

Research Article

Higher Irrigation and Nitrogen Application Coupled with Low Plant Density Increased N₂O Emission from Maize Farmland at the Oasis Area of Northwestern China

Aziiba Emmanuel Asibi^{*1}, Yao Guo³, Zhiwen Gou², Hongwei Yang², Zhilong Fan², Falong Hu², Wen Yin², Xijun Zhang² and Qiang Chai²

¹ Council for Scientific and Industrial Research, Savanna Agricultural Research Institute (CSIR-SARI), Bawku, Ghana

² State Key Laboratory of Arid land Crop Science, College of Agronomy, Gansu Agricultural University, Lanzhou 730070, China.

³ College of Life Sciences, Northwest Normal University, Lanzhou 730070, China.

* Correspondence: Qiang Chai; chaiq@gsau.edu.cn, Aziiba Emmanuel Asibi; aziibason4u@yahoo.com

Article info: -

- Received: 19 August 2025
- Revised: 26 September 2025
- Accepted: 25 October 2025
- Published: 6 November 2025

Keywords:

Crop cultivation; Greenhouse gas; Global warming; Synthetic fertilizers; Environmental sustainability

Abstract:

Farmlands are a major source of nitrous oxide (N₂O) emissions, primarily due to nitrogen fertilizer applications and associated agronomic practices. Appropriate cropping systems that optimize agronomic management are urgently needed to mitigate global warming. A two-year field experiment was conducted in 2018 and 2019 in an oasis irrigation area of Northwestern China to evaluate the effects of nitrogen rate, plant density, and irrigation level on N₂O emissions from maize fields. Treatments included three nitrogen rates (N₀ = 0, N₁ = 270, N₂ = 360 kg N ha⁻¹), three plant densities (D₁ = 75,000, D₂ = 97,500, D₃ = 120,000 plants ha⁻¹), and two irrigation levels (W₁ = 405 mm, W₂ = 324 mm) arranged in randomized complete block design. Results showed that the lowest N₂O emissions occurred under the combination of reduced irrigation (W₂ = 324 mm), moderate or zero nitrogen (N₁ or N₀), and high plant density (D₃ = 120,000 plants ha⁻¹). Conversely, the highest emissions were associated with high nitrogen (N₂ = 360 kg N ha⁻¹), low plant density (D₁ = 75,000 plants ha⁻¹), and high irrigation (W₁ = 405 mm). Overall, N₂O emissions increased with higher irrigation and nitrogen inputs. Strategic optimization of nitrogen application rate, plant density, and irrigation level can significantly reduce N₂O emissions, supporting climate-smart agriculture in arid oasis regions.

1. Introduction

The emission of greenhouse gases (GHGs) is a major driver of global warming and the most significant threat to sustainable agriculture. The Intergovernmental Panel on Climate Change (IPCC) estimates that agriculture contributes 10–12% of the global GHG emissions, and this is projected to rise by half by 2030 (Garnett, 2008). The use of synthetic nitrogen (N) fertilizers in agriculture to meet food demand would escalate GHG emissions. Effective management of nitrogen application, irrigation, and cropping systems may indirectly influence the emission of GHGs contributing to global warming.

For instance, the tier 1 Intergovernmental Panel on Climate Change (IPCC, 2013), default factor suggests that direct N₂O emission arising from mineral N fertilizer usage is 1%; thus, 10 kg N₂O-N is emitted for every ton of N fertilizer used. Estimates reveal that for every 100 units of N used in global agriculture, only 17 units are consumed by humans as food, and the rest are lost to the environment (UNEP and WHRC 2007). Larger N losses from the agricultural system are likely in the future as the human population increases and agricultural production intensifies. Nitrous oxide emission increases when available N exceeds the crop requirements (Oenema et al., 2005; Mosier et al., 2013). The mitigation challenge now is to reduce N₂O emissions per unit of N fertilizer applied and per unit of agricultural product.

Irrigation is a key factor in global crop production which can affect GHG emissions (Lal, 2004). Though irrigation influences on GHG emissions, its potential contribution to nitrous oxide emissions has been less investigated compared to other agronomic activities.

Cropping systems significantly influence GHG emissions and affect the quality and amount of crop residue left over after the cropping season (Moser et al., 2006; Matteucci et al., 2000). A comprehensive evaluation of the impacts of cropping practices on GHG emission per unit yield rather than land area will support mitigation strategies. Maize production is one of the important sources of N consumption in China (Yan et al., 2012; Huang et al., 2015). China is now one of the leading consumers of synthetic nitrogen (N) in the world, largely due to intensive cropping. However, an increase in the use of synthetic N fertilizer does not guarantee an increase in crop productivity due to diminishing returns, but rather an increase in GHG emissions.

A reduction in GHG emissions resulting from synthetic nitrogen (N) application is crucial for mitigating global warming. A two-year experiment was conducted in 2018 and 2019 at the oasis irrigation region of Northwestern China to determine whether reduced or increased irrigation, combined with modifications in plant densities and nitrogen rates, could reduce N₂O emissions.

2. Materials and Methods

The field experiment was conducted at Wuwei Experiment Station of Gansu Agricultural University from April to September in 2018 and 2019 (37° 52'20" N, 102° 50'50" E, and 1776 m a.s.l), located in the eastern part of the Hexi Corridor of Northwestern China. It is a temperate-arid location with an average annual sunshine of 2945 hours and an average annual air temperature of 7.2 °C. It also has an accumulated air temperature of 10 °C greater than 2985 °C and about 197 frost-free days. Average annual precipitation is below 150 mm, with potential evaporation of 2400 mm from 1950 to 2012.

Daily precipitation and air temperature were collected for the experimental site in 2018 and 2019 from the sub-station of Wuwei, 100 m away from the experiment site (Fig. 1).

The soil is classified as an Aridisol, a calcareous desert soil. Maize is the dominant crop cultivated in the area. The previous crop before this experiment was monoculture maize, and the treatments were applied to the same plots in both years. Soil ammonium-N (NH₄-N) and NO₃-N before the start of the experiment in each year are in Table 1.

