

Article

Response of Greenhouse Gas Fluxes to Simulated Precipitation and Related Environmental Factors in the Qinghai Lake Lakeside Wetland

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Abstract

To clarify the effects of precipitation changes on greenhouse gas (CO₂, CH₄, N₂O) emissions from the lakeshore wetland ecosystem of Qinghai Lake, this study establishes five precipitation treatments (D25%, D75%, CK, I25%, I75%) using a rainfall manipulation device. During the growing season, greenhouse gas fluxes were measured via the static chamber–gas chromatography method, while soil temperature, moisture, total carbon (TC), total nitrogen (TN), pH, electrical conductivity (EC), and aboveground and belowground biomass were simultaneously monitored. The results showed that at 11:00, both increased and decreased precipitation inhibited CO₂ and CH₄ emissions (with D25 showing the strongest inhibition for CO₂ and I75 for CH₄); however, increased precipitation promoted N₂O emissions (I75 strongest), while decreased precipitation suppressed them (D25 strongest). At 15:00, only D25 inhibited CO₂ emissions, whereas all other treatments promoted them (I75 strongest). CH₄ fluxes under all treatments were higher than those in CK, indicating a promoting effect (I25 strongest). N₂O emissions responded to precipitation changes as follows: wetting promoted emissions (I25 optimal), while drying suppressed them (D75 stronger). Correlation analyses revealed treatment- and time-specific patterns. At 11:00, significant negative correlations between CO₂ and soil temperature and significant positive correlations between CH₄ and soil temperature were observed only under I75; soil moisture was significantly positively correlated with CH₄ under D25; TN significantly inhibited all three gases under wetting treatments; and TC showed a highly significant negative correlation with N₂O under I75 ($p < 0.01$). At 15:00, soil temperature generally promoted CO₂ and CH₄ emissions (except for CO₂ under D75); soil moisture promoted CH₄; TC was negatively correlated with both CO₂ and N₂O; pH was positively correlated with CO₂ only under CK; the correlation between EC and CO₂ shifted from positive (CK) to negative (I75); aboveground biomass suppressed CO₂ under I25 and I75 but promoted N₂O under D25. In summary, precipitation changes significantly modulate greenhouse gas emissions and their relationships with soil factors, with strong temporal and treatment dependencies. Future studies should integrate long-term observations and process-based models to further quantify the comprehensive effects of precipitation changes on the greenhouse gas budget of this wetland ecosystem.



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Keywords: precipitation change; Bird Island wetland; greenhouse gases; global change; Qinghai Lake

1. Introduction

Greenhouse gas (GHG) emissions have become one of the main drivers of global warming and profoundly affect global carbon and nitrogen cycles. The Intergovernmental Panel on Climate Change (IPCC) stated in its Sixth Assessment Report that human activities and associated GHG emissions are the primary drivers of global warming [1]. Greenhouse gases are those that absorb and emit long-wave radiation from the Earth's surface. They mainly include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs). Among these, CO₂ is the most important anthropogenic GHG and has the highest atmospheric concentration. It is stable and can remain in the atmosphere for 50 to 200 years. CH₄ and N₂O are the second most important GHGs after CO₂. Although their concentrations are lower than that of CO₂, their global warming potentials over a 100-year time horizon are 28 and 265 times that of CO₂, respectively [2]. Since the Industrial Revolution, the atmospheric concentrations of CO₂, CH₄, and N₂O have increased by 47%, 159%, and 23%, respectively [1].

Global climate change has led to significant alterations in precipitation patterns in terrestrial ecosystems, manifesting as increased interannual precipitation variability and intensified seasonal rainfall fluctuations. These changes subsequently affect ecosystem structure and function [3–7]. Extreme events, such as the increased frequency of heavy rainfall and the expansion of regional drought, also cause precipitation fluctuations [8]. Changes in precipitation can alter regional greenhouse gas concentrations and exchange fluxes, thereby indicating the direction and process of ecosystem succession [9]. According to the China Climate Change Blue Book (2021), the average annual precipitation in China shows an increasing trend, with significant regional differences in precipitation changes [10].

The Qinghai–Tibet Plateau is a sensitive region to global climate change [11], Annual precipitation in the Qinghai–Tibet region shows a significant increasing trend [10]. Alpine grassland soils on the Qinghai–Tibetan Plateau have a huge carbon pool and play a pivotal role in the global terrestrial carbon cycle [12]. Qinghai Lake is located in the northeastern part of the Qinghai–Tibetan Plateau and serves as a natural ecological security barrier for this region [13]. In recent years, the water level of Qinghai Lake has been continuously rising, and these climatic and hydrological changes may significantly affect wetland greenhouse gas emissions [14]. Li et al. [15] predicted that precipitation on the Qinghai–Tibet Plateau will likely continue to increase over the next 20 to 40 years. Precipitation changes may thus have a significant impact on greenhouse gas fluxes in alpine wetlands.

The effects of precipitation changes on greenhouse gas fluxes in alpine wetlands have received increasing attention; however, the findings remain inconsistent. Changes in precipitation patterns are mainly manifested as variations in precipitation amount, precipitation intensity, and seasonal distribution of precipitation. These changes may alter carbon and nitrogen cycles in terrestrial ecosystems, and the consequent shifts in source–sink functions could further affect global change dynamics [16]. Under the most extreme precipitation scenarios, precipitation in polar and equatorial regions may increase by more than 50%, while subtropical regions may experience a 30% decrease in precipitation [8]. Changes in precipitation directly lead to variations in soil moisture and temperature, which in turn cause changes in the intensity of soil microbial activity, root respiration, and plant respiration within a certain range, thereby altering greenhouse gas emission processes [17]. Li et al. [18] conducted a laboratory precipitation simulation experiment and found that abundant rainfall helps reduce the positive feedback effect of marsh wetlands on climate change during the freeze–thaw period. Geng et al. [19] showed that soil water content is an important factor affecting greenhouse gas fluxes. Li et al. [20] set up precipitation increase and decrease treatments (50%) on the Qinghai–Tibet Plateau and found that precip-

itation amount affects plant cover, which in turn changes biomass and ultimately influences greenhouse gas fluxes. Different wetland types have different vegetation compositions and cover levels, and their responses to precipitation fluctuations may also differ. Studies on the effects of precipitation changes on greenhouse gas fluxes in alpine wetlands remain relatively limited, and the response relationships between precipitation and greenhouse gas emissions require further investigation.

In this study, a simulated precipitation control experiment was conducted at the Bird Island wetland in Gangcha County, Qinghai Lake Basin, based on previous research. Previous studies in this region have carried out simulated precipitation experiments with $\pm 50\%$ precipitation increase and reduction, preliminarily revealing the effects of precipitation changes on wetland greenhouse gas fluxes. Building on this foundation, we further established additional gradients of $\pm 25\%$ and $\pm 75\%$ precipitation treatments and observed the changes over one growing season (May to August), thereby densifying and extending the precipitation stress gradient. This approach aims to more systematically reveal the response patterns of the ecosystem to different intensities of precipitation change, and to provide a scientific reference for predicting and evaluating greenhouse gas fluxes in plateau lakeside wetlands under future climate change scenarios.

2. Materials and Methods

The Bird Island wetland of Qinghai Lake is located in the northwestern part of Qinghai Lake (Figure 1). It belongs to Gangcha County, Qinghai Province, and is situated in the northeastern part of the Qinghai–Tibet Plateau, at an altitude ranging from 3194 to 3226 m. This region has a plateau continental climate, characterized by long, cold winters and short, cool summers, with strong solar radiation. The annual average temperature ranges from $-8\text{ }^{\circ}\text{C}$ to $7\text{ }^{\circ}\text{C}$. The extreme minimum temperature can reach $-24\text{ }^{\circ}\text{C}$, and the extreme maximum temperature is $23\text{ }^{\circ}\text{C}$. Precipitation is relatively low and concentrated in summer. The annual average precipitation is approximately 426.8 to 464 mm, and evaporation is much higher than precipitation. Precipitation is mainly concentrated in the growing season from May to September, with a peak in July ranging from 99 to 467.6 mm. Winter precipitation from December to February is scarce, with a seasonal average of only about 6 mm. Strong winds occur frequently throughout the year. The soil is sandy loam, characterized by a shallow soil layer, a high gravel content, and low organic matter content, with significant salinization. The vegetation is typical alpine meadow and steppe, dominated by cold- and drought-tolerant species such as *Kobresia humilis* and *Stipa* spp. The plant community structure is simple, vegetation cover is relatively low, and the ecosystem is fragile.

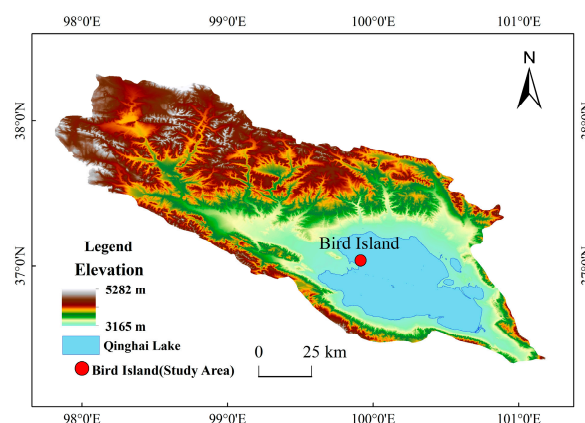


Figure 1. Location of study area (The data set is provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences. (<http://www.gscloud.cn>).

The precipitation simulation device, based on the principle of water level difference, achieves automatic rainfall. Rainwater is collected through semi-transparent PC pipes covering 75% of the area and stored in a horizontal tank. For the increase treatment, the collected water is uniformly sprayed via perforated PVC pipes onto the rainfall increase plots (Figure 2).

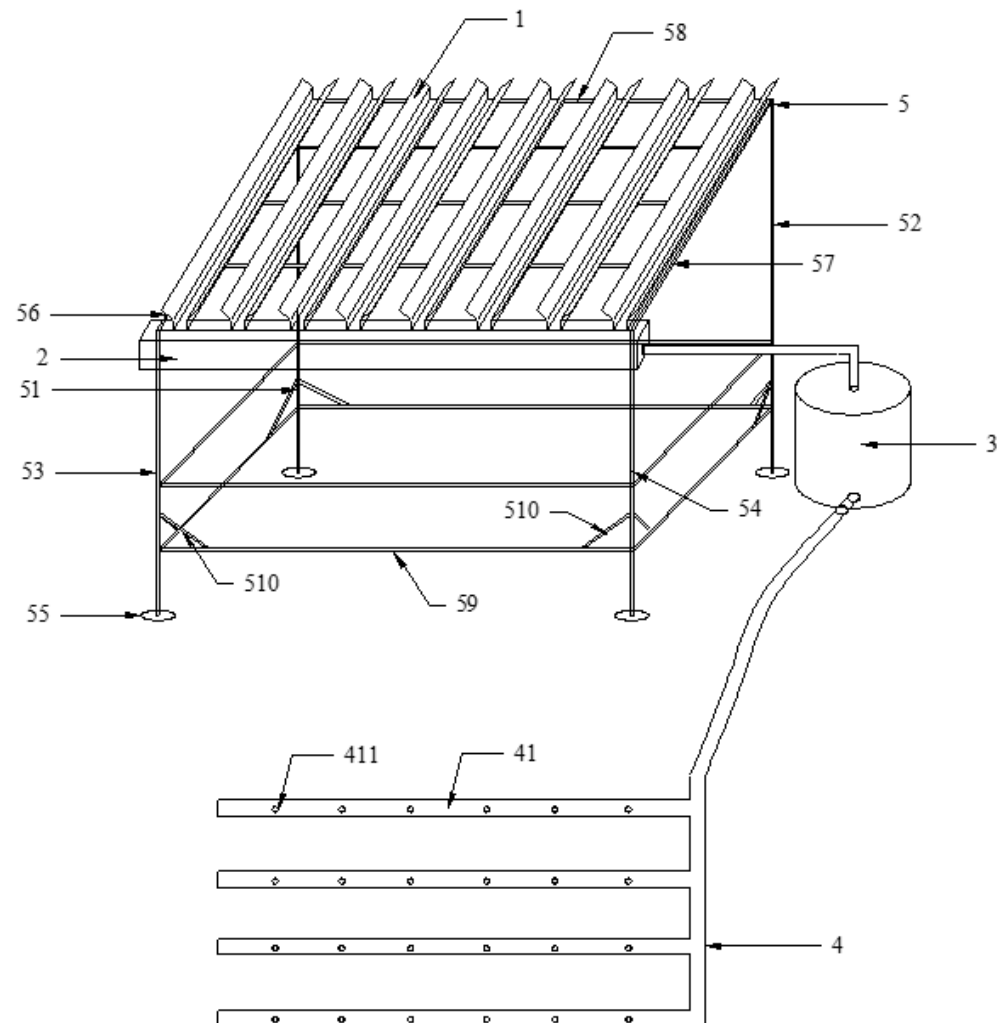


Figure 2. Schematic diagram of the precipitation simulation device [21]. 1, Rainwater diversion channel; 2, Confluence trough; 3, Lying box; 4, Irrigation device; 41, Spray hose; 411, Spray hole; 5, Support framework; 51, First horizontal pole; 52, Second horizontal pole; 53, Third horizontal pole; 54, Fourth horizontal pole; 55, Fixed chassis; 56, First steel pipe; 57, Second steel pipe; 58, Undertaken tubes; 59, Horizontal pole; 510, Slanted support tubes.

