A Comparison of Greenhouse Gas Emission Patterns in Different Water Levels in Peatlands

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Abstract: Peatlands store large amounts of carbon in wetland ecosystems. The hydrological conditions within peatlands are important factors that affect the biochemical cycle and patterns of greenhouse gas emissions in these peatlands. This study was carried out in Changbai Mountain Jinchuan peatland to investigate variations in carbon dioxide and methane emissions in peat swamps that have undergone distinct saturation conditions. Three peatland types (high water levels (S1); medium water levels (S2); low water levels (S3)) at different flood depths were selected as specific sampling points. The static box and gas chromatography methods were used at different time periods (6:00; 12:00; and 18:00) from July to September. The discharge flux of CO₂ and CH₄ slowly increased with the increase in the water level. The results indicate similarity in the fluctuation trends between the fluxes of CO₂ and CH₄ in S1 and S2 to the fluctuations of water levels. During the entire growth season, the flux range of CO₂ and CH₄ was −695.329~859.907 mg m⁻² h⁻¹ and 259.981~147.155 mg m⁻² h⁻¹, respectively. Furthermore, there was variation in mutation characteristics between two gases, the CO₂ exhibited larger mutation range (−7.08~3.40) than CH₄ (−1.79~1.26).

In terms of daily flux changes, CO₂ showed an upward trend, while CH₄ had a downward trend. These results indicate variations in saturation conditions tend to affect discharge of greenhouse gases, with subsequent effects on climate change. This study highlights potential theoretical support to reduce anthropogenic activities on peatlands. This can be achieved by undertaking measures to conserve peatlands and explore mitigation measures to minimize greenhouse gas emissions and hence impacts of climate change.

Keywords: peatland; CO₂ flux; CH₄ flux; hydrological conditions

1. Introduction

Wetland soil carbon storage contains accumulations of carbon that occur naturally. Wetland regions comprise about 4–6% of the Earth’s total land surface, and have carbon stores ranging from 4.55 × 10¹⁰ to 7.00 × 10¹⁰ metric tons. These reserves account for 30% of the total carbon stored in the soil [1–4]. The carbon density of forest soil is over three times lower than that of carbon. The “buffer” of global climate change, referred to as carbon sink, plays crucial role in the global carbon cycle and carbon balance. The degradation and depletion of marsh wetlands results in the conversion of natural wetland carbon into a significant carbon emitter. Studies indicate that the depletion of northern peatlands worldwide can lead to the release of greenhouse gases at an annual rate of 0.10 ± 0.02 Pg C·y⁻¹. This accounts for approximately 1% of the total human emissions projected for this century [5], and may impact the global environment through an increase in the mean temperature of approximately 0.35 °C [6]. This may result in a reduced plant productivity, and the enhancement of breakdown would significantly affect global climate change through the release of organic carbon. The stability of organic carbon in wetland
soil and its ability to respond to climate change are currently potential areas of intense research focus worldwide [7,8].

Under the saturated conditions of wetlands, a unique anaerobic environment is formed. Due to the high level of primary productivity and low decomposition rate under anaerobic conditions, the undecomposed plant residues will eventually accumulate to form peat, and therefore swamps develop under these climatic and hydrological conditions [9]. Peatlands are characterized by different developmental stages, as a function of water level changes and hydrological conditions. For instance, peatlands may develop through paludification of mineral soil forest, through terrestrialization of lakes, or a primary peat can be formed on bare soils of previously glaciated areas [10]. Additionally, peat can be formed under the joint influence of sphagnum and precipitation. In this case, the fen will gradually change to bog over the years [11] and, with time, the plant litter may form and cover the surface of peat. Consequently, the accumulated peat may rise and exceed the groundwater level, and the peat layer above the groundwater level becomes replenished by atmospheric precipitation, thus turning into a bog. Bogs obtain water through rainfall and nutrients via atmospheric sedimentation. An acidic and nutrient-deficient environment is conducive for the establishment and growth of dwarf shrubs and sphagnum, and the fen is affected by alkaline- and nutrient-rich groundwater with sedges, herbs and grasses [12]. Different geographical conditions may lead to the formation of different types of peatland, whether fens or bogs, which represent different stages of peat development.

