Postprint: Nitrogen Deposition Enhances N2O Emissions from Alpine Wetland Ecosystems in Northwestern Arid Regions

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Abstract

Against the backdrop of climate change, increased atmospheric nitrogen deposition affects N2O emissions from alpine wetlands in arid regions. Taking the Bayinbulak Swan Lake alpine wetland in the central Tianshan Mountains as the study area, which includes permanently flooded, seasonally flooded, and permanently dry zones under different moisture conditions, three nitrogen addition treatments were established (0, 10 kg ·hm-2 ·a-1, and 20 kg ·hm-2 ·a-1). The static chamber-gas chromatography method was used to monitor ecosystem N2O emissions during the plant growing season, and the relationship between N2O emissions and major environmental factors was investigated. The results showed that: (1) Under different moisture conditions, nitrogen addition significantly promoted ecosystem N2O emissions ($P<0.05$). Under the no nitrogen addition treatment during the plant growing season, the ecosystem N2O cumulative emission showed net uptake, while both the 10 kg ·hm-2 ·a-1 and 20 kg ·hm-2 ·a-1 treatments showed net emission. Increased nitrogen deposition significantly enhanced cumulative N2O emissions under different moisture conditions, promoting the transformation of wetland ecosystems from N2O "sinks" to "sources". (2) Nitrogen application rate extremely significantly affected ecosystem N2O emission rates ($P<0.01$). Under seasonally flooded conditions, the average ecosystem N2O emission rate (F) exhibited a multiple linear relationship with nitrogen application rate (N) and soil temperature at 5 cm depth (T): $F=-2.763+0.209N+0.151T$, $R2=0.483$, $P<0.01$. In summary, increased nitrogen deposition promoted N2O emissions from alpine wetland ecosystems in arid regions.

Full Text

Nitrogen Deposition Promotes N2O Emission from Alpine Wetland Ecosystems in the Arid Region of Northwest China

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Abstract

Against the backdrop of climate change, increasing atmospheric nitrogen deposition will affect N_2O emissions from alpine wetlands in arid regions. This study investigated the Swan Lake alpine wetland at Bayinbuluke in the central Tianshan Mountains, examining three representative water conditions: perennially flooded areas, seasonally flooded areas, and perennially dry areas. Three nitrogen addition treatments were established (0, 10, and 20 $kg \cdot hm^{-2} \cdot a^{-1}$), and N_2O emissions were monitored throughout the plant growing season using static chamber-gas chromatography. The relationships between ecosystem N_2O emissions and key environmental factors were also explored. The results demonstrated that: (1) nitrogen addition significantly enhanced ecosystem N_2O emissions across all water conditions ($P < 0.05$). Under the 0 $kg \cdot hm^{-2} \cdot a^{-1}$ treatment, the ecosystem showed net N_2O uptake during the growing season, whereas both 10 and 20 $kg \cdot hm^{-2} \cdot a^{-1}$ treatments resulted in net N_2O emissions. Increased nitrogen deposition significantly raised cumulative N_2O emissions under different water conditions, transforming the wetland ecosystem from an N_2O sink to a source. (2) Nitrogen application rate had a highly significant effect on ecosystem N_2O emission rates ($P < 0.01$). In seasonally flooded areas, the relationship between average N_2O emission rate (F), nitrogen addition (N), and soil temperature at 5 cm depth (T) followed a multiple linear equation: $F = -2.763 + 0.209N + 0.151T$ ($R^2 = 0.483$, $P < 0.01$). In conclusion, nitrogen deposition increases promote N_2O emissions from alpine wetland ecosystems in the arid region of Northwest China.

Keywords: nitrogen deposition; N_2O; ecosystem; water conditions; alpine wetland

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1. Materials and Methods

1.1 Study Area Description

The Bayinbuluke Swan Lake alpine wetland is located in Hejing County, Bayingolin Mongol Autonomous Prefecture, Xinjiang (42°40 -43°00 N, 83°40 -84°35 E), at an elevation of 2,300–3,042 m. The region has a temperate continental climate with an average annual temperature of -4.6 °C, maximum temperature of 28.0 °C, minimum temperature of -48.1 °C, and annual precipitation of 273 mm. Winter begins in mid-to-late September, with long winters, short summers, and snow cover for 139.3 days annually. The average evaporation is 1,250 mm, and relative humidity is approximately 43%-48%. Water sources are primarily snowmelt and seasonal precipitation, creating distinct seasonal wetlands.