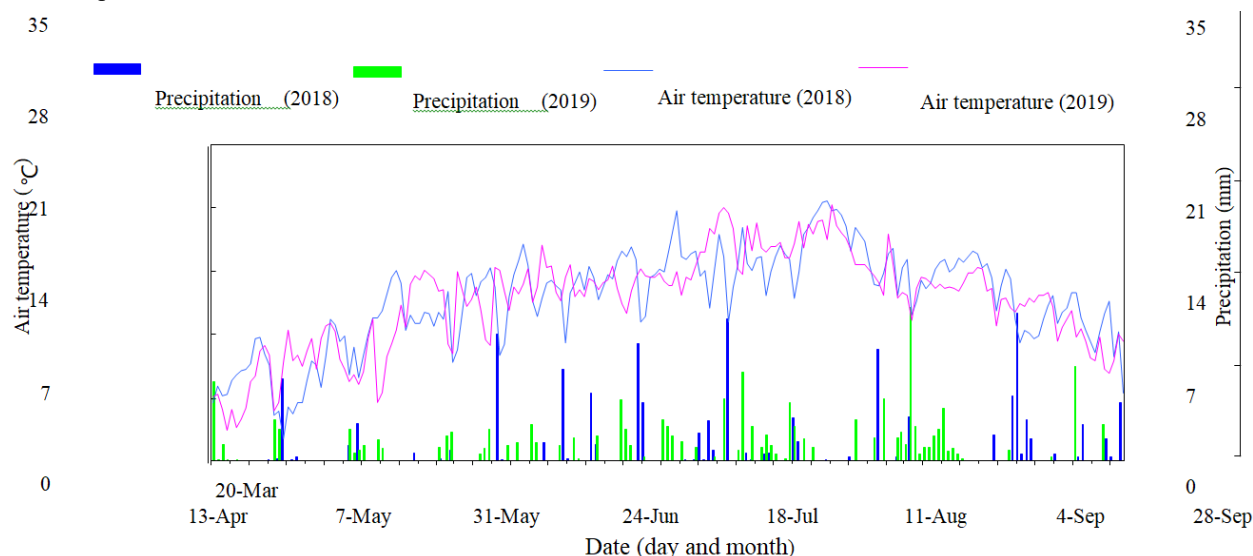


Figure 1. Air temperature and precipitation at the experimental site from March through October in 2018 and 2019.

Table 1. Soil ammonium-nitrogen (NH₄-N) and nitrate-nitrogen (NO₃-N) by soil depth layer before the start of the experiment in April of 2018 and 2019 seasons.

2018 season		
Soil depth (cm)	NH ₄ -N (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)
0–20	10.085	2.665
20–40	10.023	2.747
40–60	10.000	2.575
60–80	10.945	2.558
2019 season		
0–20	10.913	2.242
20–40	10.707	2.993
40–70	10.077	2.567
70–100	10.560	2.820
100–120	10.553	2.420

The experiment was factorial and arranged in a randomized complete block design, and each treatment had a plot size of 7 × 5 m, separated by a distance of 80 cm. There was a 50 cm high ridge between plots to reduce the potential of water movement between plots. The treatments included two irrigation levels (W₁ = 405 mm and W₂ = 324 mm) with three replications, three N fertilizer rates (N₀ = 0 kg N ha⁻¹, N₁ = 270 kg N ha⁻¹, and N₂ = 360 kg N ha⁻¹), three maize plant densities levels (D₁ = 75,000 plants ha⁻¹, D₂ = 97,500 plants ha⁻¹, and D₃ = 120,000 plants ha⁻¹).

Tillage involved moldboard plowing to a depth of 20 cm in April of both years, followed by rotary tillage to a 20 cm depth. White plastic film (120 cm wide and 0.01 mm thick) was laid on the entire soil surface as mulch on the day before sowing in each year. Maize cultivar Xianyu 335 was planted using a hand-held pressure-inject planter on 18 April 2018 and 19 April 2019.

Nitrogen fertilizer was applied in three applications, with 20% of the total N rate broadcasted and incorporated to a 20 cm soil depth using rotary tillage

before seeding. The remaining was equally split into two portions that were top-dressed at the nine-leaf collar stage of maize and at 15 d after flowering. Irrigation amounts of 90, 120, and 90 mm were applied at the nine, fourteen leaf collar, and grain-filling stages, respectively, using drip irrigation lines. Weeds were removed by hand throughout the growing season in both years and no crop diseases or pests were observed.

In each plot, a closed static chamber was set up for sampling N₂O gas. Each closed chamber (38 cm × 35 cm × 36.5 cm) was made opaque by wrapping it with bubbled aluminum foil to reduce the impact of radiation heat during gas sampling. A base collar made of stainless steel was inserted into the soil to a depth of 20 cm. A groove was made on the edge of the collar. A small fan operated by a battery inside each box, was used to mix the air inside each chamber. Gas samples were drawn out from the chamber at 0, 10, and 20 minutes using a 60 mL three-way valve syringe and injected into a sealed 150 mL aluminum plastic bag for storage (Dalian Delin Gas Packing, Liaoning, China).

Each sampling was performed between 08:00 and 12:00 h, based on the guidelines of Zou et al. (2005) and Alves et al. (2012). Samples of N₂O were collected 5–6 sampling events during the growing season between May and September in both years. The N₂O concentration in samples was analyzed within 2–3 days after collection using a gas chromatograph (GC) based on the procedure described by Zou et al. (2005). The GC system (Agilent 7890A, Wilmington, Delaware, USA) was equipped with an electron capture detector (ECD) for N₂O analysis. The conditions of the column were: Park Q 15 m × 0.53 mm × 25 µm; the injection port temperature was 150 °C; and the injection was split.

The carrier gas for the ECD was N₂ (>99% purity) with a flow rate of 60 mL min⁻¹. The detection temperature, column temperature, and column flow rate of the ECD were 300 °C, 45 °C, and 3.3 mL min⁻¹, respectively. The average N₂O fluxes were the mean of the three replicates of each treatment over the sampling dates. Nitrous oxide flux rate (mg m⁻² h⁻¹) was calculated using the following equation by Jun-fei et al. (2005):

$$F = \frac{C_2 \times V \times M_0 \times 273 / T_2 - C_1 \times V \times M_0 \times 273 / T_1}{A \times (t_2 - t_1) \times 22.4} \quad (1)$$

where F is greenhouse gas flux (mg m⁻² h⁻¹), A is area of the collar (m²), V is the volume of greenhouse gas flux (m³), M_0 is the molecular weight of greenhouse gas flux, C_1 and C_2 are the concentration of greenhouse gas flux before and after chamber closure (mol mol⁻¹), respectively, T_1 and T_2 are the previous and current sampling emission temperature in the chamber respectively, and t_1 and t_2 are the previous and current sampling time respectively.