According to the Hydrological Bureau of Gangcha County [22], the Niaodao area has experienced relatively abundant precipitation since 2005. The annual precipitation in this region is 420 mm. The simulated precipitation amounts corresponding to +25%, −25%, +75%, and −75% changes are approximately 525 mm, 315 mm, 735 mm, and 105 mm, respectively. This study aims to simulate the effects of extreme precipitation increase and decrease on vegetation, soil, and microorganisms in this type of wetland, thereby further elucidating the influence of precipitation on greenhouse gas emissions in such ecosystems.

The greenhouse gases in the in situ simulated rainfall experiments in the growing season were measured using the static chamber–gas chromatography method. The plot area was 40 m × 40 m, including 15 pieces 3.2 m × 2.6 m plots. The plot layout was five rows and three columns, with plots in each row being three replicates of the same

treatment. A 3 m wide buffer zone was set between adjacent subplots, a 5 m wide buffer zone was set around the plot, and a 20 cm wide runoff prevention zone was set around each plot. The chambers used in this study were made of stainless steel and consisted of two parts. The exterior of each chamber was wrapped with white foam. The opaque chambers measured 40 cm × 40 cm × 30 cm (length × width × height), and the base frame was 40 cm × 40 cm. During sampling, the base trough was filled with water to ensure an airtight seal. Each chamber was equipped with a thermometer, a fan, and a pump interface. Based on previous studies [23,24], the time window for calculating daily mean fluxes of the three gases was between 10:00 and 16:00. Therefore, sampling was conducted at 11:00 and 15:00. Ten minutes before each sampling event, the base trough was filled with water to ensure the chamber was completely sealed. Gas samples were collected at 0, 15, 30, and 45 min using 100 mL syringes equipped with three-way stopcocks. Fifty milliliters of air were collected in each airtight syringe and immediately transported to Qinghai Normal University for laboratory analysis. Greenhouse gas (CO₂, CH₄, and N₂O) concentrations were determined using a gas chromatograph (Agilent Technologies, Santa Clara, CA, USA). CO₂ was detected with a thermal conductivity detector (TCD), CH₄ with a flame ionization detector (FID), and N₂O with a ⁶³Ni electron capture detector (ECD). All three gases were separated using an HP-5 capillary column (30 m × 0.32 mm × 0.25 μm, 19091J-413) at a flow rate of 6.5 mL/min in constant flow mode. The injector temperatures were 250 °C for CO₂ and CH₄, and 200 °C for N₂O, while the detector temperature was 300 °C for all gases. The carrier gases were hydrogen (for TCD), nitrogen (for FID), and argon-methane (for ECD).

Before measuring the concentration of each sample, two standard gas samples were injected for calibration. The greenhouse gas flux was calculated using the following formula:

$$F = \rho \times \frac{V}{A} \times \frac{P}{P_0} \times \frac{T_0}{T} \times \frac{dC}{dt}$$

where F (mg·m⁻²·h⁻¹) is the measured gas emission flux, ρ (g/L) is the measured gas density under standard conditions, V (m³) is the air volume in the sampling box, A (m²) is the area covered by the sampling box, P (hPa) is the air pressure at the sampling point, P_0 (hPa) is the atmospheric pressure under the standard state, T_0 (K) is the absolute temperature of the air under the standard state, T (K) is the absolute temperature of the air in the sampling box under the standard state, and dC/dt is the rate of change in the concentration of the air in the sampling box.

During sampling, soil temperature and soil volumetric water content at a depth of 10 cm were collected using a soil temperature recorder (Hangzhou Top Instrument Co., Ltd., Hangzhou, Zhejiang, China) with a precision of 0.01 °C and a portable sand moisture meter (JK-100F) with a precision of 0.1%, Zero calibration of the soil moisture meter: After powering on, the display should read 00.0 ± 0.5 in air. If not, slowly adjust the “ZERO” knob on the instrument using a flat-head screwdriver until the reading meets the requirement. From May to September 2020, aboveground biomass was sampled in three replicate plots under each precipitation treatment (including the natural control). A 25 cm × 25 cm quadrat was randomly placed in each plot. Vegetation within the quadrat was clipped at ground level. After removing litter, the plant material was sealed in self-sealing bags and transported to the laboratory for further analysis. The samples were deactivated in a forced-air drying oven at 105 °C, then dried at a constant temperature of 65 °C for 24 h. The dry matter mass was weighed and converted to obtain aboveground biomass. Soil total carbon (TC) and total nitrogen (TN) in the 0–10 cm layer were determined using an ECS4024 elemental analyzer (EAI Company, Jersey City, NJ, USA). After clipping and removing aboveground vegetation, soil samples were collected from the 0–10 cm and 10–20 cm layers in each plot,

respectively, and air-dried for subsequent analysis. The air-dried soil samples were passed through a 2 mm sieve. The sieved soils (<2 mm) were then thoroughly mixed, ground, and passed through a 0.25 mm sieve for further use. Subsequently, all soil samples were accurately weighed (20.0 mg) using an analytical balance, with a precision of 0.0001 g and prepared for measurement. To guarantee the reliability and reproducibility of the analytical results, four replicate sample packets (5 ± 0.001 mg each) were prepared for each soil sample. Soil total nitrogen (TN) and total carbon (TC) were subsequently determined via high-temperature combustion, with final values expressed as the mean of four repeated measurements. Soil pH was determined using a PHS-25 pH meter. Soil samples (1.00 g) from the 0–10 cm and 10–20 cm layers that had passed through a 2 mm sieve were mixed with ultrapure water at a soil-to-water ratio of 1:25 (w/v), thoroughly shaken, and allowed to stand for 30 min prior to measurement. Soil electrical conductivity (EC) was measured using a DDS-307 conductivity meter. Soil samples (10.00 g) from the 0–10 cm and 10–20 cm layers that had passed through a 2 mm sieve were mixed with 50 mL of deionized water and thoroughly shaken, and filtered to obtain a clear solution for EC measurement. The dynamic changes in all measured variables were then analyzed graphically.

Prior to Pearson's correlation analysis, residual normality tests and Levene's test for homogeneity of variances were performed on CO_2 , N_2O , CH_4 fluxes, as well as above-ground and belowground biomass. The results indicated that all variables satisfied the assumptions of normality ($p > 0.05$) and homogeneity of variances ($p > 0.05$), thereby meeting the prerequisites for Pearson's correlation analysis.

All data were processed using Excel 2024. The relationships between greenhouse gas fluxes and environmental factors under different precipitation treatments were analyzed using IBM SPSS Statistics 21. Greenhouse gas emission trends under different precipitation conditions, as well as trends in various physicochemical environmental factors, were analyzed and visualized using OriginPro 2025 software.

3. Results

3.1. Responses of Greenhouse Gases to Precipitation Changes

3.1.1. Response of CO_2 Flux to Precipitation Changes

Monitoring of CO_2 fluxes in the Bird Island wetland ecosystem during the growing season under different precipitation treatments revealed that, throughout the observation period, CO_2 emissions at both 11:00 and 15:00 generally increased to a peak and then decreased. The peak CO_2 emission occurred in late June. At 11:00, the total CO_2 emissions under all precipitation treatments were lower than those under the natural control (CK). The overall order was: CK ($761.78 \text{ mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) > I75% ($640.2 \text{ mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) > I25% ($541.5 \text{ mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) > D75% ($489.5 \text{ mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) > D25% ($22 \text{ mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ lower than CK) under all precipitation treatments. Compared with CK, the CO_2 emission fluxes under the I25%, I75%, D25%, and D75% treatments decreased by 220. 28 $\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 121.58 $\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 368.22 $\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, and 272.28 $\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, respectively. Among them, the D25% treatment showed the largest reduction ($22 \text{ mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ lower than CK), indicating that the D25% treatment had the strongest inhibitory effect on CO_2 uptake. At 15:00, except for the D25% treatment, which inhibited CO_2 emissions, treatments promoted CO_2 emissions. Among these, I75% showed the strongest promoting effect, with emissions 216 $\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ higher than CK, while D25% reduced emissions by 130.4 $\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ compared to CK. These results indicate that the effect of precipitation change on CO_2 flux is clearly time-dependent, with moderate precipitation reduction (D25%) suppressing CO_2 uptake during the day (Figure 3).

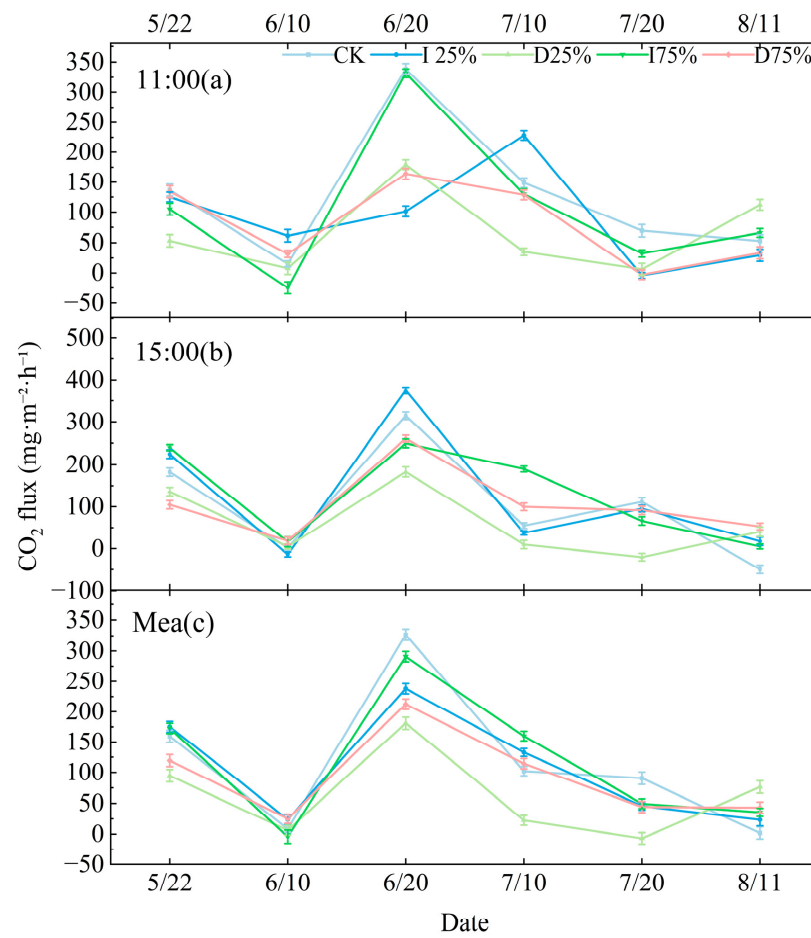


Figure 3. Variation trend of CO₂ emission flux in Bird Island wetland under different precipitation treatments, (a) CO₂ emission flux at 11:00, (b) CO₂ emission flux at 15:00, (c) average CO₂ emission flux at 11:00 and 15:00 (Note: n = 3, error bars represent the standard error of the mean).

