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Inorganic nitrogen fertilizer and high N application rate promote N_2O emission and suppress CH_4 uptake in a rotational vegetable system

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ABSTRACT

Understanding the influence of management practices on greenhouse gas (GHG) emissions from greenhouse cropping is of great importance for assessing the environmental impacts of the greenhouse cropping industry and improving its sustainability. A tomato–cucumber–tomato rotation experiment was carried out in a typical solar greenhouse in northwest China with four treatments including two irrigation levels (regular (RI) and low (LI)) and two fertilizer types (organic fertilizer (N1) and inorganic fertilizer (N2)). Greenhouse gas fluxes (nitrous oxide, N_2O, and methane, CH_4) were measured regularly using the closed chamber method during the three growing seasons, along with soil water-filled pore space (WFPS), temperature, mineral-N concentration and nitrobacteria, nitrosomonas and denitrifying bacteria abundance. Over the rotation, the soil acted as a source for N_2O and a sink for CH_4, with the mean fluxes of 0.12 mg N_2O-N m^{-2} h^{-1} and -0.31 mg CH_4-C m^{-2} h^{-1}, respectively. The stepwise multiple linear regressions indicated that WFPS and soil temperature accounted for significant portion of N_2O emission and CH_4 uptake variations, respectively for both fertilizer types. Fertilization rate and type resulted in much greater difference of cumulative GHG emission between treatments than the irrigation level. Inorganic fertilizer with higher nitrogen application rate usually resulted in higher cumulative N_2O emission and lower CH_4 uptake than organic fertilizer application. Over the rotation, total greenhouse emission (GHGt) and greenhouse emission intensity (GHGI) on average followed the same order of RIN2 > LIN2 > LIN1 > RIN1 with N_2O emission as the dominant component for each treatment. Overall, organic fertilizer with proper water application under drip irrigation can effectively mitigate greenhouse gas emissions and maintain relatively high and stable vegetable yields in solar greenhouse cropping in northwest China.

1. Introduction

Growing vegetables under solar greenhouse conditions has gained popularity in recent years, reaching 4 million hectares in China in 2015 (Yu and Zhou, 2016). Relative to field conditions, the growing environment in greenhouses is greatly modified, due to major reductions in wind speed (Zhang and Lemeur, 1992), higher relative humidity (Jolliet and Bailey, 1992), and higher temperature (Rajasekar et al., 2013). These modifications to the soil-plant interface will have implications for greenhouse gas (GHG) emissions from soils inside greenhouses. However, most research on GHG emissions from agriculture is based on field studies (Laville et al., 2011; Wang et al., 2015; Htun et al., 2017). Only recently studies have focused on crop production under greenhouse conditions, with most GHG studies restricted to an individual vegetable cropping season (Chen et al., 2018; Han et al., 2017; Hou et al., 2016) and typically with a focus on either fertilization or irrigation (Zhang et al., 2016; Han et al., 2017).

Globally, agriculture accounts for 60 % of nitrous oxide (N_2O) and 50 % of methane (CH_4) emissions from anthropogenic sources (Smith et al., 2007). Both N_2O and CH_4 are powerful greenhouse gases with global warming potentials (GWP) of 265 and 28 times that of CO_2 for a 100-year timescale (Myhre et al., 2013). Denitrification and nitrification

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are considered to be the main processes producing N_2O in soils. Methane is mainly produced by methanogenic archaea, which decompose organic matter under anaerobic condition, such as flooded paddy fields (Katayanagi et al., 2012). Oxidation of CH_4 is carried out by methanotrophs and other CH_4 oxidizing microbes under aerobic conditions, with forest, grassland and arable soil systems being net consumers of CH_4 (Wu et al., 2018).

Many soil environmental factors could affect GHG emissions, particularly soil water availability and soil temperature. Clayton et al. (1997) suggested that when both soil water and mineral-N content were not limiting, N_2O fluxes would rise steeply with increasing temperature, and the positive relationship between N_2O fluxes and soil temperature could be linked to enhanced organic matter decomposition, oxidation, microbial and root activities at relatively high temperatures (~ 20–30 □, Tercero et al., 2015). Generally, N_2O emission from soil increases with rising temperature, peaking at 20–35 ℃ (Parton et al., 2001). However, the source of N_2O emission can vary depending on temperature, as the ratio of nitrification to denitrification sourced N_2O was found to decrease with increasing temperature in both organic and mineral horizons of forest soil (Sun et al., 2019). Unlike soil temperature, a bell-shaped function was applied to describe the relationship between N_2O and water filled pore space (WFPS), with the greatest N_2O production occurring at WFPS of 50–60% (Laville et al., 2011). Whereas, at WFPS of 60–70%, denitrification is the dominant N_2O source (Case et al., 2012). Soil CH_4 uptake is also positively correlated with soil temperature, and yet negatively correlated with soil moisture for cultivated maize (Liu et al., 2016), planted woodland (Wu et al., 2018), and rain-fed potato (Wang et al., 2015). Others have suggested that soil CH_4 uptake can be suppressed at both low and high soil moisture contents, through the inhibition of methanotrophs activities or through the limitation of CH_4 and O_2 diffusion and transport (Del Grosso et al., 2000; Ran et al., 2017).

Nitrogen (N) addition to soils has an important impact on N_2O emissions and CH_4 oxidation (Acton and Baggs, 2011; Cui et al., 2016; Wu et al., 2018). Previous studies have shown that inorganic fertilizer application tended to lead to a greater cumulative N_2O and CH_4 emission than organic fertilizer over a relatively short period during a growing season (Meijide et al., 2007; Qin et al., 2010; Ozlu and Kumar, 2018). This is because inorganic N fertilizer tends to be highly labile and is readily available for nitrification and denitrification processes. Nitrogen application has been reported to inhibit CH_4 oxidation by promoting ammonia oxidation (Acton and Baggs, 2011), while others suggested that addition of N to soil could promote (Wang et al., 2015) or have no effect (Htun et al., 2017) on CH_4 oxidation. Crop GHG emissions are typically reported at a kg ha^{-1} basis, however an alternative metric, GHG intensity (GHGI) defined as the ratio of GHG emission to crop yield, is proposed to link GHG emissions to crop yield (Shang et al., 2011). Greenhouse gas intensity can be reduced through optimized management practices that achieve high yields, whilst maintaining low GHG emissions (Mosier et al., 2006). The addition of organic matter to soil can improve soil quality in a variety of ways, including provision of other nutrients (Liu et al., 2014), which has been shown to be able to increase yields in canola, barley, oats, tomato and cucumber cultivation (Barton et al., 2016; Fan et al., 2020). Specifically, a long-term experiment conducted in Rothamsted, UK, indicated that organic fertilizer application (farmyard manure) maintained an increasing tendency for crop yields in the long-term cultivation although yield reduction occurred sporadically (> 166 years, Johnston et al., 2009; > 158 years, Johnston and Poulton, 2018). Therefore, the improvements to crop yields and/or decreases of cumulative gas emissions associated with addition of organic fertilizer often led to reduced GHGI. In addition, Sainju (2016) reported that the GWP and GHGI decreased curvilinearly with decreasing N fertilization rate.

