Effects of Different Land Use Types on Soil N2O Flux in the Loess Plateau (Postprint)

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Abstract

Nitrous oxide (N2O) is one of the important greenhouse gases in the atmosphere, exerting a significant influence on global climate warming. Changes in land use patterns represent key factors affecting N2O emissions, particularly in ecologically fragile semi-arid regions where the underlying mechanisms are more complex. However, systematic studies are currently lacking regarding how the complex and diverse land use patterns in China' s semi-arid regions influence soil N2O emissions and the key driving factors controlling these emissions. To address this, the present study selected four typical land use patterns in the central Loess Plateau of Gansu—spruce forest (Picea asperata), alfalfa grassland (Medicago sativa), abandoned land, and wheat field—as research subjects, employed the static chamber-gas chromatography method to monitor soil N2O flux, and integrated soil physicochemical property data to reveal the key driving factors regulating soil N2O emissions under different land use patterns. The results demonstrated: (1) Compared with abandoned land, spruce forest and alfalfa grassland significantly increased soil water content, whereas wheat field enhanced the contents of ammonium nitrogen (NH+4-N) and nitrate nitrogen (NO-3-N). (2) Alfalfa grassland and wheat field significantly elevated nitrate reductase (NR) and nitrite reductase (NIR) activities compared with abandoned land, with NR and NIR activities in all treatments decreasing with soil depth. (3) Under different land use patterns, soil N2O flux exhibited a trend of initially increasing then decreasing with vegetation growth stages. Compared with abandoned land, total soil N2O emissions from spruce forest and alfalfa grassland decreased by 34.2% and 23.3%, respectively, while wheat field significantly increased emissions by 32.47%. (4) Random forest analysis indicated that soil temperature exerted the greatest influence on soil N2O emission flux. Compared with abandoned land and wheat field, artificial forestland and grassland demonstrated superior emission reduction effects. In future vegetation restoration and ecological remediation efforts, attention should be devoted to optimizing the allocation proportions of "agriculture-forest-grassland" land use patterns, with

appropriate increases in the proportion of artificial forestland and grassland to achieve dual objectives of ecological benefits and emission reduction.

Full Text

Preamble

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Abstract

Nitrous oxide (N_2O) is a crucial greenhouse gas in the atmosphere that significantly influences global climate warming. Changes in land use patterns represent a critical factor affecting N_2O emissions, particularly in ecologically fragile semiarid regions where the underlying mechanisms are more complex. However, systematic research remains lacking on how the complex and diverse land use types in China' s semiarid regions influence soil N_2O emissions and what key driving factors control these emissions. To address this knowledge gap, this study examined four typical land use types in the central Gansu Loess Plateau: *Picea asperata* forest, *Medicago sativa* grassland, abandoned land, and wheat fields. Soil N_2O fluxes were monitored using the static chamber-gas chromatography method, combined with soil physicochemical property data, to reveal the key drivers regulating soil N_2O emissions under different land use patterns.

The results demonstrated that: (1) Compared to abandoned land, the *Picea asperata* forest and *Medicago sativa* grassland significantly increased soil water content, while wheat fields elevated ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) concentrations. (2) The *Medicago sativa* grassland and wheat fields significantly enhanced nitrate reductase (NR) and nitrite reductase (NiR) activities compared to abandoned land, with enzyme activities decreasing with soil depth across all treatments. (3) Soil N_2O fluxes under different land use types showed an initial increase followed by a decrease during vegetation growth stages. Total soil N_2O emissions decreased by 34.2% and 23.3% in the *Picea asperata* forest and *Medicago sativa* grassland, respectively, but increased by 32.47% in wheat fields compared to abandoned land. (4) Random forest analysis identified soil temperature as the most influential factor affecting soil N_2O flux. Overall, artificial forest and grassland systems exhibited superior emission reduction effects compared to abandoned land and wheat fields. Future vegetation restoration and ecological rehabilitation efforts should optimize the proportional allocation of "forest-grass-cropland" land use patterns and appropriately increase the coverage of artificial forests and grasslands to achieve dual objectives of ecological benefits and emission mitigation.

