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Interactive effects of irrigation and nitrogen management on greenhouse gas emissions and resource efficiency in alfalfa production

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Introduction: Mitigating agricultural greenhouse gas (GHG) emissions while maintaining forage productivity is a key challenge under global carbon-neutrality goals. To evaluate the environmental and agronomic trade-offs of irrigation and nitrogen management, a field experiment was conducted in an arid region of Northwest China.

Methods: Twelve irrigation-nitrogen treatment combinations were applied to alfalfa (*Medicago sativa* L.) to quantify N₂O, CO₂, and CH₄ fluxes, global warming potential (GWP), and resource-use efficiencies.

Results: Results showed that soil water-filled pore space and available nitrogen strongly regulated N₂O emissions, with peaks occurring within one week after irrigation or fertilization. Excessive water and nitrogen inputs significantly increased GHG emissions and reduced irrigation water productivity (IWP) and partial factor productivity of nitrogen (PFPN).

Discussion and Conclusion: Conversely, the high-water, moderate-nitrogen regime (300 mm irrigation + 120 kg N ha⁻¹) achieved a balanced outcome—sustaining high yield while reducing cumulative N₂O emissions by 29.5–93%, total GWP (LCA-based) by 24.1%, and greenhouse gas emission intensity (GHGI) by 29.0% relative to conventional high-input management (W2N3). These preliminary findings suggest a water-nitrogen synergy zone that improves yield-GHG trade-offs, though multi-year validation is required.

KEYWORDS

crop yield, GHG emissions, global warming potential, *Medicago sativa* L, sustainable management, water-nitrogen interactions

1 Introduction

Global warming has emerged as one of the world's most pressing environmental challenges. Given the growing international interest in sustainable development, many nations have set targets to achieve carbon neutrality by the second half of the 21st century (Pawłowski and Rydzewski, 2024). Agricultural ecosystems are significant sources of greenhouse gases (GHGs), contributing 10–12% of global emissions (Shukla et al., 2022). Grasslands, a vital component of agricultural ecosystems, provide critical ecological functions. In particular, grasslands play a crucial role in biodiversity conservation, soil and water management, and regulation of carbon and nitrogen cycles (Wright, 2006). Both forage security and environmental sustainability must be addressed in order to achieve sustainable agricultural development with limited land resources under global climate change.

Irrigation and nitrogen management can improve crop growth and yield (Wang et al., 2024), impacting agricultural productivity and GHG emissions from grasslands. Under optimal irrigation and fertilization practices, water and nitrogen uptake by plant roots is promoted, leading to enhanced resource use efficiency and reduced soil GHG fluxes; as such, higher crop yield and lower GHG emissions are achieved. However, in arid and semi-arid regions, irrigation substantially boosts crop yield while increasing soil GHG emissions, particularly N_2O and CO_2 fluxes (Qin et al., 2024; Tan et al., 2025). Moreover, nitrogen fertilizers applied to soil are primarily lost through irrigation-induced leaching (NO_3^-) and microbial-mediated emissions (N_2O , NO , NH_3), exceeding crop uptake and causing environmental issues (Yoon et al., 2019). In particular, intensive water and nitrogen management can significantly increase N_2O emissions. For instance, emission factors observed in intensive systems can exceed the Intergovernmental Panel on Climate Change (IPCC) default value of 1.0%, highlighting the need for region-specific assessments. Conversely, high irrigation levels (>120 mm) decrease CH_4 oxidation rates by 42–79% due to enhanced pore water saturation of soil (Ning et al., 2022; Zhang et al., 2017a).

Alfalfa (*Medicago sativa* L.) is a widely cultivated and highly nutritious fodder plant, known as the “king of forage crops.” Alfalfa has an excellent capacity for biological nitrogen fixation through root nodules, reducing its need for nitrogen fertilizers (Robertson et al., 2000). However, low nitrogen rates limit root nodule development, which in turn restricts nitrogen supply to leguminous crops. Rational nitrogen management influences interactions between legume root exudates and soil microbes, altering carbon and nitrogen cycles and consequently affecting soil GHG emissions (Du et al., 2024; Zong et al., 2025). Under

water-saturated conditions, denitrification in the crop rhizosphere can cause localized surges in N_2O emissions (Zhang et al., 2021). The combination of irrigation and nitrogen application exacerbates GHG emissions in intensive agricultural ecosystems (Qu et al., 2025). Thus, optimizing irrigation and fertilization regimes to balance crop productivity and emission reductions—by adjusting soil moisture and nitrogen conditions—is crucial for alfalfa production.

The lock-in effects of “water-nitrogen inputs – yield gains – GHG emission reductions” are complex in grasslands. For example, in the arid region of northwest China, limiting nitrogen application (150–200 kg ha⁻¹) with drip irrigation (≤ 360 mm) can increase alfalfa hay yield by 18–24% and reduce global warming potential (GWP) per unit yield by 31% compared to conventional management (Kamran et al., 2022; Ning et al., 2022). However, several aspects remain less explored. First, single-factor or narrow-range designs still dominate, so water–nitrogen interactions across a full management gradient are not yet fully resolved. Second, most campaigns rely on low-frequency GHG sampling, which tends to overlook short-term emission pulses triggered by irrigation or fertilization events. Third, simultaneous consideration of forage productivity, water- and nitrogen-use efficiencies, and non- CO_2 greenhouse gas emissions—needed to quantify production–environment trade-offs—is still scarce. To address these limitations, we applied a 3×4 factorial water–nitrogen experiment coupled with high-frequency flux measurements to capture both seasonal patterns and event-driven peaks. By jointly analyzing yield, irrigation water productivity (IWP), partial factor productivity of nitrogen (PFPN), GWP and greenhouse gas emission intensity (GHGI), we evaluate the possibility of identifying a site- and year-specific water–nitrogen synergy zone under the semi-arid conditions of north-western China. This demonstrates the feasibility of maintaining crop productivity and mitigating GHG emissions through optimized irrigation and nitrogen application.

The aims of the present study were to: (a) quantify soil GHG emissions over the alfalfa growing season under different water–nitrogen regimes; (b) determine the GWP and GHGI in alfalfa systems under varying water–nitrogen conditions; and (c) examine the impacts of water–nitrogen treatments on resource use efficiency in alfalfa. A multi-gradient water–nitrogen coupling experiment was conducted in the arid region of Northwest China to investigate the response mechanisms of soil GHG emissions from alfalfa fields and quantify their GWP. The results could contribute to understanding of the greenhouse effect arising from water–nitrogen management and providing support for low-carbon agriculture.

2 Materials and methods

2.1 Experimental site

The field experiment was conducted at the Water-Saving Irrigation Experimental Station, Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas (Ministry of Education), Northwest A&F University. The experimental site is

Abbreviations: GHG, Greenhouse Gas; GWP, Global Warming Potential; GHGI, Greenhouse Gas Emission Intensity; LCA, Life Cycle Assessment; IWP, Irrigation Water Productivity; PFPN, Partial Factor Productivity of Nitrogen; WFPS, Water-Filled Pore Space; EF, Emission Factor; IPCC, Intergovernmental Panel on Climate Change; SI, International System of Units; N, Nitrogen; P, Phosphorus; K, Potassium.

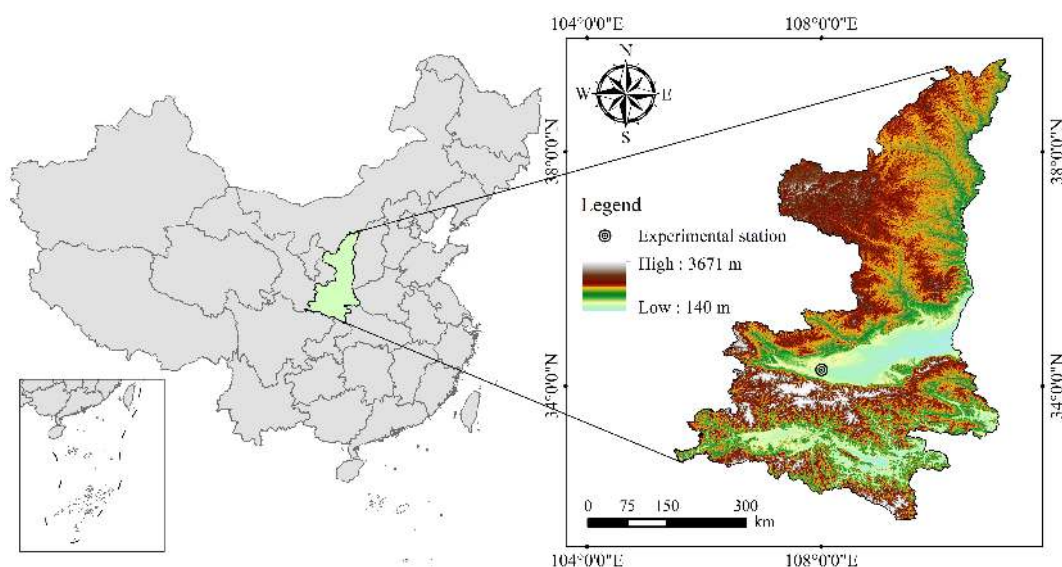


FIGURE 1
An overview map of the study area in Yangling, Shaanxi Province, China.

located in the Yangling Demonstration Zone, Xianyang, Shaanxi Province, Northwest China (108°24' E, 34°20' N; [Figure 1](#)). This area is situated in the western part of the Guanzhong Plain with a long-term average annual temperature of 12.9 °C. The long-term mean annual precipitation at the study site is 632 mm (1981–2020 climatology), whereas the experimental year (2023–2024) received 578.7 mm of precipitation according to observations from the on-site meteorological station. To ensure realistic soil-moisture scenarios, the three irrigation levels (W0, W1, W2) were designed after analyzing the 1981–2020 rainfall distribution: about 70% of annual precipitation falls between June and September, often as high-intensity events $\geq 10 \text{ mm day}^{-1}$. The irrigation schedules therefore mimicked dry-year (W0), average-year (W1) and wet-year (W2)

moisture regimes by supplementing 0, 100 and 300 mm, respectively, during the spring and early-summer gaps when alfalfa root uptake is highest. The timing and quantity of irrigation were therefore aligned with the seasonal rain. Precipitation and temperature data for the study area in the experimental period were obtained from a meteorological station within the experimental site ([Figure 2](#)). The soil type is classified as Haplic Cambisol characterized by a clay-loam texture and a field capacity of $\sim 22.4\%$ (gravimetric moisture content) in the 0–20 cm surface layer. The basic physicochemical properties of the surface soil were measured prior to sowing: pH (potentiometric method), 8.5; total nitrogen (Kjeldahl method), 1.0 g kg^{-1} ; available phosphorus (Olsen method), 15 mg kg^{-1} ; nitrate nitrogen (continuous flow analysis), 23 mg kg^{-1} ; ammonium nitrogen

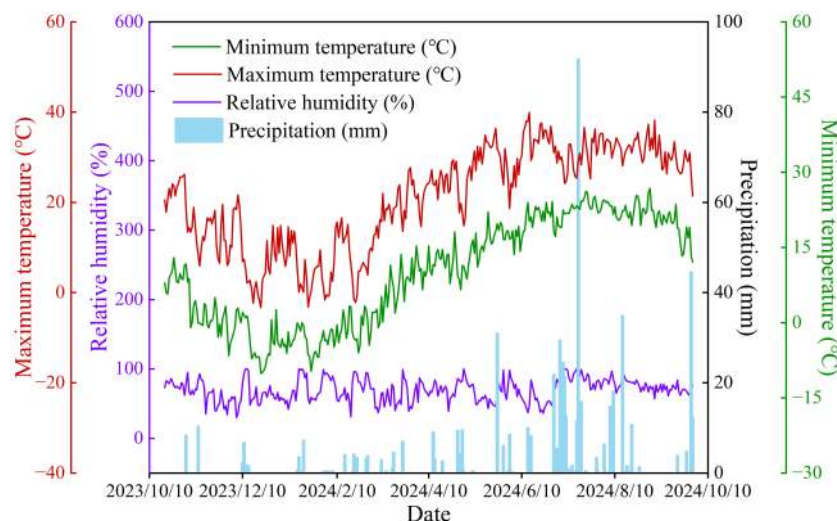


FIGURE 2
Daily temperature and precipitation over the alfalfa growing season (2023–2024).

