Effects of Precipitation Gradient on Diurnal Variation in Greenhouse Gas Emissions from the Headwater Wetland of Qinghai Lake (Postprint)

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Abstract

Water is the primary limiting factor affecting the growth and development of alpine ecosystems. To investigate the effects of different water conditions on greenhouse gas emission characteristics in wetlands, the Wayanshan headwater wetland in the Qinghai Lake basin was selected as the study site. Utilizing wetlands with different hydrological characteristics, the 24-hour greenhouse gas emission patterns were monitored using the static chamber-gas chromatography method. The diurnal variation trends of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) were examined under CK (control treatment), +25% (25% precipitation increase treatment), -25% (25% precipitation reduction treatment), +75% (75% precipitation increase treatment), and -75% (75% precipitation reduction treatment) conditions in August (peak growing season) of 2020 and 2021. The results showed: (1) CO2 emissions ranged from 47.52~123.71 mg · m-2 · h-1, CH4 flux ranged from -8.50~6.74 g · m-2 · h-1, and N2O flux ranged from -15.82~6.90 g · m-2 · h-1. (2) Under CK, +25%, and +75% treatments, the diurnal variations of CO2, CH4, and N2O exhibited net emission; under -25% treatment, CO2 showed net emission while CH4 and N2O showed net uptake; under -75% treatment, CO2 and N2O showed net emission while CH4 showed net uptake. Significant differences existed among different precipitation treatments ($P<0.05$). (3) CO2 showed a significant positive correlation with 0~10 cm soil temperature ($P<0.05$) and a significant negative correlation with soil moisture ($P<0.05$); CH4 showed a significant negative correlation with soil temperature ($P<0.05$) and a significant negative correlation with soil moisture ($P<0.05$); N2O showed a positive correlation with soil temperature ($P<0.05$), while CK treatment showed a negative correlation with soil moisture and precipitation reduction treatments showed a positive correlation ($P<0.05$), but without a clear pattern. (4) Minor succession occurred in the plant community under different water treatments. The balance of soil moisture and temperature significantly influenced greenhouse gas fluxes in this region, and imbalance should

be avoided to prevent increased greenhouse gas emissions.

Full Text

Effects of Precipitation Gradient on Diurnal Variation of Greenhouse Gas Emissions from Source Wetlands of Qinghai Lake

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Abstract

Water is the main limiting factor affecting the growth and development of alpine ecosystems. To explore the effects of different water conditions on greenhouse gas emission characteristics from wetlands, the Wayan Mountain source wetland in the Qinghai Lake Basin was selected as the study object. Using the static chamber-gas chromatography method, we monitored emission characteristics of greenhouse gases from wetlands with different moisture conditions and investigated the diurnal variation trends of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) under control (CK), +25% (precipitation increase treatment), -25% (precipitation reduction treatment), +75% (precipitation increase treatment), and -75% (precipitation reduction treatment) conditions during the growth season. The results showed that: (1) CO_2 flux ranged from 47.52~123.71 $mg \cdot m^{-2} \cdot h^{-1}$, CH_4 flux ranged from -15.82~6.90 $\mu g \cdot m^{-2} \cdot h^{-1}$, and N_2O flux ranged from -8.50~6.74 $\mu g \cdot m^{-2} \cdot h^{-1}$. (2) The diurnal variation of CO_2, CH_4, and N_2O in CK, +25% and +75% treatments showed emission status; CO_2 in -25% treatment showed emission status while CH_4 and N_2O showed absorption status; CO_2 and N_2O in -75% treatment showed emission status while CH_4 showed absorption status, with significant differences among different precipitation treatments ($P<0.05$). (3) CO_2 had a significant positive correlation with soil temperature ($P<0.05$) and a significant negative correlation with soil moisture ($P<0.05$); CH_4 had a significant negative correlation with soil temperature ($P<0.05$) and a significant negative correlation with soil moisture ($P<0.05$); N_2O had a positive correlation with soil temperature ($P<0.05$), while it had a negative correlation with soil moisture in CK treatment and a positive correlation in precipitation reduction treatments ($P<0.05$), but without obvious regularity. (4) Small-scale succession of plant communities occurred under different water treatments. The balance of soil moisture and temperature has a significant impact on greenhouse gas emission fluxes in this area, and imbalance should be avoided to prevent increased greenhouse gas emissions.

