data and found that the temperature sensitivity of ecosystem respiration in different climate zones is cold temperate > temperate > tropical [38]. Chen and Tian [39] found that the Q_{10} values (2.5–5.5) in northern forests are higher than those in temperate forests (1.1–5.6), and research results of Janssens et al. [40] on the Q_{10} values (4.3–16) of soil in the North European beech forest also confirm the effect of latitude on the temperature sensitivity of soil respiration.

Although the soil CO_2 emission intensity is not high throughout the growing season, the high Q_{10} values indicate that soil CO_2 flux in this region is more sensitive to temperature fluctuations. In the context of global climate change, studying the feedback mechanism of soil carbon emissions in high-altitude areas in response to atmospheric temperature changes is an important task in global carbon emission estimation.

5. Conclusions

During the growing season, measurements of soil greenhouse gas flux and analysis of soil physicochemical properties were conducted for four *Larix gmelinii* forests. The results showed that the four forest types of soils are acidic, and all are sources of CO_2 emissions. GWP indicates that CO_2 flux plays an absolutely dominant role in affecting the greenhouse effect in this region. Soil temperature was the main factor affecting CO_2 flux; as a result, the moss–*Larix gmelinii* forest located in the valley and with the lowest average soil temperature had the lowest soil CO_2 emission flux. Considering the interactive effects of temperature and water content could better explain the variation in soil CO_2 flux in the moss–*Larix gmelinii* forest and *Rhododendron dauricum*–*Larix gmelinii* forest, and Q_{10} indicated that the soil CO_2 flux in the moss–*Larix gmelinii* forest was more sensitive to temperature changes. Due to its geographical location, the moss–*Larix gmelinii* forest has a higher soil moisture content and is more prone to an anaerobic environment, which also makes it a CH_4 emission source, while other forest types are CH_4 sinks. In addition, since the moss–*Larix gmelinii* forest has the highest soil organic carbon content, total nitrogen content, and Q_{10} value, its soil carbon emission situation, out of the four forest types, should be given more attention in the context of global warming. Soil temperature, water content, and their interactions affect the soil CH_4 fluxes of the *Ledum palustre*–*Larix gmelinii* forest, herbage–*Larix gmelinii* forest, and *Rhododendron dauricum*–*Larix gmelinii* forest. All four forest types are sources of N_2O emissions, but lower temperatures during early spring cause them to absorb N_2O superficially, and the effects of the environmental factors on N_2O flux varied among different forest types. Except for the *Ledum palustre*–*Larix gmelinii* forest, multiple regression analysis showed that the addition of the interactive effects of soil temperature and water content could better explain the changes in N_2O flux in the three other forest types.

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