TABLE 1 Irrigation and nitrogen management for the alfalfa growing season in 2023–2024.

Treatment	Irrigation volume (mm)			Total irrigation volume (mm)	Nitrogen rate (kg ha ⁻¹)
	First harvest	Second harvest	Third harvest		
W0N0	0	0	0	0	0
W0N1	0	0	0	0	60
W0N2	0	0	0	0	120
W0N3	0	0	0	0	180
W1N0	40	30	30	100	0
W1N1	40	30	30	100	60
W1N2	40	30	30	100	120
W1N3	40	30	30	100	180
W2N0	120	90	90	300	0
W2N1	120	90	90	300	60
W2N2	120	90	90	300	120
W2N3	120	90	90	300	180

(continuous flow analysis), 8 mg kg⁻¹; total organic matter (dichromate oxidation method, Walkley-Black), 15.5 g kg⁻¹; and bulk density (cutting ring method), 1.48 g cm⁻³.

2.2 Experimental design

The experiment was carried out between October 2023 and October 2024. To ensure that the experimental design aligns with local agronomic practices, the irrigation and fertilization levels were established based on regional water availability and the actual water and nitrogen requirements of alfalfa in the study area. The Yangling region has an average annual precipitation of approximately 630 mm, mostly occurring from June to September. The irrigation levels (W0: 0 mm, W1: 100 mm, W2: 300 mm) were all within the conventional supplemental irrigation range for local alfalfa production (100–350 mm). The irrigation treatments were therefore designed primarily for comparison purposes under different water conditions in relation to greenhouse gas (GHG) emissions and yield performance.

The nitrogen application rates (N0: 0 kg ha⁻¹, N1: 60 kg ha⁻¹, N2: 120 kg ha⁻¹, N3: 180 kg ha⁻¹) were based on the locally recommended fertilization range for alfalfa (60–180 kg ha⁻¹), covering low to high levels typically observed in production. Such a design provides regionally applicable insights into the balance between agronomic productivity and environmental sustainability under variable water–fertilizer regimes. A total of 12 water–nitrogen management schemes were established (Table 1), with each replicated three times across 36 plots. The plots (2 m × 2 m each) were separated by 1 m-wide isolation strips and furrows. Seeds of the alfalfa variety WL63HQ (Autumn Sleep Grade 5) were obtained from Zhengdao Seed Industry Co., Ltd. (Beijing, China) and sown at a rate of 25 kg ha⁻¹ with a row spacing of 20 cm. The fertilizers used in the experiment included superphosphate (46% P₂O₅,

75 kg ha⁻¹), potassium fertilizer as K₂O (90 kg ha⁻¹), and urea (46% N). Urea (46% N) were applied with a basal-to-topdressing ratio of 4:6. Basal nitrogen fertilizer (40%) was applied at sowing on October 15, 2023, followed by two topdressings (30% each) on March 14 (first harvest) and June 4 (second harvest), 2024. Irrigation took place on March 14 and April 14 (first harvest), June 4 (second harvest), and August 11 (third harvest), 2024. Alfalfa crops were mowed at the initial flowering stage, with three harvests scheduled annually on May 15, July 20, and September 27, 2024. Standard agronomic practices were maintained consistently across all treatments to isolate the effects of water and nitrogen. Prior to sowing, rotary tillage was performed to prepare a uniform seedbed. Basal fertilizers (Phosphate and Potassium) were incorporated into the soil during tillage to ensure adequate nutrient supply. During the growing season, integrated pest and weed management (using standard insecticides and manual weeding) was applied uniformly when necessary to prevent biotic stress. Harvest operations were conducted mechanically at a stubble height of 3 cm.

2.3 Gas sampling and analysis

2.3.1 Field sampling and measurements

Soil GHG emissions are primarily concentrated in spring, summer, and autumn (Yang et al., 2025). Therefore, gas sampling was conducted from the first regreening stage (March 13, 2024) to the last harvest (September 28, 2024) of alfalfa using a static dark chamber method, and gas chromatography was adopted to measure N₂O, CO₂, and CH₄ fluxes in field plots (Ning et al., 2020). The sampling chamber was made of stainless steel, consisting of a top chamber (30 cm × 30 cm × 30 cm) and a base (filled with water in a 3 cm-deep trough to seal the chamber). The chamber was placed at the center of each plot, with the base edge level with the ground surface. After sealing the chamber, a 30-ml syringe was used to

collect gas samples at 0, 10, 20, and 30 min, resulting in four samples per treatment. Soil temperature (0–5 cm) within the chamber was measured during sampling. Gas samples were collected every 7–10 days between 9:00 and 11:00 AM. After irrigation and fertilization, consecutive alternate-day sampling was initiated on day 1 and continued for 7–10 days. Additional measurements were taken after heavy rainfall (>10 mm).

2.3.2 Calculation of GHG emission fluxes

The peak area of the sample gas was measured using an Agilent 7890B gas chromatograph (Santa Clara, CA, USA). The gas concentration was calculated from the peak area using Equation 1:

$$C_S = \frac{A_S \times C_0}{A_0} \quad (1)$$

where C_S represents the concentration of the target gas in a given sample (ppm, ppb); A_S is the peak area of the sample gas; C_0 is the certified concentration of the standard gas (N_2O : 350 $\mu L m^{-3}$, CO_2 : 500 $mL m^{-3}$, CH_4 : 2 $\mu L m^{-3}$); and A_0 is the peak area of the standard gas.

The GHG emission flux at the sampling time was determined based on the linear regression slope of gas concentration in four consecutive samples per treatment using Equation 2 (Liu et al., 2017):

$$F = \frac{M}{22.4} \times \frac{273}{273 + T_a} \times 60 \times H \times \frac{dC}{dt} \quad (2)$$

where F is the gas flux (N_2O , CH_4 : $\mu g m^{-2} h^{-1}$; CO_2 : $mg m^{-2} h^{-1}$); M is molar mass ($g mol^{-1}$); T_a is chamber air temperature ($^{\circ}C$); H is chamber height (m); and dC/dt is the concentration change rate ($\mu L L^{-1} min^{-1}$ for CO_2 ; $nL L^{-1} min^{-1}$ for N_2O and CH_4). Eq. (2) assumes ideal-gas conditions at 1 atm and T_a .

2.3.3 Quantification of cumulative GHG emissions

The cumulative GHG emissions over the alfalfa growing season were calculated using Equation 3 (Zhang et al., 2021):

$$GF = \sum_{i=1}^n \frac{F_{i+1} + F_i}{2} \times (t_{i+1} - t_i) \times 24 \times K \quad (3)$$

where GF denotes the cumulative emission of the measured gas (N_2O : $kg N ha^{-1}$, CO_2 and CH_4 : $kg C ha^{-1}$); F_i is the gas emission flux at the i -th sampling time (N_2O and CH_4 : $\mu g m^{-2} h^{-1}$; CO_2 : $mg m^{-2} h^{-1}$); $(t_{i+1} - t_i)$ is the time interval between two consecutive measurements (days); K is the unit conversion factor (N_2O and CH_4 : 10^{-5} , CO_2 : 10^{-2}); and n is the total number of measurements.

2.4 Soil and forage sampling and analysis

2.4.1 Determination of soil properties

Soil sampling was conducted at the same time of gas sampling throughout the experiment. After each gas collection, soil temperature at a 5 cm depth was recorded outside the chamber using a soil thermometer. Then, soil samples were taken from the 0–20 cm depth using a 5-cm diameter soil auger, and the moisture

content was determined using the oven-drying method. Available nitrogen was extracted with 1 mol/L KCl at a soil-to-solution ratio of 1:10 (w/v), and quantification of NO_3^- and NH_4^+ contents was conducted using a SEAL AA3 continuous flow analyzer (Norderstedt, Germany).

Water-filled pore space (WFPS) was calculated using Equation 4 based on the method of Bergsma et al. (2002):

$$WFPS = \left(\frac{\theta}{1 - \frac{\rho_b}{\rho_p}} \right) \times 100 \quad (4)$$

where $WFPS$ denotes the water-filled pore space (%); θ is the volumetric moisture content determined using the cutting ring method (%); ρ_b is the soil bulk density ($g cm^{-3}$); and ρ_p is the particle density (typically assumed to be $2.65 g cm^{-3}$).

2.4.2 Evaluation of forage yield and resource use efficiency

Three 50 cm $\times$ 50 cm quadrats were established in each field plot. During the initial flowering stage, alfalfa crops were harvested at a 3-cm stubble height and transported to the laboratory for oven drying. Forage samples were first inactivated at $105^{\circ}C$ for 15 min and then dried at $65^{\circ}C$ until constant weight. Alfalfa hay yield for each treatment was calculated and converted to a per-hectare basis ($kg ha^{-1}$).

Irrigation water productivity (IWP) was obtained as the ratio of alfalfa hay yield to total irrigation volume using Equation 5 (Kamran et al., 2022), and partial factor productivity of nitrogen (PFPN) was calculated as the ratio of alfalfa hay yield to nitrogen rate using Equation 6 (Kamran et al., 2022):

$$IWP = \frac{Y}{I} \quad (5)$$

$$PFPN = \frac{Y}{N} \quad (6)$$

where IWP is the irrigation water productivity, defined as the ratio of alfalfa hay yield ($kg ha^{-1}$) to total irrigation water applied ($m^3 ha^{-1}$), with units of $kg m^{-3}$ (i.e., kilograms of dry yield per cubic meter of irrigation water). $PFPN$ is the partial factor productivity of nitrogen ($kg kg^{-1}$), Y is the alfalfa hay yield ($kg ha^{-1}$), I is the total irrigation volume ($m^3 ha^{-1}$), and N is the nitrogen rate ($kg N ha^{-1}$).

2.5 Estimation of N_2O emission factor, GWP, and GHGI

The N_2O emission factor (EF) was estimated using Equation 7 (IPCC, 2014):

$$EF = \frac{GF_F - GF_N}{N_F} \times 100 \quad (7)$$

where EF represents the N_2O emission factor (%); GF_F and GF_N are the cumulative N_2O emissions from fertilized and unfertilized treatments, respectively ($kg N ha^{-1}$); and N_F is the nitrogen rate ($kg N ha^{-1}$).