Keywords: greenhouse gas; static chamber–gas chromatography; source-sink effect; soil moisture; precipitation simulation; Qinghai Lake Basin

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Introduction

Wetland ecosystems are sensitive and fragile. Under the influence of climate change and precipitation variation, wetland biological communities, evapotranspiration rates, hydrogeology, hydrochemistry, and biota have all changed, which further affects carbon and nitrogen cycling processes in wetland ecosystems. Wetlands become important carbon sinks under long-term waterlogged anaerobic conditions that lead to organic matter accumulation. However, under the influence of human activities and climate change, the carbon sink function of wetlands has weakened, and wetlands have gradually become sources of greenhouse gas emissions due to accelerated organic matter decomposition.

Temperature and water are the main environmental factors affecting wetland ecosystem respiration, but aboveground and belowground biomass and soil physicochemical properties also affect carbon emissions. Differences in soil physicochemical properties are regulated by precipitation through soil water content, which in turn affects soil carbon and nitrogen transformation. Soil moisture is the main manifestation of precipitation change and is an important environmental factor limiting production and soil nutrient cycling in alpine meadow ecosystems on the Qinghai-Tibet Plateau. When soil moisture is below the optimal level, soil nitrogen supply increases with increasing water content; when soil moisture reaches 60% of water holding capacity (WHC), organic carbon decomposition rates and emissions are maximized.

Soil moisture determines soil anaerobic conditions, which affect methane-producing bacterial activity and the degree of anaerobic decomposition of organic matter. Studies have shown that methane emissions from high-water-level zones are higher than from low-water-level zones because the increased anaerobic soil layer enhances methanogen activity. Soil moisture content between 60%~90% of field capacity shows an increasing trend in CO_2 emission rates, and emissions increase with increasing moisture. In high-altitude wetland systems, N_2O emission fluxes show an increasing trend with increasing water content. Davidson found that 60% WHC is the critical value for the denitrification process to produce large amounts of N_2O; when water content exceeds this value, the nitrification rate gradually weakens while the denitrification rate increases and begins to emit large amounts of N_2O, which is gradually reduced to N_2. If water content continues to increase, N_2O emissions decrease accordingly.

Due to the uniqueness of the Qinghai-Tibet Plateau, there are few studies on greenhouse gas responses under precipitation simulation. The ecosystem is extremely sensitive to climate change, making it an ideal place to study the effects of climate change on soil greenhouse gas dynamics. According to analysis of spatial distribution of precipitation on the plateau from 1961–2017, the overall pattern shows a decreasing trend from southeast to northwest. The southeastern plateau is a high-value area for warm-season precipitation totals, with precipitation exceeding 500 mm, mainly in eastern Tibet and western Sichuan, while the Qaidam Basin and western Tibet receive less than 100 mm.

1.1 Study Area Overview

The Qinghai Lake Basin is located in a basin surrounded by mountains, with Datong Mountain to the north, Qinghai South Mountain to the south, Riyue Mountain to the east, and Tianjun Mountain to the west. The basin elevation is above 3,000 m and serves as a major ecological security barrier in northeastern Qinghai-Tibet Plateau, representing a typical freeze-thaw erosion area on the plateau whose environmental changes have been a focus of domestic and international attention. Wetlands account for a significant portion of the basin area.