The N₂O fluxes were expressed as mg m⁻² h⁻¹, and emissions were calculated for each plot by linearly interpolating the gas emissions between sampling dates under the assumption that the measured fluxes represented the average daily fluxes. The cumulative emissions of N₂O were calculated according to the equation by Cheng-Fang et al. (2012):

$$CE = Z (F_i + F_{i+1}) / (2 \times 10^{-3} \times t \times 24) \quad (2)$$

Where CE is the cumulative emission (g m⁻²), F_i and F_{i+1} are the measured fluxes of two consecutive sampling days (mg m⁻² h⁻¹), and t is the number of days between two successive sampling days (d).

In this study, global warming potential (GWP) is defined as the sum of the cumulative CO₂-eq emission (including CO₂) as described by IPCC. (2013):

$$GWP = (\text{Cumulative N}_2\text{O emission} \times 298) \quad (3)$$

Therefore, the emission of N₂O was converted into CO₂ equivalence (CO₂-e).

Data were analyzed at $P < 0.05$ using the mixed effects option of SPSS software, 17.0 (IBM Co., Chicago, IL, USA), with treatment factors as fixed effects and replicate as a random effect. Due to significant year-by-treatment interactions for most of the variables evaluated in the study, treatment effects were assessed separately for each year. Treatment means were analyzed using Fisher's protected least significant difference test.

3. Results

During the first 30 days after planting in 2018 and 2019, nitrous oxide emissions were recorded as highest at 0.010 mg m⁻² h⁻¹ in both W1 (405 mm) and W2 (324 mm). The emission then rose steadily to 0.047 mg m⁻² h⁻¹ and 0.055 mg m⁻² h⁻¹ in 2018 and 2019 as the highest (Fig. 2). Fluxes rose to their peaks in W1 and W2 at 90 days after planting and declined continuously till 150 days in the 2018 and 2019 cropping seasons.

The highest nitrogen rate, N2 (360 kg N ha⁻¹) in 2018 and 2019, led to the highest N₂O emission (Fig. 2). Nitrous oxide fluxes reached their peak at 0.222 mg m⁻² h⁻¹ and 0.225 mg m⁻² h⁻¹ in both 2018 and 2019 at 90 days after planting. It declined from that pitch till 150 days after planting. The same trend was observed in N1 (270 kg N ha⁻¹) and N0 (0 kg N ha⁻¹), where N0 recorded the least emissions in both years.

Lowest plan density (D1) 75,000 plants ha⁻¹ recorded the highest nitrous oxide emission in 2018 and 2019 (Fig. 2). The emissions were observed to be lower during the first 30 days after planting, but rose at 60 and 90 days after planting at the pitches of 0.170 mg m⁻² h⁻¹ in D1 in 2018 and 0.223 mg m⁻² h⁻¹ in D1 in 2019. Similar pitches and declining trends were observed in D2 and D3 in 2018 and 2019. Emissions declined after 90 days of plant establishment and continued till 150 days.

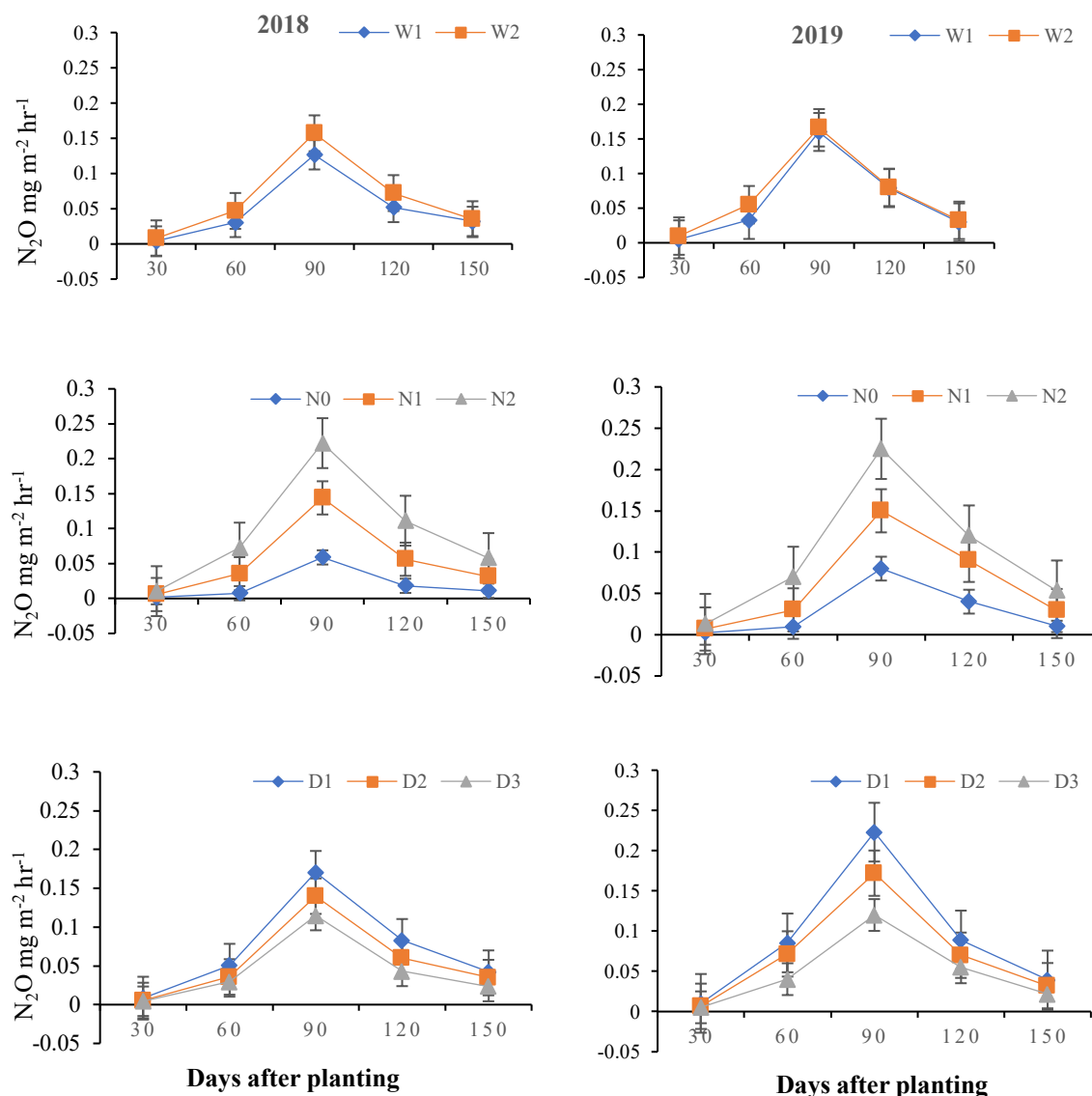


Figure 2. Seasonal N_2O fluxes for maize in 2018 and 2019 as affected by irrigation level, nitrogen rate, and plant density. The vertical bars represent the standard errors at the least significant difference, $P < 0.05$, among treatments within a measurement date. N_0 , 0 kg N ha^{-1} ; N_1 = 270 kg ha^{-1} ; N_2 = 360 kg ha^{-1} ; D_1 = 75,000 plants ha^{-1} ; D_2 = 97,000 plants ha^{-1} ; D_3 = 120,000 plants ha^{-1} .