3.1.2. Response of CH₄ Flux to Precipitation Changes

At 11:00, CH₄ emissions showed a slowly increasing trend, with peaks occurring on August 11. The peak values under each treatment were as follows: CK, 36.2 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I25%, 25.2 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; D25%, 30.7 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I75%, 12.8 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; and D75%, 22.4 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Although some treatments showed higher emissions than CK at certain time points, the total CH₄ fluxes under all treatments throughout the growing season were lower than those under CK. The overall order was CK > D25% > I25% > D75% > I75%. These results indicate that both precipitation reduction and increase inhibited CH₄ emissions. Among them, the I75% treatment showed the strongest inhibition. Compared with CK, the CH₄ fluxes under the I25%, I75%, D25%, and D75% treatments decreased by 47.5, 56.5, 26.4, and 77.3 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, respectively. At 15:00, CH₄ emissions showed a “W”-shaped increasing trend. Emissions under all treatments were higher than those under CK. The peak values under each treatment were as follows: CK, $-0.2 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I25%, 17.9 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; D25%, 20.1 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I75%, 13.8 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; and D75%, 11 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Throughout the growing season, the total CH₄ fluxes under each treatment were as follows: I25% (22.7 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > I75% (21.1 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > D25% (16.7 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > D75% (13.7 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > CK ($-17.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). Thus, the I25% treatment showed the strongest promotion of CH₄ emissions. The CH₄ emission flux under the I25% treatment was 67.2 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ higher than that of CK (Figure 4).

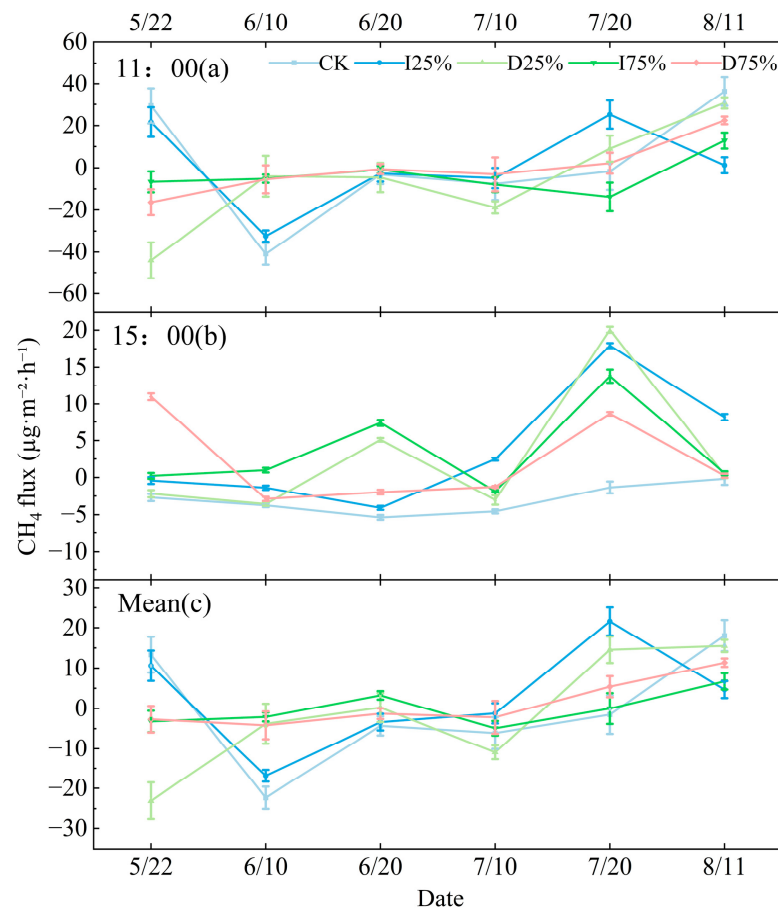


Figure 4. Variation trend of CH_4 emission flux in Bird Island wetland under different precipitation treatments, (a) CH_4 emission flux at 11:00, (b) CH_4 emission flux at 15:00, (c) average CH_4 emission flux at 11:00 and 15:00 (Note: $n = 3$, error bars represent the standard error of the mean).

3.1.3. Response of N_2O Flux to Precipitation Changes

At 11:00, N_2O emissions under the precipitation reduction treatments and the CK group showed a “W”-shaped increasing trend, while under the precipitation increase treatments, N_2O emissions first increased and then decreased. The peaks for each treatment occurred in June, with values as follows: CK, $6.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I25%, $6.2 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; D25%, $3.6 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I75%, $10.3 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; and D75%, $1.6 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Throughout the growing season, total N_2O emissions under all four precipitation treatments were higher than those under CK. The N_2O emission fluxes followed the order: I75% ($16.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > I25% ($7.8 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > CK ($-4.2 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > D25% ($-5.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > D75% ($-11.4 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). Compared with CK, the N_2O emission flux under I75% was $21.1 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ higher, while under I25% it was $12 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ higher. In contrast, the N_2O emission fluxes under D25% and D75% were $1.7 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and $7.2 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ lower than CK, respectively. Among all treatments, I75% exhibited the strongest promoting effect on N_2O emissions, whereas D75% showed the strongest inhibitory effect. At 15:00, N_2O emissions first increased and then decreased, with peaks also occurring in June. The peak values were: CK, $9.7 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I25%, $16.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; D25%, $7.7 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; I75%, $11.4 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$; and D75%, $7.3 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Throughout the growing season, the two precipitation increase treatments significantly promoted N_2O emissions, while the two reduction treatments inhibited them. The total N_2O emissions were as follows: I25% ($29.7 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > I75% ($16.5 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > CK ($2.4 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > D25% ($-4.2 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) > D75% ($-14.0 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). Among them, I25% showed the strongest promotion effect, significantly increasing N_2O emissions by $27.3 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$.

compared with CK. D75% showed the strongest inhibition effect, with N_2O emissions $16.4 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ lower than those under CK (Figure 5).

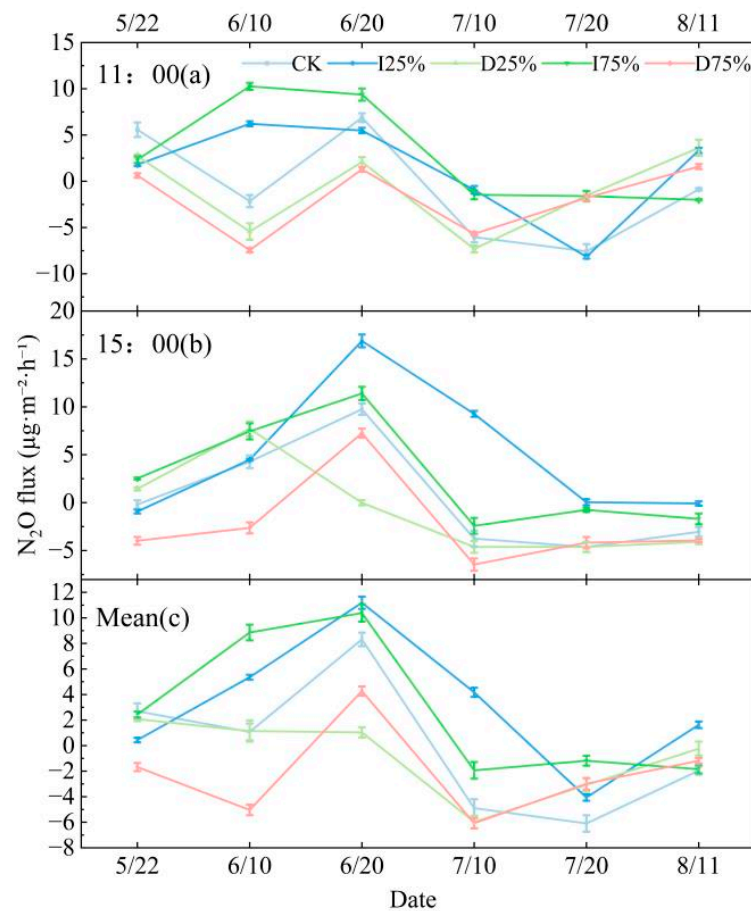


Figure 5. Variation trend of N_2O emission flux in Bird Island wetland under different precipitation treatments, (a) N_2O emission flux at 11:00, (b) N_2O emission flux at 15:00, (c) average N_2O emission flux at 11:00 and 15:00 (Note: $n = 3$, error bars represent the standard error of the mean).

3.2. Effects of Physicochemical Properties on Greenhouse Gas Emissions Under Different Precipitation Treatments

3.2.1. Effects of Soil Temperature and Soil Moisture on Greenhouse Gas Emissions Under Precipitation Changes

From late May to early August, soil temperature under all treatments showed an overall increasing trend, reflecting the seasonal warming pattern from late spring to summer. Soil temperature at 15:00 was significantly higher than that at 11:00, with the average temperature at 15:00 being 6.2°C higher than that at 11:00. This pattern is consistent with the diurnal variation in soil temperature driven by increasing solar radiation, as the soil continuously absorbs heat, forming a clear daily dynamic. At 11:00, the peak soil temperatures under each treatment were as follows: D25% (19.1°C) > I25% (18.5°C) > CK (16.5°C) > D75% (16.0°C) > I75% (15.7°C). At 15:00, the peak soil temperatures were: CK (23.9°C) > D25% (23.1°C) > D75% (22.2°C) > I75% (21.8°C) > I25% (21.6°C). Significant differences were observed among treatments (Table 1). The soil temperatures under the precipitation increase treatments (I25% and I75%) were slightly lower than those under the precipitation reduction treatments (D25% and D75%) (Figure 6).

Table 1. Analysis of differences in soil temperature and soil moisture under different precipitation treatments in the Bird Island wetland at 11:00 and 15:00 in each month of 2020.