Keywords: Loess Plateau; global climate warming; land use types; N_2O emission flux; soil temperature

1. Introduction

Nitrous oxide (N_2O) ranks among the three most important greenhouse gases in the atmosphere, with a global warming potential approximately 298 times that of carbon dioxide (CO_2) on a 100-year timescale and about 12 times that of methane (CH_4). It persists in the atmosphere for extended periods, participates in numerous photochemical reactions, and contributes to ozone depletion. Anthropogenic N_2O emissions are increasing at a rate of 0.2-0.3% annually, with recent emissions reaching approximately 17.0 $Tg \cdot a^{-1}$. Human activities, particularly changes in land use and extensive fossil fuel consumption, represent important causes of increased greenhouse gas emissions and global warming. Consequently, reducing greenhouse gas emissions from production and daily life has become a critical common development goal for all nations.

The primary task in mitigating N_2O emissions involves clarifying the mechanisms of nitrification and denitrification in soils. These two processes are key to soil N_2O production. Nitrification refers to the microbial conversion of ammonium salts to oxidized nitrogen forms such as NO_2^- and NO_3^- under aerobic conditions, while denitrification is a microbial ecological process where denitrifying bacteria convert nitrate and nitrite compounds into nitric oxide (NO), N_2O, and dinitrogen (N_2) under anaerobic conditions. Land use changes directly or indirectly affect N_2O production, consumption, and diffusion processes by altering plant community composition and soil properties, thereby changing N_2O emissions. Approximately 70-90% of N_2O released from the biosphere originates from nitrification and denitrification processes in soils. Therefore, in-depth research on N_2O emissions from agricultural and forest ecosystems is essential.

Different land use types can alter plant communities and soil characteristics (such as soil temperature, moisture, bulk density, and nitrogen availability), leading to increased carbon and nitrogen availability in grassland soils and consequently enhanced N_2O emissions. N_2O emissions from cropland soils are primarily influenced by soil texture, mineral nitrogen, and organic carbon. The impact of vegetation and microbial activities on soil nitrogen cycling and transformation processes under different land use types directly determines N_2O emission rates. Meanwhile, the activities of nitrate and nitrite reductases involved in denitrification significantly influence nitrogen forms and greenhouse gas emissions in soils. Soil enzymes participate in organic matter decomposition and transformation processes, also affecting N_2O emission rates. Thus, different land use types regulate N_2O emission dynamics by altering soil nitrogen cycling and enzyme activities. Revealing the interactions between soil carbon and nitrogen metabolism under human disturbance is crucial for optimizing land management models, maintaining regional carbon-nitrogen balance, mitigating greenhouse gas emissions, and curbing climate warming.

China exhibits diverse land use patterns, and the central Gansu Loess Plateau represents one of China's most ecologically fragile regions, with structural imbalances between land resource supply and ecological carrying capacity. In recent years, under the "Grain for Green" project policy, the ecological environment and soil vegetation in this region have improved. However, greenhouse gas emission issues have not been adequately considered. To further investigate how different land use types affect soil N_2O emissions in the semiarid Loess Plateau of central Gansu, this study selected four typical land use types—*Picea asperata* forest, *Medicago sativa* grassland, abandoned land, and wheat fields—to explore the effects of land use on soil environmental factors and enzyme activities, identify key drivers of N_2O emissions, and reveal the influence patterns of different land use types on soil N_2O emissions, providing a scientific basis for regional sustainable land management and greenhouse gas emission reduction.

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2. Materials and Methods

2.1 Study Area Description

The experimental site is located in the Anding District of Dingxi City, Gansu Province (34°26 -35°35 N, 103°52 -105°13 E), within the Soil and Water Conservation Monitoring Station [Figure 6: see original paper]. This region features a temperate semiarid climate with abundant sunlight, large temperature variations, and an average annual precipitation of approximately 391 mm, concentrated between July and September. The altitude is around 2000 m, and the area belongs to the rain-fed agricultural zone of the Loess Plateau in central Gansu. The region experiences chronic drought and water scarcity with sparse vegetation. The "Grain for Green" project was officially launched in this area in 1999, converting original cropland into forest and grassland land use types. The main tree species include *Picea asperata* and *Platycladus orientalis*, herbaceous vegetation primarily consists of *Medicago sativa* and *Onobrychis viciifolia*, and major crops include spring wheat (*Triticum aestivum*), maize (*Zea mays*), and potato (*Solanum tuberosum*).

