Effects of Conservation Tillage on Soil N2O Emissions from Cropland in the Semi-arid Loess Plateau Region (Postprint)

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Abstract

Nitrous oxide (N2O) is one of the important greenhouse gases in the atmosphere and has attracted considerable attention in the context of global climate warming, with farmland soil being its primary emission source. Among the numerous factors affecting N2O emissions from farmland, tillage practices serve as a key factor, yet their influence on N2O emission patterns from dryland farmland soils remains unclear. Therefore, this experiment employed traditional tillage (T) as a control and established three conservation tillage practices: no-till (NT), traditional tillage + straw mulching (TS), and no-till + straw mulching (NTS). The static chamber-gas chromatography method was used to measure soil N2O emission fluxes from spring wheat fields, while concurrently measuring related factors influencing N2O emissions and spring wheat yield.

The results showed that: (1) The cumulative soil N2O emissions from spring wheat fields under different tillage practices followed the order: T > NT > TS > NTS, with the T treatment being significantly higher than the other treatments, showing increases of 15.87%, 28.08%, and 39.58% compared to the NT, TS, and NTS treatments, respectively. Additionally, compared to the T treatment, conservation tillage practices contributed to increased surface soil NH4+-N content and spring wheat yield while reducing the accumulation of NO3-N content.

(2) Correlation analysis indicated that soil temperature, soil water content, and NH4+-N content were the key factors influencing soil N2O emissions. Specifically, both soil water content and NH4+-N content showed extremely significant negative correlations with N2O emissions from spring wheat fields, while soil temperature exhibited an extremely significant positive correlation with N2O emissions. Therefore, based on economic and environmental benefits, and through comprehensive consideration of N2O

emissions and crop yield, the NTS treatment is recommended as the optimal tillage practice for the semi-arid region of the Loess Plateau.

Full Text

Effects of Conservation Tillage on N2O Emissions from Farmland Soil in the Semi-arid Loess Plateau Region

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Abstract

Nitrous oxide (N_2O) is an important greenhouse gas that has attracted considerable attention in global climate change research, with farmland soil representing its primary emission source. Among the various factors influencing N_2O emissions from farmland, tillage practices are critical, yet their effects on N_2O emission patterns from dryland farmland soils remain unclear. This study employed traditional tillage (T) as a control and established three conservation tillage treatments: no-tillage (NT), traditional tillage with straw mulching (TS), and no-tillage with straw mulching (NTS). Soil N_2O emission fluxes from spring wheat fields were measured using static chamber-gas chromatography, while concurrently measuring factors influencing N_2O emissions and spring wheat yield.

The results demonstrated that cumulative N_2O emissions across treatments followed the order: T > NT > TS > NTS. The T treatment exhibited significantly higher emissions than other treatments, increasing by 15.87%, 28.08%, and 39.58% compared with NT, TS, and NTS, respectively. Additionally, relative to T, conservation tillage practices enhanced surface soil nitrogen content and spring wheat yield while reducing N_2O emissions. Correlation analysis revealed that soil temperature, water content, and nitrogen content were key factors affecting soil N_2O emissions. Specifically, soil water content and nitrogen content showed extremely significant negative correlations with N_2O emissions from spring wheat fields, whereas soil temperature showed an extremely significant positive correlation. Therefore, based on both economic and environmental benefits and considering both N_2O emissions and crop yield, the NTS treatment represents the optimal tillage practice for semi-arid regions of the Loess Plateau.

Keywords: greenhouse gases; conservation tillage; tillage measures; spring wheat; correlation; Loess Plateau

Introduction

Global climate warming has become increasingly severe, driven primarily by rising greenhouse gas concentrations. Nitrous oxide (N_2O) ranks among the three major greenhouse gases contributing to climate change, possessing substantial warming potential and a long atmospheric residence time, with concentrations increasing at an annual rate of 0.25% and significantly impacting global climate patterns. Agricultural activities constitute the main factor influencing soil N_2O emissions, with farmland representing an important emission source that accounts for approximately 60% of global N_2O emissions. Dryland farmland is widely distributed and not only plays a crucial role in agricultural production in China but also serves as a major source of atmospheric N_2O. Consequently, investigating N_2O emission characteristics from dryland farmland soils and developing strategies to mitigate greenhouse gas emissions is critically important.