The field observation site was established at the comprehensive observation station in the Wayan Mountain wetland of Qinghai Lake Basin, with geographic coordinates of 100°5 41 E, 37°44 34 N, at an elevation of 3,720–3,850 m. This is the source wetland of the Wayanqu tributary of the Shaliu River. The vegetation is relatively simple, with the dominant species being Kobresia humilis, accompanied by Carex tristachya, Lobularia maritima, and Potentilla anserina. Vegetation coverage exceeds 85%, with bare patches accounting for less than 5%. The soil is primarily swamp soil and meadow soil with a thickness of about 1.7 m. The wetland soil surface is seasonal frozen soil, with perennial frozen soil underneath. Meteorological observations show that the surface begins to freeze around mid-October, thaws in early June the following year, with a freezing period of 145 days. Air temperature changes are consistent with surface temperature changes, peaking in July. Annual precipitation at the experimental station is 587.5 mm, concentrated in the May–September growing season.

1.2.1 Precipitation Gradient Selection

The simulated precipitation gradients were approximately 525 mm (-25% reduction), 315 mm (-75% reduction), and 735 mm (+75% increase). The purpose was to simulate the effects of extreme precipitation increase and decrease on vegetation, soil, and microorganisms in this wetland type, thereby determining impacts on ecosystem greenhouse gases.

1.2.2 Greenhouse Gas Flux Observation

Samples were collected during the peak growing season in August. Observation plots were established for precipitation increase/decrease treatments and control groups (CK). This study used the static opaque chamber principle to measure land-atmosphere exchange fluxes, with an observation frequency of every 4 hours. During flux measurement, water was injected into the groove for sealing, and the opaque chamber was placed over the ground groove. The first gas sample was collected at 0 minutes, followed by samples every 15 minutes for a total of 5 collections, with 30 ml per sample. After collection, samples were transported to the laboratory for analysis.

Gas concentrations were analyzed using an Agilent 7890B gas chromatograph, and gas exchange fluxes were calculated using the formula:

$$F = \rho \cdot V/A \cdot (P/P_0) \cdot (T_0/T) \cdot (dc/dt)$$

where: F is the greenhouse gas emission flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$ or $\mathrm{\mu g \cdot m^{-2} \cdot h^{-1}}$); is the density of the measured gas under standard state ($\mathrm{kg \cdot m^{-3}}$); V is the static chamber volume ($\mathrm{m^3}$); A is the area covered by the static chamber ($\mathrm{m^2}$); P is the atmospheric pressure at the sampling point (Pa); P_0 is the standard atmospheric pressure (Pa); T_0 is the absolute temperature under standard state (K); T is the absolute temperature inside the chamber during sampling (K); and dc/dt is the rate of change of the measured gas concentration over time.

1.2.3 Precipitation Simulation Device

The automatic water diversion device for simulated precipitation includes a support frame, rainwater diversion trough, collection trough, horizontal tank, and spray device. The support frame consists of horizontal and vertical rods. The rainwater diversion trough includes first and second baffles with a U-shaped longitudinal section. The collection trough is an open-top structure with several interfaces connecting to horizontal tanks. The spray device contains several parallel spray pipes with equally spaced spray holes.

The device uses inclined rainwater diversion troughs to collect rainwater into collection troughs, which then flow into horizontal tanks and are sprayed through the spray device. The heights of the diversion trough, collection trough, horizontal tank, and spray device decrease sequentially, utilizing gravity for water collection and distribution without consuming additional electricity or fuel.

1.2.4 Soil Physicochemical Properties

During sampling, soil temperature (with 0.01°C precision) and soil water content (with 0.01% precision) were measured at 0–10 cm and 10–20 cm depths using a soil thermometer (TZS-2X) and soil moisture sensor (JK-100F). Aboveground biomass (selecting plants for drying and weighing) and belowground biomass (using 25 cm × 25 cm soil samples, removing soil and drying) were collected under different precipitation treatments. Soil samples from 0–10 cm and 10–20 cm depths were randomly collected to determine total carbon, total nitrogen, and electrical conductivity.

1.2.5 Data Statistics and Analysis

SPSS 21.0 software was used for correlation analysis between greenhouse gas fluxes and soil moisture/temperature, significance difference analysis of greenhouse gas fluxes among different precipitation treatments, and multiple comparison analysis of soil physicochemical properties. Origin 2018 software was used for figure preparation.