To comprehensively evaluate the environmental impact of the alfalfa production system, the net global warming potential (GWP,

kg CO₂-eq ha⁻¹) was calculated using a Life Cycle Assessment (LCA) approach. This method integrates both direct soil GHG emissions and indirect emissions associated with agricultural inputs (fertilizer production, irrigation electricity, and diesel fuel). The calculation is expressed as shown in Equations 8 and 9:

$$GWP = GWP_{soil} + GWP_{inputs} \quad (8)$$

$$GWP_{inputs} = \sum (Amount_i \times EF_i) \quad (9)$$

where GWP_{inputs} represents the GWP from agricultural inputs (kg CO₂-eq ha⁻¹). The carbon emission factors (EF_i) were adopted from recent literature on Chinese agriculture: 8.3 kg CO₂-eq kg⁻¹ for N fertilizer production, 0.79 kg CO₂-eq kg⁻¹ for P₂O₅, 0.55 kg CO₂-eq kg⁻¹ for K₂O, 2.66 kg CO₂-eq mm⁻¹ for irrigation water (electricity), and 55.4 kg CO₂-eq ha⁻¹ for diesel fuel consumption during tillage and harvest (Chen et al., 2011; Zhang et al., 2017b).

Regarding the soil component (GWP_{soil}), the calculation included cumulative CH₄ and N₂O emissions converted to CO₂-equivalents over a 100-year horizon (with warming potentials of 28 and 265, respectively), as shown in Equation 10:

$$GWP_{soil} = 28GF_{CH_4} + 265GF_{N_2O} \quad (10)$$

where GWP_{soil} represents the GWP from direct soil fluxes (kg CO₂-eq ha⁻¹). It is important to note that chamber-measured soil CO₂ fluxes were excluded from the calculation. While soil respiration is a significant carbon flux, the static dark chamber method captures only ecosystem respiration (an output) without accounting for photosynthetic carbon uptake (an input). Including these fluxes would erroneously inflate the net carbon balance (Shang et al., 2019). Thus, our approach represents a conservative estimate focusing on non-CO₂ gases and input-based emissions.

Greenhouse gas emission intensity (GHGI) was defined as the LCA-based GWP per unit of crop yield based on Equation 11 (IPCC, 2014):

$$GHGI = \frac{GWP}{Y} \quad (11)$$

where $GHGI$ is the GHG emission intensity (kg CO₂-eq t⁻¹) and Y is the alfalfa hay yield (t ha⁻¹).

2.6 Statistical analysis

After data processing with Excel 2016 (Microsoft Corp., Redmond, WA, USA), statistical analyses were performed using IBM SPSS Statistics 20.0 (IBM Corp., Armonk, NY, USA). Two-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test was used to identify differences in cumulative GHG emissions, crop yield, IWP, PFPN, GHGI, and GWP among treatments. Pearson correlation and linear regression were applied to assess relationships between GHG fluxes and soil properties. Graphs were generated using Origin 2023 (OriginLab Corp., Northampton, MA, USA). Prior to ANOVA, normality of residuals (Shapiro–Wilk test) and homogeneity of variances (Levene's test) were examined. All variables met both assumptions ($P > 0.05$).

3 Results

3.1 Soil physicochemical dynamics in relation to GHG emissions

During the experimental period, the daily maximum and minimum temperatures in the study area were 39.9°C and −10.1°C, respectively, with the total precipitation reaching 578.7 mm. The average daily temperature over the alfalfa growing season ranged from −6.7°C to 31.6°C (Figure 2). Soil temperatures (0–5 cm) exhibited consistent trends across treatments and showed clear seasonal variation, primarily driven by air temperature and precipitation (Figure 3a). Under different irrigation treatments, the average soil temperature for W0 (21.35°C) was slightly, but not significantly, higher than that of W1 (20.94°C) and lower than that of W2 (21.64°C). WFPS varied prominently due to irrigation and rainfall, showing repeated wet-dry cycles. WFPS increased with higher irrigation volumes, ranging between 24.52–75.23% for W0, 27.82–77.08% for W1, and 31.02–83.06% for W2. Within each irrigation cycle, WFPS gradually decreased over time in similar patterns (Figure 3b). Under different nitrogen treatments, soil available nitrogen contents (0–20 cm) displayed comparable

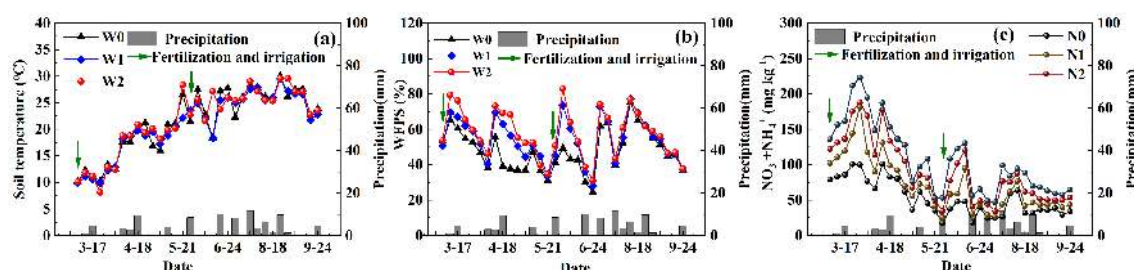


FIGURE 3

Temporal dynamics of soil physicochemical properties under different levels of irrigation (W0: 0 mm, W1: 100 mm, W2: 300 mm) and nitrogen application (N0: 0 kg ha⁻¹, N1: 60 kg ha⁻¹, N2: 120 kg ha⁻¹, N3: 180 kg ha⁻¹) during the alfalfa growing season. (a) Soil temperature at 0–5 cm depth, (b) Water-filled pore space (WFPS) at 0–20 cm depth, and (c) Soil available nitrogen content.

seasonal changes, with temporary increases followed by declines after irrigation or rainfall. The sum of soil NO_3^- and NH_4^+ contents ranged from 13.7 to 232.18 mg kg^{-1} , and higher irrigation volumes or nitrogen rates maintained elevated soil nitrogen levels for longer durations. Soil available nitrogen contents trended downward over the alfalfa growing season (Figure 3c).

The relationships between GHG emission fluxes and soil physicochemical properties were assessed using correlation analysis. During the alfalfa growing season, N_2O fluxes linearly increased with rising soil temperature and available nitrogen content, and higher fluxes were observed within the WFPS range of 50–60%. CO_2 fluxes peaked at soil temperatures between 15°C–20°C and decreased linearly with increasing WFPS, with higher fluxes at WFPS of 35–45%. CH_4 fluxes were negatively correlated with soil temperature and positively correlated with soil WFPS and available nitrogen content. Further, the relative contributions of soil physicochemical properties to N_2O , CO_2 , and CH_4 emission fluxes were assessed using linear regression. Regression equations were established for each gas emission flux against soil temperature, WFPS, and available nitrogen content. WFPS did not show significant linear correlations with N_2O , CO_2 or CH_4 fluxes ($P >$

0.05; Figure 4), probably because soil moisture rarely reached the critical thresholds for sharp emission pulses under the semi-arid conditions of this study, leaving mineral N as the dominant short-term driver.

3.2 N_2O fluxes and cumulative emissions

N_2O fluxes frequently rose within a week of N application or ≥ 10 mm rainfall and then subsided, with the largest pulses in W2N3 (Figures 5a–c). Because background variability was high and the routine sampling interval was 7–10 d, we confined our inference to treatment-level cumulative emissions rather than to exact lag times. W2 resulted in the greatest fluctuation in N_2O fluxes over the alfalfa growing season (Figure 5c), followed by W1 (Figure 5b), and the smallest variation was observed for W0 (Figure 5a). Among the three harvest cycles, N_2O fluxes were highest in the second cycle (1.09–469.35 $\mu\text{g m}^{-2} \text{h}^{-1}$) compared to the first (1.09–326.24 $\mu\text{g m}^{-2} \text{h}^{-1}$) and third (5.01–199.68 $\mu\text{g m}^{-2} \text{h}^{-1}$) cycles under each irrigation level. In the third harvest cycle, N_2O fluxes exhibited similar trends between W0 and W1, both of which were significantly lower than W2. Under

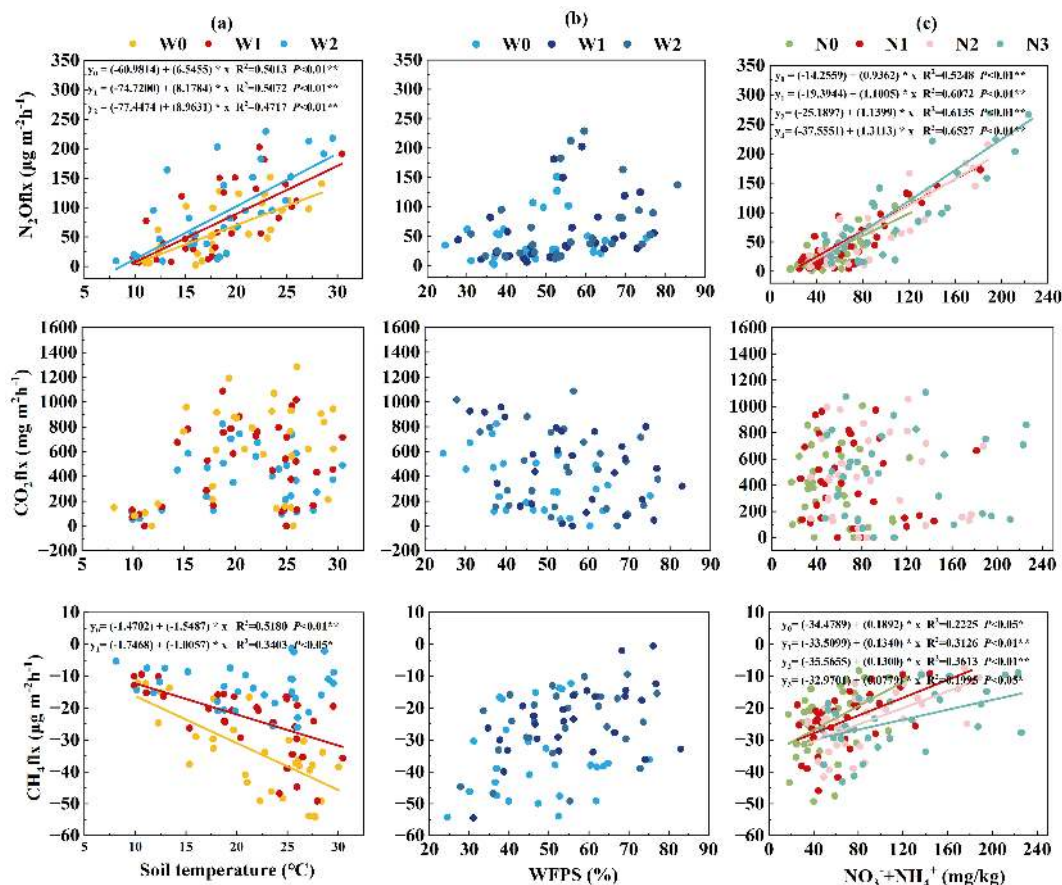


FIGURE 4

Relationship between greenhouse gas emission fluxes and (a) soil temperature at 0–5 cm depth, (b) soil available nitrogen content at 0–20 cm depth, and (c) water-filled pore space (WFPS). * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$; NS indicates no significance. Each data point represents the mean of three replicates for irrigation or nitrogen treatments. Only significant correlations ($P < 0.05$) are displayed; the complete panel is provided in Supplementary Image 1.