Hydrological conditions play a crucial role in preserving the structure and function of the wetland ecosystem. Hydrological circumstances have a significant impact on several non-biological aspects of the wetland ecosystem. These aspects, in turn, influence the biological communities within the wetland ecosystem [2]. Studies have demonstrated that the consistent hydrological process in wetland ecosystems significantly enhance the process of nitrogen cycling [13,14]. The aquatic rhythm often has a significant effect on the production of carbon dioxide and the oxidation of methane. This, in turn, impacts the rate at which carbon accumulates [15]. The research findings indicate that, as seasons change, the hydrological regulations in wetlands are more influenced by natural precipitation than other factors, consequently influencing the carbon cycle [16]. The hydrologic rhythm typically pertains to fluctuations in the daily, nocturnal, monthly, seasonal, or annual patterns [17]. Precise hydrological legislation will have a significant impact on the accumulation of carbon inside the aquatic ecosystem. In Australia, a study to investigate impact of hydrological patterns on carbon distribution through analysis of the stable isotope $^{13}$C in water bodies and surrounding biological weight revealed the significant influence of the regular hydrological law to the carbon content in water bodies [18]. Additionally, it was discovered that nutritional levels in the research area of the Amazon rainforest exhibit a high degree of stability, which can be attributed to the hydrological laws peculiar to this region [19].

Water-level changes caused by climate change and human interference may affect the carbon exchange in peatlands. Precipitation is an important environmental factor, which not only affects the vegetation on peat ground, but also cause fluctuations water-level depth (WTD) [20]. Temperatures above freezing point will change the time and amplitude of the hydrological fluxes that occur during the growth season. An experience model is used to simulate the three-climate scenario. The runoff on the ground enters local rivers, lakes, and wetlands. These runoffs either evaporate or enter the ocean via the surface-drainage network. During a drought period, the groundwater level is transported upward to the root area. Deeper groundwater flow, covering a longer distance, can be discharged to wetlands and rivers in the lower reaches [21]. Groundwater is supplied by and flows from the topographic heights, while these flows lead to, and discharge occurs, at lower terrains [22]. For example, if there is excess water, forest hills can be used as water sources (i.e., groundwater supply), and then be used for water exchange (i.e., underground emissions) when evaporation occurs following the precipitation period. In addition to climate change, changes in land use and land coverage related to humans can also lead
to changes in water levels and peatland functions. Large areas of peatland are used for agriculture or forestry. As one form of environmental interference, research found that the blocking ditch that occurred in the first two years after wetness significantly increased groundwater levels [23]. In Europe, more than half of the total peatland has been dried for agriculture or forestry [24]. Since the 1970s, about 6 million hectares of peatland in Finland have been altered [25]. The construction of a reservoir can improve the local water levels and submerge peatland [18]. The construction of highways or railways usually forms an embankment, and these embankments may cause water to accumulate in peatland or cause peatland to become dry [26]. The dams built by beavers lead to water storage by peatland, and are an important part of the landscape of the northern region [27]. Vitamin plants can quickly grow after recovery is achieved using moss layer transfer technology. This recovery technology can successfully restore the hydrology of peat, but the establishment of peat moss carpets may take several years [28].

Various environmental conditions, including temperature, soil freezing state, human activity intensity, and hydrological variations, might influence the release of greenhouse gases in wetland soil [29]. A study revealed that the emissions of greenhouse gases from artificial wetlands were 2–10 times higher than those from natural wetlands [30]. Typically, fluctuations in water levels play a crucial role in determining the presence of aerobic or anaerobic conditions at various depths inside wetlands. When the synthesis of methane and methane oxidation was regulated, it was discovered that organic carbon accumulated differently in vegetation at various groundwater levels, with higher accumulation being observed in continuously flooded areas as compared to other vegetation areas [31,32]. Organic sediments have high capacity to retain water, resulting in a groundwater level that is lower than the sediment. The rates of methane generation and methane emissions in the continuous-saturated area exhibit only marginal disparities, with no statistically significant distinction. The rate of similar occurrences is largely diminished when methane is stored within sandy casters.

In brief, the existing body of research pertaining carbon dioxide and methane emissions from wetland soil primarily focuses on investigating the carbon density, the ecological implications of changes in solid carbon function, wetland hydrology, soil volume, and greenhouse gas levels. There is currently inadequate knowledge regarding these aspects. The objective of this research endeavor is to discern the variations in carbon dioxide and methane emission depths within peat swamps that have undergone distinct saturation conditions. To achieve this, quantities of carbon dioxide and methane emissions will be monitored in conjunction with hydrological conditions.