Results

2.1 Variation Patterns of Greenhouse Gas Fluxes Under Different Precipitation Treatments

Diurnal variation of CO_2 flux: The diurnal variation patterns of CO_2 flux under three different water conditions were basically consistent, showing emission sources. The CO_2 flux range was 47.52–123.71 $mg \cdot m^{-2} \cdot h^{-1}$. Under reduced precipitation treatments, CO_2 diurnal variation showed a bimodal pattern, with peaks occurring at 11:00 and 19:00. The peak emission value was 292.99 $mg \cdot m^{-2} \cdot h^{-1}$, and the lowest valley value was -6.46 $mg \cdot m^{-2} \cdot h^{-1}$. Under different water treatments, the peak emissions of each treatment were delayed to 15:00, possibly due to higher temperatures. [Figure 2: see original paper]

Diurnal variation of CH_4 flux: The diurnal variation patterns of CH_4 flux under three different water conditions showed differences and unclear patterns. All four treatments showed emission status except the -25% treatment, which showed absorption status. The CH_4 flux range was -15.82–6.90 $\mu g \cdot m^{-2} \cdot h^{-1}$. Unlike CO_2, the CH_4 flux range was -5.42–5.90 $\mu g \cdot m^{-2} \cdot h^{-1}$. Each treatment showed maximum values during nighttime or early morning when temperatures were low. [Figure 3: see original paper]

Diurnal variation of N_2O flux: The diurnal variation patterns of N_2O flux under three different water conditions were basically consistent, showing emission sources. The N_2O flux range was -8.50–6.74 $\mu g \cdot m^{-2} \cdot h^{-1}$. Except for the -25% treatment which showed emission status, all other treatments showed absorption status. The absorption mean was -1.31–1.11 $\mu g \cdot m^{-2} \cdot h^{-1}$, and the emission mean was 1.93 $\mu g \cdot m^{-2} \cdot h^{-1}$. [Figure 4: see original paper]

Daily average changes of three greenhouse gases: The daily average changes of all three greenhouse gases showed emission status. The daily average CO_2 flux was 47.52–123.71 $mg \cdot m^{-2} \cdot h^{-1}$. Under reduced precipitation treatments, CH_4 diurnal variation showed absorption status, while under increased precipitation and control treatments, it showed emission status. The absorption mean was -1.31 $\mu g \cdot m^{-2} \cdot h^{-1}$, and the emission mean was 1.93 $\mu g \cdot m^{-2} \cdot h^{-1}$. All treatments showed emission status except the -25% treatment, which showed absorption status. The absorption mean was -1.31 $\mu g \cdot m^{-2} \cdot h^{-1}$, and the emission mean was 1.93 $\mu g \cdot m^{-2} \cdot h^{-1}$. [Figure 5: see original paper]

2.2 Correlation Characteristics Between Soil Moisture, Soil Temperature and Greenhouse Gas Fluxes Under Different Precipitation Treatments

Soil moisture showed an upward trend across all treatments. CO_2 flux was negatively correlated with soil moisture under the -25% treatment (P<0.05) and highly significantly negatively correlated under the -75% treatment (P<0.01). CH_4 flux was positively correlated with soil moisture under the -25% treatment (P<0.05) and highly significantly negatively correlated under the -75% treatment (P<0.01). N_2O flux was negatively correlated with soil moisture in the CK treatment (P<0.05) and positively correlated in precipitation reduction treatments (P<0.05). [Figure 6: see original paper]

Soil temperature trends were basically consistent across all four treatments, with peaks appearing at 15:00. Soil temperature differences were significant among different precipitation treatments (Table 1, Table 2). CO_2 flux was positively correlated with soil temperature under the -25% treatment (P<0.05) and negatively correlated under the +75% treatment. CH_4 flux was positively correlated with soil temperature under the -25% treatment (P<0.05) and negatively correlated under the +75% treatment. N_2O flux was positively correlated with soil temperature under the -25% treatment (P<0.05) and negatively correlated under the +75% treatment. [Figure 7: see original paper]

