Field Crops Research xxx (xxxx) 108715

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Enhancing resource use efficiency of alfalfa with appropriate irrigation and fertilization strategy mitigate greenhouse gases emissions in the arid region of Northwest China

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ARTICLE INFO

Keywords:
Greenhouse gases emissions
Yield-scaled emissions
Nitrogen use efficiency
Nitrogen cycling
Supplemental irrigation

ABSTRACT

Context: With the increasing global warming concerns, appropriate agronomic practices for improving crop yields while reducing greenhouse gases (GHGs) emissions are essential for sustainable agricultural production. However, little information is available if these benefits can be achieved simultaneously in arid pastoral agriculture systems with irrigation and nitrogen (N) management.

Research question: We assumed that the local practiced irrigation (600 mm) and N (300 kg ha^{-1}) applications for spring wheat in the arid regions of Northwest China are excessive, and optimizing irrigation-N rates would improve the resource use efficiency of alfalfa and reduce GHGs emissions.

Methods: A two-year field study (2015–2016) was conducted to investigate the effects of irrigation regimes (I_L, 300 mm; I_M, 450 mm; and I_H, 600 mm) and N application rates (F_0, 0; F_L, 150; F_M, 225; and F_H, 300 kg ha^{-1}) on forage yield, resource use efficiency, and GHGs emissions from alfalfa fields. The GHGs emissions during alfalfa growing seasons were assessed by analyzing gas samples using the static chamber-gas chromatography method.

Results: High irrigation and N application (I_HF_H) was associated with elevated GHGs emissions, global warming potential, and greenhouse gas intensity, but lower irrigation water productivity (IWP) and partial factor productivity of N (PFP_N). Reducing the irrigation and N rates decreased the GHGs emissions but differently affected alfalfa yield and resource use efficiencies. Among all the treatments, I_MF_L and I_HF_L resulted in the highest alfalfa yields, IWP, and PFP_N. However, I_MF_L showed a good trade-off between yield benefits and environmental performance manifested by lower GHGs emissions, GWP, and GHGI. The I_MF_L reduced the cumulative emissions of nitrous oxide by 67.83% and 67.16%, carbon dioxide by 31.05% and 34.60%, GWP by 61.72% and 70.40%, and GHGI by 74.37% and 79.78%, while increased alfalfa yield by 49.24% and 46.45%, IWP by 99.05% and 94.97%, and PFP_N by 198.44% and 192.90% compared to I_HF_H. Regardless of all the treatments, the alfalfa field acted as a CH_4 sink during both crop-growing seasons.

Conclusions: Our results suggest that the application of 450 mm irrigation and 150 kg N ha^{-1} could be used as an appropriate management strategy for enhancing resource use efficiencies and mitigating GHGs emissions, GHGI, and GWP from alfalfa fields.

Significance: The findings can provide an opportunity for greenhouse gas mitigation without alfalfa forage yield reduction following the proper irrigation and fertilization regimes in the arid region of northwest China and areas with similar agro-climatic conditions.

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https://doi.org/10.1016/j.fcr.2022.108715
Received 3 May 2022; Received in revised form 6 October 2022; Accepted 8 October 2022
0378-4290/© 20XX

1. Introduction

In recent decades, drastic global warming caused by unprecedented emissions of greenhouse gases (GHGs) has become a serious environmental concern. Nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) are the major GHGs contributing to global warming (Snyder et al., 2009; Wang et al., 2016). Agriculture is considered a relevant contributor to GHGs emissions and is responsible for approximately 52% and 84% of global CH_4 and N_2O emissions, respectively (Li et al., 2020). Agricultural production must be increased by 70% for the projected 9.1 billion global population by 2050 (Kamran et al., 2018). Given the limited arable land, intensive agricultural production practices are critical for meeting the future food, feed, and fiber demands (Chen et al., 2015; Sapkota et al., 2020). However, the sustained GHGs emissions with intensified agriculture will further impact the global warming and climate change scenarios (Scheer et al., 2013).

In arid and semi-arid regions, supplemental irrigations play a key role in boosting crop production but are inextricably linked with stimulating soil GHGs emissions (Li et al., 2020; Mehmood et al., 2019). Soil moisture is considered a major driver regulating GHGs emissions because it directly governs soil biogeochemical activities and substrate availability (Ghani et al., 2022; Sapkota et al., 2020). Excessive irrigation limit soil aeration and can stimulate denitrification and anaerobic soil organic matter decomposition, resulting in higher N_2O and CH_4 emissions (Oertel et al., 2016). In addition, high irrigation volumes stimulate CO_2 fluxes by increasing plant biomass and soil microbial activity (Scheer et al., 2013). Irrigation events are likely to result in greater soil CO_2 emissions if the soil is less frequently irrigated or receives less precipitation (Sapkota et al., 2020; Zornoza et al., 2016). Recently, an overall shift toward reduced irrigation strategies in several crops has been proposed to mitigate GHGs emissions by optimizing soil nitrogen (N) and carbon (C) turnover (Hou et al., 2020; Li et al., 2018; Zhang et al., 2020). However, the farming systems and climatic conditions are highly diverse, and the concept of reduced irrigation for sustainable crop productivity and GHGs mitigation necessitates a site-specific implementation strategy.

Nitrogen fertilizers regulate soil NO_3^--N and NH_4^+-N reserves, which are the essential N pools taken up by plants. However, excessive fertilization decreases N use efficiency (Chen et al., 2015) and increases N losses, with potential negative impacts on the environment, ecosystem functions, and biodiversity (Abalos et al., 2014; Millar et al., 2018). The overuse and misuse of N fertilizers in China have increased environmental pollution in terms of higher N_2O emissions (Lyu et al., 2019; Ning et al., 2022). An exponential relationship between soil N_2O emissions and N fertilization was observed when the inputs exceeded the optimum rates (Shcherbak et al., 2014), while a reasonable N application did not affect N_2O emissions (Yu et al., 2021). The inhibition of methane monooxygenase enzyme activity with the increase in soil NH_4^+ contents and high osmotic pressure caused by NO_3-N increases CH_4 emissions (Bodelier and Laanbroek, 2004). Instead, the response of soil CO_2 emissions to N fertilizer application is dependent on soil organic matter (Niu et al., 2010). Recent studies have proposed that matching fertilizer inputs to crop yield potential maximizes fertilizer use efficiency, reduces losses, and can mitigate GHGs emissions (Tan et al., 2017; Yu et al., 2021; Zhang et al., 2020).

In general, N fertilizers are considered less important for legume crops because of their potential for atmospheric N fixation. However, symbiotic N_2 fixation and nodulation stability differ based on crop growth periods and soil conditions (Elgharably and Benes, 2021; Hungria and Vargas, 2000). Several studies have shown that supplemental N can promote early crop growth and development during low N fixation (Hannaway and Shuler, 1993), low soil N availability period, seasonal re-greening, and after harvests (Hartwig and Soussana, 2001; He et al., 2018; Raun et al., 1999; Vasileva and Pachev, 2015). With the impressive development of China's dairy industry, forage demand has increased in response to severe protein feed shortages across the country (Hou et al., 2021). To meet the growing forage demands, alfalfa (*Medicago sativa* L.) is widely cultivated in arid and semi-arid regions of Northwest China. However, forage yield and quality of alfalfa are greatly constrained by scarce rainfall, high evaporation, poor soil fertility, and soil salinity in these regions. Soil salinity and water deficit conditions restrict the nodule development and the capacity of biological N_2 fixation (Elgharably and Benes, 2021; Hungria and Vargas, 2000; Sadowsky, 2006), which limits N supply in legumes. Therefore, several studies have shown the potential positive effects of supplemental irrigations and N fertilization to boost alfalfa forage productivity, quality, and profitability in these regions (Sha et al., 2021; Wen et al., 2018; Wu et al., 2020). In addition, multiple alfalfa harvests (4–6) are achieved in each crop season, which removes a relatively large amount of soil moisture and nutrients. Given these conditions, high irrigations and fertilization are prevalent in the local pastoral production system (Hu et al., 2019; Sha et al., 2021). We hypothesized that despite contributing to yield gains, these intensive management practices exacerbate environmental issues and challenges such as rising GHGs emissions. Furthermore, we hypothesized that optimizing the irrigation and N application rates for enhanced resource use efficiency of alfalfa would decrease the resource losses and, therefore, reduce the GHGs emissions in the region. To test these hypotheses, we measured the forage yield, resource use efficiency, and GHGs emissions from alfalfa fields and assessed their relationships under the farmers' conventional management and various levels of reduced irrigations and N application rates. Results of this study would help to seek effective irrigation and N management for achieving sustainable alfalfa yields and high resource use efficiency reconciled with low GHGs emissions in the arid regions of Northwest China.

2. Materials and methods

2.1. Description of the experimental site

Field experiments were conducted in 2015 and 2016 at the Experimental Research Station of Lanzhou University (103° 05 'E, 38° 38' N), located in the Hexi Corridor, Gansu province, China. The research site is an irrigation-dependent oasis with a typically arid continental climate, abundant sunlight, high evaporation, and critically scarce rainfall. The annual sunshine accounts for about 3000 h, and the region enjoys a frost-free period of 175 days. The average annual air temperature and precipitation in the research area were 7.8 °C and 110.7 mm, respectively. The potential annual evapotranspiration reaches 2644 mm. Soil is classified as 'Aridisols' with a sandy loam texture (68% Sand, 23% Silt, and 9% Clay). The top soil layer (0–20 cm) has a pH of 8.5, organic matter of 9.34 g kg^{-1}, total N content of 0.92 g kg^{-1}, available phosphorus of 20.3 mg kg^{-1}, and available potassium of 54.5 mg kg^{-1}. Soil organic matter was determined by Walkley–black method (Nelson and Sommers, 1996), total N contents by the Kjeldahl method (Bremner, 1996), available phosphorous by Olsen method (Zhang et al., 2018), and available potassium by Dirks–Sheffer method (Mehlich, 1953). Air temperature and precipitation during both crop growing seasons were obtained from the local meteorological station and presented in Fig. 1.