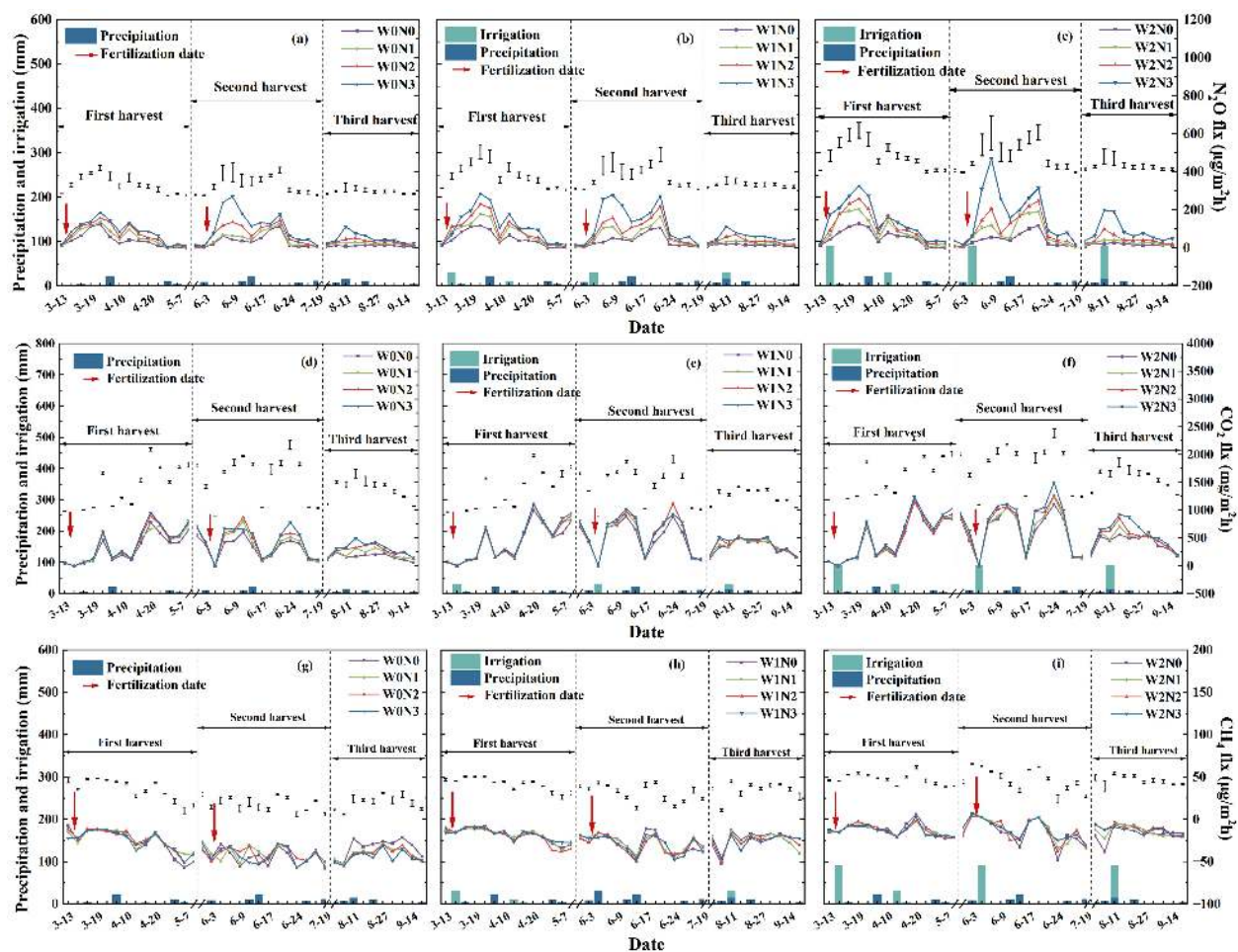


FIGURE 5

Greenhouse gas emission fluxes from unfertilized (N0) and nitrogen-fertilized (N1–N3) alfalfa fields under different irrigation treatments (W0: No irrigation, W1: Low water level, and W2: High water level). (a–c) N_2O fluxes, (d–f) CO_2 fluxes, and (g–i) CH_4 fluxes.

different nitrogen treatments, N_2O fluxes trended upward with higher nitrogen rates. In the third harvest cycle without topdressing, there were significantly lower N_2O fluxes across all nitrogen treatments than in the first and second cycles. The average N_2O flux peaked in W2N3, and was lowest in W0N0.

Cumulative N_2O emissions were significantly affected by fertilization and its interactions with irrigation (Figures 6a–c). Combined irrigation and nitrogen application significantly increased cumulative N_2O emissions over the alfalfa growing season, and emissions increased proportionally with higher treatment levels. ANOVA results showed significant differences in cumulative N_2O emissions among nitrogen treatments, but not among irrigation treatments (Figures 6a, b). During the three harvest cycles, cumulative N_2O emissions decreased with lower nitrogen rates across all irrigation treatments and were lowest in the third cycle, with the highest in the first cycle. Cumulative N_2O emissions peaked in W2 (2.72 kg ha⁻¹) and N3 (3.63 kg ha⁻¹) (Figures 6a, b). Among the combined treatments, increasing nitrogen rate under each irrigation level elevated cumulative N_2O emissions. W2N3 produced the highest cumulative N_2O emissions (4.59 kg ha⁻¹), with the lowest observed for W0N0 (0.89 kg ha⁻¹)

(Figure 6c). These results indicate that post-fertilization N_2O emissions were a major contributor to annual totals. In particular, emissions following basal and secondary nitrogen applications accounted for ~53% of the annual cumulative N_2O emission.

3.3 CO_2 fluxes and cumulative emissions

With regard to CO_2 emission fluxes, there were significant effects of irrigation, fertilization, and their interactions (Figures 5d–f). CO_2 fluxes showed consistent patterns across treatments, with W2 exceeding W1 and N1–N3 slightly higher than N0. Distinct temporal patterns emerged in CO_2 fluxes under different water-nitrogen interactions. After fertilization and the first irrigation (March 14), maximum CO_2 flux occurred within the first week of input, but equally rapid rises followed subsequent rains; thus, timing is co-controlled by temperature and moisture, not a fixed lag. Subsequent irrigation and rainfall events triggered new peaks in CO_2 fluxes. After fertilization and the second irrigation (April 14), W0N0 maintained relatively stable CO_2 fluxes, which peaked at 1033.76 mg m⁻² h⁻¹ on day 6 and then decreased

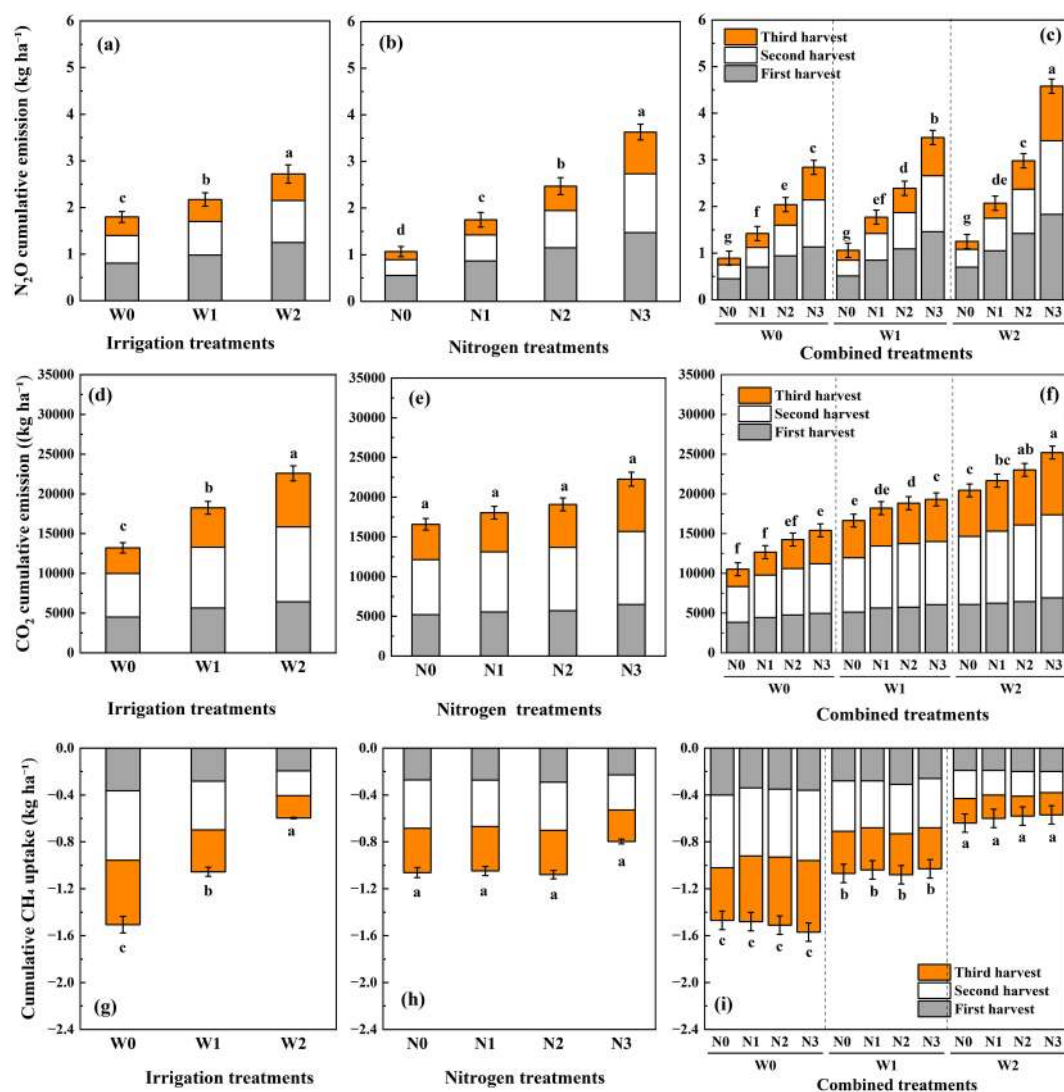


FIGURE 6

Effects of irrigation and nitrogen management on cumulative greenhouse gas emissions in alfalfa fields over three harvest cycles. (a–c) Cumulative N_2O emissions, (d–f) cumulative CO_2 emissions, and (g–i) cumulative CH_4 uptake. The stacked bars represent the contributions of the first, second, and third harvests. Different lowercase letters above the bars indicate significant differences in the total annual cumulative emissions among treatments based on the LSD test ($P < 0.05$). Error bars represent the standard error of the means ($n = 3$). Treatments: W0 (0 mm), W1 (100 mm), W2 (300 mm); N0 (0 kg ha^{-1}), N1 (60 kg ha^{-1}), N2 (120 kg ha^{-1}), N3 (180 kg ha^{-1}).

afterwards. Following rainfall, CO_2 fluxes remained persistently high for 0–6 days. Additionally, CO_2 fluxes were temperature-controlled, generally lower in the cold months (November–March) than in the warm months (April–October).