2.3 Variation Characteristics of Soil Total Nitrogen and Total Carbon Under Different Precipitation Treatments

As soil moisture increased, soil total nitrogen and total carbon content gradually increased (Figure 8). Soil total nitrogen content was lowest under the -75% treatment (11.57 $g \cdot kg^{-1}$ at 0-10 cm) and highest under the +75% treatment (14.64 $g \cdot kg^{-1}$ at 0-10 cm). Soil total carbon content was lowest under the -25% treatment (159.69 $g \cdot kg^{-1}$ at 0-10 cm) and highest under the +75% treatment (192.10 $g \cdot kg^{-1}$ at 0-10 cm). The +75% treatment was 3.06% higher than the -75% treatment.

2.4 Effects of Different Precipitation Treatments on Aboveground and Belowground Biomass and pH, EC

After increased precipitation treatment, aboveground and belowground biomass were significantly higher than under reduced precipitation treatment. The mean aboveground biomass under increased precipitation was 236.43 $g \cdot m^{-2}$, while under reduced precipitation it was 138.10 $g \cdot m^{-2}$. The mean belowground biomass under increased precipitation was 5,050.05 $g \cdot m^{-2}$, while under reduced precipitation it was 3,633.35 $g \cdot m^{-2}$. Soil pH showed a decreasing trend with increasing soil moisture, while EC showed an increasing trend (Table 3).

Plant community surveys in August 2020 and 2021 showed that the vegetation in Wayan Mountain source wetland is relatively simple, dominated by Kobresia humilis and Carex tristachya. Under different water treatments, these two species remained dominant. When water decreased, Plantago depressa coverage increased significantly. When water increased, hygrophilous plants such as Potentilla anserina increased significantly, and vegetation height increased. The +75% treatment showed significantly higher vegetation coverage and height than other treatments, indicating that increased precipitation is more suitable for vegetation growth in Wayan Mountain source wetland (Table 4).

Discussion

3.1 Effects of Different Precipitation Gradients on CO_2 Flux in Source Wetlands

All treatments were CO_2 emission sources, with the highest emissions under increased precipitation treatment, which was significantly negatively correlated with soil moisture and significantly positively correlated with soil temperature at 0–10 cm depth. The +75% treatment was the precipitation gradient that contributed most to promoting CO_2 flux emissions.

In wetland ecosystems, water affects plant productivity and litter decomposition. At constant temperature, water promotes carbon decomposition under aerobic conditions (low moisture) but inhibits it under anaerobic conditions. The oxidation reaction space in soil decreases with increasing soil moisture, reducing organic matter decomposition rates and thus decreasing CO_2 emissions. Wetland plant roots are mainly distributed in the upper soil layer (<30 cm), where relatively high temperatures affect microbial decomposition and root respiration, resulting in wetland CO_2 emissions. Our results show that CO_2 flux is positively correlated with temperature, and when temperature rises, autotrophic and heterotrophic respiration gradually increase, leading to higher CO_2 flux. The observation day soil temperature began to decrease after 15:00, and the good water-heat combination promoted root respiration and microbial decomposition activities, causing CO_2 flux to reach its peak during this period. From the perspective of all treatments, when wetland soil temperature was highest, the CO_2 emission rate and emission amount were maximized.

3.2 Effects of Different Precipitation Gradients on CH_4 Flux in Source Wetlands

CH_4 flux showed both absorption and emission states. Soil moisture determines soil anaerobic conditions, which affect methanogen activity and the degree of anaerobic decomposition of organic matter. When precipitation increases, CH_4 emissions also increase. Previous studies have shown that as soil moisture content increases, alpine soils change from CH_4 absorption to emission, consistent with our results. The transmission process of wetland methane emissions occurs mainly through plant aerenchyma and intercellular spaces. Under different treatments in Wayan Mountain source wetland, plant abundance and height under increased precipitation treatment were significantly higher than under reduced precipitation treatment, showing significant correlation with soil temperature.