2.2. Experimental design and treatments management

Alfalfa stands were established in Fall 2014 with a seeding rate of 22 kg ha^{-1} and row spacing of 20 cm. The experiment was organized in a randomized complete block design with a split-plot arrangement. The irrigation regimes, I_L (300 mm), I_M (450 mm), and I_H (600 mm), were assigned to main plots, and N application rates including F_0 (0 kg ha^{-1}), F_L (150 kg ha^{-1}), F_M (225 kg ha^{-1}), and F_H (300 kg ha^{-1}) as split plots. Overall, the experiment comprised twelve different treatments (I_LF_0, I_LF_L, I_LF_M, I_LF_H, I_MF_0, I_MF_L, I_MF_M, I_MF_H, I_HF_0, I_HF_L, I_HF_M, and I_HF_H), and each treatment had four replicates. The surface irrigations were pro-

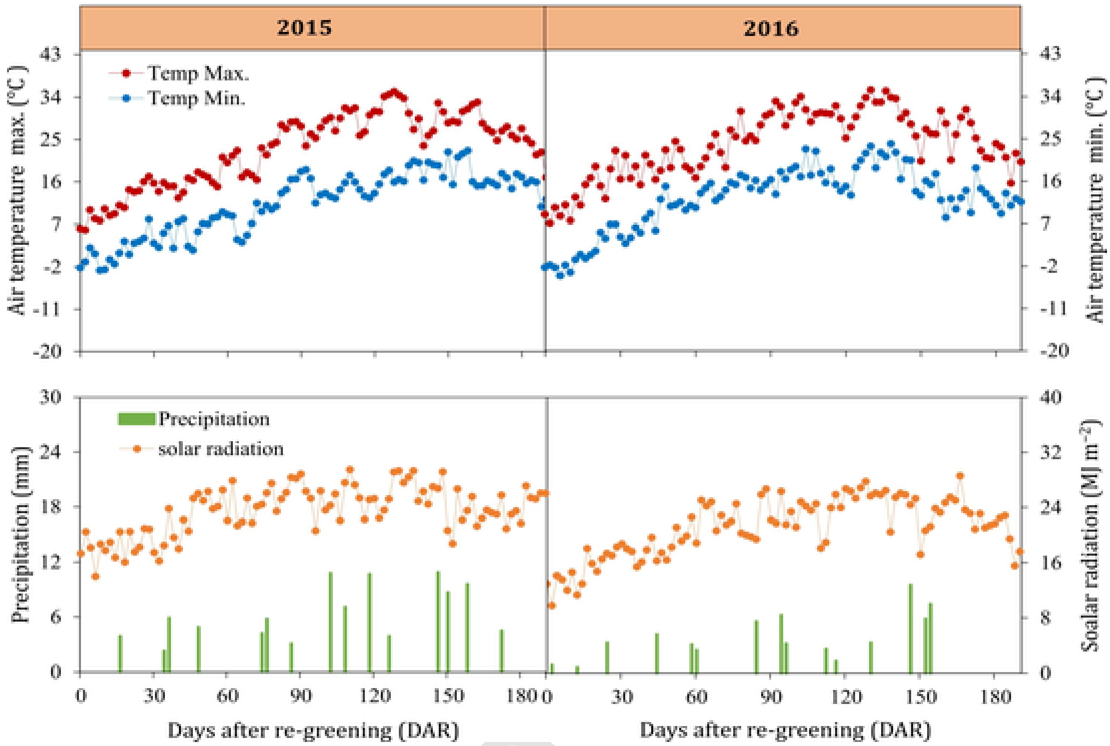

Fig. 1. Daily minimum (min.) and maximum (max.) temperature, rainfall, and solar radiation at the experimental site in 2015 and 2016. The specific date of the year corresponding to days after re-greening (DAR) is presented in Table S1 of supplementary data.

vided at 0 DAR (days after re-greening, 30%), 63 DAR (35%), and 123 DAR (35%). Water flow meters were used to measure the irrigation water applied to each plot. Urea (46% N) was used as the N source and applied in split doses before irrigation events (60% at first irrigation and 40% at second irrigation). Irrigation and N application timings were similar to local farmers' practices. Each treatment plot was 10 m × 10 m (100 m^2), separated by 1.2 m wide isolation belts, and a ridge was placed between plots. The partitioning ridges of each subplot were covered with impervious plastic film membranes to prevent lateral infiltration. Regardless of treatments, all plots were subjected to the same crop management practices, such as weeding and plant protection.

2.3. Soil sampling and analysis

For the determination of soil mineral N contents, four soil samples (0–20 cm) at each sampling interval were collected for each treatment near the gas chambers using a steel corer (3 cm diameter). Each sample was a composite of three subsamples within the treatment plot and represented as a single replicate. Soil samples were passed through a mesh (3.0 mm) and extracted with 2 mol L^{-1} KCl (1:5 soil: solution). The NH_4^+ and NO_3^- contents were determined using a continuous flow analyzer (Auto Analyzer 3, Seal Analytical, UK). Soil sampling dates corresponded to the gas sampling and were used for relating to GHGs emission fluxes (Wang et al., 2016).

Parallel to GHGs sampling, three soil samples (0–20 cm) were taken from each plot with an auger (3 cm diameter) for soil moisture. Moisture contents were evaluated gravimetrically by oven-drying the samples and were expressed as soil water-filled pore spaces (WFPS) using the equation (Zhang et al., 2020):

$$\text{WFPS}(\%) = \frac{\textit{Gravimetric water content } (\%) \times \textit{Soil bulk density}}{1 - \textit{soil bulk density}/2.65} \times 100$$

2.4. Greenhouse gas sampling and measurements

The GHGs fluxes were simultaneously determined in situ using the static chamber-gas chromatography (GC) method (Ning et al., 2020). Soil samplings for GHGs were carried out by using specially-made static chambers. The chamber consists of a rectangular stainless-steel base frame (50 cm width × 50 cm length × 10 cm height), permanently fixed in each plot, and a mobile top cover box (50 cm × 50 cm × 50 cm). Each base has a well-shaped groove (5 cm in depth) at the top and was filled with water to seal the rim of the chamber during sampling. The top cover box was made of stainless frames equipped with circulating fans to ensure gas mixing. The chambers were covered with a sponge and aluminum foil layer to minimize the inside air temperature changes during sampling. The chambers were also equipped with electronic thermometers for measuring the inside air temperature. In general, soil GHGs fluxes were determined once a week, and samplings were intensified twice a week after irrigation, N fertilization, and precipitation events. After placing the chamber on pre-fixed bases, four gas samples were taken within 30 min (0, 10, 20, and 30 min) using a polypropylene syringe (50 mL) fitted with a nylon stopcock from 8:30–11:00 a.m. Samples were immediately transported to the laboratory for analysis, and specific procedures and operating parameters were employed using LGR N_2O Analyzer (908–0015–0000, Los Gatos Research, USA) and LGR CH_4/CO_2 Analyzer (908–0011–0001, Los Gatos Research, USA). The CH_4, N_2O, and CO_2 fluxes were calculated by linear regression slope between concentration and time:

$$J = \frac{dc}{dt} \bullet \frac{M}{V0} \bullet \frac{P}{P0} \bullet \frac{T0}{T} \bullet H \tag{1}$$

Where J is the measured gas of N_2O (μg m^{-2}h^{-1}), CH_4 (μg m^{-2}h^{-1}), and CO_2 (mg m^{-2}h^{-1}), dc/dt is the linear regression slope of gas concentration at the time approaching zero, M is the molar mass of the measured gas (g mol^{-1}), P is the atmospheric pressure (Pa), T is the absolute temperature (K); V0, P0, and T0 are the volume (mL), absolute temperature (K), and pressure (Pa) at standard conditions, H is the height of the chamber (cm).

The cumulative N_2O, CH_4, and CO_2 fluxes (kg ha^{-1}) were estimated following the equation (Afreh et al., 2018):

$$C \quad = \sum_{i=1}^{n} \left(F_{i+1} + F_i\right)/2 \times \left(t_{i+1} - t_i\right) \times 24 \tag{2}$$

Where C is the cumulative GHG emissions (N_2O, CH_4, and CO_2) during the whole crop growing period, F is the daily flux values of gases emissions (N_2O, CH_4, and CO_2), i is the ith measurement, (t_{i+1}-ti) is the number of days between two adjacent measurements, and n is the total number of measurements.

2.5. Global warming potential and greenhouse gas intensity

Global warming potential (GWP) is an indicator used for assessing the potential effects of GHGs on global warming. The GWP (kg CO_2-eq ha^{-1}) was calculated based on the default GWP values per unit mass of N_2O (265 times) and CH_4 (28 times) measured over a 100-year time frame that of CO_2 emissions (IPCC, 2013):

$$\mathrm{GWP} = 265 \times Y_{N_2O} + 28 \times Y_{CH_4} \tag{3}$$

Where Y_{N2O} is the cumulative N_2O emissions (kg ha^{-1}), and Y_{CH4} is the cumulative CH_4 emissions (kg ha^{-1}).

Greenhouse gas intensity (GHGI) is a comprehensive indicator of environmental and economic benefits and represents the GHGs balance per unit of crop productivity (hay yield for alfalfa). The GHGI (kg CO_2-eq t^{-1}) was calculated using the following equation (Afreh et al., 2018):

$$\mathrm{GHGI} = \frac{GWP}{\mathrm{Totalyield}} \tag{4}$$

Where GWP is the global warming potential, and total yield is the seasonal cumulative alfalfa forage yield (t ha^{-1}).

2.6. Calculation of irrigation water productivity

The irrigation water productivity (IWP, kg m^{-3}) was calculated as the ratio of alfalfa hay yield (kg ha^{-1}) to the total amount of irrigation water applied (m^{-3}).

$$\mathrm{IWP} = \frac{Alfalfa \quad hay \quad yield}{Amount \quad of \quad irrigation \quad applied} \tag{5}$$

2.7. Calculation of partial productivity factor of nitrogen

The PFP_N for N fertilizer (kg kg^{-1}) is defined as the ratio of crop yield (hay yield for alfalfa) per unit of N fertilizer applied and calculated as follows (Tan et al., 2017):

$$\mathrm{PFP}_N = \frac{Alfalfa \quad hay \quad yield}{Amount \quad of \quad N \quad fertlizer \quad applied} \tag{6}$$

2.8. Determination of alfalfa forage yield

Alfalfa was harvested during the early bloom period (10% blooming), and a total of six harvests were obtained in both growing seasons. The schedule for each harvest is provided in Table S1. At each harvest, three representative quadrats (1 m × 1 m) were randomly selected at the centre of each plot and clipped to a height of about 5 cm to determine alfalfa productivity. Forage dry biomass was determined after oven-drying the samples at 75 °C. Hay yield was calculated on a dry matter basis.

2.9. Statistical analysis

Data in figures and tables are presented as the mean of four replicates ± SD (n = 4). Analysis of variance (ANOVA) was performed with SPSS 20.0 (IBM Corp., USA) to determine the effects of irrigation, nitrogen, and their interaction on alfalfa yield, IWP, PFP_N, GHGs, GWP, and GHGI. Treatment means were compared using Tukey's significant difference test at $P < 0.05$ and $P < 0.01$. Datasets were tested for normality (Shapiro-Wilk's Normality Test) and equality of error variance (Levene's test) before statistical analysis. Relationships of GHGs with environmental variables and resource use efficiency (IWP and PFP_N) of alfalfa under different years were checked for normality, and linear and nonlinear regression analyses were performed. Figures were constructed using Excel 2010 (Microsoft Corp., USA) and Origin 9.1 (Origin Lab Corp., USA).

