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Preliminary N_2O Emissions of Major Vegetable Cropping Systems in Peri-urban Hanoi, Vietnam

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Abstract

Crop management practices in intensive vegetable production can influence nitrous oxide (N_2O) emissions from soils. This study quantified seasonal N_2O emissions and N_2O emission intensities, and investigated the factors driving emissions in different vegetable management practices. Emissions from four typical vegetable crops (two choy sums, a mustard, and a cabbage) were intensively measured over the 2016 autumn season on farms in Van Noi and Dang Xa communes in the Hanoi peri-urban area. Different N_2O emissions were observed in the four leafy vegetable crops. The average daily emissions varied from 12.15 g to 40.08 g N_2O-N ha^{-1} and the autumn season N_2O emissions varied from 1.13 kg to 8.45 kg N_2O-N ha^{-1} across the four crops. The greatest daily and season emissions were from cabbage, and the lowest were from mustard. Emission intensities varied among the types of vegetables and was the lowest at the mustard farm (37 kg CO_2-e t^{-1}), indicating that the crop management practices increased the mustard yield but retained a low N_2O emission rate. Practices responsible for high N_2O emissions were overuse of nitrogen fertilisers and furrow irrigation. An improvement in the farmers' adoption of best practices in fertiliser application and irrigation could reduce N_2O emissions without affecting crop productivity.

Keywords

N_2O emissions, vegetables, crop management practices, Hanoi peri-urban, nitrogen fertilisers.

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Introduction

Methane and nitrous oxide have global warming potential indexes relative to carbon dioxide of 25 and 298, respectively

(IPCC, 2014). Agricultural activities are responsible for 84% of global N_2O emissions (Smith, 2008). Globally, vegetable production is estimated to contribute 9.5×10^7 kg N_2O-N yr^{-1} (Rashti *et al.*, 2015a). Average N_2O emissions in subtropical climates have been measured at 1.6-1.9 kg N ha^{-1} yr^{-1}, and 0.8-0.9 kg N ha^{-1} yr^{-1} in temperate climates (Bouwman *et al.*, 2002; Stehfest & Bouwman, 2006). Vegetable production in the United States has been shown to contribute the highest N_2O emissions at the rates of 6.5-8.5 kg N_2O-N yr^{-1} (Mummey *et al.*, 1998). Dryland crops including vegetables account for 30% of total greenhouse gas emissions (mostly N_2O) from the agricultural sector in Vietnam (Ministry of Natural Resources and Environment, 2014).

Crop management practices affect N_2O emissions. Intensive vegetable cropping practices including high rates of nitrogen fertiliser, frequent irrigation, and tillage practices, combined with planting short-term crops with multiple harvests, all contribute to N_2O emissions (Rashti *et al.*, 2015a). These factors are not yet well understood for vegetable cropping systems in some developing countries, including Vietnam (Chapuis-Lardy *et al.*, 2007), making the estimation and mitigation of N_2O emissions difficult.

The Hanoi peri-urban region is an important area for vegetable production in Vietnam, with around 40 different vegetables grown on 12,000 hectares of agricultural land, accounting for 31% of agricultural production in the Hanoi area (Tam, 2016). Vegetable production in this region is likely to increase (Everaarts *et al.*, 2015) because vegetable production has higher returns per hectare to growers compared to rice or other crops (Ha, 2008). The increasing consumer demand for vegetables from the major city of Hanoi provides opportunities for vegetable producers in the Red River Delta (Huong *et al.*, 2013).

Farms in this region are small, with an average size of 2,360m^2 (Van Hoi *et al.*, 2009). High demand for vegetables in Hanoi has resulted in intensive vegetable production of four to eight vegetable crop seasons a year with relatively short fallow periods (Huong *et al.*, 2013; Everaarts *et al.*, 2015). The intensive vegetable production systems are supported by a high level of inputs, especially nitrogen fertilisers, potentially resulting in high N_2O emissions (Mosier & Kroeze, 2000; Stehfest & Bouwman, 2006).

Studies of agricultural greenhouse gas emissions and their driving factors are limited in Vietnam. There are some studies on greenhouse gas emission in rice crops (Oo *et al.*, 2013; Pandey *et al.*, 2014; Thu *et al.*, 2016; Trinh *et al.*, 2017), which focused primarily on methane (CH_4) in paddy fields with flooded conditions. No publications of GHG emissions from vegetable production have been found by the author in Vietnam. There are no N_2O flux data from vegetables in Vietnam, so the contribution of vegetable crops to the emissions budget is unknown.

In addition, given the paucity of greenhouse gas data for the horticulture sector (Huang *et al.*, 2012; Rowlings *et al.*, 2013), there is a need to determine which management practices can reduce total greenhouse gas emissions while maintaining productivity. Using emission intensity as an indicator could encourage better practices to optimise crop yields and reduce emissions in order to achieve the global climate change goal of low carbon agriculture (Norse, 2012). Emission intensity is the whole crop N_2O emissions per unit of crop yield and can be used to compare the emission impacts of different agricultural practices (Groenigen *et al.*, 2010). It is an indicator for the evaluation of nitrogen use efficiency and identification of greenhouse gas emission mitigation strategies (Chen *et al.*, 2011; Venterea *et al.*, 2011).

To address this research gap, this study measured N_2O emissions and calculated N_2O emission intensities from intensive production of three different vegetables across four farms in peri-urban Hanoi. Management practices influencing N_2O emissions were examined to develop recommendations to reduce N_2O emissions.

Materials and Methods

Field gas measurements were conducted. Nitrous oxide emissions (N_2O) were measured in a small number of crops across four farms to identify some of the factors causing variations in emissions.