Changes in cumulative CO_2 emissions indicated significant effects of irrigation and irrigation-fertilization interactions (Figures 6d–f). ANOVA results revealed that cumulative CO_2 emissions differed significantly among irrigation treatments, but not among nitrogen treatments (Figures 6d, e). Specifically, cumulative CO_2 emissions increased with higher irrigation volumes, reaching 22,586.17 kg ha^{-1} for W2. Within each irrigation treatment, cumulative CO_2 emissions exhibited a mild upward trend with increasing nitrogen rate. The lowest annual cumulative CO_2 emission was observed for W0N0 (10,530.18 kg ha^{-1}) and the highest

for W2N3 (25,206.11 kg ha^{-1}) (Figure 6f). Emissions following irrigation and fertilization accounted for ~1.56% of the annual cumulative CO_2 emissions across treatments.

3.4 CH_4 fluxes and cumulative emissions

CH_4 emission fluxes were significantly responsive to irrigation, but not to fertilization or their interactions (Figures 5g–i). All field plots consistently functioned as CH_4 sinks throughout the experimental period. Soil CH_4 uptake was transiently reduced after wetting, yet the response was inconsistent; only irrigation level significantly affected the seasonal sink strength. CH_4 fluxes decreased with increasing irrigation volume, ranging from –77.95

$\mu\text{g m}^{-2} \text{h}^{-1}$ (W0) to $-8.14 \mu\text{g m}^{-2} \text{h}^{-1}$ (W2). No distinct temporal pattern in CH_4 fluxes was observed across treatments. The effects of irrigation on cumulative CH_4 uptake were also significant (Figures 6g–i). Cumulative CH_4 uptake decreased with increasing irrigation volume, from 1.50 kg ha^{-1} (W0) to 0.60 kg ha^{-1} (W2) (Figure 6h). Emission peaks following irrigation and fertilization contributed $\sim 1.02\%$ to the annual cumulative CH_4 emission.

3.5 Forage yield and resource use efficiency

Irrigation, fertilization, and their interactions all exhibited highly significant effects on alfalfa hay yield (Figure 7). Higher irrigation volumes led to improved alfalfa yields. Across all irrigation treatments, alfalfa yields increased initially and then decreased over successive harvest cycles. The mean yield was highest in the second harvest cycle ($7,811.0 \text{ kg ha}^{-1}$) followed by the third cycle ($5,232.4 \text{ kg ha}^{-1}$), and the lowest yield was recorded for the first cycle ($3,799.1 \text{ kg ha}^{-1}$). Under W0 and W1 treatments, alfalfa yield increased with higher nitrogen rates, peaking at $6,069.46 \text{ kg ha}^{-1}$ for N3. Under W2 treatment, alfalfa yield peaked at $6,876.73 \text{ kg ha}^{-1}$ for N2 and then declined with higher nitrogen input; N3 resulted in lower alfalfa yield than N2 and had no significant difference compared to N1. The annual yield across irrigation-nitrogen treatments ranged from $18,907.30 \text{ kg ha}^{-1}$ (W2N2) to $11,811.79 \text{ kg ha}^{-1}$ (W0N0).

The effects of irrigation, fertilization, and their interactions on IWP were highly significant (Table 2). IWP was lower under W2 than under W1; however, this comparison is restricted to only two irrigated levels (W1 and W2) and should therefore be treated as indicative rather than a statistically robust trend. Across nitrogen treatments, IWP initially increased and then declined with increasing N rate. Among different nitrogen treatments, the highest IWP was observed for N2, exceeding that of N0 by 26.2% (W1) and 39.6% (W2). Under the combined treatments, IWP peaked in W1N3 (6.82 kg m^{-3}), followed by W1N2 (6.67 kg m^{-3}) in the second harvest cycle.

W2N2 improved IWP by 10.9% compared to the conventional high-water, high-nitrogen regime W2N3.

The PFPN patterns also indicated highly significant effects of irrigation, fertilization, and their interactions (Table 2). PFPN increased with higher irrigation volumes, while it negatively responded to nitrogen rate under each irrigation level. Among all combined treatments, the highest PFPN was recorded for W2N1 ($300.55 \text{ kg kg}^{-1}$), and the lowest for W0N3 (94.87 kg kg^{-1}). W2N2 achieved a favorable balance between alfalfa yield and nitrogen use efficiency, improving PFPN by 56.9% compared to W2N3.

3.6 Climate response to GHG emissions

To assess the climate response to GHG emissions in alfalfa fields under water-nitrogen management, ANOVA was conducted for EF, GWP, and GHGI across treatments. All three parameters showed significant differences in relation to irrigation, fertilization, and their interactions (Table 3). EF showed an upward trend with increasing irrigation volume. Under both W0 and W2 levels, EF rose with higher nitrogen rates. Under the W1 level, N2 produced the lowest EF (1.10%). The highest EF value (1.86%) was observed for W2N3, which also recorded the greatest GWP and GHGI values under combined treatments. When incorporating indirect emissions from agricultural inputs, the total GWP for W2N3 reached $3721.54 \text{ kg CO}_2\text{-eq ha}^{-1}$. Compared to W2N3, W2N2 achieved favorable trade-offs, reducing EF (by 29.1%), total GWP (by 24.1%), and GHGI (by 29.0%). This reduction was primarily driven by lower nitrogen fertilizer inputs, mitigating both direct soil emissions and upstream industrial carbon costs. In summary, soil GHG emissions showed a strong positive response to high water and nitrogen inputs, while the high-water, medium-nitrogen regime effectively reduced GHG emissions from alfalfa production. The highest N_2O emission factor (1.86%) under W2N3 approached twice the IPCC default (1.0%), while optimized treatments ($\leq 120 \text{ kg N ha}^{-1}$) fell within ranges reported for alfalfa systems (0.4–1.7%; Fernández-Ortega et al., 2024; Kamran et al., 2022).

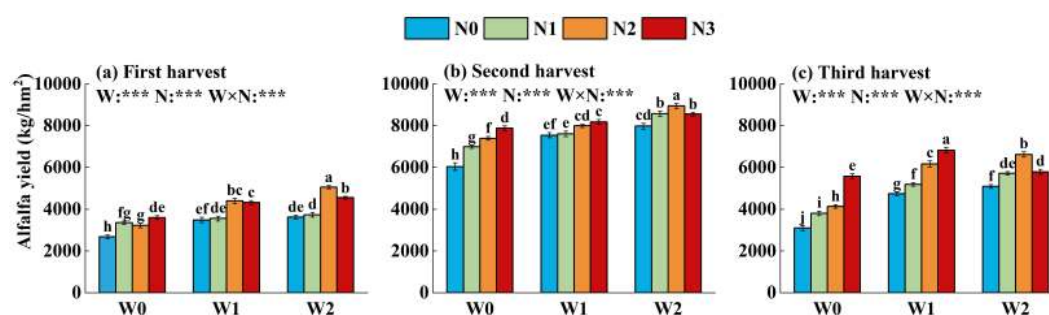


FIGURE 7

Effects of water-nitrogen treatments on alfalfa yield over three harvest cycles. (a) Yields in the first harvest cycle, (b) Yields in the second harvest cycle, and (c) Yields in the third harvest cycle. Significant differences between treatments are indicated by different lowercase letters above error bars. *** $P < 0.001$. W0: No irrigation, W1: Low water level, W2: High water level, N0: no fertilization, N1: Low nitrogen level, N2: Moderate nitrogen level, and N3: High nitrogen level.

TABLE 2 Effects of water-nitrogen treatments on irrigation water productivity (IWP) and partial factor productivity of nitrogen (PFPN) in alfalfa fields.

Irrigation treatment	Nitrogen treatment	IWP (kg m ⁻³)			PFPN (kg kg ⁻¹)
		First harvest	Second harvest	Third harvest	
W0	N0	–	–	–	–
	N1	–	–	–	235.92 ± 4.38c
	N2	–	–	–	122.99 ± 2.38f
	N3	–	–	–	94.87 ± 1.74h
W1	N0	2.90 ± 0.11b	6.29 ± 0.10c	3.95 ± 0.08d	–
	N1	2.96 ± 0.10b	6.35 ± 0.11c	4.33 ± 0.07c	272.65 ± 5.55b
	N2	3.66 ± 0.10a	6.67 ± 0.06b	5.14 ± 0.12b	154.73 ± 2.91e
	N3	3.60 ± 0.09a	6.82 ± 0.10a	5.70 ± 0.11a	107.44 ± 1.88g
W2	N0	1.01 ± 0.02e	2.22 ± 0.04e	1.41 ± 0.02g	–
	N1	1.03 ± 0.03e	2.38 ± 0.03d	1.59 ± 0.02f	300.55 ± 5.44a
	N2	1.41 ± 0.02c	2.49 ± 0.04d	1.84 ± 0.03e	171.92 ± 2.78d
	N3	1.27 ± 0.02d	2.37 ± 0.02d	1.61 ± 0.03f	105.04 ± 1.48g
Water		***	***	***	***
Nitrogen		***	***	***	***
W × N		***	***	***	***

Data are means ± standard error (n = 3). Different lowercase letters within the same column indicate significant differences between treatments. ***P < 0.001.

4 Discussion

4.1 Enhancement of soil N₂O emission fluxes by water-nitrogen interactions

N₂O is produced mainly through microbial nitrification and denitrification processes, and soil N₂O emissions are highly sensitive to soil moisture content, temperature, and nitrogen availability (Qian et al., 2025). Irrigation can indirectly promote N₂O emission fluxes. In the absence of nitrogen application, increased irrigation levels had a limited effect on soil N₂O emissions from alfalfa fields. However, when nitrogen was applied, irrigation markedly enhanced N₂O emissions, possibly because increased soil moisture content indirectly contributed to N₂O emissions by improving NO₃⁻N availability (Ullah et al., 2016). It has been reported that elevated WFPS levels are associated with enhanced soil denitrification (Anderson et al., 2019). N₂O emission fluxes were promoted by soil WFPS, as indicated by their significant positive correlation observed in this study. The underlying mechanism is that high irrigation levels (WFPS 50–60%) facilitated soil denitrification. This finding is consistent with the denitrification thresholds reported by Bracken et al. (2021) and Wang et al. (2023).

The application of nitrogen fertilizer resulted in considerably higher soil N₂O emissions in alfalfa fields, as nitrogen application elevated soil available nitrogen content, providing ample substrates for nitrifying and denitrifying bacteria (Xun et al., 2022). N₂O emission fluxes were positively driven by soil available nitrogen content, based on the results of correlation and regression analyses.