Until recently, few studies have investigated the effects of irrigation and fertilization on GHGs emissions from greenhouse soils. In addition, most previous studies on GHGs emission for a vegetable system have been conducted for a single growing season, and mainly concentrated on the effects of either fertilizer or irrigation, without consideration of the interaction between them. The objectives of this study were to (1) compare the GHG emissions and GHGI of different irrigation levels and fertilizer types; and (2) evaluate the correlation between GHG fluxes and soil variables in a greenhouse system growing tomatoes and cucumber in a two-year rotation.

2. Material and methods

2.1. Site description

This study was conducted in a solar greenhouse located at Shiyanghe Experimental Station, China Agricultural University, in Gansu province of northwest China (N 37°49′24″, E 102°52′30″, 1581 m above sea level). The region experiences an arid continental climate with a mean annual precipitation of 164 mm, average annual temperature of 8 ℃ and an annual sunshine duration of more than 3000 h. The groundwater table is 30–40 m below the ground surface. The soil at the experimental site is classified as an Aridisol (USDA definition; USDA, 2014) with a sandy loam texture. Prior to the start of the experiment, the soil had a bulk density of 1.43 g cm^{-3}, field capacity of 34 % (cm^3 cm^{-3}), soil organic matter of 14 g kg^{-1}, a total N of 0.08 %, available P content of 73 mg kg^{-1}, available K content of 2.14 % and pH of 8.4.

The rotation examined here was tomato (*Solanum lycopersicum cv. Oyadi*), cucumber (*Cucumis sativus* L.), and tomato, which is a typical greenhouse rotation in Northwest China, lasting from April 2016 to August 2017. The solar greenhouse (no additional lighting was used) was east-west oriented and covered with transparent polyethylene film. The greenhouse was not heated and was vented when temperatures exceeded 30 ℃, via a 0.5 m wide vent at the top of greenhouse. Typically, the ventilation system remained open from late April, and further venting was provided from late May until harvest in August by rolling up the lower 70 cm of the greenhouse walls. In winter, straw mats covered the top of the greenhouse to maintain interior temperatures > 5 ℃, and the ventilation opened approximately 20 cm for about 5 h from midday.

2.2. Experimental design

Prior to transplanting the first crop of the rotation, the soil was flooded and fully ploughed to homogenize the soil. The greenhouse was split into three blocks with four plots (measuring 5.4 × 1.9 m each) in each block. Plots were hydrologically isolated to a depth of 1.2 m, and four treatments arranged in each block under a randomized complete block design. The soil was covered with transparent polyethylene to reduce soil evaporation and maintain soil temperature. The treatments consisted of two irrigation levels, regular (RI) and low (LI) and two fertilizer types, organic (N1) and inorganic (N2), thus there were four treatments (RIN1, RIN2, LIN1, and LIN2), and each treatment was replicated three times.

2.3. Crop management

Each plot contained four rows, with 12 tomato plants or 18 cucumber plants in each row for the tomato and cucumber growing season, respectively. Drip irrigation was used for all treatments with 18 drip emitters for each row at a flow rate of 3.5 l h^{-1} for each emitter under standard pressure (Dayu Irrigation Group Co., Ltd, China). All treatments received the same volume of irrigation for the first two irrigation events following plant transplanting to ensure the survival of plants, the irrigation treatment was then applied thereafter. During the 2016 tomato season, irrigation was applied when average soil water content (0–60 cm depth) in a neighboring monitored study in the same solar greenhouse reached ~70 % of field capacity (Fan et al., 2020, in press). Irrigation water was applied to bring the soil to 90 % of field capacity for RI treatments while the LI volume was set at 70 % of the RI volume.

Based on the findings of the first tomato growing season, irrigation frequency was adjusted to every 5–7 days during the cucumber and 2017 tomato seasons, with irrigation volumes/amounts of 13.5 and 9.5 mm each plot for RI and LI respectively for each irrigation event. Therefore, a total of 284.8, 192.0 and 186.0 mm irrigation water was applied for RI and 237.5, 156.0 and 142.2 mm was applied for LI treatments, during the 2016 tomato, cucumber and 2017 tomato season, respectively (Fig. 1, a).

Considering that manure has to be applied at a much greater level than the one the locals commonly use if the N rate for organic fertilizer treatment matches the rate of inorganic fertilizer treatment, we decided to apply different N rates for organic and inorganic fertilizer treatments in the study, following the local practice. Fertilizer application was scheduled according to the practice of local farmers. For each N1 plot, fermented cattle manure at a total N, P and K rate of 300, 200 and 300 kg N ha^{-1} was applied as basal dressing in each of the two tomato seasons. For each N2 plot, N, P and K rate of 122, 103 and 221 kg ha^{-1} was applied in 2016 tomato and N, P and K rate of 216, 180 and 495 kg ha^{-1} was applied in 2017 tomato, in the form of urea, $Ca(H_2PO_4)_2{\cdot}H_2O$, and K_2SO_4, respectively. Both basal dressing was applied into the top 20 cm of soil through ploughing. No basal dressing was applied for each fertilizer treatment during the cucumber season. Differently, for top dressing applications in N1, the commercial organic fertilizer nutrient enhancing formulation (Nutrient Enhancing Balancer, Agmorinc. Inc, USA. organic ≥ 2.3 %, a total N rate ≥ 0.14 %, $P_2O_5 \geq 0.03$ %, $K_2O \geq 0.04$ %) was used for the 2016 tomato season, and another commercial organic fertilizer (Zaoshengjin, Qingdao Help Bioscience Co., Ltd. China. organic matter ≥ 280 g/L, a total N rate ≥ 60.1 g/L, $P_2O_5 \geq 1.0$ g/L, $K_2O \geq 44.4$ g/L) was used for the cucumber and 2017 tomato. These top dressed commercial organic fertilizers were used primarily not to add direct nutrient input, but to enhance the utilization of organic fertilizer in the soil. For N2 treatments, urea mixed with $Ca(H_2PO_4)_2{\cdot}H_2O$ and K_2SO_4 was used as top dressing for all the three seasons, and the fertilizer rate is shown in Table 1.

2.4. Data collection

Fluxes of N_2O and CH_4 were measured using the closed chamber method (Htun et al., 2017). An opaque chamber (50 × 50 × 50 cm) was placed in the center of north-south direction for each plot. Matched stainless-steel frames with a groove in the top were inserted in the soil at the depth of 10 cm at the beginning of the study, and chambers were hermetically closed using water in the groove to avoid gas leakage from the chamber (Htun et al., 2017). The gas chambers were closed only during the gas collection. Each chamber was equipped with a temperature sensor and an electric fan to homogenize the gas in the chamber. The temperature in the chamber was recorded by installing a temperature sensor inside the chamber (Digital thermometer, Yusong Electronic, China) before and after gas sampling, and the average of the two measurements was used to calculate gas fluxes by Eqs. (1)–(3).