All factors (irrigation level, nitrogen rate, and plant density) and their interactions greatly affected nitrous oxide emissions regardless of the days after planting and the season of cultivation (Table 2). For instance, N_2O emission increased from 30 days after planting till 90 days after planting and decreased thereafter till harvest under all the treatments (Fig. 2), hence the significant differences observed in Table 2.

In the second season of cultivation, nitrous oxide emission increased substantially in all durations after planting and declined thereafter for all the treatments. Nitrous oxide emission increased with an increase in irrigation level and in increase in N application, but decreased with N_0 and N_1 rate of application. Nitrous oxide emissions also increased with lower plant density but reduced correspondingly with an increase in plant density levels, leading to significant differences.

Table 2. Summary ANOVA of irrigation levels (W), Nitrogen levels (N), Plant density (D), and their interaction on nitrous oxide emissions ($\text{mg m}^{-2} \text{h}^{-1}$).

	2018 season					2019 season				
	30 days	60 days	90 days	120 days	150 days	30 days	60 days	90 days	120 days	150 days
Irrigation level (W)	***	***	***	***	***	***	***	***	***	***
Nitrogen rate (N)	***	***	***	***	***	***	***	***	***	***
Plant density (D)	***	***	***	***	***	***	***	***	***	***
W*N	***	***	***	***	***	***	***	***	***	***
W*D	***	***	***	***	***	***	***	***	***	***
N*D	***	***	***	***	***	***	***	***	***	***
W*N*D	***	***	***	***	***	***	***	***	***	***

*** $P < 0.001$.

Interactively, reduced irrigation coupled with all the other factors increased nitrous oxide emissions in 2018 and 2019 (Table 3). Plant density also influenced N_2O emissions significantly in a decreasing order. This implies that lower irrigation and all plant density treatments are insufficient to control nitrous oxide emissions on farms until the nitrogen rate is reduced.

The decreasing order of nitrous oxide emission under nitrogen levels and increasing plant density, and the increasing order of irrigation levels from W1 to W2 were the same in both growing seasons. There were variations in emissions at the water management levels, with higher levels in the 2019 growing season. A similar trend was identified for plant density. Generally, N_2O emissions were higher in 2019 compared to 2018.

Table 3. Effect of irrigation and nitrogen level interactions on nitrous oxide emissions ($\text{mg m}^{-2} \text{h}^{-1}$).

Irrig. level	N-rate	2018 season					2019 season				
		30 days	60 days	90 days	120 days	150 days	30 days	60 days	90 days	120 days	150 days
W ₁	N ₀	0.002e	0.007e	0.042f	0.007f	0.009e	0.002d	0.009d	0.009f	0.012f	0.008f
	N ₁	0.004d	0.025d	0.124d	0.050d	0.030c	0.005c	0.053c	0.057d	0.067e	0.028d
	N ₂	0.007c	0.059b	0.213b	0.098b	0.057a	0.008b	0.116b	0.132b	0.157b	0.053b
W ₂	N ₀	0.002e	0.008e	0.076e	0.029e	0.014d	0.002d	0.009d	0.029e	0.091d	0.013e
	N ₁	0.008b	0.046c	0.164c	0.063c	0.033b	0.009b	0.056c	0.064c	0.145c	0.031c
	N ₂	0.014a	0.086a	0.231a	0.124a	0.058a	0.018a	0.150a	0.178a	0.241a	0.054a
Pr > F		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

*** $P < 0.001$. The means of each column are not significantly different at the 5% level

In the 2018 cropping season, W₁ (405 mm) and W₂ (324mm) all had significant differences in N_2O emissions at 30 and 150 days after planting (Table 4). It was similar at 60 days except the interaction of W₁×D₂ and D₃; and W₁×D₁, W₂×D₂ at 90 and 120 days after planting in 2018.

In 2019, the interactions of W₁×W₂ with plant densities at 30 days were not significant in W₁×D₂ and

D₃, W₁×D₁, and W₂×D₃. Likewise, at 60 days after planting W₁×D₁ and W₂×D₂, W₁×D₃ and W₂×D₃ were also not significant. At 90 days after planting in 2019, significant differences were not observed in W₁×D₂ and W₂×D₂. However, at 120 and 150 days after planting, significant differences existed in all these interactions.

Table 4. Effect of irrigation and plant density level interactions on nitrous oxide emissions ($\text{mg m}^{-2} \text{h}^{-1}$).

Irrig. level	Plant density	2018 season					2019 season				
		30 Days	60 days	90 days	120 days	150 days	30 days	60 days	90 days	120 days	150 days
W ₁	D ₁	0.005c	0.039c	0.162b	0.066b	0.041b	0.006c	0.076b	0.088b	0.107d	0.038b
	D ₂	0.004d	0.028e	0.123d	0.055c	0.032d	0.005d	0.061c	0.063c	0.076e	0.030d
	D ₃	0.003e	0.025e	0.095e	0.035e	0.022f	0.004d	0.043d	0.046e	0.055f	0.020f
W ₂	D ₁	0.012a	0.063a	0.179a	0.100a	0.043a	0.014a	0.095a	0.153a	0.215a	0.040a
	D ₂	0.007b	0.044b	0.157b	0.066b	0.037c	0.008b	0.083b	0.066c	0.145b	0.034c
	D ₃	0.005c	0.034d	0.135c	0.051d	0.025e	0.007c	0.038d	0.052d	0.118c	0.023e
Pr > F		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

*** $P < 0.001$. The means of each column are not significantly different at the 5% level

Nitrogen rates and plant densities interactions had significant differences in all the cropping seasons (Table 5). In 2018, significant differences were not ob-

served in N₀×D₁ and D₂, and N₂×D₂ and D₃ at 30 days after planting. At 60 and 90 days after planting,

differences did not exist in N0×D2 and D3, and N2×D2 and D3, likewise N0×D2 and D3 in the same year.

In 2019, the relationship between nitrogen and densities was also highly significant ($P<0.001$). How-

ever, there were no observed differences in N0×D1, D2, and D3, and N1×D1 and D2, likewise N2×D2 and D3 at 30 days after planting. At 60 and 90 days in 2019, significant differences were not observed in N0×D1, D2, and D3; N1×D1 and N2×D3, and N0×D1 and N0×D2.