2.2 Experimental Design

Based on field surveys of ecological and vegetation characteristics in the study area and review of relevant literature, sample plots were established in April 2022 in vegetation areas with similar soil types and disturbance histories. Four different land use types were selected as treatments: *Picea asperata* forest (PA), *Medicago sativa* grassland (MS), abandoned land (AL), and wheat field (WF) (Table 1). The *Picea asperata* forest was artificially planted and received no further intervention after establishment. The *Medicago sativa* grassland was planted and then fenced, with no further management after establishment. The abandoned land was left fallow since 2018, naturally recovering with sparse weed distribution and no management measures. The wheat field was cultivated from wasteland in 2018, planted with spring wheat "Gan Chun No. 25" as the test variety, using conventional tillage with base fertilizer applied at sowing (150.0 $kg \cdot hm^{-2}$ urea and 62.5 $kg \cdot hm^{-2}$ calcium superphosphate). For each treatment, three 20 m × 20 m fixed sampling areas were randomly selected, with a 0.5 m × 0.5 m fixed gas sampling zone established in each plot for gas sample collection. During the 2022 vegetation growing season, soil (0–20 cm) and gas samples were collected every two weeks (at the beginning and middle of each month) and brought back to the laboratory for analysis.

2.3 Soil Sample Collection

Soil samples were collected three times during the 2022 plant growing season. Based on scholars' classification of plant growth stages, these were defined as the initial growth stage (mid-April), middle growth stage (mid-July), and late growth stage (mid-October). Soil cores were collected using a soil auger following the five-point sampling method at depths of 0–10 cm and 10–20 cm. After removing impurities, samples were placed in ziplock bags, stored in a cooler with ice packs, and transported to the laboratory for analysis. Upon arrival, samples were divided into two portions: one portion of fresh soil was passed through a 2 mm sieve, stored in a 4°C refrigerator for determination of fresh sample indicators including soil water content, nitrate nitrogen, and ammonium nitrogen; the other portion was air-dried, sieved to remove impurities, and used for determination of dry sample indicators including nitrate reductase and nitrite reductase activities.

2.4 Gas Sample Collection

Soil N_2O flux was measured using the static chamber-gas chromatography method. A 50 cm × 50 cm × 50 cm open-bottom dark chamber was employed, equipped with two air mixing fans on the top to ensure uniform air mixing during flux measurement. The chamber walls were made of thin stainless steel and wrapped with insulation material to minimize temperature changes inside the chamber. During gas sample collection, the chamber and base were sealed with water. After chamber closure, air samples (100 mL each) were collected from inside the chamber at 8-minute intervals (at 0, 8, 16, 24, and 32 minutes) using a 60 mL polypropylene syringe equipped with a three-way stopcock. Samples were immediately transported to the laboratory and analyzed using a gas chromatograph to determine N_2O flux and characterize emission patterns under different treatments.

2.5 Data Analysis

To compare differences in soil physicochemical properties among treatments, soil layers, and growth stages, one-way ANOVA and independent samples t-tests were performed using SPSS 26.0, with Origin 2021 used for plotting. The Hmisc package in R 4.3.3 was used to calculate correlation coefficients between soil environmental factors and N_2O emissions, while the rfPermute package was employed to analyze key physicochemical factors influencing N_2O emissions. All statistical analyses were completed in R 4.3.3, with figures generated using ggplot2.

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3. Results

3.1 Soil Temperature

Different land use types significantly affected soil temperature. The soil temperature variation trends across treatments were generally consistent, showing an initial increase followed by a decrease with vegetation growth stages. Throughout the vegetation growing season, the WF treatment exhibited higher soil temperatures than other treatments, with the ranking WF > AL > MS > PA [Figure 2: see original paper].

3.2 Soil Water Content

Different land use types significantly influenced soil water content. Compared to AL, PA and MS treatments significantly increased soil water content ($P < 0.05$), while WF significantly decreased soil water content ($P < 0.05$), with the ranking PA > MS > AL > WF. Across the entire soil profile (0–20 cm), soil water content gradually increased with soil depth. During the vegetation growing season, soil water content showed a decreasing then increasing trend [Figure 3: see original paper].

3.3 Effects on Soil Nitrate and Ammonium Nitrogen

Compared to AL, the WF treatment significantly increased soil NO_3^--N content by 25.20% and NH_4^+-N content by 21.28% ($P < 0.05$). During the vegetation growing season, NO_3^--N content under PA, MS, and AL treatments showed a decreasing then increasing trend, while under WF it showed an increasing then decreasing trend. NH_4^+-N content under PA, MS, and AL treatments exhibited a decreasing then increasing pattern, while under WF it showed a gradual decline. Across different land use types, NO_3^--N and NH_4^+-N contents in the 0–10 cm soil layer were significantly higher than in the 10–20 cm layer ($P < 0.05$) [FIGURE:4, FIGURE:5].