Gas samples were taken via a rubber sampling port in the top of the chamber once a week before the first irrigation event for all the three growing seasons. Gas samples were collected on the second, fifth and tenth day after an irrigation event, between 0900 and 1100 h, during the 2016 tomato season (Lou et al., 2003). During the cucumber and 2017 tomato seasons, gas samples were collected in the morning before each irrigation event and then again at 2–5 days after the irrigation event. For each sampling event, gas samples were taken at 0, 15, 30, 45, and 60 min following chamber closure. Gas samples were analyzed for N_2O and CH_4 concentration using gas chromatography (Agilent 7890A, USA). The gas fluxes were calculated as follows:

$$F = (dc/dt) \times H \times M \times P/(R \times (273 + T)) \quad (1)$$

$$c = a + bt \ (dc/dt = b) \quad (2)$$

$$c = a + bt + dt^2 \ (dc/dt = b) \quad (3)$$

where, F is the gas flux (mg m^{-2} h^{-1}), c is the concentration of N_2O or CH_4 (mg L^{-1}), t is the time of chamber closure (h), dc/dt was derived according to the Eqs. (2) and (3), a, b, d are parameters derived from the

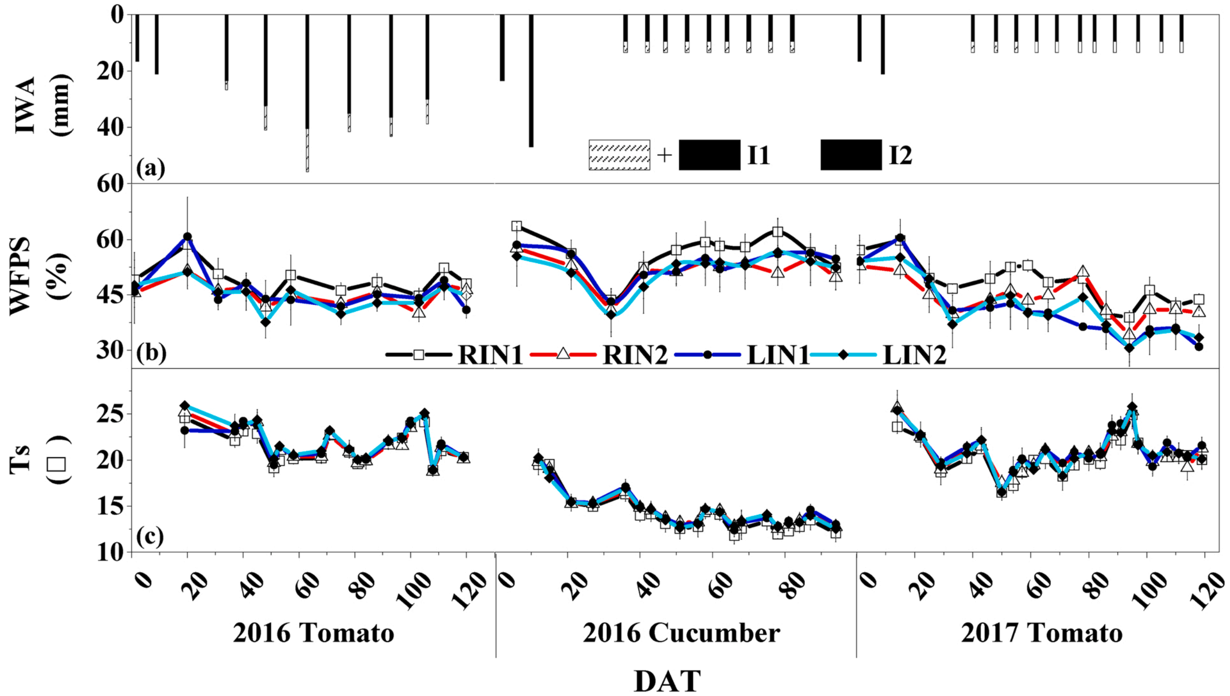

Fig. 1. Irrigation water amount (IWA, a), surface soil water filled pore space (WFPS, b) and soil temperature (Ts, c) over the tomato – cucumber – tomato rotation. Where: RIN1 is regular irrigation with organic fertilizer, RIN2 is regular irrigation with inorganic fertilizer, LIN1 is low irrigation with organic fertilizer, LIN2 is low irrigation with inorganic fertilizer, and DAT is days after transplanting. Data points represent mean value (n = 3) and the bar indicates one standard error to the mean.

Table 1

Fertilizer application rate for the organic and inorganic fertilizer types for each season. For organic treatments, fermented cattle manure was used as the basal application during the 2016 tomato and the 2017 tomato seasons and N, P, K fertilizer in the form of urea, $Ca(H_2PO_4)_2{\cdot}H_2O$ and K_2SO_4, respectively was applied for inorganic fertilizer during the three growing seasons.

Season	Organic Fertilizer Treatments (kg ha^{-1})						Inorganic Fertilizer Treatments (kg ha^{-1})					
	Basal dressing			Top dressing[a]			Basal dressing			Top dressing		
	N	P	K	N	P	K	N	P	K	N	P	K
2016 Tomato	300	200	300	1.4	<0.4	0	122	103	221	300	103	188
2016 Cucumber	-[b]	–	–	25.3	<0.4	15.5	–	–	–	300	150	450
2017 Tomato	300	200	300	31.6	<0.5	19.4	216	180	405	144	–	135

[a] Top dressing for the organic fertilizer treatment was with nutrient enhancer products, for tomato 2016 this was Nutrient Enhancing Balancer (NEB; organic matter $\geq$ 2.3 %, total N $\geq$ 0.14 %, $P_2O_5 \geq 0.03$ %, $K_2O \geq 0.04$ %) and for cucumber 2016 and tomato 2017 this was Zaoshengjin (organic matter $\geq$ 280 g/L, total N $\geq$ 60.1 g/L, $P_2O_5 \geq 1.0$ g/L, and $K_2O \geq 44.4$ g/L) for cucumber-2016 and tomato-2017. These were applied as organic nutrient enhancers rather than as direct nutrient supply.

[b] Not applied.

linear and nonlinear function for the relationship between gas concentration and time (Htun et al., 2017), H is the chamber height above soil (m), M is the molecular weight of N_2 in N_2O or of C in CH_4 (28 g N_2O-N mol^{-1}, 12 g CH_4-C mol^{-1}), P is the air pressure at the site (kPa), R is the universal gas constant (J mol^{-1} K^{-1}), T is the mean temperature (℃) in the chamber for each sampling.

Soil bulk density was measured at depths of 0–10 cm using a stainless steel corer including an open hollow cylinder (50.00 mm in ring depth and 50.46 mm in internal diameter) before transplanting in 2016. Soil temperature at 10 cm depth was measured before and after gas sampling with a geothermometer (TP101 Electronic Thermometer, Wuqiang, Hebei, China). Soil samples were taken at the soil surface (i.e. 0–10 cm) before and after each irrigation event for soil water content and soil mineral – N content (NO_3^--N and NH_4^+-N). Soil samples were collected for 11, 11 and 14 times during the 2016 tomato, 2016 cucumber and 2017 tomato season, respectively. The gravimetric method was used for soil water content measurement.