There were stepwise rises in N₂O fluxes from low nitrogen (N1) to high nitrogen (N3) treatments compared to the unfertilized control (N0), and the fluxes had strong positive correlation with soil available nitrogen content that surged immediately after fertilization. NO₃⁻N is considered the primary source of nitrogen for N₂O emissions. Excessive nitrogen not absorbed by alfalfa roots remains in the soil, serving as substrates for microbial nitrification and denitrification, consequently stimulating N₂O emissions (Jiang et al., 2025; Wang et al., 2024). These findings emphasize the importance of optimizing irrigation and nitrogen rates to control soil N₂O emissions from alfalfa cultivation. Given the 7–10 d routine sampling interval, we confine our interpretation to treatment-level cumulative emissions (Figures 6a–c) rather than to exact lag times.

4.2 Effects of water-nitrogen interactions on soil CO₂ flux and emission dynamics

Soil CO₂ fluxes in alfalfa fields reflected combined microbial and root respiration, with a smaller contribution from carbonate dissolution (Bai et al., 2021). Nitrogen fertilization stimulated microbial mineralization and root metabolic activity, thereby increasing CO₂ release during N transformation processes (Hauck, 1981; Snyder et al., 2009; Kong et al., 2020). Short-term CO₂ pulses appeared immediately after irrigation and fertilization, consistent with observations under fixed-moisture conditions (Pan et al., 2023). However, the strength of these responses differed among growth stages, indicating that water-nitrogen (W-N)

TABLE 3 Effects of water-nitrogen treatments on N₂O emission factor (EF), total global warming potential (GWP), and greenhouse gas emission intensity (GHGI) (LCA-based).

Treatment		EF (%)	GWP (kg CO ₂ -eq ha ⁻¹)			GHGI (kg CO ₂ -eq t ⁻¹)		
			First harvest	Second harvest	Third harvest	First harvest	Second harvest	Third harvest
W0	N0	–	250.41 ± 2.80 l	89.96 ± 0.71 l	50.36 ± 2.28 l	93.73 ± 1.65 l	14.89 ± 0.58 j	16.27 ± 0.49 j
	N1	0.87	675.13 ± 13.17 i	281.06 ± 15.82 i	95.24 ± 3.44 k	201.07 ± 9.29 i	40.20 ± 5.84 h	25.03 ± 0.43 h
	N2	0.96	1095.72 ± 2.44 g	497.69 ± 5.20 g	134.33 ± 4.94 j	339.73 ± 9.09 d	67.29 ± 1.27 f	32.47 ± 0.93 f
	N3	1.07	1497.71 ± 9.02 d	748.41 ± 5.58 d	208.08 ± 3.60 f	415.65 ± 21.09 b	94.90 ± 3.11 c	37.27 ± 0.79 e
W1	N0	–	379.26 ± 1.17 k	189.05 ± 5.01 j	149.80 ± 0.91 i	109.07 ± 4.59 k	25.06 ± 1.63 i	31.58 ± 0.35 f
	N1	1.17	826.17 ± 7.13 h	404.76 ± 5.83 h	193.78 ± 2.90 g	232.59 ± 4.03 h	53.20 ± 2.84 g	37.34 ± 1.60 e
	N2	1.10	1246.94 ± 5.03 e	616.32 ± 7.73 e	243.55 ± 5.27 d	283.56 ± 5.96 g	77.03 ± 2.05 e	39.47 ± 0.72 d
	N3	1.34	1707.59 ± 8.33 b	883.49 ± 9.94 b	331.94 ± 3.06 b	395.03 ± 6.22 c	107.97 ± 3.12 b	48.59 ± 0.37 c
W2	N0	–	648.73 ± 3.47 j	363.30 ± 4.46 h	300.72 ± 2.43 c	179.05 ± 3.18 j	45.55 ± 1.28 h	59.05 ± 3.72 b
	N1	1.36	1101.53 ± 0.80 f	607.41 ± 10.23 f	344.54 ± 3.94 b	295.10 ± 8.59 f	70.77 ± 2.91 f	60.25 ± 3.50 b
	N2	1.44	1559.97 ± 0.68 c	831.82 ± 6.70 c	431.41 ± 3.60 a	308.57 ± 4.68 e	92.94 ± 1.90 d	65.17 ± 2.54 a
	N3	1.86	1979.94 ± 61.36 a	1173.25 ± 9.31 a	568.35 ± 13.80 a	434.93 ± 60.30 a	137.10 ± 1.61 a	98.08 ± 2.51 a
Water			***	***	***	***	***	***
Nitrogen			***	***	***	***	***	***
W×N			**	***	***	**	***	***

Data are means ± standard error (*n* = 3). Different lowercase letters within the same column indicate significant differences among treatments based on the LSD test at *P* < 0.05. Asterisks indicate the significance levels of the analysis of variance (ANOVA): * *P* < 0.05, ** *P* < 0.01, and *** *P* < 0.001; NS indicates no significance. GWP and GHGI values include both direct soil emissions and indirect emissions from agricultural inputs (LCA-based). Percentage reductions of GWP and GHGI mentioned in the text are calculated relative to the conventional high-input reference W2N3 (300 mm irrigation + 180 kg N ha⁻¹); EF is computed against the corresponding N0 treatment.

interactions do not exert a uniform influence throughout the season.

The interaction was strongest during early regrowth. Following irrigation, CO₂ fluxes increased sharply, reflecting the rewetting-induced activation of soil microbes documented in dryland systems (Zhai et al., 2011; Badaou and Sahin, 2025). These pulses overlapped with nitrogen addition, which provided readily available substrates for microbial decomposition and root respiration, producing higher peaks than those reported in single-factor experiments (Pan et al., 2023). The highest fluxes occurred on days 7 and 6 after irrigation, highlighting the system’s sensitivity to combined moisture and nutrient inputs. During peak biomass, CO₂ fluxes were driven mainly by temperature and sustained soil moisture, whereas nitrogen effects weakened. Irrigation maintained higher soil moisture and supported root and microbial respiration, resulting in notably greater cumulative CO₂ emissions under W2 than W0. This pattern aligns with evidence that adequate moisture enhances autotrophic and heterotrophic respiration when plant growth is vigorous (Wang et al., 2022). After harvest, CO₂ fluxes declined and W-N interactions were minimal. Reduced root activity and lower belowground carbon allocation (Kong et al., 2020) diminished nitrogen-induced differences, while irrigation produced only moderate variation through soil moisture regulation.

Overall, W-N interactions had their strongest effects immediately after irrigation during early regrowth, whereas

temperature and sustained moisture largely controlled cumulative CO₂ emissions. This stage-dependent behavior explains the varying responses among harvest periods and underscores the combined influence of moisture pulses and plant phenology on CO₂ dynamics in semi-arid alfalfa systems.

4.3 Functional stability of soil CH₄ sinks under water-nitrogen regimes

CH₄ is produced by methanogenic archaea through anaerobic decomposition of soil organic matter. Under aerobic conditions, methanotrophic microorganisms consume CH₄ as an energy source along with O₂. Therefore, the soil functions as a CH₄ source when CH₄ production by methanogens exceeds its oxidation by methanotrophs, and shifts to a CH₄ sink when methanotrophs become dominant (Angle et al., 2017). During alfalfa cultivation, different water-nitrogen regimes did not significantly affect CH₄ fluxes, supporting the results from earlier pot and field experiments showing that alfalfa soils consistently act as CH₄ sinks (Fernández-Ortega et al., 2024; Kamran et al., 2022; Ning et al., 2020). However, previous studies collected monthly data from static chamber measurements or considered only one irrigation level, which contrasts with our high-frequency (daily) measurements across three irrigation and four nitrogen levels. The results showed that

even pronounced wet-dry cycles and nitrogen pulses did not stimulate CH₄ uptake or cause net emissions, highlighting the robustness of the soil sink function under intensive management. Based on the positive correlation between soil CH₄ emission fluxes and WFPS, high WFPS levels under intensive irrigation likely improved soil porosity and structure, creating anaerobic conditions favorable for methanogenic activity. Similarly, [Chen et al. \(2021\)](#) reported that high soil moisture content reduced O₂ availability, expanding anaerobic zones and enhancing CH₄ production by methanogens. Although WFPS showed no significant linear correlation with CH₄ fluxes ([Figure 4](#)), non-linear or threshold moisture effects may exist; these could not be tested with the present single-year dataset, so only significant linear relationships are retained in [Figure 4](#) and the complete matrix is provided in [Supplementary Image 1](#).

The effect of nitrogen application on CH₄ emissions remains inconclusive. Nitrogen rate did not significantly affect CH₄ emissions from alfalfa production, although findings from other crops may offer useful insights. For example, nitrogen fertilization has been identified as a major factor affecting CH₄ emissions in cotton systems ([Bai et al., 2021](#)). In wheat systems, moderate nitrogen levels may enhance CH₄ oxidation, while excessive fertilization or topdressing can inhibit methanotrophic activity, resulting in increased CH₄ emissions ([Hütsch et al., 1993](#)).

4.4 Trade-offs, synergies, and resource use efficiencies of water and nitrogen

Irrigation and fertilization play essential roles in achieving high yield and quality of alfalfa in arid and semi-arid regions ([Ma et al., 2024](#)). While nitrogen application increased annual alfalfa yield compared to the control, there was a non-linear yield response to nitrogen rate. This pattern is attributed to the role of nitrogen as a key determinant of crop productivity. When applied at optimal levels, nitrogen improves alfalfa yield by promoting cell division and growth and enhancing dry matter accumulation ([Lv et al., 2025](#); [Ma et al., 2024](#)). However, excessive nitrogen input may suppress rhizobial nitrogen fixation, reducing nitrogen use efficiency ([Hu et al., 2019](#)). Our results indicated that high nitrogen application (N3) did not improve alfalfa yield, potentially due to reduced nitrogen use efficiency and increased GHG emissions. Additionally, alfalfa yield increased progressively with higher irrigation levels, consistent with previous findings by [Jia et al. \(2018\)](#) under a single nitrogen level. The rate of yield increase was amplified under moderate nitrogen application and peaked when the nitrogen level reached 120 kg ha⁻¹. During the alfalfa growing season, substantial rainfall in June–August 2024 provided sufficient soil moisture, leading to the highest crop yield in the second harvest. It has been suggested that moderately increasing fertilization and irrigation promotes improvements in fresh forage yield, while over-fertilization with poor irrigation management can lead to yield reduction ([Kandelous et al., 2012](#)). No yield reduction due to irrigation was observed in the present study, possibly because the applied water volumes did not exceed the critical threshold.

Within a suitable soil moisture range, appropriate fertilization notably improved alfalfa productivity ([Mu et al., 2025](#)).

IWP and PFPN are key indicators for evaluating water and fertilizer management in agricultural systems, and both of them are strongly affected by irrigation and fertilization strategies. [Wen et al. \(2024\)](#) suggested that IWP increases with higher irrigation volumes within a specific range, whereas [Djaman et al. \(2020\)](#) reported the opposite pattern. In this study, IWP decreased as irrigation volume increased, and increasing nitrogen application improved IWP under each irrigation level, suggesting a synergistic interaction between water and fertilizer inputs. Appropriate fertilization can promote root growth and distribution, enhancing water and nutrient uptake, thereby improving IWP under water-limited conditions. Additionally, it has been shown that PFPN increases first and then declines with increasing nitrogen rate over a reasonable range ([Mu et al., 2025](#)). This suggests that moderate nitrogen input enhances crop yield, whereas excessive nitrogen application causes fertilizer loss and environmental risk. Results of this study showed that PFPN declined with increasing nitrogen rate across all irrigation levels, indicating that excessive nitrogen input did not necessarily improve fertilizer use efficiency. Coordinated water and fertilizer management during alfalfa cultivation achieved the dual goals of “managing water through fertilizer” and “enhancing fertilizer use efficiency through water.” The water-fertilizer synergy was maximized under combined application of appropriate irrigation and nitrogen levels, effectively improving alfalfa yield and resource use efficiency. For example, both PFPN and IWP peaked under moderate nitrogen application (180 kg ha⁻¹) with high irrigation (300 mm).

