Article

Seasonal Dynamics of Greenhouse Gas Emissions from Island-like Forest Soils in the Sanjiang Plain: Impacts of Soil Characteristics and Climatic Factors

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Abstract: Using the static chamber–gas chromatography method, this study investigates the flux characteristics of CO2, CH4, and N2O in the soils of three typical island-like forests in the Sanjiang Plain during the growing season (May to September), as well as their relationships with environmental factors. The results indicate that the soils of the Broadleaf mixed forest, Quercus mongolica forest, and Betula platyphylla forest act as emission sources for CO2 and N2O, with average fluxes of 433.92, 452.41, and 358.17 µg m⁻² h⁻¹ for CO2 and 12.48, 13.02, and 10.51 µg m⁻² h⁻¹ for N2O, respectively. The differences among forest types are not significant. All three forest types serve as sinks for CH4, with average fluxes of −22.52, −23.29, and −0.76 µg m⁻² h⁻¹. The Betula platyphylla forest has a significantly weaker absorption intensity compared to the other types (p < 0.01). The measured environmental factors collectively explain 66.58% of the variability in greenhouse gas fluxes in the island-like forests, with soil temperature, soil moisture, and total nitrogen content being the main influencing factors in the region. Rising temperatures favor the emission of CO2 and N2O and the absorption of CH4 in all three forest types. Increased soil moisture inhibits the absorption of CH4 in the Broadleaf mixed forest and Quercus mongolica forest, while higher levels of alkali-hydrolyzed nitrogen enhance the N2O flux in the Quercus mongolica forest. Soil organic carbon and soil pH significantly influence only the greenhouse gas fluxes of the Betula platyphylla forest.

Keywords: seasonal dynamics; island-like forest; greenhouse gas emissions

1. Introduction

Wetland ecosystems play a crucial role in the global carbon and nitrogen cycles, with their soil greenhouse gas fluxes significantly influencing global climate change [1]. The Sanjiang Plain wetlands, located in Northeastern China and formed of the alluvial plains of the Heilong, Songhua, and Wusuli rivers, represent one of the largest wetland ecosystems in China and one of the most extensive freshwater wetlands globally. Despite considerable research on soil greenhouse gases in the Sanjiang Plain, which has predominantly focused on various wetland types, there has been limited attention paid to greenhouse gas emissions from forest ecosystems. Notably, studies on soil greenhouse gas fluxes in insular forests within wetlands are particularly scarce [2–5].

Insular forests in wetlands are unique wetland ecosystems that develop on elevated highlands or mounds within wetlands, swamps, or lakes [6]. These “islands” are relatively dry compared to their surrounding wetland environments due to their higher elevation.
Consequently, insular forests often exhibit rich plant diversity, including various trees, shrubs, and herbaceous plants. Compared to non-forested wetlands with open water bodies, insular forests may have higher carbon sequestration levels [7]. Additionally, the more complex understory and litter layers in these forests can influence carbon dioxide emissions [8].

While it is well known that wetland ecosystems are significant sources of CH₄, the soils of insular forests within wetlands generally have good aeration due to the influence of tree and shrub root systems. This aeration reduces the opportunities for CH₄ production under anaerobic conditions [9,10]. Variations in soil properties and aboveground vegetation can lead to differences in microbial community structure and function, which are key drivers of greenhouse gas production. The differences between insular forests and traditional wetlands may be reflected in the microbially mediated processes of CH₄ and N₂O production and consumption [11–13].

In summary, the complexity and variability of ecological conditions in insular forests and traditional wetlands lead to different greenhouse gas emission patterns. Therefore, it is essential to measure the soil CO₂, CH₄, and N₂O fluxes of insular forests to estimate the greenhouse gas emissions in these areas. This study aims to measure the soil CO₂, CH₄, and N₂O fluxes of three typical and representative insular forests in the Sanjiang Plain, analyze the source and sink functions of soils for these gases, and explore the relationship between greenhouse gas fluxes and environmental factors. The findings are expected to provide essential data and theoretical references for the overall greenhouse gas accounting of the Sanjiang Plain.