Soil water-filled pore space (WFPS) was calculated as follows:

$$WFPS(\%) = \frac{gravimetric\ water\ content\ (\%)}{1 - soil\ bulk\ density/2.65} \times soil\ bulk\ density \tag{4}$$

For soil mineral – N content, 10 g fresh soil was mixed with 1 M KCl, via shaking for 1 h, the slurry was then passed through a filter (ID:102, Fushun Civil Affairs Filter Company, Liaoning, China). Colorimetric determination of NO_3^--N and NH_4^+-N by using a continuous flow autoanalyzer (Auto Analyzer 3, Bran + Luebbe, SEAL Analytical GmbH, Germany). Soil samples were also collected from each plot at a depth of 5–30 cm for soil nitrobacteria, nitrosomonas and denitrifying bacteria abundance analyses at the flowering and fruit setting and fruit bearing and harvesting stages during the cucumber and 2017 tomato seasons.

To determine crop yield, twenty tomato or cucumber plants were randomly marked within each plot and mature tomatoes and cucumbers harvested from those plants. Harvesting was conducted every 3–5 days until all fruits on those marked plants were collected. Tomatoes and cucumbers were weighed immediately after harvesting, and yield for marked plants determined as the sum of the fresh weight. Then the vegetable yield for per ha was calculated according to the plant density.

Meteorological data inside the greenhouse including air temperature, solar radiation, relative humidity and air pressure were measured using an automatic weather station (Hobo, Onset Computer., USA).

2.5. *Cumulative gas emission, total greenhouse gas emission and greenhouse gas intensity calculations*

The seasonal cumulative emission of N_2O and CH_4 was calculated for each treatment according to:

$$CE = \sum\left[((F_i + F_{i+1})/2) \times 10^{-3} \times d \times 24 \times 10\right] \tag{5}$$

where, CE is seasonal cumulative emission (kg ha^{-1}) for each gas, F_i and F_{i+1} are the measured fluxes of two consecutive sampling days (mg m^{-2} h^{-1}), and d is the time interval between two adjacent sampling days.

The total GHG emission for both N_2O and CH_4 was derived as CO_2 equivalent according to Eq. (6) (Myhre et al., 2013):

$$GHGt = 265 \times CE_{(N_2O)} + 28 \times CE_{(CH_4)} \tag{6}$$

where, *GHGt* is the total greenhouse gas emission (kg CO_2-eq ha^{-1}).

Greenhouse gas emission intensity (GHGI) was calculated using Eq. (7):

$$GHGI = GHGt/yield \tag{7}$$

Where, *GHGI* is the total *GHGt* emission per unit of fresh vegetable yield (kg CO_2-eq ha^{-1} per kg yield).

2.6. *Statistical analysis*

ANOVA analysis was performed to compare the differences in soil variables, mean N_2O and CH_4 fluxes, CE of N_2O and CH_4, GHGt and GHGI during each growing season by a mixed model with irrigation (two levels), fertilizer (two types) and their interaction as fixed factors and block as random factor. Treatment means were separated using LSD test at the significance level of 0.05. Stepwise multiple linear regressions were conducted between log-transformed N_2O flux and CH_4 flux with soil WFPS, soil temperature and mineral-N content at a soil depth of 10 cm. The soil variables were determined for the day of gas collection using linear interpolation of the observed data either side of the day of interest. Statistical analyses were carried out using SPSS 20.0 (SPSS Inc., USA, 2011).

3. Results

3.1. *Soil water-filled pore space, soil temperature and soil mineral-N content at 0–10 cm soil*

No significant difference was found between treatments for soil variables during each growing season. Soil water-filled pore space in the soil top 10 cm ranged from 37.6 –60.8%, 39.6–63.4% and 30.6–60.5% during the 2016 tomato, cucumber, and 2017 tomato season, respectively (Fig. 1). WFPS generally decreased to the minima at the end of the seedling period due to the prolonged period without irrigation. Soil temperature at 10 cm depth ranged between 18.8 –25.9, 11.8–20.3 and 16.5–25.8 ℃ during the 2016 tomato, cucumber, and 2017 tomato season, respectively (Fig. 1). Soil NO_3^--N and NH_4^+-N content to 10 cm depth ranged from 9.0–154.5 and 0.8–5.6 mg kg^{-1} dry soil, respectively over the rotation, peaking at 20 and 31 DAT in the 2016 tomato season, respectively. Soil NO_3^--N and NH_4^+-N contents were 22.9 and 0.3 mg kg^{-1} lower, respectively during the cucumber season than the tomato seasons. On average, soil NO_3^--N and NH_4^+-N contents across the rotation were 35.2 mg kg^{-1} greater and 0.58 mg kg^{-1} lower, respectively in N2 than N1 treatments (Fig. 2).

3.2. Soil nitrobacteria, nitrosomonas and denitrifying bacteria

The temporal trend in abundance of soil nitrobacteria, nitrosomonas and denitrifying bacteria was similar between treatments (Fig. 3). The abundance all peaked during the late cucumber season. The soil nitrobacteria and nitrosomonas abundance was 0.63–9.94 and 1.27–10.00 times greater than soil denitrifying bacteria, respectively, while soil nitrobacteria abundance was 2.14 and 0.54 times that of soil nitrosomonas during the cucumber and 2017 tomato season, respectively. Abundance of nitrosomonas was significantly greater in RIN1 than RIN2 and LIN1 at the end of the rotation, although no significant differences were found between treatments for other occasions. Inorganic fertilizer application increased denitrifying bacteria abundance and the overlap of nitrobacteria and nitrosomonas abundance compared with organic fertilizer application, under RI condition in particular.

3.3. Greenhouse gas emission fluxes and relationship between fluxes and soil variables

Greater N_2O emissions often occurred following an irrigation or fertilization event (Figs. 1 and 4), and were typically associated with WFPS > 50 % and soil temperatures of 12–20 °C, as experienced during the cucumber season. Flux of N_2O peaked at 1.19 and 1.04 mg N_2O-N m^{-2} h^{-1} for RIN2 and LIN2, respectively at 37 DAT, which was 2 days after irrigation during the 2016 tomato season. There was a significant difference ($p < 0.001$) in mean N_2O flux between two fertilizer types during the 2016 tomato season, with 0.09 and 0.25 mg N_2O-N m^{-2} h^{-1} for organic fertilizer and inorganic fertilizer, respectively. Mean N_2O flux was 0.02 mg N_2O-N m^{-2} h^{-1} greater ($p < 0.05$) in RI than LI and the interaction of irrigation level and fertilizer type had significant effect on mean N_2O flux with RIN2 having the significantly higher value than other treatments during the 2017 tomato season. However, no significant difference between treatments was found during the 2016 cucumber season.

Methane fluxes were smaller during the two tomato seasons than the cucumber season, within the range of -0.70–0.05, -1.73–0.27 and -0.82–-0.01 mg CH_4-C m^{-2} h^{-1} for the 2016 tomato, cucumber and 2017 tomato, respectively (Fig. 4). During the cucumber season, the extremely higher CH_4 uptake along with lower WFPS occurred at 27 and 36 DAT, which was 17 and 26 days after an irrigation event. There was no significant difference between treatments during the 2016 tomato and cucumber seasons while the organic fertilizer had significantly greater uptake of mean CH_4 than the inorganic fertilizer treatments during the 2017 tomato season ($p < 0.05$).