3. Results

3.1. Precipitation and temperature

Alfalfa crop received about 94.2 and 49.3 mm of rainfall during the first and second crop growing seasons (Fig. 1), accounting for 78.2% and 65.3% of the total annual rainfall in 2015 and 2016, respectively. About 68% of rainfall was less than 5 mm, too little to be effectively utilized by crops. Monthly mean air temperatures were comparable in both alfalfa-growing seasons, except for July to September 2016, when mean temperatures were relatively higher than in 2015. During the alfalfa growing seasons, daily mean air temperature ranged from 1.9 °C to 26.5 °C in 2015 and 2.2–29.4 °C in 2016 (Fig. 1).

3.2. Soil moisture and inorganic N content

During both alfalfa-growing seasons, the dynamics of soil moisture (expressed as WFPS) showed several drying–wetting cycles following irrigation events. In general, the WFPS values remained higher for several days after irrigation events and then declined gradually within each irrigation cycle (Figure S1). The WFPS increased with the irrigation amounts, and I_H treatment maintained the highest WFPS values during both alfalfa-growing seasons compared to I_L and I_M treatments. On the other hand, WFPS was lower for low, and medium N fertilized plots compared to high fertilized plots under each irrigation level. The variations among treatments were more distinct from 12 to 35 days after each irrigation event (Figure S1).

Soil inorganic N contents showed comparable seasonal dynamics during both alfalfa growth seasons. Soil NO_3^- in the top 20 cm soil profile ranged between 6.33 and 24.66 mg $kg^{-1,}$ and NH_4^+ contents ranged from 2.05 to 13.69 mg kg^{-1} during 2015 and 2016, respectively (Figure S2 and S3). Irrigation and N fertilization events improved soil inorganic N concentration, and maximum NO_3^- contents were observed during 12–18 DAR and 69–75 DAR for all treatments (Figure S2). High irrigation and N fertilizer rates maintained greater NO_3^- contents for a longer period. However, NH_4^+ contents were higher at low irrigation and N fertilizer rate and tended to decrease with the increase in irrigation levels at various sampling intervals during alfalfa growing seasons (Figure S3).

3.3. Seasonal pattern and cumulative N_2O emissions

Seasonal dynamics of N_2O emissions fluxes showed a clear pattern following the irrigation and N application events, and two peak fluxes were observed during each alfalfa-growing season (Fig. 2). The first N_2O peak fluxes (116.54–134.08 μg m^{-2} h^{-1}) were achieved at 12 DAR, and the second peak fluxes (146.48–154.51 μg m^{-2} h^{-1}) at 69 DAR in response to N fertilizer application following irrigations at re-greening and 63 DAR, respectively. Irrigation alone at 123 DAR showed little ef-

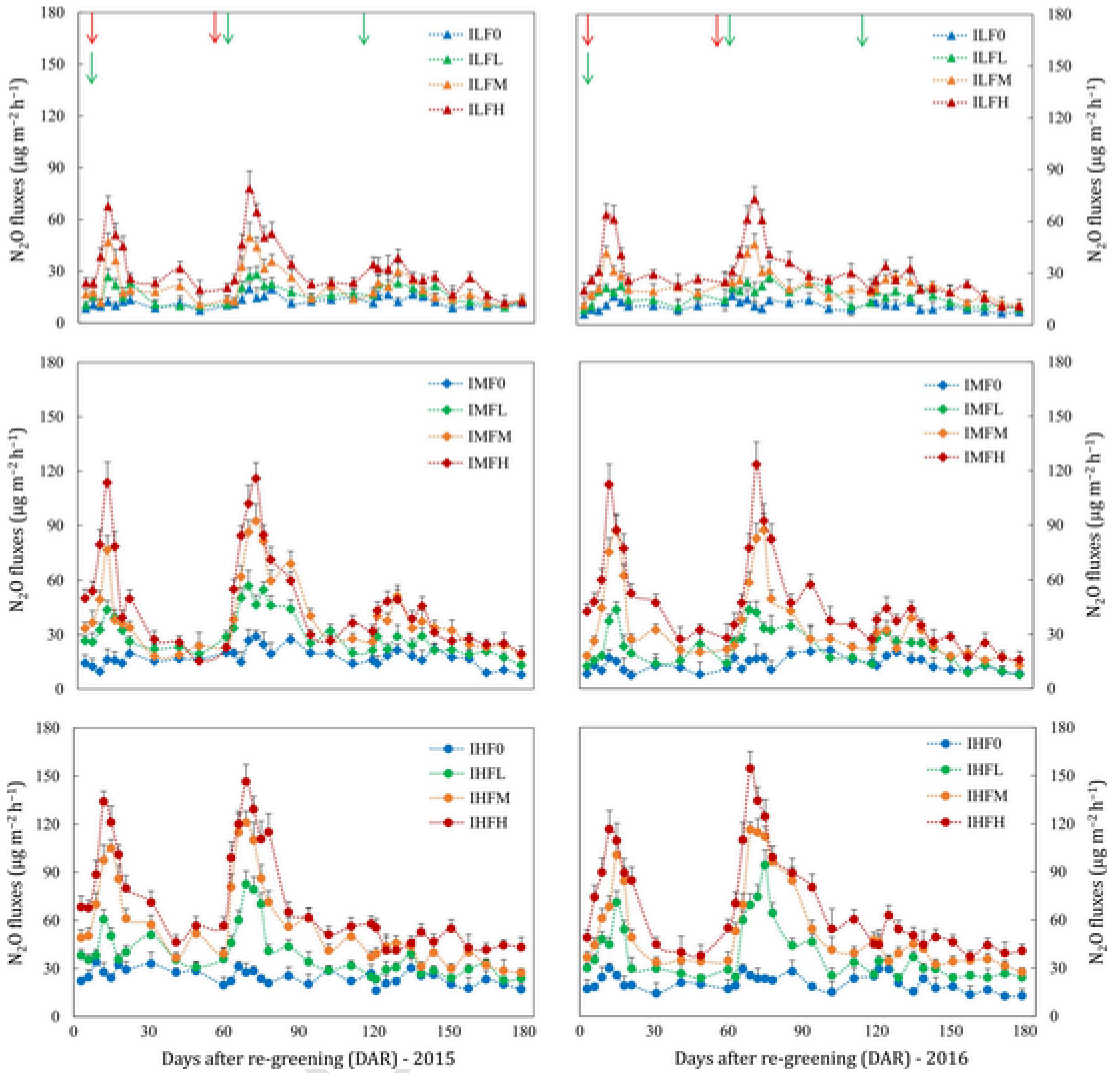

Fig. 2. Effects of different irrigation (I) and nitrogen (F) treatments on seasonal dynamics of soil N_2O fluxes during alfalfa-growing period in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Red and green arrows indicate fertilization and irrigation events, respectively. I_L, I_M, and I_H represent irrigation amounts of 300, 450, and 600 mm, while F_0, F_L, F_M, and F_H represent nitrogen application rates of 0, 150, 225, and 300 kg ha^{-1}, respectively.

fect on stimulating N_2O emissions fluxes during the later crop growing period (Fig. 2).

Cumulative N_2O emissions were significantly affected by irrigation regimes (I), N application rates (F), and their interaction (I × F) (Fig. 3). Cumulative N_2O emissions showed an increasing trend with the increase in irrigation and N application rates, and the highest emissions were achieved for I_H (1.93 and 1.79 kg ha^{-1}) and F_H (1.96 and 1.92 kg ha^{-1}) treatments in 2015 and 2016, respectively (Fig. 3). Regarding the interactive effects, the increase in N application rate under each irrigation regime increased the cumulative N_2O emissions, and the highest emissions were achieved for I_HF_H (2.86 and 2.71 kg ha^{-1}), followed by I_HF_M (2.25 and 2.12 kg ha^{-1}) treatment. The lowest emissions were perceived for I_LF_0 (0.50 and 0.46 kg ha^{-1}), I_LF_L (0.67 and 0.69 kg ha^{-1}), I_MF_0 (0.73 and 0.57 kg ha^{-1}), and I_MF_L (0.92 and 0.89 kg ha^{-1}) treatments in 2015 and 2016, respectively (Fig. 3). The N_2O emissions for I_LF_0, I_LF_L, I_MF_0, and I_MF_L treatments were decreased by 82.5% and 83.0%, 76.6% and 74.5%, 74.5% and 79.0%, 67.8% and 67.2% compared to I_HF_H in 2015 and 2016, respectively.

3.4. Seasonal pattern and cumulative CH_4 uptake

The alfalfa field acted as a CH_4 sink throughout the experimental period, indicated by negative CH_4 values (Fig. 4). Following each irrigation event, CH_4 sink fluxes appeared, but these fluxes were reduced in magnitude with the increase in N fertilizer amounts. The highest CH_4 fluxes were perceived at 15 DAR (−47.40 and −50.47 μg m^{-2} h^{-1}), 72 DAR (−60.96 and −62.96 μg m^{-2} h^{-1}), and 139 DAR (−43.84 and −49.95 μg m^{-2} h^{-1}) following the effects of irrigation and fertilization events at re-greening, 63 DAR, and 123 DAR, respectively (Fig. 4).

The average cumulative CH_4 uptake in 2015 was lower by 10.28% than in 2016. The cumulative CH_4 uptake increased linearly with the increase in irrigation amounts, and the highest uptake was observed for I_H treatment (−1.21 and −1.29 kg ha^{-1}), followed by I_M (−1.13 and −1.20 kg ha^{-1}) in 2015 and 2016, respectively (Fig. 5). On the contrary, CH_4 uptake linearly decreased with the increase in N application rates, and the values were less negative at higher N rates (Fig. 5). Among the irrigation and N combined effects, the highest CH_4 uptake was observed for I_HF_0 (−1.52 and −1.59 kg ha^{-1}), followed by I_MF_L (−1.28 and −1.37 kg ha^{-1}), and I_HF_L (−1.29 and −1.36 kg ha^{-1}); while the lowest uptake was observed for I_LF_H (−0.81 and −0.93 kg ha^{-1}), I_MF_H (−0.91 and −0.98 kg ha^{-1}), and I_HF_H (−0.92 and −1.04 kg ha^{-1}) treatments in 2015 and 2016, respectively (Fig. 5).