The Loess Plateau, located in north-central China, is characterized by unique regional features of drought and soil erosion. Spring wheat, as one of the principal crops in this region, has become a preferred cultivation choice due to its strong drought resistance, short growth period, and substantial yield potential. To better elucidate the effects of soil physicochemical properties and environmental factors on N_2O emissions under conservation tillage, this study examined spring wheat fields in the Loess Plateau under different tillage practices. The research analyzed N_2O emission characteristics and influencing environmental factors across different tillage treatments, explored their correlations, revealed the mechanisms affecting farmland soil N_2O emissions, and identified optimal tillage strategies for increasing yield while reducing emissions. This work provides a theoretical basis for regional food production security and ecological environmental protection.

Materials and Methods

1.1 Study Area Overview

The study was conducted at the Comprehensive Dryland Agriculture Experimental Station of Gansu Agricultural University in Anjiapo Village, Anding District, Dingxi City, Gansu Province (35°64 N, 104°64 E). The region experiences a temperate semi-arid climate at an average elevation of 2000 m, with an annual mean temperature of 6.4°C and accumulated temperature $ 10°Cof2239.1°C · d.Annualaverageprecipitationis394.1mm, concentratedbetweenJuneandSeptember, whileannualpotentialeva freeperiodof140days, andrepresentsatypicalsemi−aridrain−fedagriculturalzone.Theexperimentalsiteisfla cm^{-1}, organicmattercontentis12.01g · kg{-1}, totalnitrogenis0.76g·kg^{-1}, andtotalphosphorusis1.19g · kg{-1}$.

1.2 Experimental Design

The field experiment was established in [year] and has been maintained continuously since inception, with this study focusing on data from [year]. The local spring wheat cultivar 'Ganchun [number]' was used as the test crop, sown on [date] at a seeding rate of 187.5 $kg \cdot hm^{-2}$. Each plot measured [size] m^2 with three replicates per treatment, totaling twelve plots arranged in a randomized complete block design. Base fertilizer was applied at sowing as a one-time application of [amount] $kg \cdot hm^{-2}$ diammonium phosphate and [amount] $kg \cdot hm^{-2}$ urea.

Four treatments were established: (1) Traditional tillage (T)—three plowing and two harrowing operations performed from harvest to winter solstice; (2) No-tillage (NT)—no tillage operations throughout the year, no straw mulching; (3) Traditional tillage with straw mulching (TS)—same tillage as T with straw uniformly returned to the plot after harvest; and (4) No-tillage with straw mulching (NTS)—no tillage with straw mulching as in TS.

1.3 Soil Gas Collection and Analysis

Soil N_2O fluxes were measured using the static chamber-gas chromatography method. Sampling was conducted at fixed times between 9:00-11:00 (when temperatures approximate the daily mean) at regular intervals during the growth period. The sampling device consisted of a 50 cm × 50 cm × 50 cm bottomless stainless steel dark chamber, wrapped with foam insulation to minimize internal temperature fluctuations. The top chamber was equipped with two air-mixing fans, with side ports for power connection, gas sampling, and temperature measurement. The base measured 50 cm × 50 cm × 20 cm and featured a water-filled sealing groove.

During measurement, the stainless steel base was fixed in the soil, and the groove was filled with water to ensure an airtight seal for gas sample collection. Immediately after chamber closure, the first 100 mL gas sample was collected using a syringe, followed by two additional samples at 8-minute intervals over a 40-minute period. Samples were transported to the laboratory in coolers and analyzed by gas chromatography within one week.

The N_2O emission flux F ($mg \cdot m^{-2} \cdot h^{-1}$) during the measurement period was calculated using the following equation:

$$F = \rho \times \frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273}{273 + T}$$

where is the gas density under standard conditions ($mg \cdot cm^{-3}$), V is the chamber volume (cm^3), A is the chamber base area (m^2), $\Delta c / \Delta t$ is the rate of change in N_2O concentration ($L \cdot L^{-1} \cdot min^{-1}$), and T is the mean temperature inside the chamber during sampling (°C).

Cumulative emissions M ($kg \cdot hm^{-2}$) over the entire growth period were calculated as:

$$M = \sum_{i=1}^{N-1} [F_i \times 0.5 \times (t_{i+1} - t_i) \times 24 \times 10^{-2}]$$

where F_i is the N_2O emission flux at the i-th sampling ($mg \cdot m^{-2} \cdot h^{-1}$), t_i is the day of the i-th sampling, and N is the total number of samplings.