The relationships between gas fluxes and soil variables were found to vary by fertilizer types. Soil WFPS was the only soil variable found significant in the regression model and explained 18.4 % of the N_2O fluxes variation for organic fertilizer application ($p < 0.001$), while the combined WFPS and soil NH_4^+-N content accounted for 25.5 % of the total N_2O fluxes variation ($p < 0.001$) for N2 treatments. For CH_4 uptake, soil temperature could explain the 13.0 % of the total variation with negative coefficient for organic fertilizer treatments. Meanwhile, the percentage of soil temperature and soil NO_3^--N combined in explaining the soil CH_4 variation was 18.6 % for inorganic fertilizer application (Table 2).

3.4. Total greenhouse gas emission and emission intensity

Cumulative N_2O emission was much lower for all treatments during the 2017 tomato season than the other two seasons, with RIN2 having the highest CE of 2.0 kg N_2O ha^{-1} (Fig. 5). Interaction of irrigation level and fertilizer type had no significant influence on CE of N_2O over the rotation. Fertilizer type significantly ($p < 0.001$) affected the CE of N_2O during the 2016 tomato season with ~ 4 times greater cumulative emission from N2 than N1. Inorganic treatment had greater CE of N_2O over the rotation than the organic treatment under both regular and low irrigation levels (8.8 ± 2.5, 20.4 ± 2.2, 8.2 ± 1.0, and 18.5 ± 2.4 kg ha^{-1} for RIN1, RIN2, LIN1, and LIN2, respectively).

The net CH_4 uptake by the soil ranged from 4.2 to 15.9 kg ha^{-1} over the entire rotation and was greater during the cucumber season than the two tomato growing seasons. There was no significant interaction of irrigation level and fertilizer type for CH_4 uptake during each growing season, but RIN1 generally had the highest uptake (Fig. 4). Organic fertilizer resulted in 3.6 kg ha^{-1} greater net CH_4 uptake than inorganic fertilizer treatments during the 2017 tomato season ($p < 0.05$) and net CH_4 uptake was greater for N1 than N2 by 6.9 kg ha^{-1} for the rotation

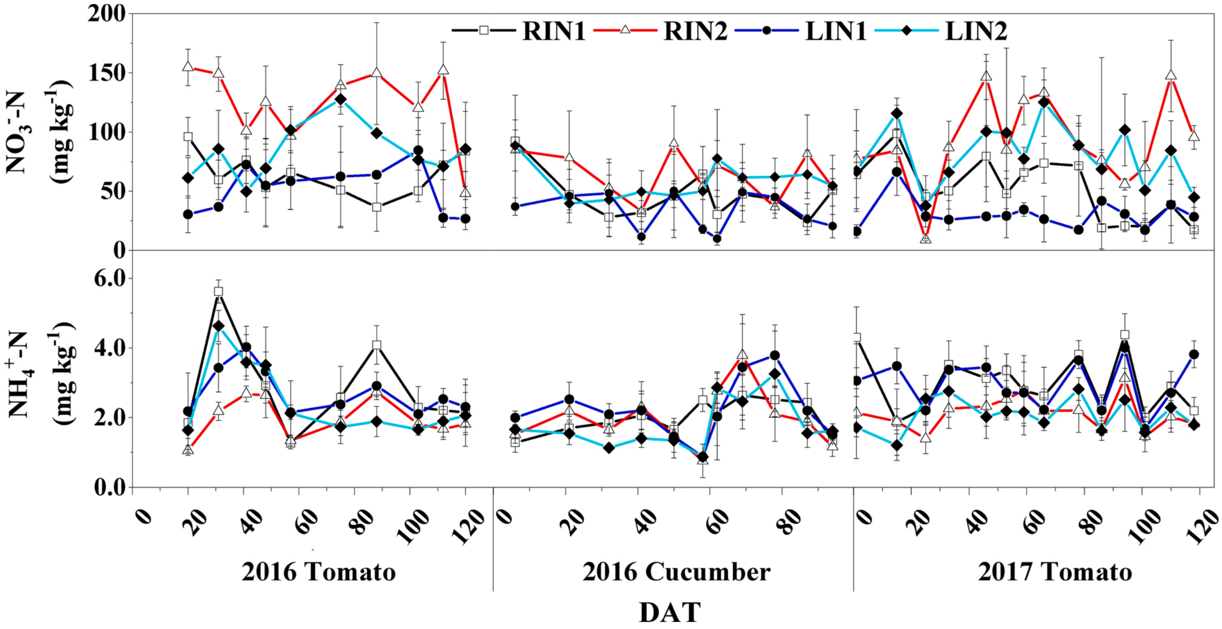

Fig. 2. Soil NO_3^--N and NH_4^+-N concentration (mg kg^{-1}) in 0 – 10 cm soil over the tomato – cucumber – tomato rotation. Where: RIN1 is regular irrigation with organic fertilizer, RIN2 is regular irrigation with inorganic fertilizer, LIN1 is low irrigation with organic fertilizer, LIN2 is low irrigation with inorganic fertilizer, and DAT is days after transplanting. Data points represent mean value ($n = 3$) and the bar indicates one standard error to the mean.

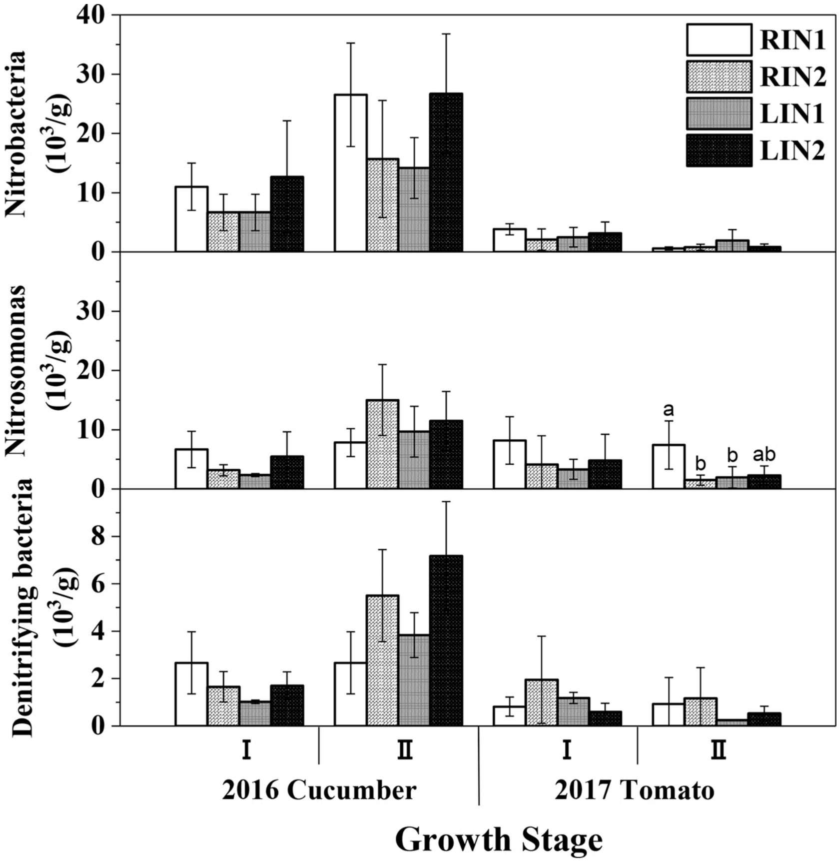

Fig. 3. Abundance of soil nitrobacteria, nitrosomonas and denitrifying bacteria under four treatments for the flowering and fruiting setting stage (I) and fruit bearing and harvesting stage (II) during the 2016 cucumber and 2017 tomato seasons. RIN1 is regular irrigation with organic fertilizer, RIN2 is regular irrigation with inorganic fertilizer, LIN1 is low irrigation with organic fertilizer, and LIN2 is low irrigation with inorganic fertilizer. Columns followed by different letters are significantly different at $p < 0.05$.