3.4 Nitrate Reductase Activity

Soil nitrate reductase (NR) activity varied significantly among land use types during the vegetation growing season [Figure 6: see original paper]. During the initial and middle growth stages, NR activity was highest under the WF treatment, while during the late growth stage, NR activity under the MS treatment was significantly higher than other treatments ($P < 0.05$). In the vertical soil profile, NR activity in the 0–10 cm layer was significantly higher than in the 10–20 cm layer ($P < 0.05$). Compared to AL, WF and MS treatments increased soil NR activity by 31.56% and 15.56%, respectively, while PA treatment decreased it by 2.39%.

3.5 Nitrite Reductase Activity

Soil nitrite reductase (NiR) activity also differed significantly among land use types during the vegetation growing season [Figure 7: see original paper]. During the initial and middle growth stages, NiR activity was highest under the WF treatment, while during the late growth stage, NiR activity under the MS treatment was significantly higher than other treatments ($P < 0.05$). Compared to AL, WF and MS treatments significantly increased soil NiR activity by 30.73% and 25.20%, respectively ($P < 0.05$). Across different land use types, soil NiR activity showed an overall increasing then decreasing trend with growth stages, being significantly higher in the middle stage than in the initial and late stages ($P < 0.05$). In the vertical soil profile, NiR activity in the 0–10 cm layer was significantly higher than in the 10–20 cm layer ($P < 0.05$).

3.6 Dynamic Changes in N_2O Emission Fluxes

During the vegetation growing season, soil N_2O emission fluxes under different land use types exhibited distinct seasonal variation patterns [Figure 8: see original paper]. In the initial growth stage, N_2O flux gradually increased with rising temperatures. During the middle growth stage, all treatments reached their maximum emission fluxes. In the late growth stage, N_2O flux slowly declined and stabilized with decreasing temperatures. Overall, the WF treatment showed significantly higher N_2O emission fluxes and cumulative emissions than other treatments throughout the growing season, with a pulse emission peak occurring in the initial stage.

3.7 Cumulative N_2O Emissions

Cumulative soil N_2O emissions under different land use types showed significant variation [Figure 9: see original paper]. Compared to AL, the WF treatment significantly increased cumulative N_2O emissions by 32.47% ($P < 0.05$), while

PA and MS treatments significantly reduced emissions by 34.2% and 23.3%, respectively ($P < 0.05$).

3.8 Relationships Among Environmental Factors, Enzyme Activities, and N_2O Flux

Correlation analysis revealed that soil temperature was significantly positively correlated with N_2O emission flux ($P < 0.05$), while soil water content was significantly negatively correlated with N_2O flux ($P < 0.05$). Soil temperature also showed significant positive correlations with NR and NiR activities ($P < 0.05$). Random forest analysis indicated that soil temperature was the most important factor influencing N_2O emissions, representing the key driving factor [Figure 10: see original paper].

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4. Discussion

4.1 Effects of Land Use Types on N_2O Fluxes

During the vegetation growing season, soil N_2O emissions under different land use types showed an initial increase followed by a decrease, with peak emissions occurring in the middle growth stage. This pattern likely resulted from frequent but low-intensity precipitation events and higher temperatures during the middle stage, which created moist soil conditions conducive to microbial survival and activity, accelerating nitrification and denitrification processes and thereby promoting increased N_2O emissions. Additionally, frequent wet-dry cycles created numerous anaerobic microsites in the soil surface. When soil water content was high, denitrification was the dominant process for N_2O production; when soil water content decreased, nitrification became more important. Therefore, while nitrification may be the primary N_2O production process, denitrification cannot be ignored during the middle growth stage.

A notable finding was the pulse emission peak in the WF treatment during the initial growth stage. Different land use types altered fundamental soil properties, leading to significant differences in cumulative N_2O emissions. In this study, the WF treatment showed the highest soil N_2O cumulative emissions, consistent with findings by Wu et al. The high emissions resulted from two synergistic effects: First, base fertilizer application significantly increased nitrogen concentration and availability, providing substrates for nitrifying and denitrifying bacteria and ultimately leading to substantially elevated soil N_2O cumulative emissions. Second, long-term tillage in cropland promoted organic matter mineralization, releasing large amounts of ammonium and nitrate nitrogen that further stimulated microbial metabolism and increased N_2O emissions. In contrast, the relatively minimal human disturbance in PA and MS treatments contributed to reduced N_2O emissions.