	Treatment	11:00		15:00	
		Soil Temperature (°C)	Soil Moisture (%)	Soil Temperature (°C)	Soil Moisture (%)
22 May	CK	8.7 ± 0.2 c	43.2 ± 0.8 b	17.2 ± 0.1 c	58.2 ± 0.5 a
	I25%	10 ± 0.4 a	55.4 ± 1.5 d	20 ± 0.5 a	52.5 ± 1.0 c
	D25%	9.8 ± 0.1 a	51.4 ± 1.5 a	19.5 ± 0.7 ab	59.2 ± 2.6 a
	I75%	9.2 ± 0.2 b	48.3 ± 1.3 a	19.7 ± 0.4 ab	54.2 ± 0.6 b
	D75%	9.3 ± 0.2 b	46.9 ± 0.5 c	19.0 ± 0.2 b	51.9 ± 1.2 c
10 June	CK	13.5 ± 0.1 c	53.5 ± 1.0 d	15.0 ± 0.3 b	62.2 ± 0.4 b
	I25%	15.9 ± 0.8 a	59.9 ± 0.1 a	16.5 ± 0.3 a	60.5 ± 1.0 d
	D25%	14.4 ± 0.5 b c	55.7 ± 0.6 b	15.5 ± 0.3 b	60.8 ± 0.3 a
	I75%	14.7 ± 0.9 b	55.9 ± 0.8 b	15.2 ± 0.1 b	62.7 ± 0.6 c
	D75%	14.5 ± 0.3 b c	53 ± 0.3 c	16.1 ± 0.4 a	58.6 ± 0.7 c
20 June	CK	12.5 ± 0.2 a	63.6 ± 1.8 a	21.2 ± 0.4 ab	66.3 ± 1.6 a
	I25%	12.8 ± 0.5 a	64.3 ± 2.0 ab	21.6 ± 0.4 a	65.9 ± 3.6 b c
	D25%	11.6 ± 0.6 b	62.0 ± 1.0 b	21.4 ± 0.3 ab	64.3 ± 2.8 a
	I75%	13.2 ± 0.1 a	65.6 ± 1.0 c	20.4 ± 0.5 c	66.6 ± 3.3 c
	D75%	11.0 ± 0.1 b	59.4 ± 0.6 b	20.7 ± 0.3 b c	64.8 ± 2.5 b
10 July	CK	12.3 ± 0.2 d	79.2 ± 1.9 a	23.9 ± 0.6 a	86.3 ± 0.3 b
	I25%	14.8 ± 0.2 b	76 ± 2.1 b	20.5 ± 0.2 d	89.3 ± 1.4 b
	D25%	16.4 ± 0.4 a	75.3 ± 1.3 b	22.8 ± 0.1 b	85.3 ± 2.2 b
	I75%	13.0 ± 0.2 c	92.6 ± 1.7 b	21.7 ± 0.9 c	84.1 ± 2.0 c
	D75%	12.3 ± 0.4 d	83.1 ± 1.4 a	21.5 ± 0.3 c	83.7 ± 2.0 a
20 July	CK	15.4 ± 0.3 a	62.4 ± 0.8 b	19.8 ± 0.5 a	67.5 ± 0.8 d
	I25%	15.9 ± 0.8 b	61.3 ± 0.3 d	19.3 ± 0.3 a	69.5 ± 0.6 d
	D25%	13 ± 0.3 a	66.7 ± 1.2 d	18.7 ± 0.2 b	68.9 ± 1.0 a
	I75%	15.7 ± 1.0 b	69.7 ± 0.6 a	18.7 ± 0.2 b	69.7 ± 0.3 c
	D75%	16.0 ± 0.6 b	64.5 ± 0.6 c	19.5 ± 0.3 a	66.6 ± 0.8 b
11 August	CK	16.5 ± 0.3 b c	72.7 ± 0.4 d	23.0 ± 0.4 a	64.4 ± 0.4 d
	I25%	18.5 ± 0.3 a	87.2 ± 0.4 a	21.7 ± 0.2 b	79.1 ± 0.2 b
	D25%	19.1 ± 0.6 a	89.1 ± 0.3 b	23.1 ± 0.3 a	75 ± 0.3 a
	I75%	16.7 ± 0.6 b	86.3 ± 0.2 c	21.8 ± 0.2 b	80.9 ± 0.1 c
	D75%	15.8 ± 0.3 c	80.1 ± 0.1 c	22.2 ± 0.7 b	74.1 ± 0.4 b

Note: Values are means ± standard deviation. Different lowercase letters indicate significant differences ($p < 0.05$) in each index between different time points within the same treatment.

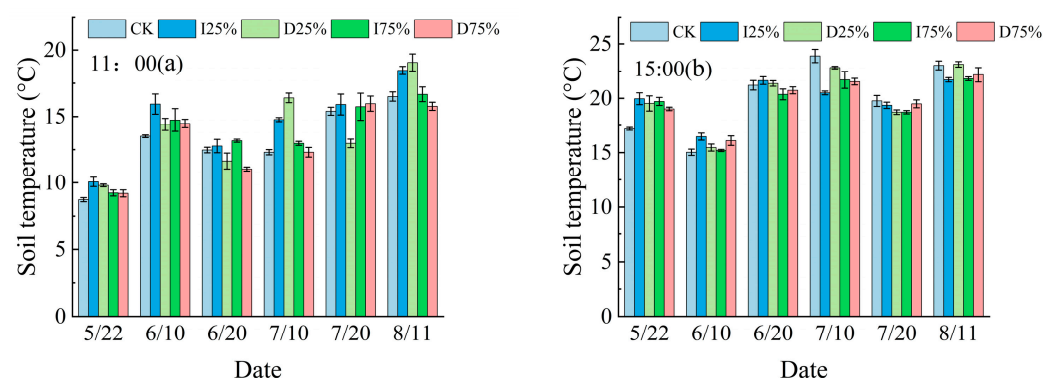


Figure 6. Dynamic trend of soil temperature in Niaodao wetland under different precipitation treatments (Note: $n = 3$, error bars represent the standard error of the mean). (a) Seasonal trend of soil temperature at 11:00. (b) Seasonal trend of soil temperature at 15:00.

The relationships between greenhouse gas fluxes and soil temperature at 11:00 and 15:00 under different precipitation treatments in the Bird Island wetland in 2020 are shown in Table 2. At 11:00, compared with the CK group, both precipitation reduction and increase resulted in inhibition of CO_2 emissions by soil temperature. The inhibition effect

followed the order: I75% > D75% > D25% > I25% > CK. However, a significant negative correlation between CO₂ flux and soil temperature was observed only under the I75% treatment ($p < 0.05$). Compared with CK, soil temperature promoted CH₄ uptake under the I25% treatment. Under the other treatments, soil temperature promoted CH₄ emissions, with a significant positive correlation between CH₄ flux and soil temperature observed under I75% ($p < 0.05$). N₂O showed negative correlations with soil temperature under all treatments, although none reached statistical significance. These results indicate that, regardless of precipitation increase or reduction, soil temperature inhibited CO₂ and N₂O emissions, while under I75%, soil temperature significantly promoted CH₄ emissions. At 15:00, with precipitation increase or reduction, soil temperature promoted CO₂ emissions. The promotion effect followed the order: D25% > I75% > I25% > D75% > CK. However, a significant negative correlation between CO₂ flux and soil temperature was observed only under D75% ($p < 0.05$). For N₂O, soil temperature inhibited emissions under the precipitation increase treatments (I25% and I75%) but promoted emissions under the precipitation reduction treatments (D25% and D75%); none of these correlations reached statistical significance. Soil temperature promoted CH₄ emissions under all treatments, with the promotion effect following the order: I25% > D25% > D75% > I75% > CK. These results indicate that at 15:00, soil temperature promoted CO₂ and CH₄ emissions, while under the precipitation increase treatments, soil temperature inhibited N₂O emissions.

Table 2. Relationships between greenhouse gas fluxes and soil temperature and soil moisture under different precipitation treatments in the Bird Island wetland at 11:00 and 15:00 in 2020.

Treatment	Greenhouse Gas	11:00		15:00	
		Soil Temperature (°C) Correlation Coefficient r (n = 6, p -Value)	Soil Moisture (%) Correlation Coefficient r (n = 6, p -Value)	Soil Temperature (°C) Correlation Coefficient r (n = 6, p -Value)	Soil Moisture (%) Correlation Coefficient r (n = 6, p -Value)
CK	CO ₂	$r = -0.629$ (n = 6, $p = 0.181$)	$r = -0.776$ (n = 6, $p = 0.070$)	$r = -0.978$ (n = 6, $p = 0.001$) *	$r = -0.158$ (n = 6, $p = 0.764$)
	N ₂ O	$r = -0.483$ (n = 6, $p = 0.332$)	$r = 0.179$ (n = 6, $p = 0.735$)	$r = 0.002$ (n = 6, $p = 0.997$)	$r = 0.434$ (n = 6, $p = 0.392$)
	CH ₄	$r = 0.100$ (n = 6, $p = 0.851$)	$r = -0.171$ (n = 6, $p = 0.745$)	$r = -0.674$ (n = 6, $p = 0.142$)	$r = 0.365$ (n = 6, $p = 0.479$)
I25%	CO ₂	$r = -0.772$ (n = 6, $p = 0.072$)	$r = -0.305$ (n = 6, $p = 0.557$)	$r = -0.873$ (n = 6, $p = 0.023$) *	$r = -0.734$ (n = 6, $p = 0.096$)
	N ₂ O	$r = -0.351$ (n = 6, $p = 0.496$)	$r = 0.419$ (n = 6, $p = 0.408$)	$r = -0.783$ (n = 6, $p = 0.066$)	$r = -0.100$ (n = 6, $p = 0.851$)
	CH ₄	$r = -0.910$ (n = 6, $p = 0.012$) *	$r = -0.558$ (n = 6, $p = 0.250$)	$r = 0.453$ (n = 6, $p = 0.368$)	$r = 0.968$ (n = 6, $p = 0.002$) *
D25%	CO ₂	$r = -0.873$ (n = 6, $p = 0.023$) *	$r = -0.734$ (n = 6, $p = 0.096$)	$r = -0.416$ (n = 6, $p = 0.412$)	$r = -0.944$ (n = 6, $p = 0.005$) *
	N ₂ O	$r = -0.783$ (n = 6, $p = 0.066$)	$r = -0.100$ (n = 6, $p = 0.851$)	$r = 0.341$ (n = 6, $p = 0.509$)	$r = 0.781$ (n = 6, $p = 0.067$)
	CH ₄	$r = 0.453$ (n = 6, $p = 0.368$)	$r = 0.968$ (n = 6, $p = 0.002$) *	$r = 0.053$ (n = 6, $p = 0.921$)	$r = 0.707$ (n = 6, $p = 0.116$)
I75%	CO ₂	$r = -0.984$ (n = 6, $p = 0.0003$) *	$r = -0.637$ (n = 6, $p = 0.174$)	$r = -0.711$ (n = 6, $p = 0.113$)	$r = -0.213$ (n = 6, $p = 0.686$)
	N ₂ O	$r = -0.853$ (n = 6, $p = 0.031$) *	$r = -0.642$ (n = 6, $p = 0.169$)	$r = -0.909$ (n = 6, $p = 0.012$) *	$r = -0.652$ (n = 6, $p = 0.161$)
	CH ₄	$r = 0.963$ (n = 6, $p = 0.002$) *	$r = 0.685$ (n = 6, $p = 0.133$)	$r = -0.534$ (n = 6, $p = 0.276$)	$r = 0.466$ (n = 6, $p = 0.352$)
D75%	CO ₂	$r = -0.927$ (n = 6, $p = 0.008$) *	$r = -0.621$ (n = 6, $p = 0.187$)	$r = -0.958$ (n = 6, $p = 0.003$) *	$r = -0.358$ (n = 6, $p = 0.488$)
	N ₂ O	$r = -0.331$ (n = 6, $p = 0.524$)	$r = 0.526$ (n = 6, $p = 0.284$)	$r = 0.594$ (n = 6, $p = 0.213$)	$r = 0.655$ (n = 6, $p = 0.158$)
	CH ₄	$r = 0.594$ (n = 6, $p = 0.213$)	$r = 0.655$ (n = 6, $p = 0.158$)	$r = -0.429$ (n = 6, $p = 0.3$)	$r = -0.419$ (n = 6, $p = 0.408$)

Note: * indicates significant correlation at the 0.05 level; n = 6 represents the number of repeated measurement days for each treatment.