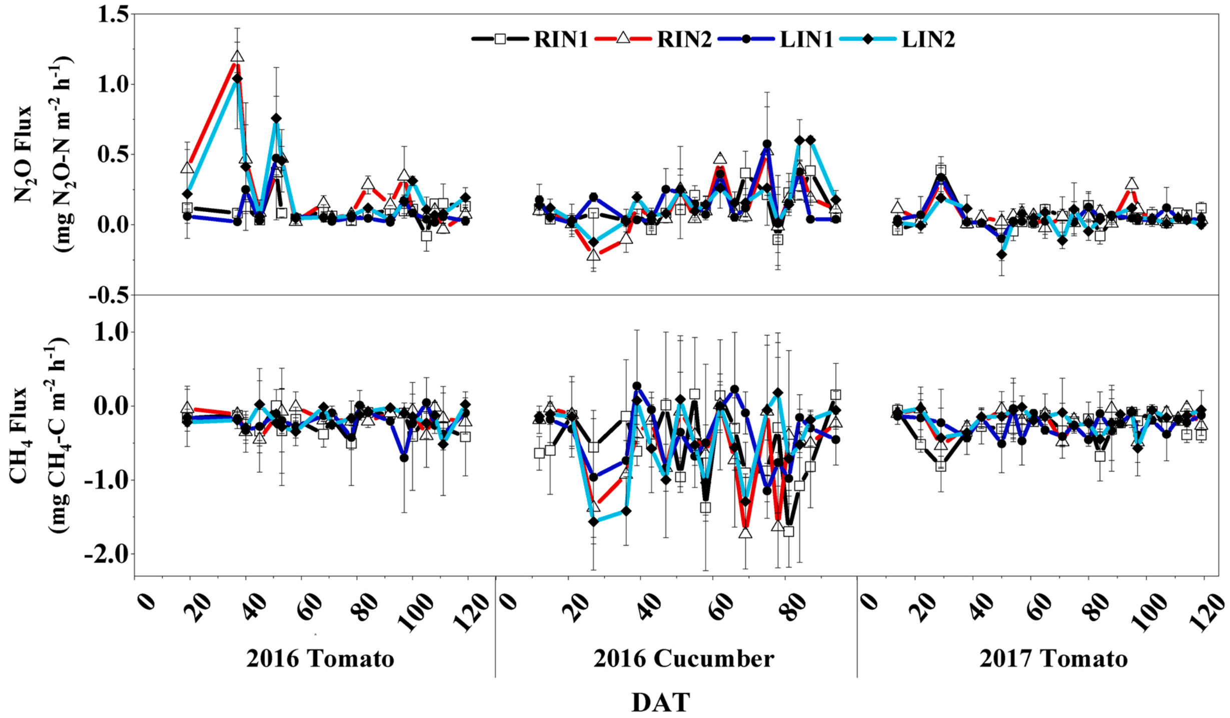

Fig. 4. N_2O and CH_4 fluxes during the 2016 tomato, 2016 cucumber and 2017 tomato seasons. RIN1 is regular irrigation and organic fertilizer, RIN2 is regular irrigation with inorganic fertilizer, LIN1 is low irrigation with organic fertilizer, LIN2 is low irrigation with inorganic fertilizer and DAT is days after transplanting. Data points represent mean value ($n = 3$) and the bar indicates one standard error to the mean.

Table 2
The stepwise multiple linear regression model for the two fertilizer types, to assess the effects of the soil environmental variables of water filled pore space (WFPS; %), soil temperature (Ts; ℃), soil NO_3^--N and NH_4^+-N concentration (mg kg^{-1}) on N_2O emission (mg N_2O-N m^{-2} h^{-1}) and CH_4 uptake (mg CH_4-C m^{-2} h^{-1}) fluxes. N1: organic fertilizer; N2: inorganic fertilizer.

GHG	Treatment	Regression Model	R^2	*p*
N_2O	N1	$Y(logN_2O) = 0.023 * WFPS - 2.197$	0.184	<0.001
	N2	$Y(logN_2O) = 0.037 * WFPS + 0.229 * NH_4^+\text{-N} - 3.238$	0.255	<0.001
CH_4	N1	$Y(CH_4) = -0.029 * Ts + 0.876$	0.130	<0.001
	N2	$Y(CH_4) = -0.027 * Ts - 0.003 * NO_3^-\text{-N} + 1.010$	0.186	<0.001

(Fig. 5). Besides, regular irrigation level led to greater CH_4 uptake than low irrigation level treatment by 7.3 kg ha^{-1} over the rotation.

The yield comparison between the four treatments could be found in Fan et al. (2020). Briefly, organic fertilizer with regular irrigation level resulted in the greatest yield for the three growing seasons although the difference between treatments was not significant ($p > 0.05$). The GHGt for the entire rotation and averaged GHGI across the three growing seasons of the four treatments followed the same order of RIN2 > LIN2 > LIN1 > RIN1 (Fig. 4). Over the three growing seasons, GHGt ranged from 31 to 3590 kg CO_2-eq ha^{-1} and GHGI ranged from 0.0002 to 0.0258 kg CO_2-eq ha^{-1} per kg of yield across all treatments. The main factor of irrigation and the interaction of irrigation level and fertilizer type were found insignificant during each of the three seasons. During the 2016 tomato season, GHGt and GHGI were significantly greater ($p < 0.001$) for N2 than N1 treatments, with the difference between N2 and N1 larger than 2805 kg CO_2-eq ha^{-1} and 0.0214 kg CO_2-eq ha^{-1} per kg of yield, respectively. During the 2016 cucumber season, GHGt was similar for all treatments, ranging from 702 to 1036 kg CO_2-eq ha^{-1}, and the averaged GHGI across four treatments was 0.0114 ± 0.0023 kg CO_2-eq ha^{-1} per kg of yield. Both GHGt and GHGI was largely reduced during the 2017 tomato season with RIN2 having the greatest GHGt and GHGI, 341 kg CO_2-eq ha^{-1} and 0.0028 kg CO_2-eq ha^{-1} per kg of yield, respectively.