2. Materials and Methods

2.1. Study Area

The research was conducted in the Longwan National Nature Reserve in Tonghua City, Jilin Province, which is located at 42°16′–42°26′ N and 126°13′–126°32′ E, and with a height ranging from 632.51 m to 640.51 m. Jinchuan Peatland evolved from Quaternary Crater Lake, with a flat and open valley bottom and a gradient from northeast to southwest. According to the changes in water level, three different development stages of peatlands (S1, S2, and S3) were set. The development of peatland is intricately linked to the change in hydrological conditions. Paludification is a steady process where the frequency and duration of saturation diminish over time, leading to the gradual accumulation of material and the eventual formation of peatland. The hydrological circumstances and peatland characteristics of the three selected sampling places in this study different stages of peatland development align closely with the starting, intermediate, and development stages of peatland. The research region has a moderate continental climate and experiences high rainfall and high temperature. The study area is characterized by an average temperature of 4.1 °C per year, a precipitation of approximately 704.2 mm per year, evaporation of around 1276.1 mm per year, an annual average sunlight duration of 2550 h, and the frost-free season lasts from 110 to 120 days. The peatlands in this area sustain a notable abundance
of species, including sedges, cattails, and reeds, and the wetland comprises a number of primary communities, including the birch (*Betula ovalifolia*) + sedge (*Carex schmidtii*); *C. schmidtii* + *typha* (*Thelypteris palustris*); *C. schmidtii* + reed (*Phragmites australis*); *C. schmidtii*; *C. tenuiflora*; and *Ph. australis* + *C. schmidtii* (Figure 1).

![Figure 1. Location of the Jinchuan wetland and our study site.](image)

2.2. Methodology and Data Collection Process

The collection of greenhouse gases (carbon dioxide and methane) was carried out using the static box method. The rectangular high-density polyethylene (HDPE) base, measuring 50 cm × 20 cm (0.25 m²), has open tops and bottoms. Three bases were positioned at S1, S2, and S3, each with a different water-level gradient. The bottom-removable rectangular plastic storage container measuring 50 cm × 50 cm × 50 cm was positioned at the base for collection. Three repeated static boxes were established at each sampling site to enable the estimation of the standard error. The static boxes were positioned at a minimum distance of 2 m from one another, and the ambient temperature, as well as the temperature of greenhouse gases within each static box during sampling, were documented. The procedure involves collecting gas using 100 mL syringes. The collection took place from July to September, encompassing the summer and autumn seasons. Each collection was carried out every 15 days, at three specific times during the day: 6:00, 12:00, and 18:00. Prior to sampling, we checked that the sample bag was empty and verified on-site that it was free of air. For each collection interval of 5 min, gas samples of 100 mL each were obtained and placed in individual, 100 mL vacuum bags. This process was repeated 6 times for each bag, leading to a total of 18 samples [33].

A 2 m long aluminum alloy tube with a diameter of 5 cm was inserted at three distinct water-level gradients, namely S1, S2, and S3. Throughout each gas-collection procedure, the water-level-depth measuring equipment was utilized to gauge and document the water level within the aluminum alloy tube.

2.3. Analysis of the Sample

Upon retrieval of the sample, an Agilent 1890B (Santa Clara, CA, USA) gas chromatograph spectrometer was used. The samples were placed into a 30 mL vacuum test sample bottle using a Luer valve syringe. The sample container was then placed in an automated inlet and prepared for testing. The sample underwent gas chromatography, employing either a flame ion detector (FID, Agilent 1890B, USA) or an electronic capture
detector (ECD, Agilent 1890B, USA) for online analysis to identify the levels of CO$_2$ and CH$_4$ present in the sample. Stainless steel filling columns were used to contain CO$_2$ and CH$_4$. A 60/80 mesh column was loaded with 13× color-spectrum pillars containing CH$_4$. A 60/80 mesh Porapak-Q color-spectrum column was also loaded with CH$_4$ and CO$_2$, using high-purity nitrogen at a flow rate of 30 mL/min. The temperature of the FID detector was set at 250 °C, while the column temperature was maintained at 55 °C. The carrier used AR-CHA (5 mL/min), the ECD detector was set at a temperature of 350 °C, and the column temperature was maintained at 55 °C. An analysis of the peak areas corresponding to CO$_2$ and CH$_4$ was conducted. Then, the gas concentration was calculated using the provided formula based on the peak area by follow equations:

$$C = C_s / \overline{S}_{peak} \times S_{peak}$$  \hspace{1cm} (1)

$C$ represents the concentration of a gas; $C_s$ represents the concentration of a standard gas; $\overline{S}_{peak}$ represents the average peak area of the standard gas; $S_{peak}$ represents the peak area of the standard gas.