Table 5. Effect of nitrogen rate and plant density interactions on nitrous oxide emissions ($\text{mg m}^{-2} \text{h}^{-1}$).

N-rate	Plant density	2018 season					2019 season				
		30 Days	60 days	90 days	120 days	150 days	30 days	60 days	90 days	120 days	150 days
N ₀	D ₁	0.002f	0.011f	0.066g	0.025g	0.018g	0.003e	0.015f	0.026g	0.070g	0.016g
	D ₂	0.002f	0.008g	0.057h	0.021h	0.013h	0.002e	0.008f	0.022g	0.057h	0.012h
	D ₃	0.001g	0.004g	0.053h	0.008i	0.003i	0.002e	0.006f	0.009h	0.028i	0.002i
N ₁	D ₁	0.007c	0.050c	0.176d	0.081d	0.041d	0.008bc	0.074c	0.084d	0.138d	0.038d
	D ₂	0.006d	0.034d	0.150e	0.052e	0.031e	0.007c	0.057d	0.054e	0.101e	0.029e
	D ₃	0.004e	0.022e	0.106f	0.035f	0.023f	0.005d	0.033e	0.043f	0.081f	0.021f
N ₂	D ₁	0.016a	0.091a	0.269a	0.142a	0.069a	0.020a	0.167a	0.252a	0.275a	0.064a
	D ₂	0.008b	0.066b	0.212b	0.107b	0.060b	0.010b	0.150b	0.119b	0.173b	0.055b
	D ₃	0.008b	0.062b	0.185c	0.085c	0.045c	0.009b	0.082c	0.094c	0.150c	0.041c
Pr > F		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

*** $P<0.001$. The means of each column are not significantly different at the 5% level

Irrigation and nitrogen level interactions had a significant difference in nitrous oxide emissions in both cropping seasons (Table 6). In 2018, W1×N0×D1 and D2, D3, W1×N2×D2, and D3 did not significantly differ at 30 days after planting. A similar trend occurred at 60 days after sowing, while 90 days after planting W1×N0×D2 and D3 had no significant differences. At 120 days after planting in the same year, a similar trend occurred in W1×N0×D2, D3, and W1×N2×D1 and D2.

In 2019, W1×N0×D1, D2, D3, W1×N1×D2, W1×N1×D3 had no significant difference in N₂O emissions. The interaction of W1×N2×D1, and D2 and D3 had also no significant differences. At 60 days after planting in 2019, W1×N0×D1, D2, and D3, W1×N2×D1 and D2 had no significant difference, likewise W1×N1×D1 and W1×N2×D3. At 90 days after planting, a similar trend was observed.

Table 6. Effect of irrigation level, nitrogen rate, and plant density interactions on nitrous oxide emissions ($\text{mg m}^{-2} \text{h}^{-1}$).

Irrig. level	N-rate	Plant density	2018 season					2019 season				
			30 days	60 days	90 days	120 days	150 days	30 days	60 days	90 days	120 days	150 days
W ₀	N ₀	D ₁	0.002h i	0.009h ij	0.056l	0.012l	0.017 i	0.003fg	0.017ij	0.014j	0.021 o	0.016 k
		D ₂	0.002h ij	0.009h ij	0.037 m	0.005 m	0.008 j	0.002fg	0.008j	0.008j	0.009 p	0.007l
		D ₃	0.001j	0.002j	0.033 m	0.004 m	0.001 k	0.001g	0.004j	0.004j	0.006 q	0.001 n
W ₁	N ₁	D ₁	0.005f	0.045f	0.145g	0.077f	0.037 e	0.006e	0.079d e	0.082f	0.098 k	0.035 g
		D ₂	0.004g	0.016h	0.132h	0.050 h	0.030 g	0.005ef	0.050f g	0.053g	0.063l	0.027i
		D ₃	0.003h	0.014h	0.094j	0.021 k	0.023 h	0.003fg	0.031h i	0.035i	0.042 n	0.021j
W ₁	N ₂	D ₁	0.008d	0.062c d	0.283a	0.108 b	0.070 a	0.010bc	0.132c	0.169b	0.201 b	0.065a
		D ₂	0.006e	0.058d e	0.198e	0.108 b	0.060 b	0.007cd e	0.124c	0.130c	0.154f	0.055c
		D ₃	0.006e	0.057d e	0.159f	0.079e	0.042 d	0.007de	0.093d	0.097d e	0.116i	0.039f
W ₂	N ₀	D ₁	0.002h i	0.013h i	0.076k	0.038i	0.018 i	0.003fg	0.014j	0.039h i	0.119 h	0.017 k
		D ₂	0.002h i	0.006ij	0.077k	0.036j	0.018 i	0.003fg	0.007j	0.036i	0.105j	0.017 k
		D ₃	0.001ij	0.006ij	0.073k	0.013l	0.004 k	0.002g	0.007j	0.013j	0.049 m	0.004 m
	N ₁	D ₁	0.009c	0.056d	0.207d	0.085	0.044	0.011b	0.069e	0.086e	0.178e	0.041e

	d	e	e	d	d		f			
D₂	0.008d	0.052e f	0.167f	0.054 g	0.033 f	0.010bc d	0.064e f	0.055g	0.139 g	0.031 h
D₃	0.006e f	0.029g	0.119i	0.049 h	0.022 h	0.007e	0.036g h	0.050g h	0.119 h	0.021j
D₁	0.024a	0.120a	0.255b	0.176a	0.068 a	0.029a	0.203a	0.334a	0.349a	0.063 b
N₂	D₂	0.010b	0.073b	0.227c	0.106 b	0.060 b	0.012b	0.176b	0.107d	0.191c
	D₃	0.009b c	0.067b c	0.212d	0.091c	0.047 c	0.012b	0.070e	0.092e f	0.185 d
										0.043 d
Pr> F	<0.001	<0.001	<0.001	<0.00 1	<0.00 1	<0.001	<0.001	<0.001	<0.00 1	<0.00 1

*** $P < 0.001$. The means of each column are not significantly different at the 5% level

4. Discussion

The fluxes of N₂O were recorded as the lowest in both W1 (405 mm) and W2 (324 mm) (Fig. 2) at 30 and 150 days after planting. It rose at 60 and then peaked at 90 days after planting in both 2018 and 2019. The fluxes of N₂O peaked at 90 days (0.157 and 0.166 mg m⁻² h⁻¹) in 2018 and 2019 respectively, hence crop growth variability and soil processes might impact N₂O emissions during that period as described in Ashiq et al. (2021) and Wrage-Mönnig et al. (2018). The fluxes then declined steadily after 90 days in both irrigation levels.