Three representative alpine wetland ecosystems with different water conditions were selected as study objects: (1) Perennially flooded area, where the surface remains flooded year-round with water levels above 0.5 m during the growing season, dominated by *Carex rhynchophysa* with 70%-75% vegetation coverage during peak growth; (2) Seasonally flooded area, dominated by *Carex melanantha* and *Triglochin palustre* with 43%-48% vegetation coverage, where soil remains moist except in winter with water content of 30%-35% and groundwater depth of 0.6-1 m; and (3) Perennially dry area, dominated by *Agropyron cristatum* and *Carex melanantha* with 30%-35% vegetation coverage, where soil water content is 0.5 m and groundwater depth is 0.5 m, except when covered by snow in winter.

1.2 Experimental Design

A simulated nitrogen deposition in-situ control experiment was established. Environmental nitrogen deposition at Bayinbuluke alpine wetland is approximately 8 kg · hm^{-2} · a^{-1}, slightly lower than the global grassland average (10 kg · hm^{-2} · a^{-1}). Three nitrogen addition treatments were established: 0 kg · hm^{-2} · a^{-1} (control), 10 kg · hm^{-2} · a^{-1}, and 20 kg · hm^{-2} · a^{-1}, with three replicates per treatment. Nitrogen was applied as urea [$CO(NH_2)_2$] and ammonium nitrate [NH_4NO_3] in a 1:1 ratio. Nitrogen was added in three equal applications during the growing season, dissolved in water and evenly sprayed onto each plot. Control plots received equal amounts of water without nitrogen.

1.3 Sample Collection and Analysis

Gas samples were collected using static opaque chambers (0.5 m × 0.5 m × 0.5 m) with base frames (0.5 m × 0.5 m × 0.15 m) inserted into the soil. A 5 cm water channel above the base frame ensured airtight sealing during collection. During the plant growing season (May-September) in 2021, N_2O emissions were monitored for each nitrogen treatment. Sampling was conducted on three consecutive rain-free days each month between 10:00–13:00. After sealing the chamber, air inside was mixed by pumping a syringe three times. Gas samples (100 mL) were collected at 0, 5, 10, 15, 20, and 30 minutes using syringes and immediately transferred to pre-evacuated gas bags for storage. Simultaneously, soil temperature at 5 cm depth, soil water content (volumetric water content percentage), and air temperature at 30 cm above ground were measured to analyze their relationships with N_2O emissions.

N_2O concentrations were determined using an Agilent 7890A gas chromatograph (Palo Alto, USA). The N_2O emission flux was calculated as:

$$F = \rho \times V/A \times \Delta c/\Delta t \times 273.15/(273.15 + T)$$

where F is the N_2O emission flux ($g \cdot m^{-2} \cdot h^{-1}$),   is N_2O density under standard conditions (1.977 $g \cdot L^{-1}$), V is the effective headspace volume of the chamber (m^3), A is the soil surface area covered by the chamber (m^2), $\Delta c/\Delta t$ is the rate of change in gas concentration, and T is the temperature inside the chamber during sampling (°C).

Cumulative N_2O emissions were calculated as:

$$E = \sum_{i=1}^{n} (F_i \times 24 \times t_i)$$

where E represents cumulative N_2O emissions ($mg \cdot m^{-2}$), F is the N_2O emission flux ($g \cdot m^{-2} \cdot h^{-1}$), i is the sampling number, and t is the number of days in that period of the growing season.

1.4 Data Processing and Analysis

Data were initially processed using Excel 2019. SPSS Statistics 19 was used for one-way ANOVA and multiple comparisons. Pearson correlation analysis was performed between N_2O emission rates and soil temperature and moisture. Linear and quadratic functions were used for regression analysis. Stepwise linear regression was employed to analyze relationships between ecosystem N_2O emission rates and nitrogen addition, soil temperature, and water content. Random forest analysis was conducted using Anaconda, and figures were prepared using Origin 2018.

2. Results

2.1 Effects of Nitrogen Addition on N_2O Emission Rates Under Different Water Conditions

In the perennially flooded area, the average N_2O emission rate increased with nitrogen addition [Figure 1: see original paper]. Under the control treatment (0 $kg \cdot hm^{-2} \cdot a^{-1}$), the ecosystem showed N_2O uptake during most of the growing season, with average uptake rates of -1.30 ± 1.15 $g \cdot m^{-2} \cdot h^{-1}$ in June, -2.11

± 0.83 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in July, and -2.55 ± 0.34 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in August. The highest uptake occurred in July, while the lowest emission rate was observed in September. Under the 10 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, the ecosystem exhibited N_2O emissions throughout the growing season, with the highest monthly average emission rate of 9.03 ± 1.99 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in July, which was significantly higher than other months ($P < 0.05$). The average emission rate under this treatment was significantly higher than the control ($P < 0.05$). Under the 20 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, the ecosystem also showed emissions throughout the growing season, with average emission rates of 5.29 ± 1.21 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in June, 5.14 ± 0.73 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in July, 5.81 ± 0.09 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in August, and 1.46 ± 0.59 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in September. All months except September showed significant emissions.