As shown in Figure 7, soil moisture content at both 11:00 and 15:00 showed a significant increasing trend under all treatments, which is consistent with the seasonal pattern of increasing precipitation and decreasing vegetation transpiration. Significant differences in soil moisture were observed among treatments (Table 1). On most days, soil moisture at 15:00 was higher than that at 11:00, with the average soil moisture at 15:00 being 2.5% higher than that at 11:00. As reported by Dongshen Su (2019) [25], prominent lake-land breeze circulations prevail along the lakeshore of Qinghai Lake (e.g., Bird Island and Gangcha) in summer. Diurnal warming over land triggers convective uplift of water vapor, readily inducing short-duration local convective rainfall between 14:00 and 16:00. Precipitation

within this time window constitutes the primary daytime water supply for topsoil in lake-side zones during summer. Nearly 60% of short-term convective rainfall events across the entire lake basin occur from 13:00 to 15:00, which accounts for the observed diurnal soil moisture peak at 15:00. The peak soil moisture values at 11:00 were as follows: I75% (92.6%) > D25% (89.1%) > I25% (87.2%) > D75% (83.1%) > CK (79.2%). At 15:00, the peak soil moisture values were: I25% (89.3%) > CK (86%) > D25% (85.3%) > I75% (84.1%) > D75% (83.8%).

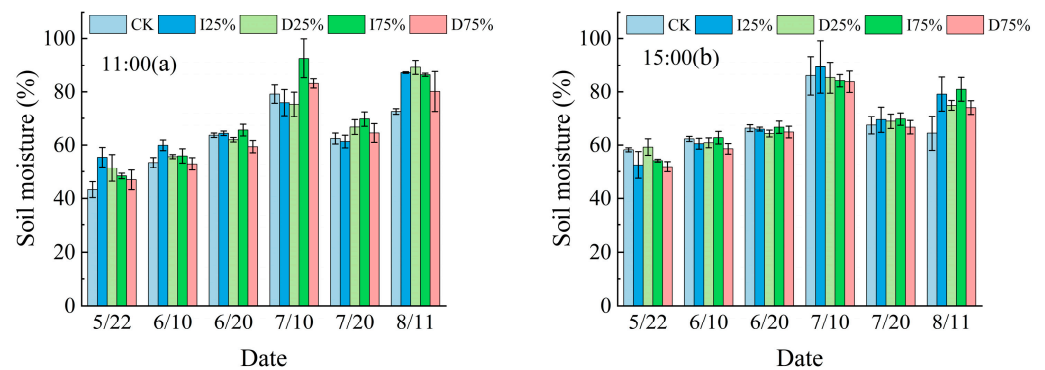


Figure 7. Dynamic trend of soil moisture in Niaodao wetland under different precipitation treatments (Note: $n = 3$, error bars represent the standard error of the mean). (a) Seasonal trend of soil moisture at 11:00. (b) Seasonal trend of soil moisture at 15:00.

Based on the relationships between greenhouse gas fluxes and soil moisture under different precipitation treatments in the Bird Island wetland (Table 2), at 11:00, compared with the CK group, soil moisture promoted CO_2 emissions under all precipitation treatments. The promotion effect followed the order: I25% > D75% > I75% > D25% > CK. However, no significant correlation was observed between CO_2 emissions and soil moisture under any treatment. N_2O emissions also showed no significant correlation with soil moisture, although positive correlations were observed under the I25% and D75% treatments. At 15:00, soil moisture inhibited CH_4 emissions only under the I25% treatment, while it promoted CH_4 emissions under all other treatments. Among these, the I75% treatment showed the strongest promotion effect. A significant positive correlation between soil moisture and CH_4 emissions was observed only under the D25% treatment ($p < 0.05$). These results indicate that CO_2 and N_2O emissions had no significant correlation with soil moisture, while the I75% treatment showed the strongest promotion effect of soil moisture on CH_4 emissions.

3.2.2. Effects of Total Nitrogen and Total Carbon on Greenhouse Gas Emissions Under Precipitation Changes

In this study, soil total nitrogen (TN) and total carbon (TC) contents in the 0–10 cm layer of the Bird Island wetland were measured from May to August 2020. The results showed that all treatments exhibited a simultaneous decrease in June. The peak TN occurred in May, while the peak TC occurred in August, indicating different seasonal patterns. The total TN content under the precipitation increase treatments was much lower than that under the precipitation reduction treatments. The overall order was: D75% ($4.8 \text{ g} \cdot \text{kg}^{-1}$) > D25% ($3.8 \text{ g} \cdot \text{kg}^{-1}$) > CK ($3.5 \text{ g} \cdot \text{kg}^{-1}$) > I25% ($2.4 \text{ g} \cdot \text{kg}^{-1}$) > I75% ($2.5 \text{ g} \cdot \text{kg}^{-1}$). A possible explanation is that precipitation increase accelerated the leaching loss of soil TN. For soil TC, the content in August was much higher than that in other months. The total TC content under the precipitation increase treatments was slightly lower than that under the precipitation reduction treatments. The overall order was: D75% ($96.9 \text{ g} \cdot \text{kg}^{-1}$) > D25% ($95.4 \text{ g} \cdot \text{kg}^{-1}$) > CK ($94.8 \text{ g} \cdot \text{kg}^{-1}$) > I75% ($94.7 \text{ g} \cdot \text{kg}^{-1}$) > I25% ($93.8 \text{ g} \cdot \text{kg}^{-1}$). These

results suggest that drought stress may have promoted the accumulation of organic carbon in the surface soil (Figure 8).

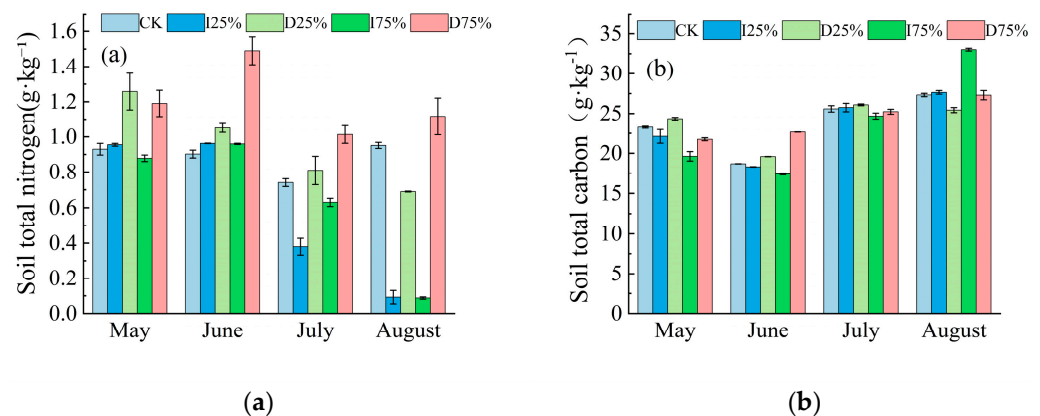


Figure 8. Dynamic trends of soil total nitrogen (TN) and soil total carbon (TC) in the 0–10 cm soil layer under different precipitation treatments in the Bird Island wetland. (Note: $n = 3$, error bars represent the standard error of the mean). (a) Seasonal trend of total soil nitrogen at 0–10 cm depth. (b) Seasonal trend of total soil carbon at 0–10 cm depth.

Table 3 shows the relationships between greenhouse gas fluxes and soil total nitrogen (TN) and total carbon (TC) contents in the 0–10 cm layer under different precipitation treatments in the Bird Island wetland. Regarding soil TN, at both 11:00 and 15:00, no significant correlations were observed between TN and CO₂, N₂O, or CH₄ emissions under any precipitation treatment, except for a significant correlation between N₂O flux and TN in the CK group ($p < 0.05$). However, certain trends were observed. At 11:00, compared with the CK group, TN inhibited CO₂ and N₂O emissions under both precipitation increase and reduction treatments. The order of inhibition intensity for CO₂ was CK > I25% > D75% > I75% > D25%, and for N₂O it was CK > D75% > D25% > I25% > I75%. For CH₄, compared with CK, TN promoted emissions only under the I25% treatment, while it inhibited emissions under all other treatments, with D75% showing the strongest inhibition. At 15:00, compared with CK, TN inhibited CO₂ emissions only under D75%, while it promoted CO₂ emissions under all other treatments, with D25% showing the strongest promotion. For N₂O, TN promoted emissions under both precipitation increase and reduction treatments, with the promotion effect following the order: I25% > D25% > I75% > D75% > CK. Regarding CH₄, TN inhibited emissions under both precipitation increase and reduction treatments, with the inhibition intensity following the order: CK > D75% > I25% > D25% > I75% (Table 3).

Regarding soil total carbon (TC), Table 3 shows that at 11:00, no significant correlations were observed between TC and CO₂ flux under any precipitation treatment ($p > 0.05$). However, a positive correlation was observed under I25%, while negative correlations were observed under the other treatments. Compared with CK, both precipitation increase and reduction treatments promoted CO₂ emissions, with the promotion effect following the order: I25% > D75% > I75% > D25% > CK. For N₂O, compared with CK, TC promoted N₂O emissions under all precipitation treatments except I75%, where TC inhibited N₂O emissions. Under I75%, a highly significant negative correlation was observed between N₂O and TC ($p < 0.01$). Regarding the relationship between TC and CH₄ flux, no significant correlations were observed under different precipitation treatments ($p > 0.05$). Compared with CK, precipitation reduction treatments shifted the correlation from positive to negative, with the correlation intensity increasing as the reduction gradient increased. Under the precipitation increase gradient, TC promoted CH₄ emissions under I25% but inhibited them under D25%. At 15:00, TC showed negative correlations with CO₂ flux under all

precipitation treatments (r ranging from -0.500 to -0.174 , $p > 0.05$), indicating that TC inhibited CO_2 emissions, although not significantly. Compared with CK, the D25% treatment strengthened this inhibition, while the other treatments weakened it. For N_2O emissions, TC showed negative correlations with N_2O flux under all treatments. Among these, highly significant negative correlations were observed under CK and I75% ($p < 0.01$), and a significant negative correlation was observed under D25% ($p < 0.05$). Compared with CK, TC promoted N_2O uptake under I75% but promoted N_2O emissions under the other treatments. For CH_4 , except for a weak negative correlation under I75%, positive correlations were observed under all other treatments, with a significant positive correlation under I25% ($p < 0.05$), indicating that TC generally promoted CH_4 emissions (except under I75%). However, compared with CK, only the I25% treatment showed a positive promotion effect of TC on CH_4 emissions, while the other treatments showed inhibition.

Table 3. Relationships between greenhouse gas fluxes and soil total nitrogen (TN) and total carbon (TC) contents in the 0–10 cm layer under different precipitation treatments in the Bird Island wetland at 11:00 and 15:00 in 2020.