It was evident that higher irrigation led to higher N₂O fluxes from the farm. These findings agree with Sapkota et al. (2020), which states that the combined effect of higher oxygen content and higher moisture content in soils induces the production of N₂O by denitrification. Several biogeochemical processes control the rate of GHG emissions from soils, some of which are greatly impacted by soil moisture, including microbial respiration.

The low fluxes of N₂O recorded in W2 (324 mm) level of irrigation can be attributed to inadequate moisture for microbial respiration to trigger N₂O emission. This observation is also in line with Roy et al. (2014), which states that limited rainfall reduces N₂O emissions. Therefore, irrigation levels at maize farms should be reduced to levels that will limit high microbial activities.

During the first 30 days of maize juvenile growth phase, the N₂O fluxes were lowest in both 0 kg N ha⁻¹, 270 kg N ha⁻¹, and 360 kg N ha⁻¹ rates in 2018 and 2019 (Fig. 2). The lower N₂O emissions recorded during the early and last days suggest that actively growing crops facilitate N₂O emission from the soil. These findings are contrary to Roy et al. (2014) assertion that applying N as side-dress at V8 instead of at planting reduced N₂O emission. The fluxes of N₂O rose at 60 and peaked at 90 days of plant establishment in both N rates 0.222 and 0.225; 0.144 and 0.150; and 0.059 and 0.080 mg m⁻² h⁻¹ in 2018 and 2019.

The decline followed the same trend until it reached its lowest point at 150 days. The level of fluxes

correlated to the rate of nitrogen application, thus 360 kg N ha⁻¹ > 270 kg N ha⁻¹ > 0 kg N ha⁻¹ in that order in 2018 and 2019, respectively. These observations agree with Wang et al. (2023) who also observed that the main factors driving GHG emission on farms were the fertilization rate. A keen observation revealed that 360 kg N ha⁻¹ led to higher N₂O fluxes in both years, with the N₂O fluxes peaking during the active growth period of maize.

Synthetic nitrogen fertilizer has often been applied at approximately 360 kg N ha⁻¹ each season by local farmers during the cultivation period of maize; it has become the primary source of agricultural GHG and reactive nitrogen (RN) emissions. This observation by Pei et al. (2023) agrees with our findings that nitrogen application at 360 kg N ha⁻¹ increased N₂O emission. Reduced or no nitrogen application on farms could limit N₂O fluxes, and matching nitrogen rates to crop growth phases can mitigate N₂O emissions.

Low plant density (D1) = 75,000 plants ha⁻¹, recorded the highest N₂O emission in 2018 and 2019, followed by plant density (D2) = 97,000 plants ha⁻¹, and (D3) = 120,000 plants ha⁻¹ (Fig. 2). These observations are in line with the findings of Xu et al. (2017) and Asi-bi et al. (2022) which states that higher plant density of maize increased grain yield, improves nitrogen use efficiency, reduces leaching, and mitigates ammonia and N₂O emissions. The above finding however, contradict the observation of Yan et al. (2017), who reported that high plant densities with crowding stress reduced the ability of plants to use soil N, resulting in a low yield and nitrogen use efficiency.

The emission of N₂O was lowest at first 30 and 150 days of the production phases of maize. The N₂O emissions had their peaks at 0.170, 0.140, 0.115 mg m⁻² h⁻¹ and 0.223, 0.172, 0.120 mg m⁻² h⁻¹ at 90 days in all plant density levels in 2018 and 2019. The emission of N₂O declined as plant density increased.

It was evident that low plant density facilitates the emission of N₂O, while higher plant density reduces the emission of N₂O at early growth and late periods, near physiological maturity of maize. A life-cycle assessment by Hou et al. (2020) showed that crop yield can increase and GHG intensity decrease without extra N

inputs if planting density is increased by 15,000 plants ha^{-1} . Optimized plant density supports the mitigation of N_2O emissions from farms.

All three factors, either combined or single (irrigation, nitrogen, and plant density), significantly affected nitrous oxide emission in 2018 and 2019 (Table 2). These findings conflict with Maharjan et al. (2014), who found that irrigation significantly increased NO_3^- leaching during the growing season but had no significant effect on direct N_2O emissions. In 2018 and 2019, irrigation, nitrogen, and plant density significantly affected nitrous oxide emission at 30, 60, 90, 120, and 150 days after planting. This observation agrees with Liu et al. (2011), who observed that significantly high N_2O and NO emissions period starts after fertilization.

Irrigation and nitrogen, irrigation and plant density, and nitrogen and plant density interactions also greatly affected nitrous oxide emissions at $P < 0.001$ in 2018 and 2019. Irrigation and nitrogen and plant density interactions in 2018 and 2019 at all days after planting, i.e., 30, 60, 90, 120, and 150 days, at $P < 0.001$. This implies that nitrous oxide emission, crop growth, and soil activities occur simultaneously.

In 2018 and 2019, at 150 days after planting, nitrous oxide emission was highest with irrigation level $\text{W1} \times \text{N2}$ (Table 3) and minimal at $\text{W1} \times \text{N1}$, but lowest at $\text{W1} \times \text{N0}$. At $\text{W2} \times \text{N2}$ in 2018 and 2019, nitrous oxide emissions were highest at 30, 60, 90, 120, and 150 days. These findings in W1 and W2 treatments align with those of Han et al. (2017), who found that varying irrigation amounts affected soil water dynamics and nitrogen turnover. Nitrous oxide fluxes were lowest at $\text{W2} \times \text{N0}$ and minimal at $\text{W2} \times \text{N1}$ in both 2018 and 2019 cropping seasons at $P < 0.001$.

In 2018 and 2019, $\text{W1} \times \text{D1}$, $\text{W1} \times \text{D2}$, and $\text{W1} \times \text{D3}$, as well as $\text{W2} \times \text{D1}$, $\text{W2} \times \text{D2}$, and $\text{W2} \times \text{D3}$, resulted to significant fluxes of nitrous oxide at 30, 60, 90, 120, and 150 days after planting (Table 4). At 30, 60, 90, 120, and 150 days after planting, nitrous oxide flux was highest in $\text{W2} \times \text{D1}$ in 2018 and 2019. In both years, the lowest nitrous oxide flux was in $\text{W1} \times \text{D3}$ and minimal in $\text{W2} \times \text{D3}$. Higher irrigation with increased plant density reduced nitrous oxide emissions. These findings contradict the findings of López-Fernández et al. (2007), who observed higher amounts of N_2O emission under maize than in areas without maize.