2. Materials and Methods

2.1. Site Description

The study site is located at the Sanjiang Plain Wetland Ecological Positioning Research Station of the Heilongjiang Province Academy of Sciences Institute of Nature and Ecology, situated within the Honghe National Nature Reserve in the northeastern part of the Sanjiang Plain, with geographical coordinates ranging from 47°42′1″ to 47°52′00″ N and 133°34′38″ to 133°46′29″ E (Figure 1). The reserve has average annual precipitation of 585 mm, mainly concentrated in July to September, accounting for over 60% of the annual rainfall, with evaporation of 1166 mm, an average annual temperature of 1.9 °C, and a frost-free period of 114–150 days. The reserve primarily consists of three types of island-like forests, Broadleaf Mixed forest (HJL), Quercus mongolica forest (MGL), and Betula platyphylla forest (BHL), where HJL and MGL are located on higher terrains of the island-like forests, and BHL typically occupies the lower edges. The community composition and soil properties of the three forest types are summarized in Tables 1 and 2.

Table 1. Community composition.

<table>
<thead>
<tr>
<th>Trees</th>
<th>Shrub</th>
<th>Herb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HJL</strong></td>
<td><strong>Acer pictum, Tilia amurensis, Betula platyphylla, Populus davidiana, Fraxinus mandshurica, Juglans mandshurica</strong></td>
<td><strong>Sambucus williamsii, Euonymus alatus, A. ginnala, Rosa acicularis, Corylus mandshurica, C. heterophylla, Lespedeza bicolor et al.</strong></td>
</tr>
<tr>
<td><strong>MGL</strong></td>
<td><strong>Quercus mongolica, T. amurensis, A. pictum, T. mandshurica, P. davidiana, B. dahurica</strong></td>
<td><strong>C. heterophylla, Eleutherococcus senticosus, E. alatus, Rhamnus dianthiflora, Berberis amurensis, L. bicolor et al.</strong></td>
</tr>
<tr>
<td><strong>BHL</strong></td>
<td><strong>B. platyphylla, Ailurus hirsute, P. davidiana</strong></td>
<td><strong>Spiraea salicifolia, Salix rosmarinifolia var. brachypoda et al.</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Stellaria radians, Anemone udensis, Paris verticillate, Polygonatum humile, Bupleurum longiradiatum, Campanula punctata, Dioscorea nipponica, Convallaria keiskei, Carex ussuriensis, C. quadeflora et al.</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Poa nemoralis, Vicia pseudo-orobus, P. odoratum, Adenophora tetraphylla, Lathyrus quinquenervius, Geranium dahuricum, S. media, Filipendula palmata, Dryopteris crassirhizoma et al.</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Deuexia angustifolia, Thalictrum simplex, Rubia sylvatica, C. schmidtii, Euquisetum sylvaticum, Potentilla fragarioides, Achillea ptarmicoides, Actaea asiatica, S. radians, Persicaria perfoliata, Lactuca sibirica et al.</strong></td>
</tr>
</tbody>
</table>
Figure 1. Geographic location of the study area.

Table 1. Community composition.

<table>
<thead>
<tr>
<th>Trees</th>
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<tr>
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<td>A. ginnala</td>
</tr>
<tr>
<td>Rosa acicularis</td>
<td>Corylus mandshurica</td>
<td>C. heterophylla</td>
</tr>
<tr>
<td>Lespedeza bicolor et al.</td>
<td>Stellaria radians</td>
<td>Anemone udensis</td>
</tr>
<tr>
<td>Paris verticillate</td>
<td>Polygonatum humile</td>
<td>Bupleurum longiradiatum</td>
</tr>
<tr>
<td>Campanula punctata</td>
<td>Dioscorea nipponica</td>
<td>Convallaria keiskei</td>
</tr>
<tr>
<td>Carex ussuriensis</td>
<td>C. quadriflora et al.</td>
<td>Poa nemoralis</td>
</tr>
</tbody>
</table>