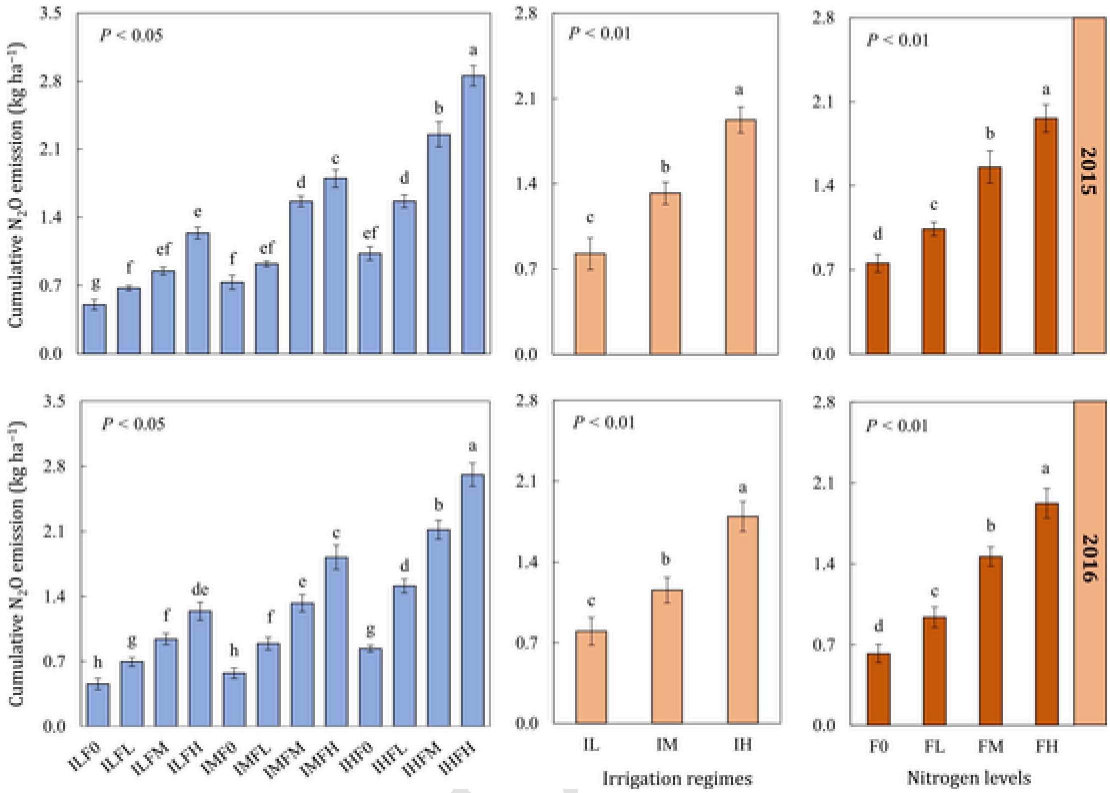

Fig. 3. Effects of different irrigation (I) and nitrogen (F) treatments on cumulative N_2O emissions in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Error bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test (at $P < 0.05$). Treatments abbreviations are similar to those described in Fig. 2.

3.5. Seasonal pattern and cumulative CO_2 emissions

Unlike other GHGs, CO_2 fluxes followed a distinct pattern during alfalfa growing seasons. Initially, CO_2 fluxes remained lower from 0 to 59 DAR but sharply increased and reached peak fluxes at 72–78 DAR (680.43 –702.50 mg m^{-2} h^{-1}) following the effect of the second irrigation and N application (Fig. 6). Thereafter, CO_2 emissions fluxes declined gradually in all treatments until 119 DAR. However, after the third irrigation, CO_2 fluxes increased and reached the second peak curve at 139–144 DAR (624.23–668.45 mg m^{-2} h^{-1}) (Fig. 6).

Irrigation regimes and N application rates significantly affected the cumulative CO_2 emissions in both years. The cumulative CO_2 emissions increased significantly with the increase in irrigation and N application rates, and the highest emissions were achieved for I_H (16146 and 15343 kg ha^{-1}) and F_H (17100 and 16507 kg ha^{-1}) treatments in 2015 and 2016 (Fig. 7). The differences in CO_2 emissions between I_L and I_M treatments were lower than I_H, even non-significant in 2016. The interaction effect of irrigation and N was also significant in both years. At each irrigation regime, increasing N rates linearly increased the CO_2 emissions, and I_MF_H (17075 and 16541 kg ha^{-1}), I_HF_M (17438 and 16217 kg ha^{-1}), and I_HF_H (18856 and 18452 kg ha^{-1}) treatments resulted in the highest emissions in 2015 and 2016, respectively. The lowest CO_2 emissions were achieved for I_LF_0 (10588 and 11043 kg ha^{-1}), I_LF_L (11154 and 11905 kg ha^{-1}), and I_MF_L (13002 and 12567 kg ha^{-1}), respectively (Fig. 7).

3.6. Global warming potential and greenhouse gas intensity

Irrigation regimes, N rates, and their interaction significantly (P < 0.01) affected the GWP in both years (Table 1). The GWP values were significantly increased by irrigation and N application, and the higher the application rates, the greater were GWP values obtained (Table S2). Among the irrigation and N interactive effects, the greatest GWP values were achieved for I_HF_H (731.13 and 688.56 kg ha^{-1}) and I_HF_M (566.92 and 528.79 kg ha^{-1}) treatments (Table 1). Conversely, reducing the irrigation and N application rates decreased the GWP, and the lowest values were achieved for I_LF_0 (101.05 and 86.62 kg ha^{-1}) and I_LF_L (146.34 and 151.82 kg ha^{-1}) in 2015 and 2016, respectively.

The GHGI was significantly affected by the irrigation and N regimes and their interactions (Table 1). In 2015, no significant difference in GHGI was observed between I_L (13.18 kg t^{-1}) and I_M (13.68 kg t^{-1}) treatments, but the GHGI was significantly increased at a high irrigation rate (I_H, 21.34 kg t^{-1}). In 2016, the GHGI initially decreased with increasing irrigation amount from I_L (15.47 kg t^{-1}) to I_M (13.40 kg t^{-1}) but increased again for I_H (20.51 kg t^{-1}) (Table S2). On the other hand, the GHGI values linearly increased with the N application rate, and the highest values were obtained for F_H treatment (28.07 and 31.72 kg t^{-1}) in 2015 and 2016, respectively (Table S2). Among irrigation and N combined effects, the highest GHGI values were obtained for I_HF_H (38.43 and 38.41 kg t^{-1}), I_HF_M (26.19 and 25.20 kg t^{-1}), and I_MF_H (22.12 and 29.06 kg t^{-1}), while the lowest values were achieved for I_LF_L (9.01 and 11.49 kg t^{-1}) and I_MF_L (9.85 and 7.77 kg t^{-1}) treatments in 2015 and 2016, respectively (Table 1). The GHGI values for I_MF_L treatment were almost similar to or lower than that of no fertilizer application treatments under different irrigation regimes (I_LF_0, I_MF_0, and I_HF_0).

3.7. Alfalfa hay yield

Results indicated significant (P< 0.01) effects of the irrigation, N fertilization, and their interactive effects on alfalfa forage yield (Fig. 8). The mean forage yield of all treatments in 2015 was 10.5% greater than that in 2016. Among the irrigation treatments, maximum forage yield was achieved for I_M (23.28 and 20.42 t ha^{-1}) and I_H (22.34 and 21.44 t ha^{-1}) treatments in 2015 and 2016, respectively (Fig. 8). On the other hand, a low N application significantly increased the alfalfa yield over that of no N application. However, F_M and F_H treatments decreased al-

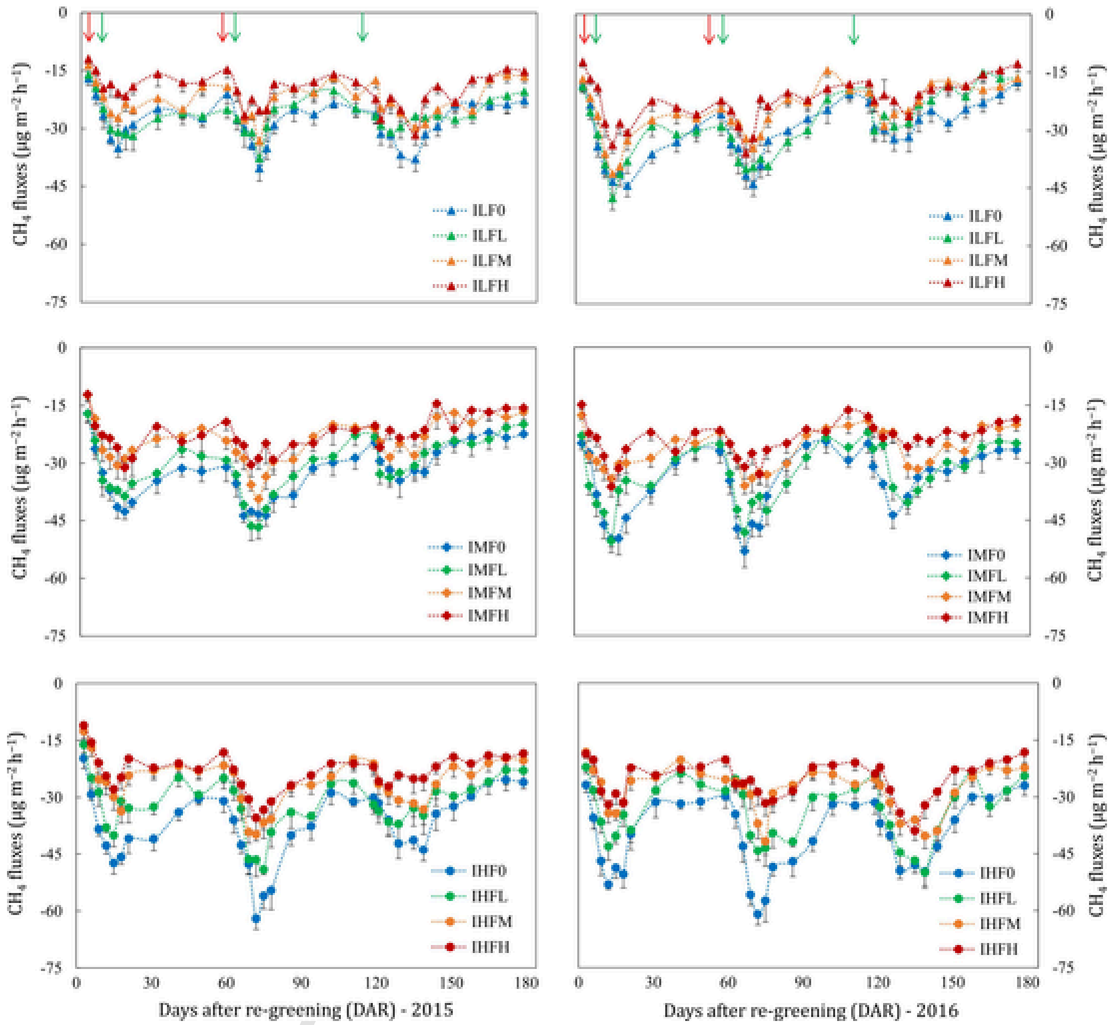

Fig. 4. Effects of different irrigation (I) and nitrogen (F) treatments on seasonal dynamics of CH_4 fluxes during alfalfa-growing period in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Red and green arrows indicate fertilization and irrigation events, respectively. Treatments abbreviations are similar to those described in Fig. 2.

falfa yield compared to the F_L treatment (Fig. 8). Analysis of the irrigation and N interactive effects showed that the highest seasonal yields were achieved with low N application under medium irrigation regime (I_MF_L,128.40 and 26.23 t ha^{-1}) and low N application under high irrigation regime (I_HF_L, 26.23 and 24.96 t ha^{-1}) (Fig. 8). On the other hand, alfalfa yield was decreased by reducing irrigation regimes regardless of N application rates, and the lowest yields were achieved for I_LF_0 (11.93 and 10.78 t ha^{-1}) and I_LF_H (13.56 and 12.04 t ha^{-1}) in 2015 and 2016, respectively.