The emissions of carbon dioxide (CO$_2$) and methane (CH$_4$) were computed as follows:

$$J = \frac{dc}{dt} \times \frac{M}{V} \times V_0 \times \frac{P}{P_0} \times \frac{T_0}{T} \times H$$  \hspace{1cm} (2)

Among these, $dc/dt$ represent the rate of the change in concentration, $M$ denotes the quality of Moore, $P$ signifies the atmospheric pressure at the sampling station, and $T$ represents the absolute temperature during sampling. $V_0$, $P_0$, and $T_0$ are the absolute temperatures at Moore volume, the atmospheric pressure, and the standard circumstances, respectively. $H$ stands for the vertical measurement of the cavity submerged in water, which determines the precise volume of gas present in the column of the color spectrum.

2.4. Data Statistics and Analysis

The first step in processing the sample data involves the use of SPSS 24 software (SPSS Inc., Chicago, IL, USA) to remove any anomalous emissions present in the data. Subsequently, a statistical analysis was performed and a graphical representation was established using the Origin software (Origin Lab Corporation, Northampton, MA, USA). This software employs linear regression to assess the correlation between temperature throughout the growth season, various water-level gradients, and emissions of CO$_2$ and CH$_4$. The study examines how variations in temperature and water-level gradients affect greenhouse gas emissions using a two-factor square analysis. The test has a significant threshold of 0.05%. The standard deviation of all error lines was used to determine the average value.

3. Results

This study revealed a significant variation in the emission rates of CO$_2$ and CH$_4$ at different water levels, with minor mutation coefficients, during a period of plant growth in Jinchuan peatland (Figure 2). Each month exhibited distinct properties of the two greenhouse gases. Carbon dioxide and methane emissions exhibited fluctuations and an overall increase, albeit of a minor magnitude. The discharge regulations are outlined as follows: In August, the absorption of carbon dioxide on 28 August was $-157.79$ mg m$^{-2}$ h$^{-1}$, with a total absorption of more than $183.45$ mg m$^{-2}$ h$^{-1}$. On 15 August, methane emissions were $45.45$ mg m$^{-2}$ h$^{-1}$. The overall emission volume of greenhouse gases in July was generally high, with the value $19.58$ mg m$^{-2}$ h$^{-1}$. The mutation coefficients of the two gases are substantial, with carbon dioxide ($-7.08$~$3.40$) and methane ($-1.79$~$1.26$) having comparatively smaller mutation values.

The extent of saturation in the research region directly impacts the rise in CO$_2$ and CH$_4$ emissions in proportion to the increase in water level in Jinchuan peatland at different development stages (Figure 3). The mean saturated depths at locations S1–S3 are
−7.5 ± 14.00 cm, −12.09 ± 14.16 cm, and −22.5 ± 23.58 cm, respectively. Overall, the concentrations of CO₂ and CH₄ rose in tandem with rising water levels. Significant fluctuations in water level led to corresponding fluctuations in the discharge flux of CO₂ and CH₄ at different development stages in peatland. The variation pattern of the carbon dioxide and methane volumes at locations S1 and S2 closely correspond to the fluctuations in the water level. However, at point S3, there is a significant disparity between the current trajectory of carbon dioxide and methane emissions and fluctuations in water level. Simultaneously, it was discovered that the flow of carbon dioxide and methane at point S1 escalated in proportion to the extent of saturation. The carbon dioxide concentration grew progressively from −230.23 mg m⁻² h⁻¹ to −61.71 mg m⁻² h⁻¹ starting from the baseline value. Methane was detected at a concentration of 50.41 mg m⁻² h⁻¹ on 12 September. The peak concentration of carbon dioxide reached its greatest value at −57.48 mg m⁻² h⁻¹ on 15 August. As the saturation subsided, the maximum flood depth at site S2 reached −35 cm. Simultaneously, the concentration of carbon dioxide rose from −3.75 mg m⁻² h⁻¹ to 101.77 mg m⁻² h⁻¹, and the volume of methane increased from 16.83 mg m⁻² h⁻¹ to 26.71 mg m⁻² h⁻¹. The peak flux in both greenhouse gases occurred simultaneously on the same day: The values were 101.77 mg m⁻² h⁻¹ and 57.85 mg m⁻² h⁻¹. At point S3, which experienced the least amount of saturation, there is a notable disparity in the emission patterns of CO₂ and CH₄ compared to the other two points. Following a decrease from −223.48 mg m⁻² h⁻¹ to −2.52 mg m⁻² h⁻¹, the overall volume changes in methane exhibited an increase from 13.69 mg m⁻² h⁻¹ to 42.27 mg m⁻² h⁻¹, followed by a strong decline to 12.85 mg m⁻² h⁻¹, which was comparatively less than the previous two data points.