Treatment	Greenhouse Gas	11:00		15:00	
		Soil Total Nitrogen ($\text{g}\cdot\text{kg}^{-1}$) Correlation Coefficient r ($n = 6$, p -Value)	Soil Total Carbon ($\text{g}\cdot\text{kg}^{-1}$) Correlation Coefficient r ($n = 6$, p -Value)	Soil Total Nitrogen ($\text{g}\cdot\text{kg}^{-1}$) Correlation Coefficient r ($n = 6$, p -Value)	Soil Total Carbon ($\text{g}\cdot\text{kg}^{-1}$) Correlation Coefficient r ($n = 6$, p -Value)
CK	CO_2	$r = 0.518$ ($n = 6$, $p = 0.293$)	$r = -0.691$ ($n = 6$, $p = 0.128$)	$r = -0.340$ ($n = 6$, $p = 0.510$)	$r = -0.396$ ($n = 6$, $p = 0.438$)
	N_2O	$r = 0.867$ ($n = 6$, $p = 0.026$) *	$r = -0.797$ ($n = 6$, $p = 0.058$)	$r = -0.845$ ($n = 6$, $p = 0.034$) *	$r = -0.925$ ($n = 6$, $p = 0.008$) **
	CH_4	$r = 0.003$ ($n = 6$, $p = 0.996$)	$r = 0.223$ ($n = 6$, $p = 0.672$)	$r = 0.690$ ($n = 6$, $p = 0.129$)	$r = 0.670$ ($n = 6$, $p = 0.145$)
I25%	CO_2	$r = 0.310$ ($n = 6$, $p = 0.550$)	$r = 0.038$ ($n = 6$, $p = 0.943$)	$r = 0.441$ ($n = 6$, $p = 0.382$)	$r = -0.265$ ($n = 6$, $p = 0.612$)
	N_2O	$r = -0.324$ ($n = 6$, $p = 0.531$)	$r = -0.665$ ($n = 6$, $p = 0.150$)	$r = -0.265$ ($n = 6$, $p = 0.612$)	$r = -0.441$ ($n = 6$, $p = 0.382$)
	CH_4	$r = 0.642$ ($n = 6$, $p = 0.169$)	$r = 0.651$ ($n = 6$, $p = 0.162$)	$r = 0.118$ ($n = 6$, $p = 0.824$)	$r = 0.883$ ($n = 6$, $p = 0.020$) *
D25%	CO_2	$r = -0.329$ ($n = 6$, $p = 0.525$)	$r = -0.326$ ($n = 6$, $p = 0.528$)	$r = -0.088$ ($n = 6$, $p = 0.868$)	$r = -0.500$ ($n = 6$, $p = 0.312$)
	N_2O	$r = 0.203$ ($n = 6$, $p = 0.700$)	$r = 0.088$ ($n = 6$, $p = 0.868$)	$r = -0.353$ ($n = 6$, $p = 0.493$)	$r = -0.883$ ($n = 6$, $p = 0.020$) *
	CH_4	$r = -0.406$ ($n = 6$, $p = 0.425$)	$r = -0.003$ ($n = 6$, $p = 0.996$)	$r = 0.088$ ($n = 6$, $p = 0.868$)	$r = 0.265$ ($n = 6$, $p = 0.612$)
I75%	CO_2	$r = -0.131$ ($n = 6$, $p = 0.804$)	$r = -0.310$ ($n = 6$, $p = 0.550$)	$r = 0.452$ ($n = 6$, $p = 0.368$)	$r = -0.174$ ($n = 6$, $p = 0.741$)
	N_2O	$r = -0.501$ ($n = 6$, $p = 0.312$)	$r = -0.994$ ($n = 6$, $p = 0.001$) **	$r = -0.486$ ($n = 6$, $p = 0.329$)	$r = -0.962$ ($n = 6$, $p = 0.001$) **
	CH_4	$r = -0.645$ ($n = 6$, $p = 0.166$)	$r = 0.063$ ($n = 6$, $p = 0.906$)	$r = 0.007$ ($n = 6$, $p = 0.990$)	$r = -0.061$ ($n = 6$, $p = 0.909$)
D75%	CO_2	$r = -0.142$ ($n = 6$, $p = 0.788$)	$r = -0.287$ ($n = 6$, $p = 0.582$)	$r = -0.341$ ($n = 6$, $p = 0.508$)	$r = -0.349$ ($n = 6$, $p = 0.498$)
	N_2O	$r = 0.303$ ($n = 6$, $p = 0.559$)	$r = 0.288$ ($n = 6$, $p = 0.581$)	$r = -0.691$ ($n = 6$, $p = 0.128$)	$r = -0.732$ ($n = 6$, $p = 0.098$)
	CH_4	$r = -0.717$ ($n = 6$, $p = 0.108$)	$r = -0.703$ ($n = 6$, $p = 0.119$)	$r = 0.620$ ($n = 6$, $p = 0.188$)	$r = 0.536$ ($n = 6$, $p = 0.272$)

Note: ** and * indicate significant correlations at the 0.01 and 0.05 levels, respectively. $n = 6$ represents the number of repeated measurement days for each treatment.

3.2.3. Effects of pH and Electrical Conductivity on Greenhouse Gas Emissions Under Precipitation Changes

Regarding soil pH, as shown in Table 4, at 11:00, under different precipitation treatments, a significant negative correlation between CO_2 flux and pH was observed only in the CK group ($r = -0.989$, $p < 0.05$), while no significant correlations were found under the other treatments ($p > 0.05$). Compared with CK, pH promoted CO_2 emissions under both precipitation increase and reduction treatments, with the promotion effect following the order: I75% > D25% > I25% > D75% > CK. For the relationship between pH and N_2O flux, negative correlations were observed under all treatments, although none were statistically significant. Compared with CK, pH inhibited N_2O emissions under both precipitation increase and reduction treatments, with the inhibition intensity following the order: CK > I75% > I25% > D25% > D75%. Regarding the relationship between CH_4 flux and soil pH, no significant correlations were observed under any treatment. However, a negative correlation was observed under I75%, while positive correlations were observed under the other treatments. Compared with CK, pH promoted CH_4 emissions only under

D75%, while it inhibited emissions under the other treatments. At 15:00, except for a highly significant positive correlation between CO₂ emission and pH in the CK group ($p < 0.01$), no significant correlations were observed between greenhouse gas emissions and soil pH under the other treatments. Under the D75% treatment, the relationship between CO₂ flux and pH shifted from positive to negative. This indicates that high levels of precipitation reduction cause pH increases to inhibit CO₂ emissions. For N₂O, compared with CK, both precipitation increase and reduction treatments shifted the relationship between N₂O flux and pH from positive to negative, indicating that under these treatments, an increase in pH inhibited N₂O emissions. Regarding the relationship between CH₄ flux and pH, compared with CK, pH promoted CH₄ emissions only under D75%, while it inhibited emissions under the other precipitation treatments (Table 4).

Table 4. Relationships between greenhouse gas fluxes and soil pH and electrical conductivity (EC) under different precipitation treatments in the Bird Island wetland at 11:00 and 15:00 in 2020.

Treatment	Greenhouse Gas	11:00		15:00	
		pH Correlation Coefficient r (n = 6, p -Value)	Electrical Conductivity ($\mu\text{S/cm}$) Correlation Coefficient r (n = 6, p -Value)	pH Correlation Coefficient r (n = 6, p -Value)	Electrical Conductivity ($\mu\text{S/cm}$) Correlation Coefficient r (n = 6, p -Value)
CK	CO ₂	$r = -0.989$ (n = 6, $p = 0.0002$) *	$r = -0.779$ (n = 6, $p = 0.068$)	$r = 0.976$ (n = 6, $p = 0.001$) *	$r = 0.922$ (n = 6, $p = 0.009$) *
	N ₂ O	$r = -0.175$ (n = 6, $p = 0.740$)	$r = -0.459$ (n = 6, $p = 0.359$)	$r = 0.687$ (n = 6, $p = 0.131$)	$r = 0.704$ (n = 6, $p = 0.118$)
	CH ₄	$r = 0.272$ (n = 6, $p = 0.602$)	$r = -0.075$ (n = 6, $p = 0.888$)	$r = 0.436$ (n = 6, $p = 0.389$)	$r = 0.519$ (n = 6, $p = 0.292$)
I25%	CO ₂	$r = -0.122$ (n = 6, $p = 0.818$)	$r = -0.997$ (n = 6, $p = 0.00003$) *	$r = 0.375$ (n = 6, $p = 0.465$)	$r = -0.878$ (n = 6, $p = 0.021$) *
	N ₂ O	$r = -0.448$ (n = 6, $p = 0.374$)	$r = 0.166$ (n = 6, $p = 0.754$)	$r = -0.092$ (n = 6, $p = 0.863$)	$r = -0.266$ (n = 6, $p = 0.611$)
	CH ₄	$r = 0.151$ (n = 6, $p = 0.776$)	$r = -0.953$ (n = 6, $p = 0.003$) *	$r = -0.827$ (n = 6, $p = 0.043$) *	$r = 0.517$ (n = 6, $p = 0.294$)
D25%	CO ₂	$r = 0.020$ (n = 6, $p = 0.970$)	$r = 0.546$ (n = 6, $p = 0.263$)	$r = 0.695$ (n = 6, $p = 0.125$)	$r = -0.036$ (n = 6, $p = 0.946$)
	N ₂ O	$r = -0.617$ (n = 6, $p = 0.192$)	$r = 0.370$ (n = 6, $p = 0.471$)	$r = -0.842$ (n = 6, $p = 0.035$) *	$r = 0.322$ (n = 6, $p = 0.534$)
	CH ₄	$r = 0.206$ (n = 6, $p = 0.695$)	$r = 0.462$ (n = 6, $p = 0.356$)	$r = -0.315$ (n = 6, $p = 0.543$)	$r = -0.382$ (n = 6, $p = 0.455$)
I75%	CO ₂	$r = 0.251$ (n = 6, $p = 0.632$)	$r = -0.646$ (n = 6, $p = 0.166$)	$r = 0.789$ (n = 6, $p = 0.061$)	$r = -0.972$ (n = 6, $p = 0.001$) *
	N ₂ O	$r = -0.211$ (n = 6, $p = 0.688$)	$r = -0.210$ (n = 6, $p = 0.690$)	$r = -0.095$ (n = 6, $p = 0.858$)	$r = -0.331$ (n = 6, $p = 0.522$)
	CH ₄	$r = -0.134$ (n = 6, $p = 0.800$)	$r = 0.829$ (n = 6, $p = 0.042$) *	$r = 0.096$ (n = 6, $p = 0.857$)	$r = -0.390$ (n = 6, $p = 0.445$)
D75%	CO ₂	$r = -0.352$ (n = 6, $p = 0.494$)	$r = -0.877$ (n = 6, $p = 0.022$) *	$r = -0.810$ (n = 6, $p = 0.051$)	$r = -0.807$ (n = 6, $p = 0.053$)
	N ₂ O	$r = -0.892$ (n = 6, $p = 0.017$) *	$r = 0.033$ (n = 6, $p = 0.951$)	$r = -0.640$ (n = 6, $p = 0.170$)	$r = -0.652$ (n = 6, $p = 0.161$)
	CH ₄	$r = 0.461$ (n = 6, $p = 0.358$)	$r = 0.706$ (n = 6, $p = 0.116$)	$r = 0.487$ (n = 6, $p = 0.329$)	$r = -0.215$ (n = 6, $p = 0.683$)

Note: * indicate significant correlations at the 0.05 levels, respectively, n = 6 represents the number of repeated measurement days for each treatment.

Regarding soil electrical conductivity (EC), at 11:00, positive correlations between EC and CO₂ flux were observed only under the D25% treatment, while negative correlations were observed under the other treatments. Under the I25% treatment, a highly significant negative correlation was observed between CO₂ emission and EC ($p < 0.01$). Compared with CK, an increase in EC inhibited CO₂ emissions under the I25% treatment but promoted them under the other treatments. Under different precipitation treatments, the overall correlation intensity between EC and N₂O flux followed the order: D25% > I25% > D75% > I75% > CK. Except for negative correlations under CK and I75% ($p > 0.05$), positive correlations were observed between N₂O emission and EC under the other treatments ($p > 0.05$), indicating that an increase in EC promoted N₂O emissions under both precipitation increase and reduction treatments. Compared with CK, negative correlations between EC and CH₄ emission were observed only under CK and I25%, while positive correlations were observed under the other treatments. Under I25%, a significant negative correlation was observed between CH₄ flux and EC ($p < 0.05$), while under I75%, a significant positive correlation was observed ($p < 0.05$). These results indicate that the I25% treatment showed the strongest inhibitory effect of EC on CH₄ emissions, while the I75% treatment showed the strongest promotion effect. At 15:00, compared with CK, both precipitation increase and reduction

treatments shifted the correlation between EC and CO₂ flux from positive to negative. Under CK, a highly significant positive correlation was observed between CO₂ flux and EC ($p < 0.01$), while under I75%, a significant negative correlation was observed ($p < 0.05$). The overall order was: CK > D25% > D75% > I25% > I75%. Under different precipitation treatments, the overall correlation intensity between EC and N₂O flux followed the order: CK > D25% > I25% > I75% > D75%. No significant correlations were observed between N₂O flux and EC under any treatment. Regarding CH₄ flux, the overall correlation intensity with EC followed the order: CK > I25% > D75% > D25% > I75%. No significant correlations were observed. These results indicate that, under both precipitation increase and reduction treatments, EC inhibited greenhouse gas emissions. The I75% treatment showed the strongest inhibitory effect of EC on CO₂ and CH₄ emissions, while the D75% treatment showed the strongest inhibitory effect on N₂O emissions (Table 4).