The data in the table represent the range and mean values of various soil indicators from May to September.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>T (°C)</th>
<th>V (%)</th>
<th>SOC (g/kg)</th>
<th>TN (g/kg)</th>
<th>AN (g/kg)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>HJL</td>
<td>2.15–18.55 (9.83)</td>
<td>24.49–51.21</td>
<td>31.26–49.35</td>
<td>3.25–5.2 (4.33)</td>
<td>0.38–0.88 (0.61)</td>
<td>4.26–5.32 (4.94)</td>
</tr>
<tr>
<td>MGL</td>
<td>2.12–18.49 (9.79)</td>
<td>25.85–50.24</td>
<td>39.58–71.28</td>
<td>4.18–6.01 (5.12)</td>
<td>0.51–0.87 (0.68)</td>
<td>4.84–5.41 (5.12)</td>
</tr>
<tr>
<td>BHL</td>
<td>1.79–18.05 (9.27)</td>
<td>26.15–55.62</td>
<td>35.14–57.25</td>
<td>3.98–5.65 (4.64)</td>
<td>0.35–0.83 (0.58)</td>
<td>4.56–5.05 (4.82)</td>
</tr>
</tbody>
</table>

Table 2. Soil indicators.

2.2. Gas Sampling and Flux Measurement

From May to September 2023, gas sampling and measurement were conducted using the static chamber–gas chromatography method to quantify the fluxes in CO₂, CH₄, and N₂O from the soils of three island-like forests. The sampling chambers, made of stainless steel and covered with reflective paper, consisted of two parts: 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 into the groove of the base, with water added to the groove to ensure an airtight seal. The base of the sampling chamber remained stationary throughout the growing season to minimize disturbance to the vegetation and soil. A small fan was installed inside the sampling chamber to prevent gas concentration gradients. In each type of island-like forest, five replicate sampling points were randomly established, and gas samples were collected mid-month during clear weather (over a continuous period of 3–5 days) between 9:00 and 12:00. Samples were collected using a 60 mL syringe, with one gas sample taken every 10 min within a 30-minute interval (four gas samples per sampling chamber) and stored in gas bags. After collection, the concentrations of CO₂, CH₄, and
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N$_2$O gases were analyzed using an HP4890 gas chromatograph. Gas fluxes were calculated using the following formula:

\[ F = \frac{dc}{dt} \cdot \frac{M}{V_0} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \cdot H \]

In the formula, \( F \) represents the measured gas flux ((mg·m$^{-2}$·h$^{-1}$), with positive values indicating emission and negative values indicating absorption; \( \frac{dc}{dt} \) is the linear slope of the change in gas concentration with time during sampling; \( M \) is the molar mass of the measured gas; \( P \) 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 \( T_0 \) represent the molar volume of the gas, standard atmospheric pressure, and absolute temperature under standard conditions, respectively.

### 2.3. Soil Sampling and Measurement

During gas sampling, soil temperature (\( T, ^\circ C \)) at a depth of 10 cm was measured with a portable thermometer (JM624), and soil volumetric moisture content (\( V, \% \)) at the same depth was determined using a time-domain reflectometer (TDR-100). Five points from each forest type were randomly chosen, and soil drills were employed to collect mixed soil samples from a depth of 0–15 cm for the analysis of soil chemical properties. The soil organic carbon (SOC, g kg$^{-1}$) content was quantified using the K$_2$Cr$_2$O$_7$ oxidation method. Total nitrogen (TN, g kg$^{-1}$) was measured with a C/N analyzer (Elementar, Langenselbold, Germany). Available nitrogen (AN, g kg$^{-1}$) was determined by the micro-diffusion technique following alkaline hydrolysis. Soil pH was measured with a pH meter in the supernatant (1:5 soil/water) (Hach Company, Loveland, CO, USA).

### 2.4. Data Analysis

Data analysis and visualization were conducted using R (version 4.3.1). The least significant difference (LSD) test for one-way analysis of variance (ANOVA) was employed to identify differences and significance in CO$_2$ flux, CH$_4$ flux, N$_2$O flux, and soil indicators across different forest types. Principal component analysis (PCA) was utilized to evaluate the primary differences in soil properties among the various forest types. Redundancy analysis (RDA) was performed to assess the influence of each environmental factor on greenhouse gas fluxes. Pearson correlation analysis and multivariate stepwise linear regression analysis were used to identify significant environmental factors affecting the greenhouse gas fluxes in the three forest types.