4. Discussion

4.1. N_2O emissions and CH_4 uptake over the rotation

Soil N_2O emission was less than 0.3 mg N_2O-N m^{-2} h^{-1} for 90 % of sampling occasions throughout the rotation, which was in the range reported in previous studies. Hou et al. (2016) and Chen et al. (2018) both reported that N_2O emissions reached 0.3 mg N_2O-N m^{-2} h^{-1} under greenhouse tomato cultivation and N_2O fluxes were < 1.2 mg N_2O-N m^{-2} h^{-1} in field crops, such as maize, soybean and wheat, with different fertilizer and tillage management (Baggs et al., 2003; Meng et al., 2004; Ozlu and Kumar, 2018). However, N_2O peaks of > 2.5 mg N_2O-N m^{-2} h^{-1} were reported in a furrow-irrigated tomato field, with the extreme peaks occurring at the early stage of the tomato growing season (Venterea and Rolston, 2000). A peak of 1.2 mg N_2O-N m^{-2} h^{-1} was observed under the N2 treatment at 37 DAT, following irrigation and fertilizer application at 35 DAT. Similarly, Scheer et al. (2008) observed that the greatest N_2O flux of 3.0 mg N_2O-N m^{-2} h^{-1} occurred following an ammonium nitrate application and an increase in WFPS from 25 to 85 % in an irrigated cotton field.

The soil in our study was a CH_4 sink, with positive CH_4 fluxes occurring sporadically, as observed in previous studies. Methane fluxes

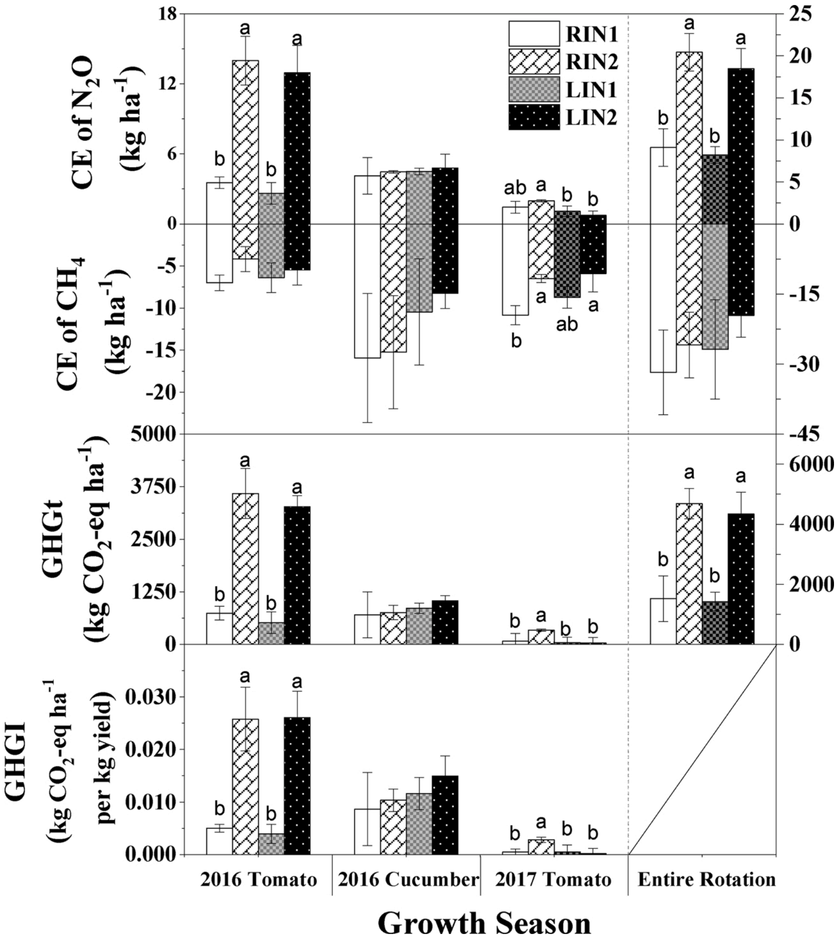

Fig. 5. Seasonal cumulative emissions (CE) of N_2O and CH_4 (kg ha^{-1}), GHGt (kg CO_2-eq ha^{-1}), and GHGI (kg CO_2-eq ha^{-1} per kg yield) under four experimental treatments for the 2016 tomato (101 sampling days), 2016 cucumber (83 sampling days) and 2017 tomato seasons (106 sampling days), and for the entire rotation. RIN1 is regular irrigation with organic fertilizer, RIN2 is regular irrigation with inorganic fertilizer, LIN1 is low irrigation with organic fertilizer, and LIN2 is low irrigation with inorganic fertilizer. Columns followed by different letters are significantly different at $p < 0.05$.

ranging from -0.4 to 0.2 mg CH_4-C m^{-2} h^{-1} were generally negative for lupin, wheat, potato and tomato field crops, whilst positive CH_4 fluxes were occasionally observed due to high soil moisture (Wang et al., 2015; Htun et al., 2017; Meng et al., 2020). In the current study, CH_4 uptake fluxes < 0.4 mg CH_4-C m^{-2} h^{-1} were found more than 90 % occasions during the two tomato seasons. However, the abnormal higher CH_4 uptake fluxes were recorded during the cucumber season, at ~ 30 DAT and ~ 70 DAT in particular, which was associated to the lower WFPS and relatively higher soil temperature (Fig. 1, b–c). Many studies suggested that soil CH_4 uptake was positively correlated with soil temperature, but negatively correlated with soil moisture (Liu et al., 2016; Meng et al., 2020). Besides, low mineral-N content during the season (no basal dressing) might be another contributing factor to the unusually large CH_4 uptake fluxes. Low soil mineral-N content was found to favor the CH_4 absorption (Song et al., 2017). On the other hand, particular growing environment inside the greenhouse (relatively high humidity and temperature) and agricultural management practices (multiple harvests in a season) could also contribute to a much different CH_4 uptake pattern inside a greenhouse from the open field of staple grain crops such as rice, maize and wheat, where most of previous studies were conducted. Few studies on gas emissions of solar greenhouse tomato – cucumber – tomato cropping systems have been reported, especially under the winter climate, and further study on the CH_4 uptake pattern and associated mechanisms under such environmental conditions is needed.

In addition, the higher CE of N_2O and cumulative CH_4 uptake in our study than in others could be due to the higher frequency of gas collection and the longer growing (and monitoring) period than those of other studies (Hou et al., 2016; Han et al., 2017; Chen et al., 2018). Some studies did not capture the gas emissions at the vegetable seedling stage or early stage of the blooming and fruit setting stage (Hou et al., 2016). He et al. (2009) suggested that with infrequent sampling, N_2O and CH_4 peaks may be missed, which will greatly influence cumulative gas emission or uptake estimation.

4.2. Comparisons of N_2O emission between fertilization treatments

By influencing the N_2O producing processes, fertilizer application had great influence on N_2O flux and its cumulative emissions during each growing season, with fertilizer N rate being the most important factor when the difference in N rate between treatments was larger than ~ 30 kg ha^{-1} in this study. The much higher N_2O emission for inorganic fertilizer treatment during the 2016 tomato season and consequently the total cumulative emission was largely due to the larger N rate in the inorganic fertilizer treatment, relative to organic treatment. Laville et al. (2011) reported that N_2O fluxes were positively correlated with the soil N content in an arable crop rotation. Meanwhile, N_2O emission in N2 treatments was greatly reduced in the 2017 tomato season when N application rate was reduced, relative to 2016 tomato season. With the similar N application rate and relatively dry soil condition during the tomato 2017 season, N_2O emission was similar between N1 and N2 treatments. The significant difference in nitrosomonas abundance indicated that the major pathways for N_2O emission might be different between N1 and N2 treatments. Vallejo et al. (2006) reported that the proportion of N_2O produced from nitrification was higher in urea application than organic fertilizer with the WFPS and soil temperature in the range of 50–85% and 3–24 ℃, respectively. Cui et al. (2016) reported that denitrification contributed 80 and 40 % to total N_2O emission for long-term organic manure and mineral fertilizer treatments, respectively, although the soil condition might not be fully favorable for anaerobic denitrification (the soil variables during the 2017 tomato season fluctuated within the range of these studies).