3.8. *Irrigation water productivity and partial factor productivity of N*

The IWP of alfalfa was significantly ($P < 0.01$) affected by irrigation, N, and their interaction (Table 1). Among the main treatment effects, the IWP initially increased as the irrigation amount increased from I_L to I_M but then significantly declined with the highest irrigation amount (I_H) (Table S2). Notably, the IWP for I_H was lower than that of the I_L in both years. Among N treatments, the highest mean IWP was achieved for F_L treatment which was greater by 33.1% and 23.8% compared to F_0. However, the IWP of F_M and F_H treatments decreased significantly compared to the F_L treatment (Table S2). Among the irrigation and N interactive effects, the highest IWP was achieved for I_MF_L (6.31 and 5.81 kg m^{-3}), followed by I_MF_M (5.48 and 4.44 kg m^{-3}), and I_LF_L (5.41 and 4.40 kg m^{-3}), while the lowest IWP was achieved for I_HF_M (3.61 and 3.50 kg m^{-3}) and I_HF_H (3.17 and 2.99 kg m^{-3}) treatment in 2015 and 2016 (Table 1).

The increase in irrigation amounts increased the PFP_N, owing to greater alfalfa yields, and the highest values were obtained for I_M (122.28 and 105.30 kg kg^{-1}) and I_H (111.46 and 106.49 kg kg^{-1}) treatments in 2015 and 2016 (Table S2). On the contrary, a significant and negative relationship existed between PFP_N and the N application rates. The F_L, F_M, and F_H treatments resulted in PFP_N of 157.42, 91.28, 58.86 kg kg^{-1} in 2015, and 143.14, 80.47, and 50.69 kg kg^{-1} in 2016, respectively (Table S2). The interaction of irrigation and N also had a significant ($P < 0.01$) effect on the PFP_N (Table 1). Among all the treatments, I_MF_L (189.36 and 174.89 kg kg^{-1}) and I_HF_L (174.69 and 166.49 kg kg^{-1}) treatments resulted in the highest PFP_N, while the lowest PFP_N was achieved for I_LF_H (45.21 and 40.12 kg kg^{-1}), I_MF_H (67.92 and 52.23 kg kg^{-1}), and I_HF_H (63.45 and 59.71 kg kg^{-1}) treatments in 2015 and 2016, respectively (Table 1).

3.9. *Relationships of GHGs emissions with resource use efficiency and soil properties*

Soil N_2O emissions fluxes showed significantly ($P < 0.01$) positive relationship with WFPS (R^2 = 0.285), NO_3^- (R^2 = 0.851), and NH_4^+ (R^2 = 0.443) contents during alfalfa growing seasons (Fig. 9). The regression analysis also revealed significant ($P < 0.01$) and negative association of CH_4 fluxes with WFPS (R^2 = 0.259) and NH_4^+ (R^2 =

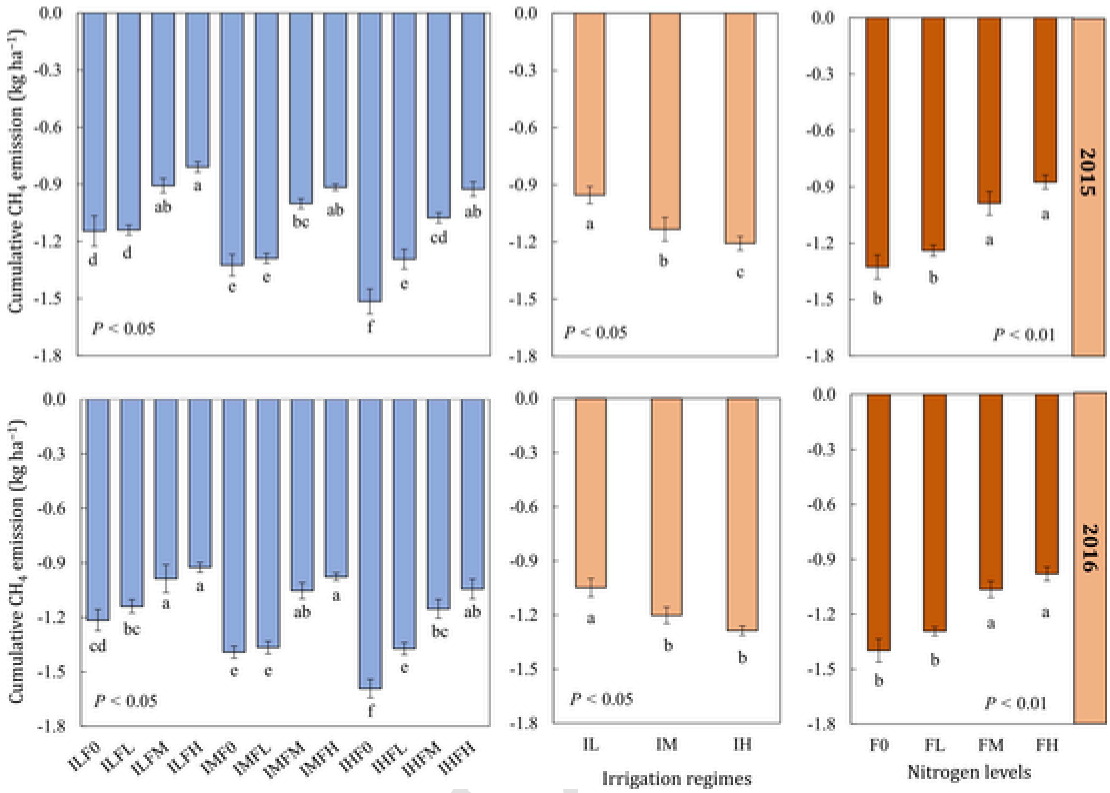

Fig. 5. Effects of different irrigation (I) and nitrogen (F) treatments on cumulative soil CH_4 uptake in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Error bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test (at $P < 0.05$). Treatments abbreviations are similar to those described in Fig. 2.

0.129) contents, but a non-significant ($P > 0.05$) relation with NO_3^- ($R^2 = 0.003$). In addition, CO_2 emissions were negatively associated with WFPS ($R^2 = 0.117$) while positively associated with NO_3^- ($R^2 = 0.182$) (Fig. 9). A non-significant ($P > 0.05$) relation of CO_2 fluxes with NH_4^+ contents ($R^2 = 0.001$) was detected in our study.

Moreover, the regression analyses also depicted a significant decline in GHGs emissions with the increased resource use efficiency (IWP and PFP_N) of alfalfa (Fig. 10). A negative and parabolic relation of N_2O ($R^2 = 0.784$), CO_2 ($R^2 = 0.687$), GWP ($R^2 = 0.508$), and GHGI ($R^2 = 0.503$) with IWP was evident in the present study. In addition, N_2O ($R^2 = 0.279$), CO_2 ($R^2 = 0.208$), and GWP ($R^2 = 0.206$) were negatively and linearly associated with PFP_N, while the GHGI followed a parabolic relation ($R^2 = 0.421$) with the PFP_N (Fig. 10).

4. Discussion

4.1. Effects of irrigation and N fertilization on alfalfa yield

Supplemental irrigation and fertilization are the major determinants for sustaining pastoral agriculture systems in arid and semi-arid regions (Djaman et al., 2020; Hu et al., 2019; Li et al., 2020). Results from the present study revealed greater alfalfa yields at high irrigation amounts, attributed to enhanced water and nutrient acquisitions, greater leaf expansion, and enhanced photosynthetic capacity of alfalfa plants, resulting in greater biomass accumulation (Li and Su, 2017; Xiao et al., 2015). The seasonal alfalfa yields obtained in the present study were the highest among those reported in arid regions of China (Hu et al., 2019; Liu et al., 2021; Sha et al., 2021; Wu et al., 2020). In 2015, rainfall was comparatively high (94.2 mm), therefore, sufficient soil water was available for crop growth, and increasing irrigation amount beyond I_M had no significant effect on increasing alfalfa yield. Whereas precipitation was lower (49.3 mm) in 2016, high irrigation was essential to meet the crop water demands and thus linearly increased alfalfa yield. These results are in agreement with the previous findings that reported a linear relationship between alfalfa yield with irrigation amount in dry regions of China (Li and Su, 2017; Liu et al., 2021). However, Hanson et al. (2008) observed a curvilinear relationship between alfalfa yield and irrigation amounts, while, Djaman et al. (2020) identified a third-order polynomial association. The discrepancy in these studies is most likely due to differences in climatic conditions at the experimental sites, which may have influenced the yield-irrigation relationship.

Literature on the use of N fertilizers in legume crops is debatable, with reports signifying both no significant benefits (Oliveira et al., 2004; He et al., 2018) and positive effects on yields and forage quality (Elgharably and Benes, 2021; Fan et al., 2016; Hungria and Vargas, 2000; Raun et al., 1999; Vasileva and Pachev, 2015). Results from our present study showed positive effects of appropriate N application (150 kg ha^{-1}) on improving alfalfa yields compared to no fertilizer application (F_0). The soil of the research area is characterized by water deficit and salinity (Yang et al., 2020), which greatly hinder nodule development and limit biological N_2 fixation. Therefore, the positive effects of F_L treatment are attributed to the regulation of early plant development at the re-greening stage by using available soil N to avoid the retention of root development, as N assimilation requires less CO_2 and energy than N fixation (Vasileva and Pachev, 2015). Another possible reason could be the beneficial effects of increased plant N uptake on the integrity of leaf chlorophyll contents, regulating the photosynthetic efficiency (Fan et al., 2016; Gao et al., 2020), resulting in higher dry matter accumulation (Miao et al., 2019; Wu et al., 2020). Similar findings of increased forage yield of alfalfa with N application in comparison to no N application have been reported in arid and semi-arid regions of China (Fan et al., 2016; Hu et al., 2019; Sha et al., 2021; Wen et al., 2018). Results also indicated that high N application (225 and 300 kg ha^{-1}) to alfalfa in the region is not conducive to improving alfalfa yields but rather associated with declining N use efficiency and elevating GHGs emissions.