### 3. Results and Analysis

#### 3.1. Characteristics of CO$_2$, CH$_4$, and N$_2$O Fluxes in Soils of Different Forest Types

During the growing season (May to September), the soils of HJL, MGL, and BHL all act as sources of CO$_2$ emissions, with emission fluxes ranging from 69.25 to 772.12, 75.26 to 897.26, and 57.62 to 758.55 mg·m$^{-2}$·h$^{-1}$, respectively. The average emission fluxes are 433.92, 452.41, and 358.17 mg·m$^{-2}$·h$^{-1}$, respectively, with MGL having the highest emissions, followed by HJL, and BHL the lowest. There are no significant differences in the average soil CO$_2$ flux among the three forest types during the growing season (\( p > 0.05 \)). The seasonal variation in soil CO$_2$ emission fluxes is consistent across all three forest types, with the lowest emissions occurring in May and peak emissions in July, generally following the order of summer > autumn > spring. There are significant monthly variations in soil CO$_2$ fluxes among the three forest types, with notable differences between BHL and MGL in all months except July, and significant differences between BHL and HJL in August and September (\( p < 0.01 \)) (Figure 2).
The results indicate that the CH$_4$ flux ranges in the soils of HJL, MGL, and BHL were, respectively $-81.25$ to $-0.93$, $-83.54$ to $-0.86$, and $-31.96$ to $38.85$ µg·m$^{-2}$·h$^{-1}$. The average CH$_4$ fluxes were $-22.52$, $-23.29$, and $-0.76$ µg·m$^{-2}$·h$^{-1}$, showing that during the growing season, all three forest types acted as CH$_4$ sinks, with MGL having the strongest, HJL the second strongest, and BHL the weakest absorption capacity. Significant differences in CH$_4$ flux were noted between BHL and the other two types ($p < 0.01$), with no significant correlation between HJL and MGL ($p > 0.05$). During the growing season, BHL soil CH$_4$ flux alternated between emission and absorption, emitting CH$_4$ in June and September, significantly differing from HJL and MGL ($p < 0.01$). It absorbed CH$_4$ in other months, with emission peaks in June (38.85 µg·m$^{-2}$·h$^{-1}$) and absorption peaks in July ($-31.96$ µg·m$^{-2}$·h$^{-1}$). The ratio of CH$_4$ emission to absorption in BHL was 1:1.12, overall acting as a CH$_4$ sink, with absorption primarily occurring in summer. Throughout the observation period, both HJL and MGL showed CH$_4$ absorption following a unimodal curve, peaking in July, with greater absorption strength in summer than in spring and autumn. There was a significant difference in CH$_4$ flux between the two in August ($p < 0.01$), but the absorption strength was comparable in other months, with no significant differences.

During the growing season, the soils of HJL, MGL, and BHL all acted as sources of N$_2$O emission, with flux ranges of 0.34–35.06, 0.62–31.05, and $-2.12$–$32.05$ µg·m$^{-2}$·h$^{-1}$, respectively. The average emission fluxes were 12.48, 13.02, and 10.51 µg·m$^{-2}$·h$^{-1}$, with MGL having the highest N$_2$O flux, being 1.04 times that of HJL and 1.24 times that of BHL. No significant differences were observed in the average N$_2$O flux among the three forest types ($p > 0.05$). Throughout the growing season, the N$_2$O fluxes of all three forest types showed a consistent seasonal pattern, peaking in July, indicating higher emissions in summer than in spring or autumn. Notably, BHL soil acted as a N$_2$O sink in May, showing significant differences from other types in May and June ($p < 0.01$), and significant differences from MGL in September ($p < 0.01$). MGL and HJL showed significant differences only in September ($p < 0.01$), with comparable overall emission strengths in other months, showing no significant differences.
3.2. PCA of Soil Properties