4.5 Optimizing water and nitrogen inputs to mitigate GWP and GHGI

Soil GHG emissions remained positive across all irrigation and nitrogen treatments, indicating that the alfalfa system acted as a net GHG source. GWP increased under higher irrigation levels with elevated nitrogen rates, suggesting that both water and nitrogen were key drivers influencing this metric. Specifically, the high GWP in intensive treatments was driven not only by soil denitrification but also by the substantial carbon footprint embedded in agricultural inputs. N₂O and CH₄ are recognized as the two most important soil-derived GHGs in GWP assessments ([Li et al., 2023](#)), and their emissions are highly sensitive to both irrigation and fertilization practices. Under arid soil conditions, CH₄ uptake often exceeds its emissions, making N₂O the dominant contributor to soil-based GWP in alfalfa systems ([Zhang et al., 2024](#)). Fertilizer application can promote microbial activity in the soil. For example, NH₄⁺-based nitrogen fertilizer provides readily available substrate for ammonia-oxidizing bacteria, stimulating soil nitrification ([Fudjoe et al., 2023](#)). However, excessive application of basal or topdressing fertilizer disrupts the balance between soil nitrogen supply and plant uptake. This could result in residual mineral nitrogen and elevated N₂O emissions, consequently increasing soil GWP.

Although this study integrated LCA to calculate comprehensive GWP, it should be noted that excluding soil CO₂ introduces uncertainty because chamber-based CO₂ respiration does not represent net ecosystem carbon exchange. Therefore, the GWP and GHGI values reported here reflect only direct non-CO₂ soil fluxes and indirect input emissions, explicitly excluding chamber-measured soil respiration. Future studies should combine chamber measurements with ecosystem-scale carbon assessments for a more complete evaluation. This approach aligns with protocols focusing on non-CO₂ greenhouse gases in short-term studies (Shang et al., 2019; Smith et al., 2020).

GHGI is a key metric for evaluating agricultural sustainability. Optimal fertilization can enhance alfalfa yield while lowering GHGI (Ma et al., 2024). This study showed that moderate nitrogen application (N2) resulted in higher alfalfa yield (by 1.15–7.02%) and lower LCA-based GHGI (by ~29.0%) compared to high nitrogen treatment (N3). The reduction in GHGI for N2 was due to the dual mitigation of direct soil N₂O emissions and the indirect carbon footprint from fertilizer production. Our LCA analysis revealed that 'hidden' carbon emissions from inputs are major drivers of GWP; optimizing the N rate to 120 kg ha⁻¹ (W2N2) effectively cut these upstream emissions by approximately 33% compared to the N3 level. Therefore, alleviating GHGI in agricultural systems requires optimized nitrogen management to lower GHG emissions and improve crop yields—dual objectives that can be simultaneously achieved by adjusting the fertilization rate. Additionally, rational irrigation management can reduce nutrient leaching and GHG emissions associated with excessive water use (Wang et al., 2025).

Aligning irrigation with crop water demand is helpful to minimize GHGI while sustaining crop productivity. Conventional practices involving high water and nitrogen inputs were associated with elevated GHGI, whereas the optimal treatment (W2N2) reduced environmental impacts, resulting in lower GHGI. This study covered only one growing season at a single site; both weather conditions and GHG emissions are known to exhibit substantial inter-annual variability. Consequently, the proposed water–nitrogen management recommendations should be viewed as site-specific and year-specific, rather than universally optimized thresholds. Multi-year, multi-location experiments are needed to test the stability and generality of the observed synergy zone.

5 Conclusions

This study explored GHG emission patterns and yield responses of alfalfa in an arid and semi-arid region under varying water and nitrogen regimes. The results demonstrated significant irrigation–nitrogen interactions affecting soil N₂O and CO₂ fluxes, with CH₄ uptake remaining relatively stable. N₂O emissions were primarily driven by nitrogen input and modulated by soil moisture fluctuations, while CO₂ fluxes were influenced mainly by irrigation.

A high irrigation regime (300 mm) combined with a moderate nitrogen rate (120 kg ha⁻¹) maintained high yield while substantially reducing cumulative GHG emissions and emission intensity.

Specifically, the W2N2 treatment achieved approximately 24.1% lower total GWP (LCA-based) and 29.0% lower emission intensity than the high-water, high-nitrogen combination (W2N3), indicating improved resource-use efficiency and environmental performance. In contrast, excessive nitrogen or insufficient irrigation caused either elevated emissions or reduced productivity.

Overall, the present single-year, single-site results suggest a possible site- and year-specific synergy region (approximately 300 mm irrigation and 120 kg ha⁻¹), which performed well in balancing yield, resource efficiency, and greenhouse gas emissions. However, because interannual variations in precipitation, temperature, and soil microbial activity can substantially influence GHG fluxes, this recommended zone should be regarded as preliminary and requires multi-year validation before being generalized to wider regions.

Despite these limitations, our findings provide several practical management implications for semi-arid alfalfa production: (1) Avoid excessive nitrogen (> 120 kg ha⁻¹) under high irrigation, as this combination sharply increases N₂O emissions without proportional yield gain. (2) A moderate nitrogen rate of ≈ 120 kg ha⁻¹ under adequate water (≈ 300 mm) simultaneously improves partial-factor productivity of nitrogen (PFPN) and maintains high biomass. (3) Under water-limited conditions, optimizing irrigation timing contributes more to irrigation–water productivity (IWP) than simply increasing nitrogen inputs.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author/s.

Author contributions

TQ: Conceptualization, Investigation, Methodology, Software, Writing – original draft. JL: Methodology, Software, Writing – review & editing. XS: Investigation, Writing – review & editing. XL: Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. JP: Methodology, Software, Writing – review & editing. SS: Funding acquisition, Project administration, Writing – review & editing. YW: Supervision, Writing – review & editing.

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Conflict of interest

The authors declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Anderson, F. L., Cooper, J. A., and Amador, J. A. (2019). Laboratory-scale evaluation of the effects of water-filled pore space on emissions of CO₂, CH₄, N₂O, and N₂ from soil-based wastewater treatment. *Water Air Soil Pollut.* 230, 245. doi: 10.1007/s11270-019-4294-7
- Angle, J. C., Morin, T. H., Solden, L. M., Narrowe, A. B., Smith, G. J., Borton, M. A., et al. (2017). Methanogenesis in oxygenated soils is a substantial fraction of wetland methane emissions. *Nat. Commun.* 8, 1567. doi: 10.1038/s41467-017-01753-4
- Badaou, A. N. A. D., and Sahin, U. (2025). Frequent irrigation in manure-fertilized soil reduces CO₂ emissions per unit yield by increasing maize silage yield. *Water Air Soil Pollut.* 236, 449. doi: 10.1007/s11270-025-08124-6
- Bai, M., Suter, H., Macdonald, B., and Schwenke, G. (2021). Ammonia, methane and nitrous oxide emissions from furrow irrigated cotton crops from two nitrogen fertilisers and application methods. *Agric. For. Meteorology* 303, 108375. doi: 10.1016/j.agrformet.2021.108375
- Bergsma, T. T., Robertson, G. P., and Ostrom, N. E. (2002). Influence of soil moisture and land use history on denitrification end-products. *J. Environ. Qual.* 31, 711–717. doi: 10.2134/jeq2002.7110
- Bracken, C. J., Lanigan, G. J., Richards, K. G., Müller, C., Tracy, S. R., Grant, J., et al. (2021). Source partitioning using N₂O isotopomers and soil WFPS to establish dominant N₂O production pathways from different pasture sward compositions. *Sci. Total Environ.* 781, 146515. doi: 10.1016/j.scitotenv.2021.146515
- Chen, X. P., Cui, Z. L., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J. S., et al. (2011). Integrated soil-crop system management for food security. *Proc. Natl. Acad. Sci.* 108, 6399–6404. doi: 10.1073/pnas.1101419108
- Chen, J., Feng, M., Cui, Y., and Liu, G. (2021). The impacts of nitrogen addition on upland soil methane uptake: A global meta-analysis. *Sci. Total Environ.* 795, 148863. doi: 10.1016/j.scitotenv.2021.148863
- Djaman, K., Smeal, D., Koudahe, K., and Allen, S. (2020). Hay yield and water use efficiency of alfalfa under different irrigation and fungicide regimes in a semiarid climate. *Water* 12, 1721. doi: 10.3390/w12061721
- Du, L., Zhong, H., Guo, X., Li, H., Xia, J., and Chen, Q. (2024). Nitrogen fertilization and soil nitrogen cycling: Unraveling the links among multiple environmental factors, functional genes, and transformation rates. *Sci. Total Environ.* 951, 175561. doi: 10.1016/j.scitotenv.2024.175561
- Fernández-Ortega, J., Fanlo, R., and Cantero-Martínez, C. (2024). Greenhouse gas emissions during alfalfa cultivation: How do soil management and crop fertilization of preceding maize impact emissions? *Field Crops Res.* 87745318, 109602. doi: 10.1016/j.fcr.2024.109602
- Fudjoe, S. K., Li, L., Anwar, S., Shi, S., Xie, J., Yeboah, F. K., et al. (2023). The impact of fertilization on ammonia-oxidizing bacteria and comammox Nitrospira communities and the subsequent effect on N₂O emission and maize yield in a semi-arid region. *Front. Microbiol.* 14. doi: 10.3389/fmicb.2023.1249668
- Hauck, R. D. (1981). Nitrogen fertilizer effects on nitrogen cycle processes. *Ecol. Bulletins* 33, 551–562.
- Hu, W., Zhang, Y.-H., Li, P., Zhang, P., Li, M.-Y., You, J.-T., et al. (2019). Effects of different levels of nitrogen fertilization on soil respiration rates and soil biochemical properties in an alfalfa grassland. *Huanjing Kexue* 40, 2858–2868. doi: 10.13227/j.hjxx.201810019
- Hütsch, B. W., Webster, C. P., and Powlson, D. S. (1993). Long-term effects of nitrogen fertilization on methane oxidation in soil of the broadbalk wheat experiment. *Soil Biol. Biochem.* 25, 1307–1315. doi: 10.1016/0038-0717(93)90045-D
- Intergovernmental Panel on Climate Change (IPCC Ed.) (2014). *Climate change 2013 – the physical science basis: Working group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. 1st ed* (Geneva, Switzerland: Cambridge University Press). doi: 10.1017/CBO9781107415324
- Jia, Q., Kamran, M., Ali, S., Sun, L., Zhang, P., Ren, X., et al. (2018). Deficit irrigation and fertilization strategies to improve soil quality and alfalfa yield in arid and semi-arid areas of northern China. *PeerJ* 6, e4410. doi: 10.7717/peerj.4410
- Jiang, F., Chang, Y., Han, J., Yang, X., and Wu, Z. (2025). Effects of long-term nitrogen fertilization on nitrous oxide emission and yield in acidic tea (*Camellia sinensis* L.) plantation soils. *Agronomy* 15:7, f1z066. doi: 10.3390/agronomy15010007
- Kamran, M., Yan, Z., Chang, S., Chen, X., Ahmad, I., Jia, Q., et al. (2022). Enhancing resource use efficiency of alfalfa with appropriate irrigation and fertilization strategy mitigate greenhouse gases emissions in the arid region of northwest China. *Field Crops Res.* 289, 108715. doi: 10.1016/j.fcr.2022.108715
- Kandelous, M. M., Kamai, T., Vrugt, J. A., Šimůnek, J., Hanson, B., and Hopmans, J. W. (2012). Evaluation of subsurface drip irrigation design and management parameters for alfalfa. *Agric. Water Manage.* 109, 81–93. doi: 10.1016/j.agwat.2012.02.009
- Kong, D., Liu, N., Ren, C., Li, H., Wang, W., Li, N., et al. (2020). Effect of nitrogen fertilizer on soil CO₂ emission depends on crop rotation strategy. *Sustainability* 12, 13. doi: 10.3390/su12135271
- Li, Z., Zhang, Q., Li, Z., Qiao, Y., Du, K., Yue, Z., et al. (2023). Responses of soil greenhouse gas emissions to no-tillage: A global meta-analysis. *Sustain. Production Consumption* 36, 479–492. doi: 10.1016/j.spc.2023.02.003
- Liu, Y., Yan, C., Matthew, C., Wood, B., and Hou, F. (2017). Key sources and seasonal dynamics of greenhouse gas fluxes from yak grazing systems on the Qinghai-Tibetan Plateau. *Sci. Rep.* 7, 40857. doi: 10.1038/srep40857
- Lv, M., Tian, D., Wang, G., Fan, T., Li, W., Hou, C., et al. (2025). Selection of alfalfa water and nitrogen management regimes based on the DSSAT model. *Sci. Rep.* 15, 12108. doi: 10.1038/s41598-025-92058-w
- Ma, H., Jiang, P., Zhang, X., Ma, W., Cai, Z., and Sun, Q. (2024). Effects of nitrogen fertilization combined with subsurface irrigation on alfalfa yield, water and nitrogen use efficiency, quality, and economic benefits. *Front. Plant Sci.* 15. doi: 10.3389/fpls.2024.1339417
- Mu, G., Jiang, Y., Li, H., Wei, S., Qi, G., Kang, Y., et al. (2025). Water-fertilizer synergistic effects and resource optimization for alfalfa production: A central composite design and response surface methodology approach. *Plants (Basel Switzerland)* 14, 731. doi: 10.3390/plants14050731
- Ning, J., He, X. Z., Hou, F., Lou, S., Chen, X., Chang, S., et al. (2020). Optimizing alfalfa productivity and persistence versus greenhouse gases fluxes in a continental arid region. *PeerJ* 8, e8738. doi: 10.7717/peerj.8738
- Ning, J., Lou, S., Guo, Y., Chang, S., Zhang, C., Zhu, W., et al. (2022). Appropriate N fertilizer addition mitigates N₂O emissions from forage crop fields. *Sci. Total Environ.* 829, 154628. doi: 10.1016/j.scitotenv.2022.154628