In the seasonally flooded area, the average N_2O emission rate also increased with nitrogen addition [Figure 2: see original paper]. Under the control treatment, the ecosystem showed N_2O uptake in June and July, with the highest average uptake rate of -3.44 ± 2.05 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in July. Other months showed emissions, with no significant differences between monthly emission rates ($P > 0.05$). Under the 10 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, the ecosystem exhibited emissions throughout the growing season, with an average emission rate of 1.56 ± 0.15 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$. Under the 20 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, emissions occurred in all months, with the highest rate of 5.61 ± 0.86 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in August and the lowest of 0.72 ± 0.18 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$ in September. The emission rate under this treatment was significantly higher than under the 10 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment ($P < 0.05$).

In the perennially dry area, the average N_2O emission rate increased with nitrogen deposition [Figure 3: see original paper]. Under the control treatment, the ecosystem showed N_2O uptake during the growing season, with average uptake rates of -0.89 ± 0.51 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$. Under the 10 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, the ecosystem functioned as an N_2O source, with average emission rates of 2.27 ± 0.43 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$. Under the 20 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, the ecosystem also acted as a source, with average emission rates of 2.55 ± 0.34 $\mathrm{g \cdot m^{-2} \cdot h^{-1}}$.

2.2 Effects of Nitrogen Addition on Cumulative N_2O Emissions Under Different Water Conditions

Cumulative N_2O emissions did not differ significantly among water conditions under the same nitrogen treatment. However, under the same water condition, nitrogen addition during the growing season significantly promoted ecosystem N_2O emissions ($P < 0.05$) [Figure 4: see original paper]. Without nitrogen addition, all three water conditions showed negative cumulative emissions, indicating N_2O uptake, with cumulative uptake amounts of -6.35 ± 2.84 $\mathrm{mg \cdot m^{-2}}$ in perennially flooded areas, -8.22 ± 1.96 $\mathrm{mg \cdot m^{-2}}$ in seasonally flooded areas, and -6.96 ± 1.81 $\mathrm{mg \cdot m^{-2}}$ in perennially dry areas, demonstrating that the ecosystem functioned as an N_2O sink. With nitrogen addition, cumulative emissions became positive. Under the 10 $\mathrm{kg \cdot hm^{-2} \cdot a^{-1}}$ treatment, cumulative emissions reached 13.35 ± 2.24 $\mathrm{mg \cdot m^{-2}}$, 12.26 ± 1.64 $\mathrm{mg \cdot m^{-2}}$, and 13.79 ±

1.38 $mg \cdot m^{-2}$, respectively—approximately 2.1, 1.5, and 2.0 times the absolute values of the control. Under the 20 $kg \cdot hm^{-2} \cdot a^{-1}$ treatment, cumulative emissions were 45.75 ± 1.21 $mg \cdot m^{-2}$, 41.37 ± 0.73 $mg \cdot m^{-2}$, and 53.57 ± 1.38 $mg \cdot m^{-2}$, respectively—7.2, 5.0, and 7.7 times the control values. Increased nitrogen application significantly promoted N_2O emissions, with the most pronounced effect in perennially dry conditions. Nitrogen addition during the growing season transformed the alpine wetland ecosystem from an N_2O sink to a source.

2.3 Relationships Between N_2O Emissions and Environmental Factors

Correlation analysis revealed that ecosystem N_2O emission rates were extremely significantly positively correlated with nitrogen addition ($P < 0.01$), but not significantly correlated with soil water content . In seasonally flooded conditions, N_2O emission rates were significantly correlated with soil temperature at 5 cm depth ($P < 0.05$). Stepwise linear regression showed that in seasonally flooded areas, the relationship between ecosystem N_2O emission rate (F), nitrogen addition (N), and soil temperature at 5 cm (T) followed a multiple linear equation:

$$F = -2.763 + 0.209N + 0.151T \quad (R^2 = 0.483, P < 0.01)$$

Random forest analysis indicated that nitrogen addition, soil temperature, and water content contributed 34.27%, 33.94%, and 31.79% to ecosystem N_2O emission rates, respectively. These results suggest that N_2O emissions from the Bayinbuluke wetland ecosystem may be comprehensively influenced by nitrogen addition, soil temperature, and water content, with nitrogen addition having the greatest contribution .

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3. Discussion

As an important component of terrestrial ecosystems, wetlands account for approximately 60%-80% of global biological sphere N_2O emissions. The primary processes for N_2O production are nitrification and denitrification, which may be influenced by regional climate, soil texture, low soil organic carbon content, and cation exchange capacity. The presence of oxygen and available active carbon are the most important prerequisites for denitrification and N_2O production. The optimal water-filled pore space for N_2O formation is around 60%-80%; at higher water content, denitrification produces N_2, while lower soil moisture produces more N_2O. When soil NO_3^- content is low or soil water content is high, N_2O uptake can occur as denitrifying microorganisms use atmospheric N_2O as the sole electron acceptor.