Principal component analysis was conducted on environmental factors, selecting PC1 (2.62) and PC2 (1.65) with eigenvalues greater than 1 for further analysis and visualization (Figure 3). The results show that the first two PCA axes account for a cumulative variance of 71.2%, with PC1 contributing 43.7% and PC2 27.5%. Soil temperature, moisture, alkali-hydrolyzed nitrogen, and total nitrogen were the main contributing variables to PC1, explaining 26.94%, 23.42%, 24.57%, and 19.6% of the variability in PC1, respectively. Soil temperature and moisture, along with alkali-hydrolyzed nitrogen, had a positive relationship with PC1, and all three showed significant positive correlations. Total nitrogen was negatively correlated with PC1. Soil organic carbon and pH were the main contributors to PC2, explaining 29.74% and 31.04% of the variability in PC2, respectively, and both were positively correlated with PC2. Overall, soil temperature and moisture and alkali-hydrolyzed nitrogen content were the main factors affecting habitat differences among the three forest types. MGL showed clear dispersion from HJL and BHL on PC2, with significant differences primarily reflected in the SOC and pH levels.

![Figure 3. PCA of soil properties.](image)

3.3. RDA of Soil Properties and Greenhouse Gas Flux

Detrended Correspondence Analysis (DCA) was applied to the greenhouse gas data, showing that the length of the DCA1 axis was 1.61, which led to the selection of Redundancy Analysis (RDA) to explore the relationships between environmental factors and greenhouse gases (Figure 4). The analysis indicated that the first and second axes explained 62.79% and 3.79% of the variability in greenhouse gases, respectively, with a cumulative explanatory power of 66.58%, effectively reflecting the relationship between environmental factors and greenhouse gases, where the first axis played a decisive role. Soil temperature and alkali-hydrolyzed nitrogen had the most significant impact on greenhouse gas fluxes, showing positive correlations with CO₂ and N₂O fluxes and a negative correlation with CH₄ flux. Monte Carlo testing indicated that, except for pH, all environmental factors significantly explained the variability in greenhouse gas fluxes (p < 0.05). Hierarchical partitioning was used to assess the contributions of six environmental factors to changes in greenhouse gas fluxes. The relative contributions were as follows: soil temperature (47.97%), alkali-
hydrolyzed nitrogen (31.51%), soil moisture content (7.93%), total nitrogen (5.73%), pH (3.86%), and soil organic carbon (3%). Permutation tests showed that, except for pH and SOC, the contributions of all environmental factors were significant \((p < 0.05)\).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{RDA of soil properties and greenhouse gas flux.}
\end{figure}

3.4. Correlation Analysis and Linear Fitting of Soil Properties and Greenhouse Gas Flux

The RDA revealed that soil environmental factors significantly impacted greenhouse gas fluxes. Correlation analyses and multiple linear regression were conducted on soil properties and gas fluxes across the three forest types to further explore the differences in how environmental factors affect greenhouse gas fluxes among these types. The correlation analysis indicated that soil CO\textsubscript{2} fluxes in the three forest types were significantly positively correlated with soil temperature, moisture content, and alkali-hydrolyzed nitrogen \((p < 0.05)\), and negatively correlated with total nitrogen (TN) \((p < 0.05)\). HJL and BHL showed significant negative correlations with soil organic carbon (SOC) \((p < 0.01)\), while MGL showed a significant positive correlation with SOC \((p < 0.01)\).

There were no significant correlations with pH across the three types \((p > 0.05)\). CH\textsubscript{4} fluxes in the three forest types were significantly negatively correlated with soil temperature and alkali-hydrolyzed nitrogen (AN) \((p < 0.01)\), with no significant correlation with soil moisture content \((p > 0.05)\). MGL’s correlations with SOC, TN, and pH differed from the other types. It showed a significant negative correlation with SOC \((p < 0.01)\), while the other types showed a significant positive correlation \((p < 0.01)\). There was a significant positive correlation with TN \((p < 0.05)\), with no significant correlations observed in the other types (Table 3).