However, it was worth noting that higher N input rate from inorganic fertilizer treatment did not lead to much larger N_2O emission during the cucumber season. We speculate that relatively higher WFPS during the season might modify the relationship of larger N input leading to greater N_2O emission. A previous study has shown that higher WFPS could stimulate denitrification, and the effect was more pronounced for organic fertilizer treatments than urea application (Vallejo et al., 2006). Tao et al. (2018) indicated that organic fertilizer input could increase denitrifying bacterial enzyme activity by about 14–56 % in a drip-irrigated soil. Therefore, the much enhanced denitrification activity in N1 than N2 might overcome the gap of potentially larger N_2O emission from high N input of N2 treatments, leading to the similar cumulative N_2O emission between these two fertilizer type treatments during the cucumber season. In the study, no significant correlation was found between N_2O emission with nitrobacteria, nitrosomonas, and denitrifying bacteria abundances indicated that the differences in specific bacterial abundance might not be precise indicators for estimating the difference in soil N_2O emission. Dandie et al. (2008) noted that denitrifier abundance was not consistently related to denitrification rates as well as N_2O emission. Therefore, the processes of nitrification and denitrification associated with functional microorganisms communities may contribute substantially to N_2O production in soils and the relative importance of those processes could be influenced by the soil properties. The mechanisms related to soil N_2O emission in agricultural fields with wide spectrum of soil properties, especially soil organic matter, nutrients, water content and temperature, need further study.

4.3. Influencing factors for CH_4 uptake

Organic fertilizer with lower N input resulted in the greater cumulative CH_4 uptake than inorganic fertilizer treatments in the current study, which was consistent with a research conducted in the same region using the same fertilizers. Meng et al. (2020) reported that about 1.1–2.1 times higher cumulative CH_4 absorption was found in manure than chemical NPK fertilizer-amended potato field when the N input rates were same for these two fertilizer types. Inorganic fertilizer provides a reactive N source, which inhibits CH_4 oxidation by promoting ammonium oxidizers (Wang et al., 2011; Krause et al., 2013). Inorganic N application was more likely to stimulate methanotrophs to oxidize NH_4^+, instead of CH_4 (Acton and Baggs, 2011). As a result, weaker CH_4 oxidization in inorganic fertilizer treatments likely led to a lower CH_4 uptake, relative to organic fertilizer treatments. For CH_4 consumption, previous studies have generally recognized that CH_4 was oxidized under aerobic soil environment and the CH_4 uptake rate was found to decrease with greater soil moisture and increase with increasing soil temperature (Liu et al., 2016; Meng et al., 2020). However, CH_4 uptake fluxes showed very little response to the changes in WFPS during each growing season in this study, while soil temperature was negatively associated with CH_4 uptake for the two fertilizer treatments. This discrepancy might be attributed to the interaction between soil water content, temperature and mineral-N content. For RI, soil mineral-N was lower in 0–10 cm soil since more soil mineral-N moved to deeper soil with larger water amount application, relative to LI. Meanwhile, higher water content was often associated with lower temperature. The intertwined relationship between these soil variables makes it difficult to interpret the correlation between CH_4 uptake with a single soil variable. Previous studies reported that accumulated mineral-N in topsoil could reduce the oxidation activities in a soybean-barley rotation system (Yonemura et al., 2014), maize field (Liu et al., 2016) and lupin-wheat rotation (Barton et al., 2013). Regular irrigation level treatments with lower soil mineral-N, higher WFPS and lower soil temperature could therefore lead to greater CH_4 uptake.

4.4. GHGt and GHGI mitigation strategies

As expected, CE of N_2O was the dominant component for GHGt and GHGI in this study, as found in other studies conducted in agricultural soils in semi-arid regions (Del Grosso et al., 2000; Mosier et al., 2006). The higher GHGt and GHGI in RIN2 and LIN2 was largely attributed to the increased N_2O emission under the inorganic fertilizer treatments.

For the inorganic fertilizer treatments, a 16 % reduction in N fertilizer rate, 37 % reduction in water application and an increase in irrigation frequency for the 2017 tomato season, relative to the 2016 tomato season, led to a decrease in N_2O production by > 80 %. Reducing N fertilizer application by 75 % led to a 51 and 25 % reduction in GHGt and N_2O respectively in a double-cropping cereal rotation (Huang et al., 2013), while another study found that a stable, moderate soil moisture had lower N_2O emission rates compared with distinct wetting and drying cycles in a tomato field (Kallenbach et al., 2010). Consequently, reducing the fertilizer rate and maintaining moderate and stable water content by increasing the irrigation frequency (but not the volume) is a useful way to reduce global warming potential. On the other hand, applying organic fertilizer with less N rate did not reduce crop yield, but resulting in much lower GHGt and GHGI in the study. Therefore, adopting organic fertilizer could be an effective alternative for reducing GHG emissions and alleviating global warming potential without compromising crop yield.

5. Conclusions

Soil acted as a strong source and sink for N_2O and CH_4 within the range of -0.22–1.19 mg N_2O-N m^{-1} h^{-1} and -1.73–0.27 mg CH_4-C m^{-1} h^{-1} respectively, in a tomato – cucumber – tomato rotation in a solar greenhouse in northwest China. The selected soil variables of WFPS, soil temperature and mineral-N content explained 13.0–25.5% N_2O and CH_4 fluxes variation, and the regression model between gas fluxes with the soil variables varied between two fertilizer types. Soil mineral-N content was found to be significant for inorganic fertilizer treatments in the regression model for both gas fluxes, but insignificant for organic fertilizer treatments. The difference of cumulative N_2O emission and CH_4 consumption between treatments was largely determined by fertilization instead of irrigation level. High N application rate was the primary factor leading to a higher N_2O emission. The different N_2O production pathways was also a potential factor resulting in N_2O emission variations between the two fertilizer types. The relative importance of the pathways in producing N_2O fluxes could be affected by soil environmental conditions, e.g. soil water content. Higher soil mineral-N content in inorganic fertilizer usually led to lower cumulative CH_4 absorption than organic fertilizer during each of the three seasons. Overall, the inorganic fertilizer treatment led to larger GHGt and GHGI than organic fertilizer treatments for the rotation. Therefore, organic fertilizer application with an appropriate irrigation level is recommended as a strategy for maintaining high yields while reducing the environmental risks in global warming potential in a drip-irrigated vegetable rotation cultivation on the Northwest China.

Declaration of Competing Interest

The authors report no declarations of interest.

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