Figure 2. Fluctuations in CO₂ and CH₄ flux levels in different months. (a) is the curve of average flux, median flux and coefficient of variation of carbon dioxide in different months. (b) is the curve of methane average flux, median flux and coefficient of variation in different months.

The temperature of the three points in the Jinchuan peatland research area shows a gradual downward trend, gradually decreasing from 33.11 ± 1.14 °C to 26.70 ± 1.42 °C (Figure 4). Simultaneously, the extent of inundation exhibits a gradual upward trajectory. The correlation study revealed that the carbon dioxide flux is positively correlated with temperature (p = 0.625) (Figure 4c), whereas the methane flux and temperature exhibit a negative association (p = 0.573) (Figure 4a). The concentration of carbon dioxide is positively correlated with temperature and the depth of saturation (p = 0.538) (Figure 4d), while the methane emission rate is positively correlated with the depth of saturation (p < 0.001) (Figure 4b). CO₂ and CH₄ switched to the lighter position (S3), with a strong correlation between the depth of saturation and these positions (p < 0.07) (Table 1). A correlation was found between the CH₄ flux volume and the temperature and flood depth of S1 (p < 0.05) (Table 1). A significant association was also found between CH₄ saturation and temperature saturation at site S3 (p < 0.01) (Table 1).
Figure 3. The depth and discharge fluxes in CO$_2$ and CH$_4$ during inundation varied from month to month. The left upper vertical axis shows the fluxes in CO$_2$ (mg m$^2$h$^{-1}$), the right upper vertical axis shows the fluxes in CH$_4$ (mg m$^2$h$^{-1}$), and the left lower vertical axis shows the water level (cm). (a) shows the relationship between carbon dioxide flux and methane flux and S1 water level. The dark yellow curve represents carbon dioxide, the light yellow curve represents methane, and the yellow shaded part shows the water level change. (b) shows the relationship between carbon dioxide flux and methane flux and S2 water level. The crimson curve represents carbon dioxide, the light red curve represents methane, and the red shaded part represents water level change. (c) shows the relationship between carbon dioxide flux and methane flux and S3 water level. The crimson curve represents carbon dioxide, the light red curve represents methane, and the red shaded part represents water level change.

Figure 4. Correlation between CO$_2$ and CH$_4$ switch fluxes, temperature, and saturated depth. Vertical axes (a,b) show the flux in CH$_4$; vertical axes (c,d) show the CO$_2$ flux; horizontal axes (a,c) show the temperature; horizontal axes (b,d) show the saturated depth. The yellow dots represent methane flux in (a,b), and carbon dioxide flux in (c,d). The yellow shaded part is the confidence interval. The yellow line shows the linear relationship between methane and temperature in (a), methane and flooding depth in (b), carbon dioxide and temperature in Figure 4c and carbon dioxide and flooding depth in (d).
Table 1. Analysis of the correlation between the flux and temperature at different sampling points, CO$_2$ and CH$_4$, saturation, and saturated depth.

<table>
<thead>
<tr>
<th></th>
<th>CO$_2$ Flux</th>
<th>CH$_4$ Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-Value</td>
<td>p-Value</td>
</tr>
<tr>
<td>S1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>2.52</td>
<td>0.12</td>
</tr>
<tr>
<td>Saturated depth</td>
<td>1.10</td>
<td>0.30</td>
</tr>
<tr>
<td>Temperature $\times$ Saturated depth</td>
<td>0.42</td>
<td>0.52</td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.13</td>
<td>0.72</td>
</tr>
<tr>
<td>Saturated depth</td>
<td>0.36</td>
<td>0.55</td>
</tr>
<tr>
<td>Temperature $\times$ Saturated depth</td>
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<td>0.48</td>
</tr>
<tr>
<td>S3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
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<td>0.10</td>
</tr>
<tr>
<td>Saturated depth</td>
<td>3.48</td>
<td>0.07</td>
</tr>
<tr>
<td>Temperature $\times$ Saturated depth</td>
<td>1.14</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Note(s): Significant codes: 0 ‘***’ 0.05 ‘.’.