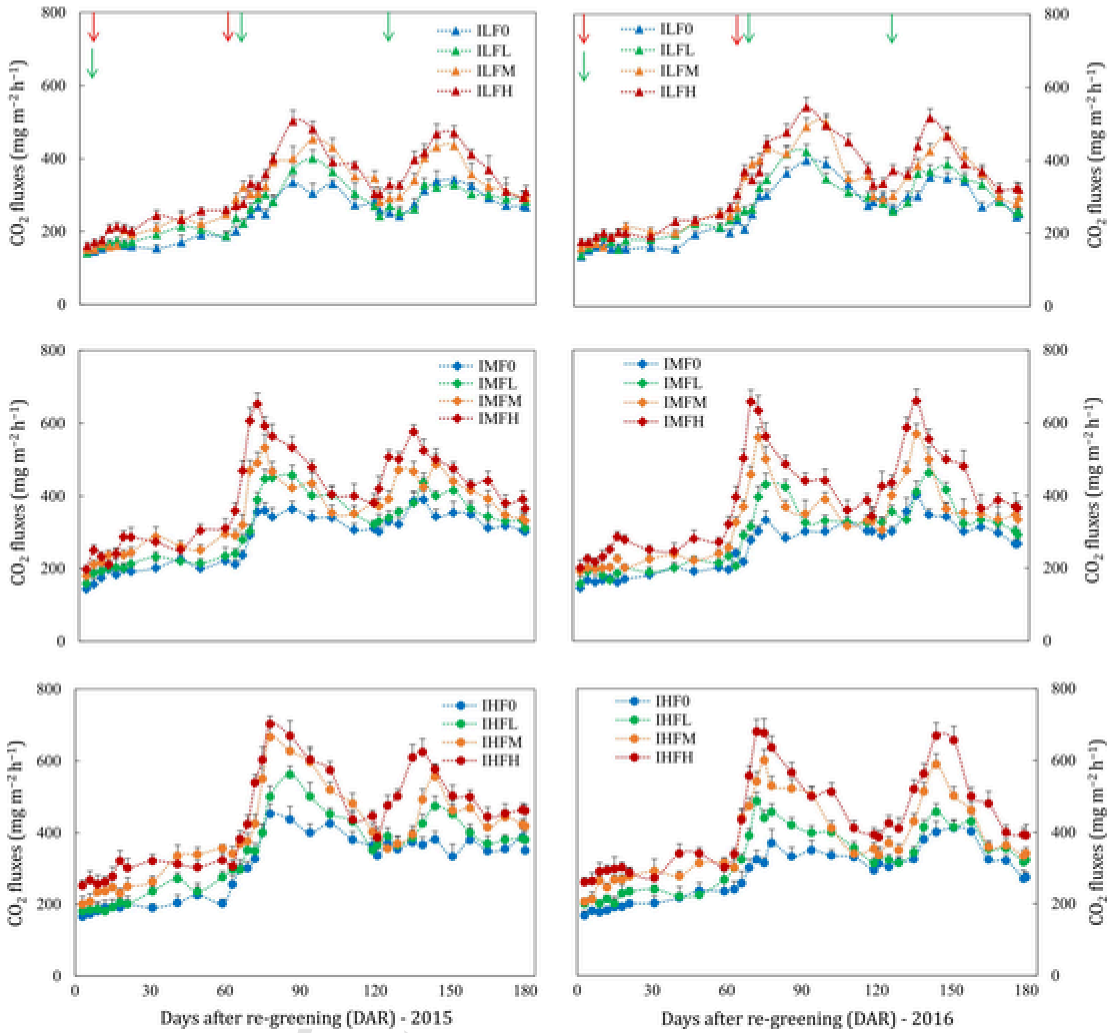

Fig. 6. Effects of different irrigation (I) and nitrogen (F) treatments on seasonal dynamics of soil CO_2 fluxes during the alfalfa-growing period in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Red and green arrows indicate fertilization and irrigation events, respectively. Treatments abbreviations are similar to those described in Fig. 2.

4.2. Effects of irrigation and N fertilization on alfalfa resource use efficiency

The IWP and PFP_N are key determinants for identifying rational irrigation and N management and improving crop economic benefits (Zhang et al., 2020). A greater IWP in 2015 was owed to better crop growing conditions, resulting in higher alfalfa yields than in 2016. Also, our results depicted that I_M treatment had the highest IWP values, while I_H had the lowest values because the yield increase among the two treatments was insignificant, but the degree of water increment was much higher in I_H treatment. Djaman et al. (2020) observed a similar IWP trend with irrigation levels in alfalfa under semi-arid conditions. In our study, the observed IWP values were comparable to previously reported values in arid regions of China (Hu et al., 2019; Liu et al., 2021; Sha et al., 2021). The F_L treatment had the highest PFP_N values among the N treatments, associated with its positive effects on boosting alfalfa yields in both years. A suitable N application promotes root activity and architecture, enhancing resource acquisitions that regulate photo-assimilates distribution in plant aboveground parts (Vasileva and Pachev, 2015), improving yield and resource use efficiencies. The decrease in PFP_N associated with excessive N application (F_M and F_H) was likely due to N-induced adverse effects on root development, reducing the nutrient and water uptake, and as a result, the alfalfa biomass (Oliveira et al., 2004; Xie et al., 2015). A previous study by Hu et al. (2019) reported IWP values of 3.45–5.36 kg m^{-3} and FPF_N values of 102.5–229.8 kg kg^{-1} for alfalfa under different irrigation (480–690 mm) and N application rates (0–180 kg ha^{-1}) in the arid region of north China, with 480 mm irrigation coupled with 180 kg N ha^{-1} resulting in the highest values (IWP, 5.36 kg m^{-3}; FPF_N, 229.8 kg kg^{-1}). Another study showed a range of IWP (2.1–3.8 kg m^{-3}) and FPF_N (24.5–145.3 kg kg^{-1}) for the alfalfa crop, and the highest values were perceived with the application of 600 mm irrigation and 135 kg N ha^{-1} (Sha et al., 2021). The IWP (2.99–6.31 kg m^{-3}) and FPF_N (40.12–189.36 kg kg^{-1}) values achieved in our present study were comparable to the reported values in these studies. However, the highest IWP values (6.31 and 5.81 kg m^{-3}) and FPF_N (189.36 and 174.89 kg kg^{-1}) were achieved with the application of 450 mm irrigation and 150 kg N ha^{-1}. These findings suggest that high irrigation and fertilization of alfalfa in the arid region do not guarantee increased resource use efficiency. Appropriate irrigation-N management, on the other hand, are more conducive to achieving optimal yields while reducing input costs and environmental impacts.

4.3. Effects of irrigation and N application on soil N_2O emissions

In agricultural soils, N_2O is produced as an intermediate during microbial nitrification and denitrification processes, governed by soil moisture (Ruser et al., 2006; Sainju et al., 2012). Results from the pre-

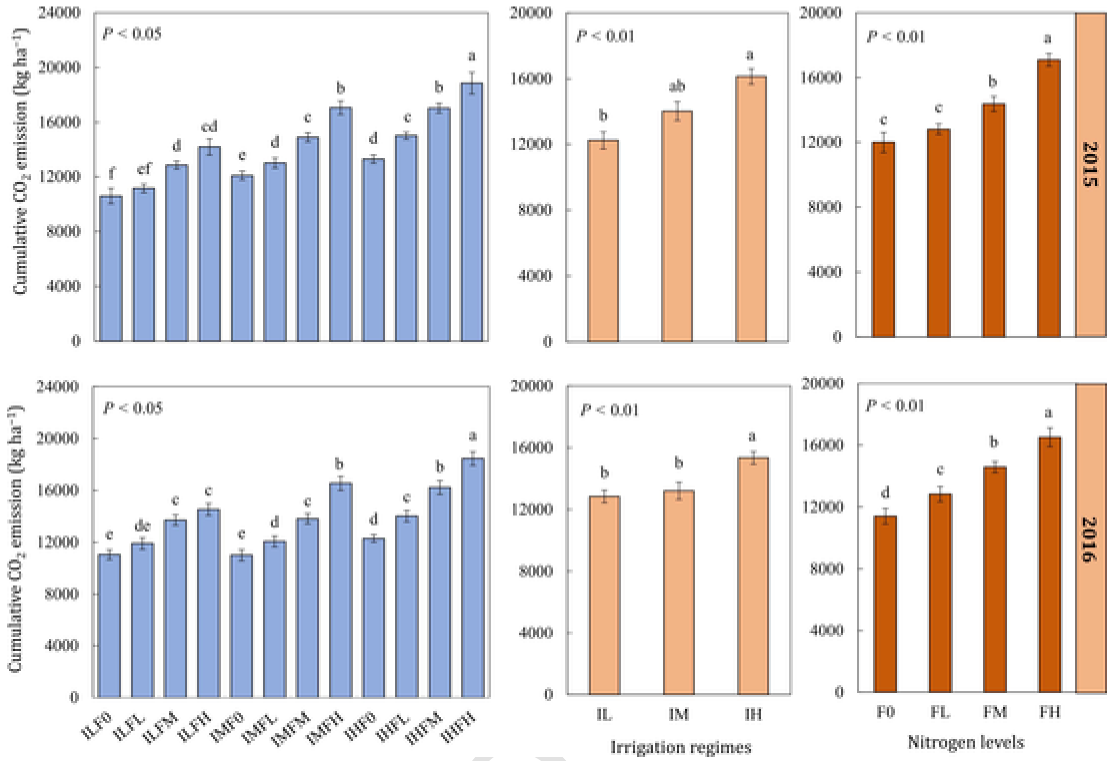

Fig. 7. Effects of different irrigation (I) and nitrogen (F) treatments on cumulative soil CO_2 emissions in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Error bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test (at $P < 0.05$). Treatments abbreviations are similar to those described in Fig. 2.

sent study depicted two distinct N_2O peak fluxes during each alfalfa-growing season, which were directly associated with enhanced soil WFPS (40.8–75.2%) and NO_3^- (14.5–22.6 mg N kg^{-1}) following the irrigation and N application. Interestingly, no distinctive N_2O emissions fluxes were detected following irrigation alone at 123 DAR, which is most likely due to low microbial activity as a result of deficient soil substrate (Schellenberg et al., 2012). Our results indicated that irrigation combined with N results in higher N_2O emissions than irrigation alone, which are consistent with findings from previous studies (Li et al., 2020; Sapkota et al., 2020; Scheer et al., 2008). The linear increase in N_2O emission with increased irrigation regimes is attributed to differences in soil water distribution patterns. Greater soil moisture availability from high irrigation regimes facilitates the formation of anoxic microsites, which are known to promote N_2O emissions, particularly in the presence of NO_3^- (Ruser et al., 2006; Sainju et al., 2012). Excessive irrigation would simultaneously and completely fill a large volume of soil pores, resulting in higher N_2O pulses from wetted soils (Wang et al., 2016). On the other hand, low irrigation regimes leave a large number of unfilled or partially filled pores, resulting in more variable and less intensive N_2O emission pulses (Sapkota et al., 2020; Zhang et al., 2020). These findings highlighted the importance of appropriate irrigation amounts with the potential of reducing N_2O emissions in arid regions by regulating soil aeration and inhibiting denitrification, as corroborated by the previous studies (Abalos et al., 2014; Li et al., 2020; Wang et al., 2016).