There was no significant correlation with pH, but the other types showed a significant negative correlation \((p < 0.05)\). HJL and BHL showed consistent correlations of N\textsubscript{2}O fluxes with environmental factors, being significantly positively correlated with temperature (T), AN, and pH \((p < 0.05)\), and negatively with SOC \((p < 0.05)\). MGL differed from the other types, showing significant positive correlations with T, moisture content (V), SOC, and AN \((p < 0.05)\), and a significant negative correlation with TN \((p < 0.01)\). Based on past experience and combined with the results of the RDA and correlation analysis, after eliminating environmental factors with strong collinearity (Variance Inflation Factor > 10),
bidirectional stepwise regression analysis was conducted on the relationships between soil greenhouse gas fluxes and environmental factors for different forest types. The results indicated that an increase in temperature was beneficial for the emission of CO$_2$ and N$_2$O and the absorption of CH$_4$ in all three forest types, while an increase in soil moisture restricted the absorption of CH$_4$ by HJL and MGL and the emission of N$_2$O by the former. SOC and pH had significant effects on the CH$_4$ flux of BHL, while AN significantly affected only the N$_2$O flux of MGL (Figure 5).

### Table 3. Fitting the relationship between soil greenhouse gas flux and soil properties.

<table>
<thead>
<tr>
<th>Forest Type</th>
<th>Gas</th>
<th>Equation</th>
<th>Adj R$^2$</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>HJL</td>
<td>CO$_2$</td>
<td>CO$_2$ = 41.67T + 25.18</td>
<td>0.93</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>CH$_4$</td>
<td>CH$_4$ = -4.85T + 1.49V - 31.49</td>
<td>0.87</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>N$_2$O</td>
<td>N$_2$O = 1.95T - 0.44V + 10.18</td>
<td>0.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>MGL</td>
<td>CO$_2$</td>
<td>CO$_2$ = 39.04T + 70.32</td>
<td>0.86</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>N$_2$O</td>
<td>N$_2$O = 0.84T + 37.05AN - 20.4</td>
<td>0.79</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>BHL</td>
<td>CO$_2$</td>
<td>CO$_2$ = 38.45T - 8.94V - 9.56SOC + 258.85</td>
<td>0.92</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>CH$_4$</td>
<td>CH$_4$ = -3.5T - 1.69SOC + 46.22pH - 120.66</td>
<td>0.78</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>N$_2$O</td>
<td>N$_2$O = 1.63T + 12.95pH - 67.08</td>
<td>0.82</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

#### 3.5. Greenhouse Gas Emissions and GWP of Different Forest Types

Global warming potential (GWP) is determined by CO$_2$, CH$_4$, and N$_2$O together. Over a 100-year period, the greenhouse effects of methane and nitrous oxide are 25 and 298 times that of carbon dioxide, respectively [14]. Calculating emissions over 5 months (May to September), the global warming potentials for the three forest types were, respectively 15,734.97 (HJL), 16,405.82 (MGL), and 13,006.69 (BHL) kg·ha$^{-1}$. Among them, MGL was the highest, and BHL was the lowest. The global warming potential from soil greenhouse gases in all three forest types was predominantly composed of CO$_2$ (99.13%–99.28%) (Table 4).
Table 4. Cumulative greenhouse gas emissions and global warming potential.

<table>
<thead>
<tr>
<th>Forest Type</th>
<th>CO\textsubscript{2} Cumulative Emissions (kg ha\textsuperscript{-1})</th>
<th>CH\textsubscript{4} Cumulative Emissions (kg ha\textsuperscript{-1})</th>
<th>N\textsubscript{2}O Cumulative Emissions (kg ha\textsuperscript{-1})</th>
<th>GWP (kg ha\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>HJL</td>
<td>15,621.12</td>
<td>0.81</td>
<td>0.45</td>
<td>15,734.97</td>
</tr>
<tr>
<td>MGL</td>
<td>16,286.76</td>
<td>0.84</td>
<td>0.47</td>
<td>16,405.82</td>
</tr>
<tr>
<td>BHL</td>
<td>12,894.12</td>
<td>0.027</td>
<td>0.38</td>
<td>13,006.69</td>
</tr>
</tbody>
</table>

4. Discussion

This study found that the three types of island-like forests were sources of CO\textsubscript{2} emissions during the observation period, consistent with most studies on greenhouse gas fluxes in the wetlands of the Sanjiang Plain [4,15,16]. Island-like forests are often located on higher hummocks within wetlands or marshes [17], where ample soil moisture and good drainage [18] facilitate respiration by plant roots and soil microorganisms [19,20], leading to the production and emission of carbon dioxide. The RDA and multiple linear regression results indicate that soil temperature is a key factor affecting soil CO\textsubscript{2} flux. As the three forest types are under similar climatic and ecological conditions [21] and are subject to similar seasonal variations, CO\textsubscript{2} emissions during the growing season are primarily determined by root respiration and soil microbial respiration [22], both processes strongly influenced by temperature [23]. This may explain why the three forest types show no significant differences in CO\textsubscript{2} flux and exhibit similar seasonal patterns throughout the growing season.