4. Discussion

Peatlands are predominantly located in tropics and in high-latitude regions. The peatland chosen for this study is situated in northeast China at a relatively high latitude. In contrast to the maximum and minimum values observed in the peat marsh at the same latitude, the findings of this research indicate relatively average distribution (Table 2). The findings of our study reveal a considerable range of CO$_2$ emission, exhibiting a maximal value comparable to that observed at an identical latitude. Contrary to the study conducted in Panama in the equatorial region, the magnitude of alterations mirrors the fluctuating pattern in our study. Additionally, the change range of CH$_4$ switch volume in this study is considerably smaller in magnitude when compared to the findings of research conducted in a region of the same latitude. Conversely, the methane flux in this study is considerably greater than that observed in research conducted in another tropical area.

Table 2. Various wetland types exhibit distinct variations in CO$_2$ and CH$_4$ fluxes.

<table>
<thead>
<tr>
<th>Study Location</th>
<th>CO$_2$ (mg m$^{-2}$ h$^{-1}$)</th>
<th>CH$_4$ (mg m$^{-2}$ h$^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changbai Mountain, China</td>
<td>$-695.33$–$859.91$</td>
<td>$-259.98$–$147.16$</td>
<td>This article</td>
</tr>
<tr>
<td>Northwest Panama</td>
<td>$719.94$–$913.18$</td>
<td>$38.78$–$48.89$</td>
<td>[28]</td>
</tr>
<tr>
<td>Southern Sweden</td>
<td>$1483$–$6665$</td>
<td>$1934$–$8888$</td>
<td>[29]</td>
</tr>
<tr>
<td>Northern Colombia</td>
<td>$1.57$–$1.97$</td>
<td></td>
<td>[30]</td>
</tr>
<tr>
<td>Northern Norway</td>
<td>$52.17$–$154.11$</td>
<td>$0.32$</td>
<td>[31]</td>
</tr>
<tr>
<td>Kampar, Indonesia</td>
<td>$-0.47$–$4.27$</td>
<td>$2.22$–$8.52$</td>
<td>[32]</td>
</tr>
<tr>
<td>Southwest Florida, FL, USA</td>
<td>$4.55$–$55.30$</td>
<td></td>
<td>[27]</td>
</tr>
<tr>
<td>San San-Pond Sak, Panama</td>
<td>$-1652$–$548$</td>
<td>$-5.10$–$77.83$</td>
<td>[31]</td>
</tr>
</tbody>
</table>

The impact of groundwater depth on peat soil and its vegetation is evident, as the expansion of water-table depth (WTD) facilitates enhanced respiration and vegetation development in peat. Arid peatland serves as a notable source of greenhouse gas emissions. The increased depth of the groundwater facilitates CO$_2$ emissions. In contrast to carbon dioxide emissions, CH$_4$ emissions are more favorable at modest groundwater levels [34]. At three locations in our study (S1, S2, and S3), CO$_2$ exhibited the highest emission volume at depths of 6 cm, $-5$ cm, and $-16$ cm, respectively. In contrast, CH$_4$ demonstrated the lowest emission volume at depths of $-30$ cm, $-20$ cm, and $-16$ cm, respectively. The
experiments in S3 were conducted in July and between 12 August and 15 August, the water levels exhibited decreasing trends in terms of the fluxes in CO2 emissions as well as CH4 emissions. If WTD is below 20 cm, and the local water level is at the surface of the peat floor, the northern temperate peatlands can be utilized for a net CO2 exchange, given the net source of CO2 is higher than 25 cm above the WTD [35]. By analyzing the volumes of CO2 and CH4, as well as the water levels, this experiment reveals that CH4 emissions increased as WTD rose, whereas CO2 emissions decreased as WTD rose. The hydrophobic and organic matter content, carbon–nitrogen conversion, microbial composition, and greenhouse gas emissions of the soil are all influenced by the drainage and flood circulation, as well as the arid and wetting conditions [36,37]. The research has indicated that variations in the chemical properties of soil and earth do not significantly affect the duration of saturation or drainage from two to four weeks. It is found that, with the increase in submergence depth, CO2 and CH4 emissions show an increasing trend, and changes in submergence depth lead to a more obvious trend of CH4 fluxes (Figure 4b,d). However, prolonged saturated or drainage conditions (24 weeks) result in substantial changes in soil volume water content, pH value, microbial biomass carbon and nitrogen, and greenhouse gas emissions [38]. The fresh organic decomposition of the flooded vegetation and soil produced the most CO2 emissions in the years following the flood [39,40]. The increased CO2 emissions persist for decades following the flood, after which they decline at a rate comparable to that of the northern lake [41]. A river located in Spain has an annual cycle of saturation (from October to March) and annual droughts (from May to June), and reduced CO2 emissions result from the arid weather conditions [42]. The growth of organic matter ore and the flow of carbon and nitrogen may be enhanced by drainage-saturated conditions that alternate between anaerobic and aerobic environments. In poor fen and bog, WTD increased plant growth, while in rich fen, WTD reduced the growth of ground-level vegetation [43]. Sphagnum is the most important plant for the accumulation of peat, and is one of the dominant species in nutrient-poor peatland [44,45]. The accumulated peat thickens continuously, and when it is exposed to the overlying water, the dominant species of sphagnum is isolated from the nutrient supply and the nutrition in the peatland becomes poorer. In the wet period, a saturated peat mound generates enough water pressure to drive the surface water downwards, which exhausts the inorganic solute in the surface water and creates an environment conducive to the invasion of sphagnum moss [46].