At 30, 60, 90, 120, and 150 days after planting in 2018 and 2019, nitrous oxide emissions peaked in the treatments $\text{N2} \times \text{D1}$ and were lowest in $\text{N0} \times \text{D3}$ (Table 5). It can be observed that emissions increased with an increase in nitrogen rate, accompanied by a decrease in plant density. These findings agree with Halvorson et al. (2008), who observed linear increases in N_2O emissions with increasing N fertilizer rate, but emission amounts varied with the growing season.

Nitrous oxide emissions tend to rise at 90 – 120 days after planting and are reduced afterwards at 150

days after planting. The interactions of $\text{N0} \times \text{D1}$, $\text{N0} \times \text{D2}$, $\text{N0} \times \text{D3}$, and $\text{W1} \times \text{D1}$, $\text{W1} \times \text{D2}$, $\text{W1} \times \text{D3}$, $\text{N2} \times \text{D1}$, $\text{N2} \times \text{D2}$, $\text{N2} \times \text{D3}$ were all significant at 30, 60, 90, 120, 150 days after planting. It was evident that the emission of nitrous oxide is simultaneous with the interaction between the soil and the crop.

In 2018 and 2019, $\text{W2} \times \text{N2} \times \text{D1}$ recorded the highest nitrous oxide emission (Table 6). This implies that reduced irrigation, combined with high nitrogen application and low plant density, facilitated nitrous oxide emissions. These findings are in tandem with Liu et al. (2011), which states that high N fertilizer and irrigation water inputs are important triggers of nitrous oxide and nitric oxide emissions. It was also evident that nitrous oxide emission was lowest in the treatments $\text{W1} \times \text{N0} \times \text{D3}$ and $\text{W2} \times \text{N0} \times \text{D3}$ at 30, 60, 90, 120, and 150 days after planting. This implies that either no nitrogen application, high irrigation with low plant density, or high irrigation with high plant density reduces nitrous oxide emission. This also implies that higher plant density reduces nitrous oxide emissions. These findings disagree with the findings of Chen et al. (2013), which indicated that proper-sparse planting might be the most appropriate planting density to mitigate GHG emissions.

Interactively, all the factors combined in the treatments produced or were significant to the emission of nitrous oxide emissions at $P < 0.001$ at 30, 60, 90, 120, and 150 days after planting in 2018 and 2019. It implies that improved management of all three factors (irrigation, nitrogen, and plant density) in crop production can support the mitigation of nitrous oxide emissions. This observation also agrees with the research of Liu et al. (2011), which states that improved management of irrigation and fertilization reduced N fertilization rate and irrigation amount and increased maize yield, and significantly decreased the N_2O and NO emissions.

The emission of nitrous oxide, however, tends to be lower at 120 and 150 days after planting in all the treatment interactions. These findings conflict with those of Ye et al. (2018), which showed that N_2O peaks occur within 1 to 8 days after irrigation. Emissions, however, tend to be highest at N2 interactions with $\text{W1} \times \text{D1}$ and $\text{W2} \times \text{N2} \times \text{D1}$ in both years. This implies that higher nitrogen rates with low plant density increased the emission of nitrous oxide. These findings agree with the findings of Liu et al. (2011), who found that N_2O and NO fluxes increased linearly with N application rate, but conflict with Klumpp et al. (2011), who state that the dominant source of N_2O fluxes was the soil N pool and not fertilizer application.

5. Conclusions

Potential mitigation strategies for GHGs from farmlands will depend greatly on improved agronomic practices. Agronomic practices such as reducing N rates and irrigation levels, while optimizing plant density, can support the mitigation of GHGs. Nitrous oxide emissions were remarkably higher at 90 days during the

maize growth stage. Therefore, nitrogen application should be adjusted near or after this period to limit N₂O emission.

Author Contributions: Conceptualization, A.E.A. and Q.C.; methodology, A.E.A.; Q.C.; W.Y.; F.H.; and Z.F.; software, A.E.A.; validation, A.E.A.; Z.F.; Y.G.; formal analysis, A.E.A.; investigation, A.E.A.; Z.G.; Y.G.; X.J.; H.Y.; resources, A.E.A.; Z.F.; F.H.; W.Y.; and Q.C.; data curation, A.E.A.; writing—original draft preparation, A.E.A.; writing—review and editing, A.E.A.; visualization, A.E.A.; supervision, Q.C.; W.Y.; F.H.; Z.F.; project administration, A.E.A.; Q.C.; W.Y.; F.H.; Z.F.; funding acquisition, Q.C.; W.Y.; F.H.; Z.F. All authors have read and agreed to the published version of the manuscript.

Funding: The Natural Science Foundation of China (U21A20218 and 32372238), the Science and Technology Program in Gansu Province (25JRRA347 and 24ZDNA008), the Young Doctor Support Project of Gansu Province (2024QB–008), the Young Teachers Research Ability Enhancement Project in Northwest Normal University of China (NWNLU–LKQN2023–09), and the Industrial Support Project of Educational Committee of Gansu Province (2025CYZC–037).

Conflicts of Interest: The authors declare no conflict of interest.