However, significant differences in CO\textsubscript{2} flux between the forest types in certain months may be due to differences in ecological adaptability and function [24–26]. For instance, different tree species may respond differently to conditions such as temperature, humidity, and light [27]. Additionally, different forest types may affect the structure and function of soil microbial communities, further influencing soil CO\textsubscript{2} emissions [28,29]. Finally, the decomposition rate of understory vegetation and fallen branches and leaves may vary among forest types, affecting the decomposition of soil organic carbon and the emission of carbon dioxide [30]. The RDA triplot shows that MGL generally has higher SOC content than HJL and BHL, and the higher carbon content in the soil may be the main reason why MGL has higher soil CO\textsubscript{2} flux than the other forest types [31]. The magnitude of soil CO\textsubscript{2} flux is the largest contributor to greenhouse gas emissions in the three forest types, and temperature is a key factor in predicting emission changes. Therefore, in the context of global climate change, monitoring and analyzing CO\textsubscript{2} flux is crucial for assessing the contribution of island-like forests in the region to the greenhouse effect.

It is generally believed that forest ecosystems are sinks for CH\textsubscript{4}, while wetland ecosystems are sources of CH\textsubscript{4} [32,33]. Good aeration in soil promotes the formation of aerobic conditions conducive to the oxidation of CH\textsubscript{4} by methanotrophic bacteria. When soil CH\textsubscript{4} concentrations are lower than atmospheric levels, the concentration difference leads to the soil’s absorption of CH\textsubscript{4}. In moist anaerobic conditions, methanogenic bacterial activity is enhanced, favoring the production of CH\textsubscript{4} [34]. This study found that BHL soil CH\textsubscript{4} fluxes were absorptive in May, July, and August, and emissive in June and September, exhibiting an alternating pattern of absorption and emission. The reason may be that BHL is located at the edge of a wetland, with vegetation characteristic of a marsh–forest transition. Its unique geographical location and hydrothermal conditions result in soil types ranging from marshy meadow soil to meadowized dark brown soil. As temperatures rise and permafrost melts, soil moisture increases, especially during the rainy seasons of July and August, raising the overall wetland water levels. The increased deep soil moisture in BHL during these seasonal waterlogged conditions results in CH\textsubscript{4} flux characteristics that differ from other forest types [35,36]. Increased soil moisture can lead forest soils to switch from absorbing to emitting CH\textsubscript{4} [37]. However, this study did not find a significant correlation between BHL soil CH\textsubscript{4} flux and soil moisture, possibly because the moisture needed for methane production or oxidation has a specific range [14,38,39]. During the observation period, the soil moisture content may have exceeded or fallen below the optimal threshold, leading to the lack of a significant correlation.
To further investigate the specific impact of moisture on CH$_4$ flux, long-term and continuous monitoring is an important task that needs to be undertaken in the future. HJL and MGL are predominantly located on low hills or high grounds along natural marshes within protected areas, with soils typically being dark brown, thin-layered, and well-drained. The overall environment favors the oxidation of CH$_4$ in the soil and the movement of CH$_4$ from the atmosphere into the soil [40]. Most studies show that the process of soil CH$_4$ oxidation intensifies with increasing temperature, thus exhibiting stronger absorption in summer compared to spring and autumn. Increased soil moisture can weaken CH$_4$ absorption and even lead to emission trends [41,42]. In this study, soil temperature and moisture are also important factors affecting CH$_4$ flux in the two forest types, and the results of the linear fitting of CH$_4$ flux with environmental factors are consistent with these conclusions.