Soil inorganic N contents are the major driving forces for microbial N_2O production (Millar et al., 2018; Schellenberg et al., 2012). Our results indicated the N_2O emission pulses were markedly intensified after applying N fertilizer with irrigation. High soil NO_3^- and moisture contents were evident during these emission pulses. These effects lasted for about two weeks after fertilization and irrigation events. The results were further validated by a significant and positive relationship of N_2O emissions fluxes with NO_3^- contents (R^2 = 0.851) and NH_4^+-N (R^2 = 0.443), which has also been confirmed across various N-managed soils (Li et al., 2020; Ning et al., 2022; Tan et al., 2017; Yu et al., 2021). The difference in cumulative N_2O emissions between F_0 and F_L was lower than that of F_M and F_H treatments. This could be attributed to efficient soil N utilization by alfalfa crops, leaving little substrate for microbial activity (Lyu et al., 2019; Scheer et al., 2013, 2008). A negative correlation between PFP_N and soil N_2O emissions in our study supported these findings. Since the F_M and F_H treatments failed to stimulate alfalfa growth compared to F_L treatment, the absorption and utilization of N decreased, and the leftover soil N reserves supported microbial-nitrification and denitrification (Millar et al., 2018; Tan et al., 2017; Yu et al., 2021), increasing the N_2O emissions. Previously, a global meta-analysis reported that N_2O emission increases exponentially once the N inputs exceed the crop demands (Shcherbak et al., 2014).

4.4. *Effects of irrigation and N application on soil CH_4 emissions*

Agricultural soils act as a source or sink for CH_4 depending on the relative ratios of methanogens and methanotrophs (Ning et al., 2020). In general, soils in well-drained areas act as a net CH_4 sink (Sainju et al., 2012; Tan et al., 2017), which was also evident in our present study. An increase in the cumulative CH_4 uptake with irrigation amounts was likely due to the stimulatory effects of soil moisture on methanotrophs activities (Li et al., 2020; Wang et al., 2016; Zhang et al., 2020). However, a previous study suggested that high irrigation regimes may limit CH_4 uptake by promoting waterlogging or anaerobic soil conditions (Del Grosso et al., 2000) because extreme wet soils restrict atmospheric CH_4 diffusion in croplands (Li et al., 2019). Given the arid climatic conditions of our study's site, soil moisture does not reach the saturation point because of the irrigation intervals and high evapotranspiration rate and does not cause a strict anaerobic condition. Instead, adequate soil moisture with irrigation increases diffusivity and improves soil porosity and air circulation, accelerating methanotrophic CH_4 oxidation (Sapkota et al., 2020). Furthermore, soil organic matter at the study site was relatively low, which may have contributed to CH_4 up-

Table 1
Interactive effects of irrigation (I) and nitrogen (F) treatments on irrigation water productivity (IWP), partial factor productivity of nitrogen (PFP_N), global warming potential (GWP), and greenhouse gas intensity (GHGI) in 2015 and 2016.

Years	Treatments	IWP (kg m^{-3})	PFP_N (kg kg^{-1})	GWP (kg ha^{-1})	GHGI (kg t^{-1})
2015	I_LF_0	3.98 ± 0.22e	NA	101.05 ± 16.07h	8.46 ± 1.22g
	I_LF_L	5.41 ± 0.09b	108.22 ± 4.04c	146.34 ± 6.21g	9.01 ± 0.18g
	I_LF_M	5.10 ± 0.19c	68.04 ± 2.49e	199.15 ± 9.94f	13.01 ± 0.65e
	I_LF_H	4.52 ± 0.15d	45.21 ± 3.62f	305.33 ± 16.98e	22.52 ± 1.37c
	I_MF_0	4.38 ± 0.07d	NA	156.99 ± 12.46g	7.97 ± 0.57g
	I_MF_L	6.31 ± 0.16a	189.36 ± 2.75a	279.87 ± 7.95e	9.85 ± 0.26fg
	I_MF_M	5.48 ± 0.17b	109.54 ± 4.02c	386.33 ± 14.03d	15.67 ± 0.42d
	I_MF_H	4.53 ± 0.22d	67.92 ± 2.84e	450.75 ± 24.03c	22.12 ± 1.03c
	I_HF_0	3.73 ± 0.18e	NA	230.17 ± 20.07f	10.25 ± 0.85f
	I_HF_L	4.37 ± 0.25d	174.69 ± 4.72b	378.25 ± 17.66d	14.45 ± 0.61e
	I_HF_M	3.61 ± 0.16e	96.25 ± 2.93d	566.92 ± 25.22b	26.19 ± 1.41b
	I_HF_H	3.17 ± 0.12f	63.45 ± 4.13e	731.13 ± 27.21a	38.43 ± 1.95a
Variation source					
	I	**	**	**	**
	F	**	**	**	**
	I × F	**	**	**	**
2016	I_LF_0	3.59 ± 0.15de	NA	86.62 ± 9.54i	8.05 ± 0.95f
	I_LF_L	4.40 ± 0.08b	88.03 ± 2.85c	151.82 ± 11.66gh	11.49 ± 0.78e
	I_LF_M	4.45 ± 0.06b	59.36 ± 4.56d	222.25 ± 15.27f	16.64 ± 1.04d
	I_LF_H	4.01 ± 0.15c	40.12 ± 3.63f	303.13 ± 26.62e	25.20 ± 2.48c
	I_MF_0	4.39 ± 0.14b	NA	112.07 ± 14.48h	5.68 ± 0.78g
	I_MF_L	5.81 ± 0.10a	174.89 ± 4.77a	203.84 ± 22.76f	7.77 ± 0.88f
	I_MF_M	4.44 ± 0.07b	88.78 ± 2.02c	322.33 ± 23.28de	16.14 ± 1.28d
	I_MF_H	3.48 ± 0.16d	52.23 ± 4.62e	455.21 ± 15.51c	29.06 ± 1.41b
	I_HF_0	3.65 ± 0.10cd	NA	177.81 ± 7.18g	8.13 ± 0.22f
	I_HF_L	4.17 ± 0.07bc	166.49 ± 5.93b	362.40 ± 18.79d	14.53 ± 0.97de
	I_HF_M	3.50 ± 0.11d	93.28 ± 2.99c	528.79 ± 27.86b	25.20 ± 1.54c
	I_HF_H	2.99 ± 0.09e	59.71 ± 2.09d	688.56 ± 33.37a	38.42 ± 1.29a
Variation source					
	I	**	**	**	**
	F	**	**	**	**
	I × F	**	**	**	**

I_L, I_M, and I_H represent irrigation amounts of 300, 450, and 600 mm, while F_0, F_L, F_M, and F_H represent nitrogen application rates of 0, 150, 225, and 300 kg ha^{-1}, respectively. Data are presented as the means of four replicates ± SD (n = 4). Different lowercase letters within each column represent significant differences among treatment means based on Tukey's significant difference test ($P \leq 0.05$).

take by limiting methanogen activity. In addition, our results suggested that high N fertilization led to reduced soil CH_4 uptake. Several factors such as the reduced activity of methanotrophic bacteria (Sainju et al., 2012), inhibition of enzyme responsible for CH_4 oxidation (Li et al., 2020), high osmotic pressure caused by high NO_3-N concentration (Bodelier and Laanbroek, 2004), toxic inhibition by nitrite and hydroxylamine produced during the nitrification (King and Schnell, 1994), and low pH toxicity (Bradford et al., 2001) may have contributed to decreasing CH_4 uptake with N fertilization.

4.5. Soil CO_2 emissions in response to irrigation and N application

Two possible explanations exist for elevated CO_2 fluxes during the late warmer alfalfa seasons (after 65 DAR). Firstly, a relatively high temperature promotes soil C mineralization (Jia et al., 2021). Secondly, more litter returned to the soil because of multiple alfalfa harvests, resulting in additional soil C inputs and stimulating soil microbial activity and biomass. Both these aspects, with adequate soil moisture as an intermediate factor, are assumed to have played a key role in regulating soil respiration in our study. These results are consistent with previous studies in which irrigation or heavy rainfall increased CO_2 emissions by stimulating microbial activity and root respiration (Abalos et al., 2014; Hou et al., 2020; Scheer et al., 2013). Besides, CO_2 emissions in this study reflect both autotrophic plant root respiration and heterotrophic microbial soil respiration. Therefore, we assume that high irrigation treatments markedly influenced soil respiration by (i) shifting the soil moisture regimes that stimulated heterotrophic soil respiration and (ii) increasing crop productivity, which increases autotrophic root respiration. The effect of N fertilization on CO_2 emissions is because of its impact on microbial development and soil respiration, both dependent on soil organic matter (Li et al., 2020). Perhaps, soil organic matter in the experimental site was lower in 2015, and only high N rates significantly affected CO_2 emissions, while emissions linearly increased with N rates due to relatively high soil organic matter in 2016. These results are consistent with previous findings that N had little effect on increasing CO_2 emissions in low organic matter soils (Niu et al., 2010), but the emissions increase significantly at any N rate in soils with sufficient organic matter (Sainju et al., 2008). Furthermore, urea is decomposed into CO_2 and water when N exceeds the crop demands (Li et al., 2020), which could be another possible reason for elevated CO_2 emissions with high N application rates in our study. At a low N application rate, most of the N is used by plants, leaving little soil residuals and having little impact on CO_2 emissions. These results were further validated by the significant and negative relationship between cumulative CO_2 emissions and PFP_N.