3.3 Effects of Different Precipitation Gradients on N_2O Flux in Source Wetlands

Precipitation affects the biological processes producing N_2O by changing soil pore oxygen content. N_2O flux emission patterns show large variability. Soil carbon and nitrogen are substrates for nitrification and denitrification processes, and changes in soil carbon and nitrogen pools significantly affect N_2O emission fluxes. There is an interaction between precipitation and temperature: precipitation lowers temperature, while temperature affects water evapotranspiration. Precipitation and evaporation jointly affect soil moisture, thereby influencing nitrification and denitrification. Increased soil moisture more easily creates anaerobic conditions. As nitrification rates weaken and denitrification rates increase, N_2O flux increases. From the perspective of all treatments, N_2O emission fluxes under increased precipitation treatment were higher than under reduced precipitation treatment. The N_2O emission flux under reduced precipitation treatment was significantly smaller than that of the other two greenhouse gases under increased precipitation treatment, indicating that increased rainfall enhances the greenhouse effect in Wayan Mountain source wetland, affecting regional carbon and nitrogen balance.

3.4 Plant Community Succession Under Different Water Treatments

The precipitation simulation device in Wayan Mountain source wetland was installed in 2020. To monitor vegetation succession, plant survey data from August during the peak growing season in 2020 and 2021 were selected (Table 4). The plant types in Wayan Mountain source wetland are relatively simple, mainly dominated by Kobresia humilis and Carex tristachya. These two species remained dominant under all water treatments. When water decreased, Plantago depressa coverage increased significantly, possibly because the moisture conditions under this treatment met the plant’ s growth requirements. When water increased, hygrophilous plants such as Potentilla anserina increased significantly, and vegetation height increased overall. The +75% treatment showed significantly higher vegetation coverage and height than other treatments, indicating that controlling precipitation at +75% is more suitable for vegetation growth in Wayan Mountain source wetland.

Conclusions

1) Under extreme precipitation treatments in the Wayan Mountain source wetland of Qinghai Lake Basin, CO_2 was in an emission state under +25% and +75% treatments. CH_4 was in an emission state under -25% treatment and in an absorption state under +25% and +75% treatments. N_2O was in an emission state under -25% and -75% treatments and in an absorption state under +25% and +75% treatments. There were significant differences in the three greenhouse gas fluxes under different water treatments. From the perspective of precipitation gradients, CO_2 contributed

more to greenhouse gases in Wayan Mountain source wetland, significantly promoting regional greenhouse gas emissions.

2) Through two consecutive years of monitoring in Wayan Mountain source wetland, soil moisture and temperature significantly affected gas fluxes under different treatments, with regular changes in soil total nitrogen and total carbon. Aboveground and belowground biomass changed with precipitation gradients. CO_2 flux under CK, increased precipitation, and reduced precipitation treatments showed an increasing trend with temperature but was generally negatively correlated with soil moisture. CH_4 flux under CK and reduced precipitation treatments showed an increasing trend with temperature but was generally negatively correlated with soil moisture. N_2O flux under CK treatment also showed an increasing trend with temperature, but the trend was not obvious under increased precipitation treatment, and it was negatively correlated with soil moisture under reduced precipitation treatment.

3) Wetland ecosystem greenhouse gas emissions are also affected by plant respiration, with hygrophilous and drought-tolerant plants showing certain distribution patterns under different water treatments. Against the background of global change, reduced precipitation leads to decreased plant height and coverage, while increased precipitation treatment is more suitable for vegetation growth. Although this study is insufficient to fully explain the "source-sink" issue, the daily flux data from the growing season are basically consistent with numerous research results and can provide theoretical references for this region and similar wetland types. Future research in this area will extend the time scale and combine microbial analysis perspectives to explore the carbon and nitrogen cycling mechanisms of wetlands.

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Note: Figure translations are in progress. See original paper for figures.