Previous studies have shown that wet-dry alternation promotes N_2O emissions. In this study, different water conditions resulted in varying N_2O emission patterns. The emission rates in the perennially dry area of Swan Lake alpine wetland were slightly higher than in other water zones, similar to those reported for alpine grasslands on the northern slope of the Kunlun Mountains and higher than those from rice paddies. This may be because nitrogen addition affects the soil carbon-to-nitrogen ratio, influencing microbial functions and altering nitrification-denitrification processes. Additionally, exogenous nitrogen input can indirectly affect soil N_2O emissions by influencing vegetation. For example, the perennially flooded area is dominated by Cyperaceae and Poaceae species, and exogenous nitrogen input may cause nitrogen supply excess in these plants, increasing plant N_2O emissions. The alkaline soil at Bayinbuluke may neutralize soil acidification caused by increased nitrogen deposition, thereby affecting N_2O emissions.

Compared with other wetland ecosystems in China, N_2O emissions from Bayinbuluke Swan Lake alpine wetland are much lower than those from Zoige alpine wetland, Qinghai-Tibet Plateau alpine grassland, and Sanjiang Plain peat wetland, possibly due to differences in nitrogen deposition levels or soil conditions across regions. Most studies have found that nitrogen addition promotes N_2O emissions, but the response thresholds vary. In Zoige alpine wetland and Sanjiang Plain peat wetland, only NH_4NO_3 application at 40 $kg \cdot hm^{-2} \cdot a^{-1}$ promoted N_2O emissions, with no effect at higher rates, possibly because excessive nitrogen input increased litter content, intensifying microbial nitrogen demand during decomposition and reducing available nitrogen in soil, thereby inhibiting N_2O emissions. This study found that N_2O emissions were extremely significantly positively correlated with nitrogen addition, likely because available nitrogen in the added fertilizer provided substrates for microbial nitrification and denitrification.

In addition to nitrogen input and soil moisture, soil temperature is a major factor affecting ecosystem N_2O emissions. Studies on the Qinghai-Tibet Plateau alpine wetland found that N_2O emission rates were significantly correlated with air temperature, soil temperature, and soil water content. However, research at Namco on the Tibetan Plateau showed no significant seasonal variation in N_2O emission rates and no linear relationship with soil temperature, though a significant positive correlation with soil water content was observed. In this study, average N_2O emission rates were significantly positively correlated with nitrogen addition but not with soil water content. Stepwise linear regression revealed that in seasonally flooded conditions, average N_2O emission rates showed a multiple linear relationship with nitrogen addition and soil temperature at 5 cm depth ($R^2 = 0.483$, $P < 0.01$). Previous research at Bayinbuluke Swan Lake alpine wetland found that daily N_2O emission rates were significantly correlated with soil temperature at 5 cm depth but not with soil temperature at 10 cm depth, which differs slightly from this study. This discrepancy may be due to changes in aboveground vegetation after nitrogen addition or the influence of atmospheric temperature on soil temperature during the study period.

The reason why N_2O emission rates showed significant relationships with nitrogen deposition and soil temperature but not with water content in seasonally flooded conditions may be related to repeated wet-dry cycles in this area. Previous studies have found that N_2O emission rates under wet-dry alternation are higher than under constant moisture conditions, as the alternation creates favorable conditions for nitrification and denitrification while altering soil aeration, affecting microbial activity, substrate availability, and N_2O diffusion pathways. This study conducted only one year of field experiments to preliminarily explore the effects of nitrogen deposition intensity on N_2O emissions under different water conditions in arid region alpine wetlands. Further research is needed to investigate the underlying mechanisms of how nitrogen deposition affects N_2O emissions from alpine wetland ecosystems.

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4. Conclusion

During the plant growing season at Bayinbuluke alpine wetland, nitrogen addition significantly promoted ecosystem N_2O emission rates across different water conditions. Without nitrogen addition, the ecosystem showed N_2O uptake, with no significant differences among water conditions. Under 10 $kg \cdot hm^{-2} \cdot a^{-1}$ and 20 $kg \cdot hm^{-2} \cdot a^{-1}$ treatments, cumulative N_2O emissions were positive, indicating that increased nitrogen deposition significantly raised ecosystem N_2O emissions and transformed the ecosystem from a sink to a source. Nitrogen application rate had a highly significant effect on ecosystem N_2O emission rates ($P < 0.01$). In seasonally flooded conditions, the relationship between average N_2O emission rate, nitrogen addition, and soil temperature at 5 cm depth followed a multiple linear equation ($R^2 = 0.483$, $P < 0.01$). In summary, nitrogen deposition increases promote N_2O emissions from alpine wetland ecosystems in the arid region of Northwest China.

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