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpls.2025.1740107/full#supplementary-material>

- Pan, S.-Y., He, K.-H., and Liao, Y.-L. (2023). Fertilization-induced reactive nitrogen gases and carbon dioxide emissions: Insight to the carbon-nitrogen cycles. *Sustain. Environ. Res.* 33, 23. doi: 10.1186/s42834-023-00185-8
- Pawłowski, A., and Rydzewski, P. (2024). Pathways to carbon neutrality: Integrating energy strategies, policy, and public perception in the face of climate change—a global perspective. *Energies* 17, 23. doi: 10.3390/en17235867
- Qian, H., Yuan, Z., Chen, N., Zhu, X., Huang, S., Lu, C., et al. (2025). Legacy effects cause systematic underestimation of N₂O emission factors. *Nat. Commun.* 16, 2775. doi: 10.1038/s41467-025-58090-0
- Qin, J., Duan, W., Zou, S., Chen, Y., Huang, W., and Rosa, L. (2024). Global energy use and carbon emissions from irrigated agriculture. *Nat. Commun.* 15, 3084. doi: 10.1038/s41467-024-47383-5
- Qu, X., Yao, W., Ji, H., Xu, Y., Jia, R., Chen, X., et al. (2025). Optimizing nitrogen fertilization and irrigation strategies to balance agroecosystem services in the wheat-maize double cropping system: A 21-year field study. *Field Crops Res.* 322, 109706. doi: 10.1016/j.fcr.2024.109706
- Robertson, G. P., Paul, E. A., and Harwood, R. R. (2000). Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science* 289, 1922–1925. doi: 10.1126/science.289.5486.1922
- Shang, Q., Ling, N., Feng, X., Zeng, X., Li, Y., Zhang, Y., et al. (2019). Soil respiration components and their temperature sensitivity under long-term fertilization practices. *Soil Biol. Biochem.* 130, 235–243. doi: 10.1016/j.soilbio.2019.01.002
- Shukla, P. R., Skea, J., Slade, R., Al Khouradajie, A., van Diemen, R., McCollum, D., et al. (2022). “Climate change 2022: Mitigation of climate change,” in *Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*, (New Delhi, India) 10, 9781009157926. doi: 10.1017/9781009157926
- Smith, P., Soussana, J.-F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., et al. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biol.* 26, 219–241. doi: 10.1111/gcb.14891
- Snyder, C. S., Bruulsema, T. W., Jensen, T. L., and Fixen, P. E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* 133, 247–266. doi: 10.1016/j.agee.2009.04.021
- Tan, M., Cui, N., Jiang, S., Xing, L., Wen, S., Liu, Q., et al. (2025). Effect of practicing water-saving irrigation on greenhouse gas emissions and crop productivity: A global meta-analysis. *Agric. Water Manage.* 308, 109300. doi: 10.1016/j.agwat.2025.109300
- Ullah, B., Shaaban, M., Hu, R., Zhao, J., and Lin, S. (2016). Assessing soil nitrous oxide emission as affected by phosphorus and nitrogen addition under two moisture levels. *J. Integr. Agric.* 12, 2865–2872. doi: 10.1016/S2095-3119(16)61353-9
- Wang, T., Cong, X., Yu, J., Zhao, H., Xu, L., Pang, G., et al. (2025). Impact of biochar and deficit irrigation on greenhouse gas emissions reduction in maize-wheat rotation systems. *Agric. Water Manage.* 315, 109547. doi: 10.1016/j.agwat.2025.109547
- Wang, Y., Li, M., Guo, J., and Yan, H. (2024). Alfalfa (*Medicago sativa* L.) nitrogen utilization, yield and quality respond to nitrogen application level with center pivot fertigation system. *Agronomy* 14, 1. doi: 10.3390/agronomy14010048
- Wang, H., Yan, Z., Ju, X., Song, X., Zhang, J., Li, S., et al. (2023). Quantifying nitrous oxide production rates from nitrification and denitrification under various moisture conditions in agricultural soils: Laboratory study and literature synthesis. *Front. Microbiol.* 13. doi: 10.3389/fmicb.2022.1110151
- Wang, W., Zhang, H., Mo, F., Liao, Y., and Wen, X. (2022). Reducing greenhouse gas emissions and improving net ecosystem economic benefit through long-term conservation tillage in a wheat-maize multiple cropping system in the Loess Plateau, China. *Eur. J. Agron.* 141, 126619. doi: 10.1016/j.eja.2022.126619
- Wen, S., Cui, N., Li, M., Gong, D., Xing, L., Wu, Z., et al. (2024). Optimizing irrigation and nitrogen fertilizer management to improve apple yield, quality, water productivity and nitrogen use efficiency: A global meta-analysis. *Scientia Hort.* 332, 113221. doi: 10.1016/j.scienta.2024.113221
- Wright, I. A. (2006). Grasslands of the world, eds J. M. Suttie, S. G. Reynolds & C. Batello. *Rome: J. Agric. Science.* 144, 185–185. doi: 10.1017/S0021859606246069
- Xun, Z., Xu, T., Ren, B., Zhao, X., Quan, Z., Bai, L., et al. (2022). Nitrogen fertilization of lawns enhanced soil nitrous oxide emissions by increasing autotrophic nitrification. *Front. Environ. Sci.* 10. doi: 10.3389/fenvs.2022.943920
- Yang, T., Jiang, J., He, Q., Shi, F., Jiang, H., Wu, H., et al. (2025). Impact of drainage on peatland soil environments and greenhouse gas emissions in northeast China. *Sci. Rep.* 15, 8320. doi: 10.1038/s41598-025-92655-9
- Yoon, S., Song, B., Phillips, R. L., Chang, J., and Song, M. J. (2019). Ecological and physiological implications of nitrogen oxide reduction pathways on greenhouse gas emissions in agroecosystems. *FEMS Microbiol. Ecol.* 95:fiz066. doi: 10.1093/femsec/fiz066
- Zhai, L., Liu, H., Zhang, J., Huang, J., and Wang, B. (2011). Long-term application of organic manure and mineral fertilizer on N₂O and CO₂ emissions in a red soil from cultivated maize-wheat rotation in China. *Agric. Sci. China* 10, 1748–1757. doi: 10.1016/S1671-2927(11)60174-0
- Zhang, L., Hou, L., Guo, D., Li, L., and Xu, X. (2017a). Interactive impacts of nitrogen input and water amendment on growing season fluxes of CO₂, CH₄, and N₂O in a semiarid grassland, northern China. *Sci. Total Environ.* 578, 523–534. doi: 10.1016/j.scitotenv.2016.10.219
- Zhang, W., Pan, Y., Wen, F., Fu, J., Hao, Y., Hu, T., et al. (2024). Extreme drought with seasonal timing consistently promotes CH₄ uptake through inconsistent pathways in a temperate grassland, China. *J. Arid Land* 16, 768–778. doi: 10.1007/s40333-024-0017-z
- Zhang, Z., Yu, Z., Zhang, Y., and Shi, Y. (2021). Finding the fertilization optimization to balance grain yield and soil greenhouse gas emissions under water-saving irrigation. *Soil Tillage Res.* 214, 105167. doi: 10.1016/j.still.2021.105167
- Zhang, Y., Zhang, X., Liu, X., Li, L., Zhang, S., Huang, S., et al. (2017b). Carbon footprint of grain production in China. *Sci. Rep.* 7, 1–11. doi: 10.1038/s41598-017-04182-x
- Zong, M., Yang, X., Sanz-Cobena, A., Jørgensen, U., Butterbach-Bahl, K., and Abalos, D. (2025). Reductions in nitrous oxide emissions in diverse crop rotations linked to changes in prokaryotic community structure. *Agric. For. Meteorology* 362, 110370. doi: 10.1016/j.agrformet.2024.110370