Additional greenhouse gas emissions are significantly influenced by agricultural practices, including the climate, vegetation, crop residue and fertilization, and inherent peat characteristics [47,48]. The combination of climate warming and reduced water levels will accelerate the deterioration of peat and the subsequent release of nutrients. The dynamic alterations in plant composition have the potential to enhance the uptake of nutrients and partially counterbalance the detrimental impacts of global warming on peat ground ecosystems [49,50]. The absorption of CO2, particularly at the deepest S1 saturated water level, declined between 12 July and 15 August. The noticeable variation in CH4 emissions at S3 could be attributed to the disparity in water-level changes. The restoration of CO2 flow after the artificial disturbance of peatland is more challenging compared to the restoration of CH4, resulting in a longer recovery period. At various water levels (S1, S2, and S3), when the water level falls within a comparable range, the emissions of CH4 remain consistent, whereas the overall fluctuations in the volume of CO2 differ from those of CH4. As an illustration, the CH4 emission rate at a depth of −30 cm at the S1 water level was 14.53 mg m⁻² h⁻¹, while at a depth of −35 cm at the S2 water level, the CH4 emission rate was 16.83 mg m⁻² h⁻¹ (Figure 2), with a value of 18.96 mg m⁻² h⁻¹. Fluctuations in groundwater levels have a direct impact on the processes of decomposition and the electron receptor capacity required for heterotrophic respiration (EAC) [31]. The groundwater level declines, and the last electronic receptor undergoes oxidation to renew and restore the efficient EAC [52]. Consequently, a decrease in groundwater levels may lead to a reduction in the release of CH4, whereas an increase in CO2 emissions may occur due to the deeper penetration of oxygen into peat, stimulating heterotrophic respiration [53].
The boundary between oxygen-rich and oxygen-depleted areas, particularly in severely degraded peatland, is characterized by a broad zone rather than a distinct transition that aligns with the groundwater level. The attributes of peat decomposition can be conserved. The repair process is unaffected by the current groundwater level [54]. While the repair process can restore movement, it does not aid in the reduction in CO$_2$; however, it has the potential to significantly amplify CH$_4$ emissions. The research has shown that CO$_2$ emissions decreased by 14% following the introduction of moist CO$_2$, whereas CH$_4$ emissions increased by a factor of 3.4 [55].