3.2.4. Effects of Aboveground and Belowground Biomass on Greenhouse Gas Emissions Under Precipitation Changes

In the Bird Island wetland, both aboveground biomass (AGB) and belowground biomass (BGB) generally showed a trend of first increasing and then decreasing, peaking in July and declining in August. From July to August, the vegetation in Qinghai Lake was in the vigorous stage of the growing season, representing the period of fastest photosynthesis and biomass accumulation, after which it gradually entered the senescence and yellowing stage. Belowground biomass also peaked in July, with a slight decline in August, roughly synchronizing with the peak of aboveground biomass, reflecting the synergistic relationship between aboveground and belowground plant growth. Significant differences were observed among treatments (Table 5). Aboveground biomass in the CK group was significantly lower than that in the precipitation treatment groups, highlighting the significant effect of precipitation regulation on aboveground biomass. The peak values in each group were: I25% ($0.82 \text{ g} \cdot \text{m}^{-2}$) > D25% ($0.60 \text{ g} \cdot \text{m}^{-2}$) > I75% ($0.53 \text{ g} \cdot \text{m}^{-2}$) > CK ($0.27 \text{ g} \cdot \text{m}^{-2}$) > D75% ($0.24 \text{ g} \cdot \text{m}^{-2}$). Throughout the growing season, the total aboveground biomass under each precipitation treatment was: I25% ($2.07 \text{ g} \cdot \text{m}^{-2}$) > D25% ($1.62 \text{ g} \cdot \text{m}^{-2}$) > I75% ($1.60 \text{ g} \cdot \text{m}^{-2}$) > D75% ($0.87 \text{ g} \cdot \text{m}^{-2}$) > CK ($0.72 \text{ g} \cdot \text{m}^{-2}$). Under the I25% treatment, aboveground biomass was $2.79 \text{ g} \cdot \text{m}^{-2}$ higher than CK; under D25%, it was $2.24 \text{ g} \cdot \text{m}^{-2}$ higher; under D75%, it was $1.59 \text{ g} \cdot \text{m}^{-2}$ higher; and under I75%, it was $2.32 \text{ g} \cdot \text{m}^{-2}$ higher. These results indicate that I25% exhibited the strongest promoting effect. Appropriate precipitation increase or reduction promoted aboveground biomass growth. The peak values of belowground biomass in each group were: CK ($0.61 \text{ g} \cdot \text{m}^{-2}$) > D75% ($0.53 \text{ g} \cdot \text{m}^{-2}$) > I25% ($0.52 \text{ g} \cdot \text{m}^{-2}$) > I75% ($0.51 \text{ g} \cdot \text{m}^{-2}$) > D25% ($0.49 \text{ g} \cdot \text{m}^{-2}$). Throughout the growing season, the total belowground biomass under each precipitation treatment was: D25% ($1.61 \text{ g} \cdot \text{m}^{-2}$) > CK ($1.59 \text{ g} \cdot \text{m}^{-2}$) > I25% ($1.44 \text{ g} \cdot \text{m}^{-2}$) > I75% ($1.39 \text{ g} \cdot \text{m}^{-2}$) > D75% ($1.29 \text{ g} \cdot \text{m}^{-2}$). Under the I25% treatment, belowground biomass was $0.15 \text{ g} \cdot \text{m}^{-2}$ lower than CK; under D75%, it was $0.30 \text{ g} \cdot \text{m}^{-2}$ lower; under I75%, it was $0.20 \text{ g} \cdot \text{m}^{-2}$ lower; and under D25%, it was $0.20 \text{ g} \cdot \text{m}^{-2}$ higher than CK. These results indicate that D25% promoted belowground biomass growth, while the other treatments all inhibited belowground biomass growth, with D75% showing the strongest inhibitory effect (Figure 9).

Based on the relationships between greenhouse gas fluxes and aboveground and belowground biomass under different precipitation treatments (Table 6), the following results were observed for aboveground biomass (AGB). For CO₂ flux, except for a positive correlation under CK, negative correlations were observed under all other treatments, although none reached statistical significance ($p > 0.05$). Compared with CK, an increase in AGB inhibited CO₂ emissions under I25%, I75%, and D75%, with I75% showing the strongest inhibitory effect ($r = -0.891$). For N₂O flux, except for a negative correlation under I75% ($r = -0.615$), positive correlations were observed under all other treatments, although

none were significant ($p > 0.05$). Compared with CK, the D75% treatment showed the strongest promotion effect, while the I75% treatment shifted from promotion to inhibition. The overall promotion effect followed the order: CK > D75% > I25% > D25% > I75%. For CH₄ flux, negative correlations were observed under CK, D25%, D75%, and I25%, with a highly significant negative correlation under CK ($r = -0.998$, $p < 0.01$). Only I75% showed a positive correlation ($r = 0.843$). Compared with CK, I75% shifted CH₄ from inhibition to promotion, while the inhibitory effects of the other treatments were weaker than that of CK. The inhibition effect followed the order: CK > I25% > D25% > D75% > I75% (with I75% showing promotion). At 15:00, for CO₂ flux, except for a weak positive correlation under D75% ($r = 0.041$), negative correlations were observed under all other treatments. Significant negative correlations were observed under I25% ($r = -0.984$) and I75% ($r = -0.847$) ($p < 0.05$). Compared with CK, an increase in AGB promoted CO₂ emissions only under D75%, while it inhibited emissions under the other treatments. The inhibition effect followed the order: I25% > I75% > D25% > CK > D75%. Regarding the correlation between N₂O flux and AGB, positive correlations were observed under CK and D25%, while negative correlations were observed under the other treatments. A highly significant positive correlation was observed under D25% ($p < 0.01$). The promotion effect followed the order: D25% > CK > I25% > D75% > I75%. For CH₄ flux, positive correlations were observed under CK, I25%, and D25%, while negative correlations were observed under I75% and D75%. Compared with CK, I25% showed the strongest promotion effect, while D75% showed the strongest inhibition effect.

Table 5. Analysis of differences in aboveground and belowground biomass under different precipitation treatments in the Bird Island wetland in each month of 2020.

Month	Treatment	Aboveground Biomass(g·m ⁻²)	Belowground Biomass(g·m ⁻²)
May	CK	0.09 ± 0.03 c	0.14 ± 0.08 a
	I25%	0.16 ± 0.05 a	0.2 ± 0.12 a
	D25%	0.14 ± 0.1 b	0.17 ± 0.06 b
	I75%	0.2 ± 0.1 a	0.17 ± 0.1 c
	D75%	0.17 ± 0.05 b	0.12 ± 0.04 a
June	CK	0.22 ± 0.04 c	0.43 ± 0.04 c
	I25%	0.61 ± 0.03 c	0.49 ± 0.08 b
	D25%	0.32 ± 0.17 a	0.52 ± 0.03 c
	I75%	0.41 ± 0.09 d	0.5 ± 0.15 d
	D75%	0.24 ± 0.08 b	0.29 ± 0.14 a
July	CK	0.27 ± 0.1 c	0.61 ± 0.13 a
	I25%	0.82 ± 0.09 a	0.31 ± 0.15 b
	D25%	0.6 ± 0.13 b	0.49 ± 0.14 c
	I75%	0.46 ± 0.06 d	0.51 ± 0.13 a
	D75%	0.22 ± 0.05 c	0.53 ± 0.15 b
August	CK	0.14 ± 0.03 d	0.41 ± 0.07 c
	I25%	0.48 ± 0.14 a	0.44 ± 0.02 a
	D25%	0.56 ± 0.14 b	0.43 ± 0.15 a
	I75%	0.53 ± 0.15 b	0.21 ± 0.13 b
	D75%	0.24 ± 0.14 c	0.35 ± 0.14 b

Note: Values are means ± standard deviation. Different lowercase letters indicate significant differences ($p < 0.05$) in each index between different time points within the same treatment.

Regarding the correlation between belowground biomass (BGB) and greenhouse gas fluxes at 11:00, for CO₂ flux, except for a positive correlation under D25%, negative correlations were observed under all other treatments, although none were significant. Compared with CK, the I25% treatment showed the strongest inhibitory effect, while

the D25% treatment shifted from inhibition to promotion of CO₂ emissions. For N₂O flux, positive correlations were observed under CK, I25%, and D75%, while negative correlations were observed under D25% and I75%. The correlation intensity followed the order: D75% > I25% > CK > I75% > D25%, with D75% showing the strongest promotion effect. For CH₄ flux, negative correlations were observed under all treatments ($p > 0.05$). Compared with CK, the inhibitory effects of all treatments were weaker than that of CK, following the order: CK > I25% > D25% > D75% > I75%. These results indicate that at 11:00, aboveground biomass mainly inhibited CO₂ and CH₄ emissions (except for I75%, which shifted CH₄ to promotion) and mainly promoted N₂O emissions. Belowground biomass generally inhibited CO₂ and CH₄ emissions, while both promotion and inhibition of N₂O were observed, with D75% showing the strongest promotion effect on N₂O. At 15:00, for CO₂ flux, negative correlations were observed under CK, I25%, and I75%, while positive correlations were observed under D25% and D75%. Compared with CK, the inhibitory effect of BGB was enhanced under I25%, while D25% and D75% shifted to promotion. The inhibition effect followed the order: I25% > CK > I75% > D75% > D25% (with D25% showing positive correlation). For N₂O flux, positive correlations were observed under CK, I25%, and D25%, while negative correlations were observed under I75% and D75%. For CH₄ flux, positive correlations were observed under CK, I25%, and I75%, while negative correlations were observed under D25% and D75%. Compared with CK, the I75% treatment showed the strongest promotion effect, while D75% showed the strongest inhibition effect. These results indicate that at 15:00, an increase in aboveground biomass under the I25% and I75% treatments significantly inhibited CO₂ emissions, with I25% showing the strongest inhibitory effect. The D25% treatment significantly promoted N₂O emissions, while I25% promoted CH₄ emissions and D75% inhibited CH₄ emissions (Table 6).

Table 6. Relationships between greenhouse gas fluxes and aboveground biomass (AGB) and belowground biomass (BGB) under different precipitation treatments in the Bird Island wetland at 11:00 and 15:00 in 2020.