Throughout the growing season, all three forest types were sources of N$_2$O emissions, consistent with most studies on soil N$_2$O fluxes in the Sanjiang Plain wetlands [43–45]. In this study, BHL showed N$_2$O absorption in May, likely due to the melting of the thick permafrost layer at the beginning of the growing season, which increased soil pore water and created hypoxic to anoxic conditions, allowing some anaerobic microorganisms, such as denitrifying bacteria, to use N$_2$O as an electron acceptor in the denitrification process when NO$_3$ is scarce, ultimately reducing N$_2$O to N$_2$ and resulting in soil N$_2$O absorption [46,47]. The digestion and denitrification processes involving soil microorganisms are the primary pathways for N$_2$O production [48]. With rising temperatures, enhanced microbial activity increases nitrification and denitrification rates [49], likely explaining why soil N$_2$O fluxes in the three forest types are higher in summer than in spring and autumn. Although there are no significant differences in average N$_2$O fluxes among the three forest types, significant differences exist between types in certain months [50]. This study also found that the impact of environmental factors on N$_2$O flux varies by forest type, with moisture content significantly affecting N$_2$O flux in HJL soils, alkali-hydrolyzed nitrogen being a major factor for MGL, and soil pH having a significant impact on BHL, potentially due to various reasons.

We know that nitrification and denitrification are complex biochemical processes influenced by many environmental factors [51], such as soil oxygen content, moisture conditions, temperature, pH, organic matter, and nutrient content [52]. In this study, different tree species compositions and ground cover types led to variations in soil organic matter content and microbial community structure and function, with different root characteristics and root exudates possibly affecting nitrogen transformation processes, and different rates of decomposition and decomposition products may also impact the nitrogen cycle [53–56]. These factors ultimately affect soil N$_2$O flux levels.

This study has two main limitations. First, while higher gas sampling frequency provides more accurate reflections of local gas flux levels, field conditions (the lack of a stable power supply) and equipment costs necessitated the use of the static chamber–gas chromatography method. This method, involving sampling, transportation, and measurement processes, indirectly reduced the sampling frequency to an average of three times per month. Despite this, our results effectively reflected the overall gas emission levels and differences between insular forests. Second, this study employed five replicate sampling points per forest type, sufficient for statistical significance. However, due to spatial heterogeneity in soil greenhouse gas fluxes influenced by soil properties and vegetation, more sampling points would provide a more accurate representation of flux levels. In future research, we will take these two limitations into account.

Currently, the quantitative comparison of soil greenhouse gas fluxes is a significant challenge in related research. Firstly, due to differences in measurement methods (the chamber method, micrometeorological method, isotope method, concentration profile method, eddy covariance method, etc.), the results exhibit certain variability and uncertainty. Secondly, factors such as gas sampling frequency, scope, and time periods can lead to different annual average flux calculations. Greenhouse gas fluxes are significantly
affected by seasonal and climatic conditions; for example, continuous greenhouse gas flux monitoring in the same area over two consecutive years may yield significant differences in annual average fluxes. Finally, the production and emission of soil greenhouse gases are extremely complex processes influenced by soil physicochemical properties, vegetation types, and atmospheric conditions (temperature, humidity, pressure, etc.), which is also why studies on greenhouse gas flux characteristics and mechanisms are usually confined to the same area. In summary, this study did not quantitatively compare results with other regions but focused on the overall emission levels and differences between different forest types in the insular forests of this area.

5. Conclusions

This study shows that the soils of the three types of island forests are sources of CO$_2$ emissions, with no significant differences in average flux. Increased soil temperature leads to increased emissions, and a higher SOC content may be the main reason why MGL soil CO$_2$ flux is higher than in other forest types. Throughout the growing season, the soils of all three forest types act as CH$_4$ sinks, but BHL has overall weaker absorption strength and exhibited CH$_4$ emissions during the observation period. Its lower elevation and different soil type from the other two are the main reasons for the significant differences in its soil CH$_4$ flux compared to the other forest types. There are no significant differences in average N$_2$O flux among the three forest types, all acting as sources of N$_2$O emissions, significantly influenced by soil temperature. The impact of other environmental factors on flux varies by forest type, with different community compositions being the main reason for variations in N$_2$O flux across some months. Throughout the growing season, the cumulative emission of CO$_2$ is the highest, holding an absolute dominant position in its contribution to the greenhouse effect among the three greenhouse gases.

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