1.4 Soil Sample Collection and Processing

During each gas sampling event, three points were randomly selected near the chamber base in each plot. Soil samples were collected using a soil auger, sieved to remove impurities, placed in sealed bags, and transported in a cooler with ice packs to the laboratory for analysis. Soil water content was determined by the aluminum box drying method (105–110°C to constant weight). Soil NO_3^--N and NH_4^+-N were extracted with potassium chloride solution and measured colorimetrically. Soil temperature at 5 cm depth was monitored continuously throughout the experiment. At wheat maturity, yield components including grain yield, plant height, spike grain number, and thousand-grain weight were determined from randomly selected areas in each plot.

Results

2.1 Dynamic Changes of Soil N_2O Emission Flux

During the entire spring wheat growth period, N_2O emission patterns were generally consistent across all treatments (Fig. 1). Emissions were low after sowing and increased steadily, with the first peak occurring approximately 15 days after sowing (likely due to base fertilizer effects), followed by a gradual decline. A second, more pronounced emission peak occurred around 45 days after sowing, reaching 0.1943 $mg \cdot m^{-2} \cdot h^{-1}$ in the T treatment, followed by TS, NT, and NTS. This peak coincided with optimal water and temperature conditions, relatively high nitrogen availability, and abundant substrates for nitrification and denitrification processes. Emissions subsequently declined until the jointing stage, with all treatments showing decreased fluxes around 60 days after sowing (possibly related to rainfall events prior to measurement). From jointing to maturity, differences among treatments diminished and stabilized, with emissions showing a gradual upward trend as temperatures increased until harvest.

2.2 Cumulative N_2O Emissions and Spring Wheat Yield

Cumulative N_2O emissions across treatments followed the order: T > NT > TS > NTS, with the T treatment significantly higher than all others (P <

0.05). Spring wheat yield and its components under different tillage practices are presented in Table 2. The NTS treatment produced the maximum grain yield, plant height, and thousand-grain weight, with significant differences from the T treatment ($P < 0.05$). Spike grain number under NTS did not differ significantly from other treatments, while plant height differed significantly from T but not from NT or TS. These results indicate that integrating spring wheat yield with N_2O emission reduction identifies NTS as the most suitable tillage practice for the semi-arid Loess Plateau region.

2.3 Dynamics of Soil NO_3^--N and NH_4^+-N

Throughout the spring wheat growth period, NO_3^--N and NH_4^+-N contents in the 0-10 cm soil layer showed distinct patterns under different tillage treatments (Fig. 3). Both nitrogen forms were relatively high in the early growth stage and decreased steadily as the season progressed, with NO_3^--N ranging from 0.0203–0.0415 $g \cdot kg^{-1}$ and NH_4^+-N from 0.0122–0.0184 $g \cdot kg^{-1}$. Overall, the NTS treatment maintained the highest NO_3^--N and NH_4^+-N levels, while the T treatment showed relatively lower concentrations, with average contents of 0.0322 $g \cdot kg^{-1}$ and 0.0143 $g \cdot kg^{-1}$, respectively. Correlation analysis (Table 3) revealed that N_2O emissions were positively correlated with NO_3^--N content but showed an extremely significant negative correlation with NH_4^+-N content ($P < 0.01$).

2.4 Influence of Environmental Factors on N_2O Emissions

Soil temperature significantly affected N_2O emissions, with correlation analysis showing that 5 cm soil temperature had the most significant relationship—an extremely significant positive correlation ($P < 0.01$). Temperature remained relatively stable across treatments, fluctuating between 6.0–28.6°C throughout the growth period (Fig. 4). Since nitrification-denitrification can occur within the 5–35°C range, temperature influences these microbial processes and consequently N_2O production. Soil water content also showed an extremely significant negative correlation with N_2O emissions ($P < 0.01$). Water content varied little among treatments, ranging from 7.26%–11.56% in the 0–10 cm layer, with the NTS treatment maintaining higher water content than other treatments throughout the growth period (Fig. 5).

Discussion

3.1 Effects of Tillage Practices on N_2O Emissions and Spring Wheat Yield

Farmland soil represents an important N_2O emission source, with production and emission influenced by various agricultural practices including tillage, fertilization, and irrigation. Previous research has demonstrated that conservation tillage offers substantial potential for reducing soil N_2O emissions. In this study, the first emission peak occurred approximately 15 days after sowing, attributed to base fertilizer application. Although some nitrogen entered the soil and was emitted through respiration, low temperatures limited microbial activity, resulting in relatively small emissions. The second peak around 45 days after sowing corresponded to rising soil temperatures, thawing of frozen soil, and full fertilizer effectiveness, providing abundant nitrogen substrates for nitrification-denitrification processes.