Treatment	Greenhouse Gas	11: 00		15: 00	
		Aboveground Biomass (g·m ⁻²) Correlation Coefficient r (n = 6, p -Value)	Belowground Biomass (g·m ⁻²) Correlation Coefficient r (n = 6, p -Value)	Aboveground Biomass (g·m ⁻²) Correlation Coefficient r (n = 6, p -Value)	Belowground Biomass (g·m ⁻²) Correlation Coefficient r (n = 6, p -Value)
CK	CO ₂	$r = 0.230$ (n = 6, $p = 0.662$)	$r = -0.288$ (n = 6, $p = 0.581$)	$r = -0.168$ (n = 6, $p = 0.751$)	$r = -0.629$ (n = 6, $p = 0.181$)
	N ₂ O	$r = 0.676$ (n = 6, $p = 0.140$)	$r = 0.051$ (n = 6, $p = 0.923$)	$r = 0.674$ (n = 6, $p = 0.142$)	$r = 0.513$ (n = 6, $p = 0.298$)
	CH ₄	$r = -0.998$ (n = 6, $p = 0.001$) **	$r = -0.729$ (n = 6, $p = 0.100$)	$r = 0.424$ (n = 6, $p = 0.402$)	$r = 0.052$ (n = 6, $p = 0.922$)
I25%	CO ₂	$r = -0.567$ (n = 6, $p = 0.240$)	$r = -0.555$ (n = 6, $p = 0.253$)	$r = -0.984$ (n = 6, $p = 0.001$) *	$r = -0.826$ (n = 6, $p = 0.043$) *
	N ₂ O	$r = 0.235$ (n = 6, $p = 0.655$)	$r = 0.835$ (n = 6, $p = 0.039$)	$r = -0.304$ (n = 6, $p = 0.557$)	$r = 0.403$ (n = 6, $p = 0.428$)
	CH ₄	$r = -0.799$ (n = 6, $p = 0.057$)	$r = -0.569$ (n = 6, $p = 0.237$)	$r = 0.950$ (n = 6, $p = 0.004$) *	$r = 0.585$ (n = 6, $p = 0.223$)
D25%	CO ₂	$r = -0.059$ (n = 6, $p = 0.911$)	$r = 0.690$ (n = 6, $p = 0.129$)	$r = -0.648$ (n = 6, $p = 0.163$)	$r = 0.084$ (n = 6, $p = 0.874$)
	N ₂ O	$r = 0.177$ (n = 6, $p = 0.738$)	$r = -0.340$ (n = 6, $p = 0.509$)	$r = 0.997$ (n = 6, $p = 0.001$) **	$r = 0.679$ (n = 6, $p = 0.138$)
	CH ₄	$r = -0.734$ (n = 6, $p = 0.096$)	$r = -0.319$ (n = 6, $p = 0.539$)	$r = 0.394$ (n = 6, $p = 0.440$)	$r = -0.406$ (n = 6, $p = 0.425$)
I75%	CO ₂	$r = -0.891$ (n = 6, $p = 0.017$) *	$r = -0.150$ (n = 6, $p = 0.776$)	$r = -0.847$ (n = 6, $p = 0.033$) *	$r = -0.101$ (n = 6, $p = 0.849$)
	N ₂ O	$r = -0.615$ (n = 6, $p = 0.194$)	$r = -0.051$ (n = 6, $p = 0.923$)	$r = -0.725$ (n = 6, $p = 0.103$)	$r = -0.110$ (n = 6, $p = 0.836$)
	CH ₄	$r = 0.843$ (n = 6, $p = 0.035$) *	$r = 0.164$ (n = 6, $p = 0.757$)	$r = -0.204$ (n = 6, $p = 0.699$)	$r = 0.738$ (n = 6, $p = 0.094$)
D75%	CO ₂	$r = -0.487$ (n = 6, $p = 0.328$)	$r = -0.183$ (n = 6, $p = 0.729$)	$r = 0.041$ (n = 6, $p = 0.939$)	$r = 0.348$ (n = 6, $p = 0.500$)
	N ₂ O	$r = 0.675$ (n = 6, $p = 0.141$)	$r = 0.893$ (n = 6, $p = 0.016$) *	$r = -0.225$ (n = 6, $p = 0.669$)	$r = -0.201$ (n = 6, $p = 0.703$)
	CH ₄	$r = -0.225$ (n = 6, $p = 0.669$)	$r = -0.201$ (n = 6, $p = 0.703$)	$r = -0.877$ (n = 6, $p = 0.022$) *	$r = -0.647$ (n = 6, $p = 0.165$)

Note: ** and * indicate significant correlations at the 0.01 and 0.05 levels, respectively. n = 6 represents the number of repeated measurement days for each treatment.

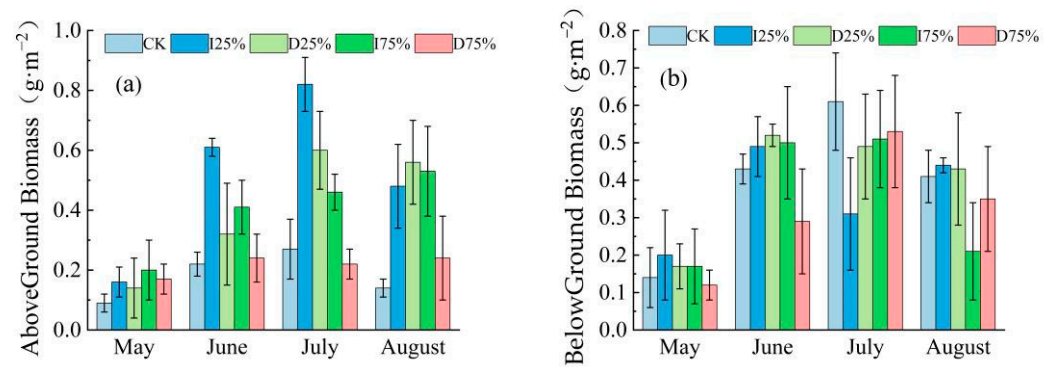


Figure 9. Dynamic trends of aboveground biomass (AGB) and belowground biomass (BGB) under different precipitation treatments in the Bird Island wetland. (Note: $n = 3$, error bars represent the standard error of the mean). (a) Seasonal trend of aboveground biomass. (b) Seasonal trend of belowground biomass.

4. Discussion

Changes in precipitation most directly affect soil moisture [26], and soil moisture variation is an important factor influencing CO₂ emissions [27]. Soil moisture affects plant and soil respiration by altering soil aeration, redox potential, pH, microbial activity, and soil carbon and nitrogen content [28]. In terms of the measured results, CO₂ efflux across all treatments peaked in late June, consistent with the seasonal rhythms of plant growth and microbial activity. Differences among treatments were as follows: at 11:00, total emissions under all precipitation treatments were lower than those under CK; at 15:00, the I75% treatment significantly promoted emissions, whereas the D25% treatment exhibited a suppressive effect. To account for these differences, we propose the following inferences: increased precipitation may enhance respiratory emissions by elevating soil water content, thereby activating microbial metabolism and accelerating organic matter mineralization; conversely, reduced precipitation may suppress emissions by inducing water limitation, which decreases microbial activity and restricts substrate availability.

CH₄ is produced during the oxidation of organic matter by methanogens under strictly anaerobic conditions in the soil [29]. Based on the measured results, the effects of precipitation treatments on CH₄ emissions exhibited distinct temporal differentiation. At 11:00, cumulative CH₄ emissions under all precipitation treatments were lower than those in the CK group, with the I75% treatment showing the most pronounced inhibitory effect. At 15:00, CH₄ emissions under all precipitation treatments were higher than those in the CK group, with the I25% treatment exhibiting the strongest promoting effect. We speculate that this may be attributable to the combined effects of high temperature and enhanced anaerobic conditions at 15:00, under which a 25% increase in precipitation (I25%) provided optimal moisture conditions, thereby maximizing methanogen activity and yielding the greatest stimulation. However, this remains a preliminary inference and requires further verification through direct observational studies. In addition, the fluctuation range of CH₄ fluxes across all treatments at 11:00 (-50 to $40 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was substantially greater than that at 15:00 (-5 to $20 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$), indicating that CH₄ emissions responded more sensitively to precipitation changes during the morning period than in the afternoon.

N₂O is mainly produced through nitrification and denitrification processes mediated by soil microorganisms. The main factors controlling N₂O emissions include soil moisture, carbon and nitrogen content, and soil pH [28]. Based on the field measurements, at 11:00, the total N₂O emissions over the entire growing season under both increased precipitation treatments exceeded those of the CK group, with the I75% treatment showing the greatest promoting effect, while the two reduced precipitation treatments suppressed

N₂O emissions, with D75% exhibiting the strongest inhibition. At 15:00, both I25% and I75% promoted N₂O emissions (with I25% being the most effective), whereas D25% and D75% exerted inhibitory effects (with D75% being the most pronounced). This trend is consistent with the results reported by Yang Ziwei and Jiang Lili [23,24]. In addition, N₂O efflux under all treatments at 15:00 was generally higher than that at 11:00, which is presumably associated with elevated soil temperature and enhanced microbial activity. Further investigations are required to refine these findings.

Numerous studies on the factors affecting greenhouse gas emissions in wetlands have shown that soil temperature and soil moisture are important environmental factors influencing CO₂, CH₄, and N₂O fluxes [30–32]. In alpine wetland ecosystems, suitable temperatures promote CO₂ emissions [33]. Soil temperature is positively correlated with CH₄ exchange. This is because Methanosaetaceae are the dominant type of methanogens, which use acetate as their sole substrate, and methane production is relatively low when temperatures decrease [34]. In this study, under the I75% treatment, a significant negative correlation was observed between CO₂ flux and soil temperature ($p < 0.05$), while a significant positive correlation was observed between CH₄ flux and soil temperature ($p < 0.05$). N₂O showed no significant correlation with soil temperature under any treatment. The specific correlations between CO₂ and CH₄ fluxes and soil temperature under I75% may be explained by the synergistic effect of extreme drought stress and temperature, which altered the dominant processes of greenhouse gas production and emission (such as microbial respiration and methane oxidation). The lack of significant correlation between N₂O and soil temperature under all treatments may be due to the combined constraints of factors such as the dominant regulatory role of soil moisture, temperature response thresholds, and nitrogen substrate availability. Under the D25% treatment, a significant positive correlation was observed between soil moisture and CH₄ emission ($p < 0.05$), while the I75% treatment showed the strongest promotion effect of soil moisture on CH₄ emissions. Precipitation increase promoted the formation of anaerobic conditions and significantly enhanced CH₄ emissions, while precipitation reduction maintained aerobic conditions and inhibited CH₄ emissions. These findings are consistent with the study by Wang et al. [35]. By altering soil moisture conditions and forming coupling effects with factors such as temperature, precipitation regulation ultimately determines the emission intensity of greenhouse gases in wetlands.

5. Conclusions

The results of this study reveal that precipitation alteration exerts divergent effects on the emission fluxes of three greenhouse gases (CO₂, CH₄, N₂O) in the lakeshore wetland of Bird Island, Qinghai Lake, and such effects are significantly regulated by observation time and precipitation manipulation intensity. At 11:00, both precipitation reduction and addition treatments suppressed CO₂ emissions, with the 25% precipitation reduction treatment (D25%) exhibiting the strongest inhibitory effect. At 15:00, only D25% inhibited CO₂ flux, while all other treatments stimulated CO₂ emissions, among which the 75% precipitation addition treatment (I75%) produced the most remarkable promotion. CH₄ showed a slow increase at 11:00, peaking on 11 August, with all treatments inhibiting CH₄ emissions, among which I75% had the strongest inhibitory effect; at 15:00, all treatments promoted CH₄ emissions, with I25% showing the best promoting effect. N₂O peaked in June at 11:00, with the increased precipitation treatments promoting N₂O emissions (I75% being the most effective), while the decreased precipitation treatments inhibited N₂O emissions (D75% showing the strongest inhibition); at 15:00, the increased precipitation group (I25% being the most effective) promoted N₂O emissions, whereas the decreased precipitation group (D75% being the most effective) inhibited N₂O emissions. Correlation analysis revealed

that greenhouse gas fluxes were statistically significantly associated with factors such as soil temperature, soil moisture, total carbon (TC), electrical conductivity, and aboveground biomass under certain treatments and at specific time points; however, the direction and significance of these associations varied with treatment intensity and time. CO₂ fluxes were significantly correlated with soil temperature, electrical conductivity, and aboveground biomass; N₂O fluxes were significantly correlated with aboveground biomass and soil TC; and CH₄ fluxes were significantly correlated with soil temperature, soil moisture, TC, and electrical conductivity. In summary, precipitation changes exert a regulatory effect on greenhouse gas emissions in the lakeshore wetlands of Bird Island, and this effect exhibits pronounced time dependence and treatment specificity. Against the backdrop of continuously rising water levels in Qinghai Lake and regional climate warming, the potential impact of increased precipitation treatments on the greenhouse effect warrants attention. Future studies should integrate long-term continuous observations with process-based models to further quantify the comprehensive contribution of precipitation changes to the carbon and nitrogen budgets of this wetland.

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