4.2 Effects of Soil Physicochemical Properties on N_2O Fluxes

Soil moisture regulates nitrification and denitrification by altering soil oxygen status and affecting nitrogen substrate diffusion to microbial communities, making it a critical factor influencing N_2O emissions. Tang et al. demonstrated that under different land use types, lower moisture content was more favorable for nitrification compared to high moisture conditions. In this study, soil water content was significantly negatively correlated with N_2O emissions, consistent with previous research. The PA treatment had the highest soil water content, while WF had the lowest. This difference may be related to vegetation cover and water movement—*Picea asperata* forest had high vegetation coverage that effectively shaded the soil surface, reducing evaporation, while the developed root system increased water infiltration, leading to increased nitrate leaching and reduced denitrification substrates, thereby decreasing N_2O emissions. Additionally, forest litter with high lignin concentrations reduced nitrogen availability, further lowering N_2O emissions.

The WF treatment showed lower soil water content due to increased plant water uptake following nitrogen application, creating more aerobic conditions that favored nitrification and N_2O release. Nitrogen fertilizer application also provided substrates for nitrifying and denitrifying bacteria, significantly increasing N_2O emissions. Besides soil moisture, soil temperature was another key driver of N_2O emissions. Although some researchers consider soil temperature less important, our random forest analysis identified it as the most influential factor, with correlation analysis showing significant positive relationships between soil temperature and N_2O flux. This result stems from temperature' s regulatory effect on soil microorganisms—nitrifying bacteria activity increases 1.5-3 fold for every 5°C temperature rise, accelerating nitrification and N_2O production. Throughout the growing season, the WF treatment maintained higher soil temperatures than PA due to lower vegetation cover, which allowed more solar radiation to reach the soil surface.

4.3 Effects of Soil Enzyme Activities on N_2O Fluxes

Nitrate reductase and nitrite reductase are two key enzymes in the soil denitrification process, and their activity levels represent important indicators of soil denitrification capacity. This study found significant positive correlations between soil N_2O emission fluxes and both NR and NiR activities, consistent with most previous research. The underlying mechanism may be that high NR activity generates substantial NO_2^-, providing ample substrate for NiR to produce hydroxylamine and subsequently N_2O. However, when enzyme activities exceed certain thresholds, catalytic reactions become more complete, reducing intermediate product N_2O accumulation. In this study, the WF treatment significantly increased both NR and NiR activities compared to other treatments, likely because base fertilizer application during wheat sowing promoted accumulation of soil inorganic nitrogen, providing sufficient substrates for nitrification and denitrification and enhancing N_2O emissions. Additionally, the relatively short phenological period of wheat meant that as crops gradually reduced their nitrogen demand, surface litter decomposition returned some nitrogen to the soil, further increasing N_2O emissions.

In contrast, the MS treatment showed lower NR activity because legumes with high biomass require substantial nitrogen uptake during growth, reducing soil nitrate and ammonium contents and consequently decreasing N_2O emissions. The MS treatment also had relatively high NiR activity, possibly due to abundant alfalfa litter that, through soil leaching, input substantial available resources into the mineral soil layer. The PA treatment, with its high soil water content, experienced nitrate leaching, reducing denitrification substrates and consequently lowering N_2O emissions.

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5. Conclusion

This study systematically investigated N_2O emission characteristics and driving factors under typical land use types in the central Gansu Loess Plateau. The main conclusions are as follows:

1. Different land use types significantly affected soil physicochemical properties. Compared to other treatments, the *Picea asperata* forest significantly reduced soil temperature and increased soil water content, while wheat fields significantly increased soil ammonium and nitrate nitrogen contents.
2. Significant differences in NR and NiR activities existed among land use types. Compared to other treatments, wheat fields significantly increased both enzyme activities due to nitrogen fertilizer application, with activities in the 0–10 cm layer significantly higher than in the 10–20 cm layer.
3. Soil N_2O fluxes under different land use types showed an initial increase followed by a decrease during the vegetation growing season. Compared to other treatments, the *Picea asperata* forest significantly reduced total N_2O emissions, while wheat fields significantly increased them. Random forest analysis identified soil temperature as the most important factor influencing N_2O flux, representing the key driving factor.

These findings provide a scientific basis for optimizing land use patterns and developing greenhouse gas mitigation strategies in the semiarid Loess Plateau region.

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