The carbon balance in the biosphere is determined by two natural processes: (1) the accumulation of carbon through photosynthesis; (2) the release of CO$_2$ and CH$_4$ through heterotrophic respiration and the decomposition of organic matter. The carbon balance of peatland is influenced by small fluctuations in groundwater and temperature. These variations enhance the decomposition rate of soil organic matter and lead to an increase in the productivity of the plant community [53,56,57]. Research has indicated that climatic warming will amplify the release of CH$_4$ from peatlands, and the production of CH$_4$ is more responsive to heating than CO$_2$ [58]. Higher temperatures are anticipated to accelerate the rate at which microorganisms decompose. Additionally, a decrease in groundwater level will result in the release of a significant amount of CO$_2$ from the soil into the atmosphere, leading to a reduction in CH$_4$ emissions [44,59,60]. Core warming can lead to an increase in the carbon turnover rate of swamp peatland by affecting the amount of moss, shrubs, and grain-based plants [61]. Methane is produced in the presence of waterlogging. Furthermore, the CH$_4$ emissions into the atmosphere are also significant, alongside the dispersion and movement of peat [62,63]. The methane oxide metabolism can convert CH$_4$ back into CO$_2$ [63]. An increase in temperature is likely to cause an increase in CH$_4$ emissions from organic soil when compared to CO$_2$ emissions [64]. The experiment reveals a linear relationship between the temperature of the growing season and the volume of CO$_2$ and CH$_4$ conversions. Temperature changes lead to both positive and negative trends in response to variations in the quantities of CO$_2$ and CH$_4$. A high water table depth indicates favorable conditions for the sequestration of atmospheric carbon. Conversely, a low WTD leads to an accelerated breakdown rate of plant organic matter, resulting in an increase in CO$_2$ emissions into the atmosphere and transforming the ecosystem into a carbon source. The wetland-DNDC modeling research has shown that a decrease in WTD results in a reduction in methane emissions within the ecosystem, while causing an increase in carbon dioxide emissions [65]. The experiment revealed a linear relationship between the variations in water level that occurred during the growing season and the volumes of CO$_2$ and CH$_4$ flips. As the water level rises, there will be an inverse and direct relationship between CO$_2$ and CH$_4$. The increase in groundwater levels notably altered the physical and chemical characteristics of the top layer of soil (0–10 cm), particularly the soil moisture and salt content. These changes could potentially impact the pace at which soil releases CO$_2$ and CH$_4$ gases [66].

Climate warming, regardless of its magnitude, can alter hydrological processes and soil microbiology, consequently impacting the emissions of CO$_2$ and CH$_4$ and the carbon storage capacity of peatland [66–68]. A bivariate analysis of the effect of water level and temperature on CO$_2$ and CH$_4$ volume demonstrated that the fluxes in CO$_2$ and CH$_4$ emissions can be influenced by temperature, water level, and the interaction between the two. There is a strong association between the depth of saturation and the amounts of CO$_2$ and CH$_4$ gases when they are in the lighter position (S3). A strong correlation exists between the CH$_4$ flux volume, temperature, and flood depth in S1. A link exists between the interaction between CH$_4$, temperature, and saturated depth in S3. Peatland is an intricate ecological–hydrological system (Figures 3 and 4). The hydrogen feedback associated with the water table depth (WTD) would enhance the influence of climate on CO$_2$ and CH$_4$ emissions [69]. The decrease in WTD will enhance the process of oxygen mineralization, thus leading to an increase in the availability of carbon substrates for the formation of methane [70]. In contrast, a low WTD can also impede the release of methane
from peatlands. This is due to the expansion of the CH$_4$ oxidation zone in the soil with an increase in the available oxygen, while the zone in which methane is created contracts in areas with oxygen-depleted, saturated soil [71–73]. Consequently, warmth impacts WTD levels by augmenting dispersion, diminishing soil moisture, and altering precipitation [74]. Simultaneously, the stimulation of vegetation and biomass by CO$_2$ might result in higher levels of moisture loss due to evaporation and transportation, while also decreasing the amount of moisture captured by the upper layer of plants [69]. The hydrological alterations may interact with the process of warming, resulting in a more intricate release of CO$_2$ and CH$_4$.

5. Conclusions

The general variations in CO$_2$ and CH$_4$ discharge at various water levels are distinct: an increase in water level results in a corresponding rise in the CH$_4$ emission fluxes. The temperature reflects the gradient change in inundation depth; that is, as the water level increases, the temperature decreases. The volume of CO$_2$ emissions increases in tandem with the decrease in CH$_4$ emissions as the temperature rises. Differences in the temperature and profundity of the inundated water will influence CO$_2$ and CH$_4$ emissions. These findings highlight theoretical support for reduction of anthropogenic activities on peatlands. This can be achieved by undertaking measures to conserve peatlands and explore mitigation measures to minimize greenhouse gas emissions and, hence, the impacts of climate change.

Author Contributions: C.P., N.Y. and M.L. designed this study; C.P., H.L. and N.Y. performed the data collection, analysis and designed the figures; C.P. and M.L. discussed the results and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Program of China (2022YFF1300905).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors appreciate the anonymous reviewers for their constructive comments and suggestions, which significantly improved the quality of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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