Throughout the entire growth period, cumulative N_2O emissions under T treatment were 15.87%, 28.08%, and 39.58% higher than NT, TS, and NTS, respectively, demonstrating that conservation tillage inhibited N_2O emissions. This inhibition likely occurred because traditional tillage creates favorable soil permeability, promoting the transition from anaerobic to aerobic conditions that enhance nitrification and gas diffusion. Additionally, good water-heat conditions during this stage increased microbial activity, strengthening nitrification-denitrification processes. As the growth period progressed, soil fertility declined, and rainfall events caused nitrogen migration from deeper to surface soil layers, while straw mulching accelerated decomposition of surface residues, further promoting N_2O production.

This study also showed that conservation tillage significantly increased spring wheat yield, with NTS producing the highest output. Previous research suggests that no-tillage improves soil organic matter and nutrient content while enhancing crop nitrogen uptake. Straw mulching promotes humus formation, increases soil aggregates, and releases nutrients for crop absorption. Additionally, the NTS treatment substantially reduces surface water evaporation during sowing, increases soil water content, and supports continuous dry matter accumulation. These findings align with previous studies demonstrating that NTS significantly improves post-anthesis dry matter accumulation and its contribution to grain yield in winter wheat. Thus, conservation tillage not only increases crop yield but also effectively reduces N_2O emissions, minimizing nitrogen loss while enhancing productivity.

3.2 Effects of Environmental Factors and Soil Nitrogen Forms on N_2O Emissions

N_2O in dryland farmland soil is primarily produced through microbial nitrification and denitrification processes, with soil temperature and moisture being particularly critical factors. This study found that soil temperature was extremely significantly positively correlated with N_2O emissions ($P < 0.01$). Temperature profoundly affects microbial activity, with denitrifying bacteria activity increasing 1.5–3.0 times for every temperature rise. Elevated soil temperature also promotes microbial respiration, creating oxygen-deficient microsites that provide anaerobic conditions for denitrification, thereby increasing N_2O production.

Soil water content was extremely significantly negatively correlated with N_2O

emissions ($P < 0.01$). This relationship may be explained by several mechanisms: increased water content inhibits nitrification processes, creates strongly anaerobic and reducing conditions, and hinders N_2O diffusion from soil to atmosphere. Under these conditions, N_2O produced by denitrification may be further reduced to N_2. Additionally, waterlogging can lead to N_2O consumption. In semi-arid regions, conservation tillage significantly improves soil aggregate structure and promotes organic matter accumulation, which can slow nitrification rates—particularly with straw incorporation—consistent with our findings.

This study also revealed that N_2O emissions were extremely significantly negatively correlated with NH_4^+-N content. In dryland soils, NH_4^+-N serves as the substrate for nitrification, which represents the primary source of surface soil N_2O. When N_2O is emitted in large quantities, NH_4^+-N is consumed through nitrification, leading to its depletion. The lack of significant correlation with NO_3^--N may be attributed to the alkaline nature of the experimental soil, which favors strong nitrification activity but weak nitrate reductase activity, making denitrification less important for N_2O production. These results highlight that soil N_2O emission characteristics vary with environmental conditions, soil properties, and nitrogen management practices.

Conclusion

Analysis of farmland soil N_2O emissions and key influencing factors under different tillage measures in the semi-arid Loess Plateau region yields the following conclusions:

1. N_2O emission fluxes under different tillage measures showed similar patterns across growth stages, peaking during the tillering period. Cumulative emissions followed the order: T > NT > TS > NTS. Considering both economic and environmental benefits, the NTS (no-tillage + straw mulching) treatment represents the optimal tillage practice for this region.

2. Correlation analysis demonstrated that soil temperature, water content, and NH_4^+-N content significantly influenced N_2O emission flux, with all relationships reaching extremely significant levels. Therefore, management strategies should focus on regulating these factors to achieve N_2O emission reductions while maintaining crop productivity.

References

Note: The reference list in the original manuscript was incomplete and contained corrupted text. A complete reference list should be compiled based on the citations mentioned in the text.

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