4.6. Response of global warming potential and greenhouse gas intensity to irrigation and N application

The GWP is regulated primarily by the emissions of N_2O and CH_4 (Afreh et al., 2018; Li et al., 2019). Positive GWP values in the present study indicated that alfalfa production systems acted as a net GHG source. High irrigation and N application increased the GWP, signifying both irrigation and N were the major driving forces in regulating GWP. Meanwhile, the contribution of N_2O to the GWP was much higher than that of CH_4, as alfalfa fields acted as CH_4 sinks. These results are consistent with findings from previous studies that identified N_2O as the primary contributor to GWP in dryland conditions because CH_4 consumption exceeded emissions (Li et al., 2020; Lyu et al., 2019). Excessive N fertilization disrupts the N balance between soil supply and plant utilization, leaving higher soil inorganic N residuals and increased N_2O emissions (Yu et al., 2021). In addition, the conventional farmers' practice of high irrigation and N application (I_HF_H) resulted in greater GHGI values. However, optimized irrigation and N application rate (I_MF_L) significantly offset the negative environmental impact and decreased the GHGI values, indicating lower GHGs emissions per kg hay yield of alfalfa compared to farmers' conventional management. The lower GHGI for I_MF_L treatment was attributed to a decrease in GWP due to lower N_2O emissions and higher alfalfa yields. The GWP of I_MF_L treatment was

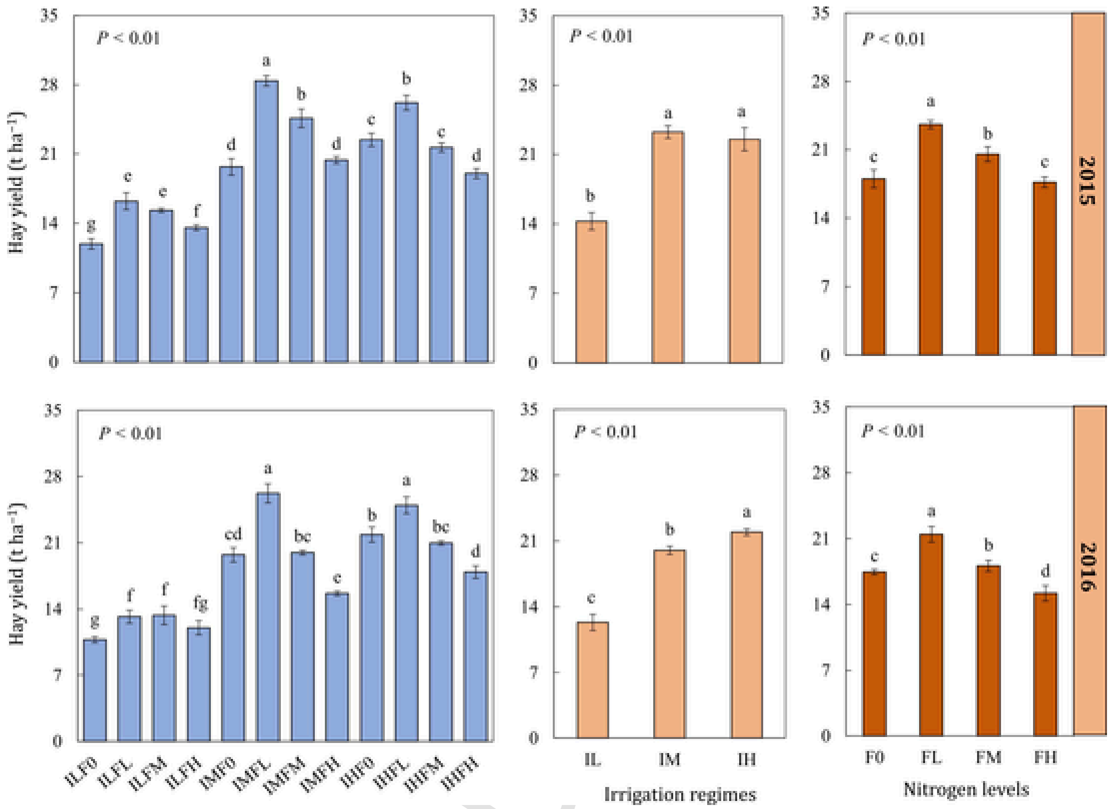

Fig. 8. Effects of different irrigation (I) and nitrogen (F) treatments on alfalfa seasonal hay yield in 2015 and 2016. Data are presented as the means of four replicates ± SD (n = 4). Error bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test (at $P^{<} < 0.01$). Treatments abbreviations are similar to those described in Fig. 2.

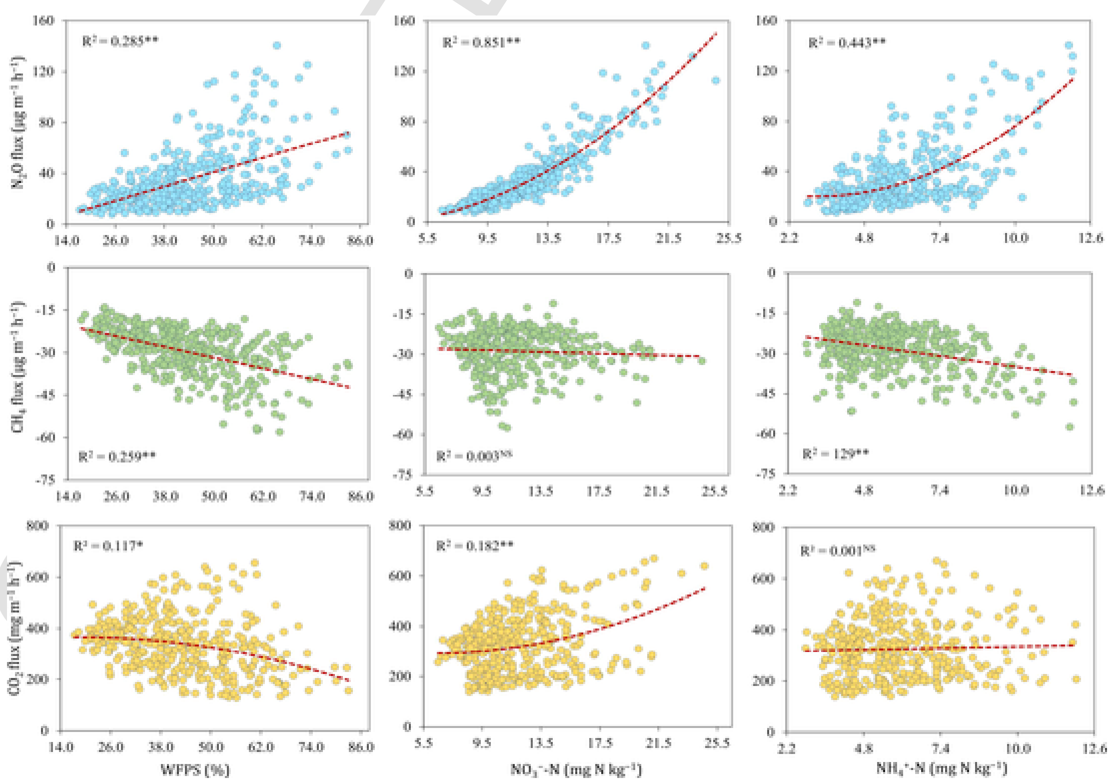

Fig. 9. Relationship of N_2O, CH_4, CO_2, GWP, and GHGI with soil moisture (WFPS) and soil mineral N contents. '* ' and '* *'indicate significance at 0.05 and 0.01 probability level, respectively, and 'NS' denotes non-significance. Each data point is the average value of two years (2015–2016) for irrigation and nitrogen treatments (n = 396).

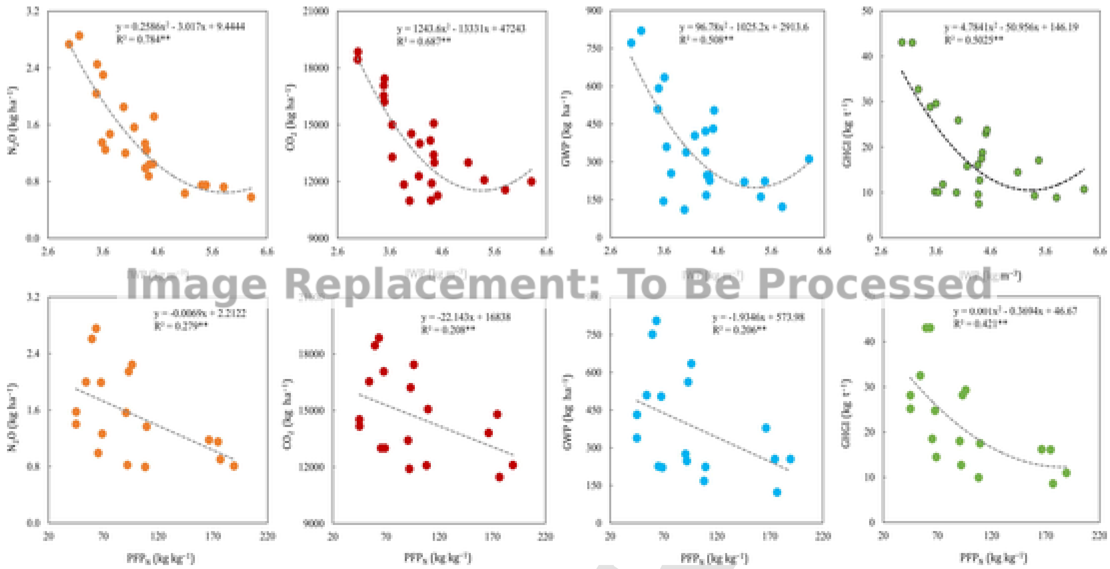

Fig. 10. Relationship of N_2O, CO_2, GWP, and GHGI with the IWP (n = 24) and PFP_N (n = 18). '* *' represent significance at 0.01 probability level

lowered by 61.72% and 70.40%, and GHGI by 74.37% and 79.78% compared to I_HF_H, respectively. Hence, strategies for mitigating GWP in arid regions should focus on reducing N_2O emissions rather than CH_4, and improving crop yields to reduce GHGI. Overall, the negative relationship of GWP and GHGI with IWP and PFP_N indicates that adopting appropriate irrigation and N application would improve the economic benefits of alfalfa production by saving input costs and mitigating the environmental impacts by lowering GWP and GHGI in arid regions of northwest China.

5. Conclusions

Results from this study showed that high irrigation regimes have the potential to boost alfalfa productivity in arid regions but at the cost of high GHGs emissions and low resource use efficiency. On the other hand, low N application was more conducive to promoting alfalfa yields and resource use efficiency with minimal environmental impacts compared to high N application rates. The I_MF_L and I_HF_L were the best treatment combinations that resulted in the highest alfalfa yields and lowered cumulative GHGs emissions. However, I_MF_L resulted in higher IWP and PFP_N, as well as lower GWP and GHGI compared to I_HF_L. Overall, our findings suggest that appropriate irrigation and N management strategy that matches crop demands would reduce GHGs emissions by increasing resource use efficiency without compromising alfalfa productivity in the arid region of northwest China. Nevertheless, the climatic variations in different arid regions, particularly precipitation amounts and soil properties, may significantly influence the relationship between the resource use efficiency and GHGs emissions in different alfalfa growing years, and the optimized irrigation and N management in this study may not be conducive to optimal alfalfa productivity and GHG mitigation in other arid regions. Therefore, future long-term studies are recommended to focus on irrigation and N management strategies in different arid areas with variable precipitation patterns and soil types to better determine how climatic variation affects treatment efficacy on resource use efficiency, alfalfa forage yields, and GHGs emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

The study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA2010010203), the Research Fund for International Young Scientists, National Natural Science Foundation of China (RFIS-32150410361), the Program of National Science and Technology Assistance (KY202002011), the Lanzhou City's Scientific Research Funding Subsidy to Lanzhou University, and the Program for Innovative Research Team of Ministry of Education (IRT_17R50).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108715.

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