6. References

- Alves, B.J.R.; Smith, K.A.; Flores, R.A.; Cardoso, A.S.; Oliveira, W.R.D.; Jantalia, C.P.; Urquiaga, S.; and Boddey, R.M. (2012). Selection of the most suitable sampling time for static chambers for the estimation of daily mean N₂O flux from soils. *Soil Biology and Biochemistry*, 46, 129–135.
- Ashiq, W.; Vasava, H.B.; Ghimire, U.; Daggupati, P.; and Biswas, A. (2021). Topography controls N₂O emissions differently during the early and late corn growing season. *Agronomy*, 11(1), 187.
- Asibi, A.E.; Yin, W.; Hu, F.; Fan, Z.; Gou, Z.; Yang, H.; and Chai, Q. (2022). Optimized nitrogen rate, plant density, and irrigation level reduced ammonia emission and nitrate leaching on maize farmland in the oasis area of China. *PeerJ*, 10, e12762.
- Chen, W.; Wang, Y.; Zhao, Z.; Cui, F.; Gu, J.; and Zheng, X. (2013). The effect of planting density on carbon dioxide, methane and nitrous oxide emissions from a cold paddy field in the Sanjiang Plain, northeast China. *Agriculture, Ecosystems & Environment*, 178, 64–70.
- Cheng-Fang, L.; Dan-Na, Z.; Zhi-Kui, K.; Zhi-Sheng, Z.; and Jin-Ping, W.; et al. (2012). Effects of Tillage and Nitrogen Fertilizers on CH₄ and CO₂ emissions and soil organic carbon in paddy fields of Central China. *PLoS ONE*, 7, e34642.
- Garnett, T. (2008). Cooking up a storm: Food, greenhouse gas emissions and our changing climate. *Food*
- Climate Research Network, Centre for Environmental Strategy, University of Surrey.
- Halvorson, A.D.; Del Grosso, S.J.; and Reule, C.A. (2008). Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. *Journal of Environmental Quality*, 37(4), 1337–1344.
- Han, B.; Ye, X.; Li, W.; Zhang, X.; Zhang, Y.; Lin, X.; and Zou, H. (2017). The effects of different irrigation regimes on nitrous oxide emissions and influencing factors in greenhouse tomato fields. *Journal of Soils and Sediments*, 17(10), 2457–2468.
- Hou, P.; Liu, Y.; Liu, W.; Liu, G.; Xie, R.; Wang, K.; ... and Li, S. (2020). How to increase maize production without extra nitrogen input. *Resources, Conservation and Recycling*, 160, 104913.
- Huang, J.; Huang, Z.; Jia, X.; Hu, R.; and Xiang, C. (2015). Long-term reduction of nitrogen fertilizer use through knowledge training in rice production in China. *Agricultural Systems*, 135, 105–111.
- IPCC. Climate Change (2013). The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker, T.F.; Qin, D.; Plattner, G.K.; Tignor, M.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535.
- Jun-fei, X.I.E. and Yu-e, L.I. (2005). Effect of soil temperature on N₂O emission in upland farm of Beijing. *Chinese Journal of Agrometeorology*, 26, 7–10.
- Klumpp, K.; Bloor, J.M.; Ambus, P.; and Soussana, J.F. (2011). Effects of clover density on N₂O emissions and plant-soil N transfers in a fertilised upland pasture. *Plant and Soil*, 343(1), 97–107.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304, 1623–1627.
- Liu, C.; Wang, K.; Meng, S.; Zheng, X.; Zhou, Z.; Han, S.; ... and Yang, Z. (2011). Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat–maize rotation field in northern China. *Agriculture, Ecosystems & Environment*, 140(1–2), 226–233.
- López-Fernández, S.; Diez, J.A.; Hernaiz, P.; Arce, A.; García-Torres, L.; and Vallejo, A. (2007). Effects of fertiliser type and the presence or absence of plants on nitrous oxide emissions from irrigated soils. *Nutrient Cycling in Agroecosystems*, 78(3), 279–289.
- Maharjan, B.; Venterea, R.T.; and Rosen, C. (2014). Fertilizer and irrigation management effects on nitrous oxide emissions and nitrate leaching. *Agronomy Journal*, 106(2), 703–714.
- Matteucci, G.; Dore, S.; Reibmann, C.; Stivanello, S.; and Buchmann, N. (2000). Soil respiration in beech and

spruce forest in Europe: Trends, controlling factors, annual budgets and implications for the ecosystem carbon balance. In Schulze E.D. (Eds.). Carbon and nitrogen cycling in European forest ecosystems. Springer Verlag, Berlin, Germany, 217–236.

Moser, S.B.; Feil, B.; Jampatong, S.; and Stamp, P. (2006). Effects of pre-anthesis drought, nitrogen fertilizer rate, and variety on grain yield, yield components, and harvest index of tropical maize. *Agricultural water management*, 81(1-2), 41–58.

Mosier, A.; Syers, J.K.; and Freney, J.R. (Eds.). (2013). *Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment*. Island Press Vol. 65.

Oenema, O.; Wrage, N.; Velthof, G.L.; van Groenigen, J.W.; Dolfing, J.; and Kuikman, P.J. (2005). Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystems*, 72, 51–65.

Pei, Y.; Chen, X.; Niu, Z.; Su, X.; Wang, Y.; and Wang, X. (2023). Effects of nitrogen fertilizer substitution by cow manure on yield, net GHG emissions, carbon and nitrogen footprints in sweet maize farmland in the Pearl River Delta in China. *Journal of Cleaner Production*, 399, 136676.

Roy, A.K.; Wagner-Riddle, C.; Deen, B.; Lauzon, J.; and Bruulsema, T. (2014). Nitrogen application rate, timing and history effects on nitrous oxide emissions from corn (*Zea mays* L.). *Canadian Journal of Soil Science*, 94(4), 563–573.

Sapkota, A.; Haghverdi, A.; Avila, C.C.; and Ying, S.C. (2020). Irrigation and greenhouse gas emissions: a review of field-based studies. *Soil Systems*, 4(2), 20.

UNEP and WHRC (2007). *Reactive Nitrogen in the Environment: Too much or too little of a good thing*. United Nations Environment Programme.

Wang, H.; Ren, H.; Han, K.; He, Q.; Zhang, L.; Zhao, Y.; ... and Liu, P. (2023). Sustainable improvement strategies for summer maize yield, nitrogen use efficiency and greenhouse gas emission intensity in the North China Plain. *European Journal of Agronomy*, 143, 126712.

Wrage-Mönnig, N.; Horn, M.A.; Well, R.; Müller, C.; Velthof, G.; and Oenema, O. (2018). The role of nitrifier denitrification in the production of nitrous oxide revisited. *Soil Biology and Biochemistry*, 123, A3–A16.

Xu, C.; Huang, S.; Tian, B.; Ren, J.; Meng, Q.; and Wang, P. (2017). Manipulating planting density and nitrogen fertilizer application to improve yield and reduce environmental impact in Chinese maize production. *Frontiers in Plant Science*, 8, 1234.

Yan, P.; Pan, J.; Zhang, W.; Shi, J.; Chen, X.; and Cui, Z. (2017). A high plant density reduces the ability of maize to use soil nitrogen. *PLoS ONE*, 12(2), e0172717.

Yan, Y.; Tian, J.; Fan, M.; Zhang, F.; Li, X. and Christie, P.; et al. (2012). Soil organic carbon and total nitrogen in intensively managed arable soils. *Agriculture, Ecosystems and Environment*, 150, 102–110.

Ye, X.H.; Han, B.; Li, W.; Zhang, X.C.; Zhang, Y.L.; Lin, X.G.; and Zou, H.T. (2018). Effects of different irrigation methods on nitrous oxide emissions and ammonia oxidizers microorganisms in greenhouse tomato fields. *Agricultural Water Management*, 203, 115–123.

Zou, J.W.; Huang, Y.; Jiang, J.Y.; Zheng, X.H.; and Sass, R.L. (2005). A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles*, 19, GB2021.