Research area

The research was conducted in two peri-urban areas: Van Noi commune in Dong Anh District and Dang Xa commune in Gia Lam District in Hanoi, Vietnam (**Figure 1**). These locations are typical vegetable production regions, supplying vegetables to a population of around 7.8 million in Hanoi city. The Van Noi commune has about 120ha of vegetable production land, of which 60ha is for intensive production (People's Committee of Van Noi Commune, 2015). The Dang Xa commune has 45ha of vegetable production land, which was previously used for rice production (People's Committee of Dang Xa Commune, 2015).

The annual rainfall of Hanoi is approximately 1700-1900mm, mainly from May to September. The average annual temperature is 23-24°C. The average maximum temperature in summer/autumn is 30°C and the average minimum in winter/spring is 12.5°C (Bureau of Meteorology in Vietnam during 2010-2015).

A survey of 30 farmers in each commune was conducted to characterise their crops growing at the time of the survey. The results are shown in **Table 1**.

Most of the farmers in Van Noi planted mix leafy vegetables such as flower choy sum and mustard, while most of the farmers in Dang Xa preferred cabbage and mustard in the autumn season (**Table 1**).

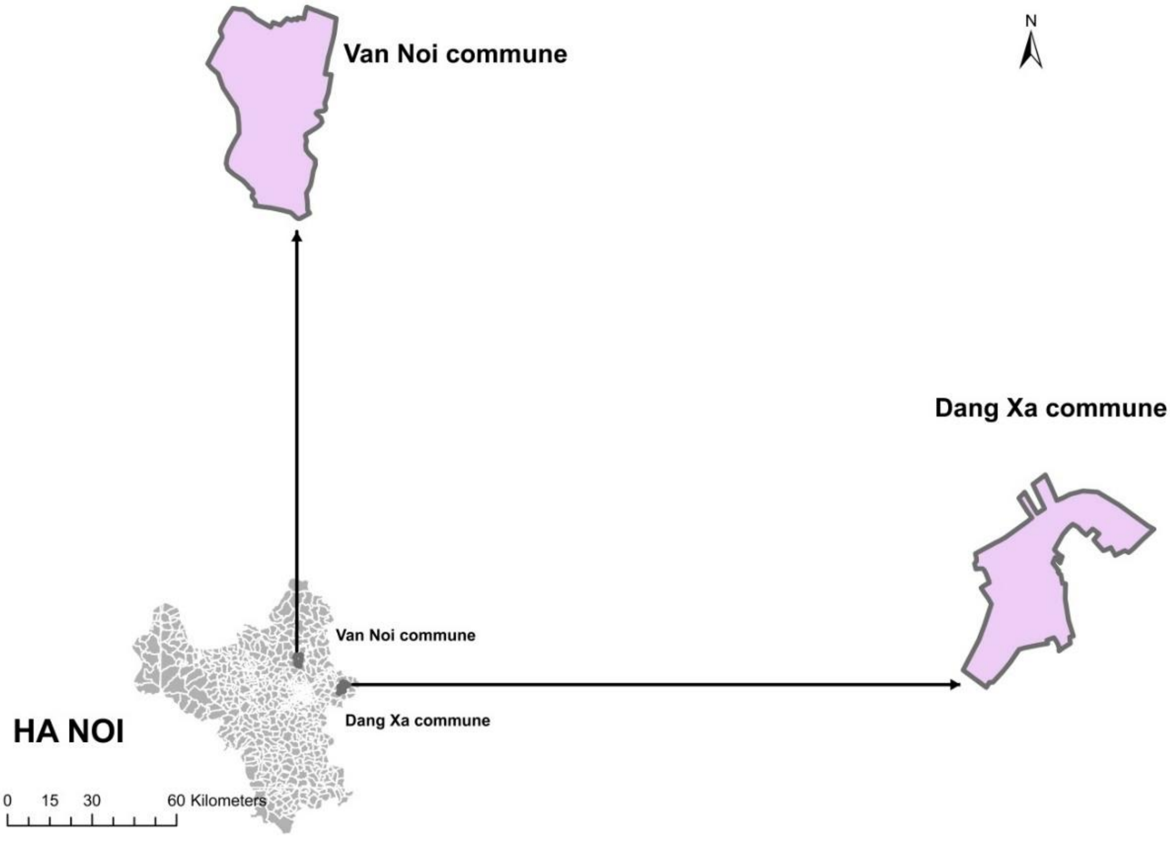

Figure 1. The study area maps of Van Noi and Dang Xa communes, Hanoi, Vietnam

Table 1. Farm vegetable production in Van Noi and Dang Xa

Commune	Crop name	Number of growers	Number of plots	Total area (m^2)	Crop yield (kg $ha^{-1}season^{-1}$)
Van Noi (n = 30)	Flower choy sum	5	7	1.104	1.410
	Mustard	6	6	1.792	1.825
	Luffa	2	2	620	1.700
	Malabar nightshade	7	7	1.752	7.015
	Mixed crops*	10	13	7.664	16.030
Dang Xa (n = 30)	Cabbage	17	29	20.740	64.850
	Flower choy sum	6	14	5.680	7.465
	Mustard	20	23	9.228	10.516
	Luffa	6	9	3.456	16.550
	Malabar nightshade	1	1	360	1.120
	Mixed crops*	5	12	4.432	4.625

*Note: *Mixed crops means growing more than two crops in the same plot.*

Two villages were selected from each commune. In each of the four villages, one farm was selected for N_2O emission measurement. These farms were selected because they grew common vegetable species (choy sum, mustard, and cabbage) and represented the typical alluvial soil type in this region. Gas measurements were taken from one vegetable crop on each farm, with cabbage and mustard from one farm each and choy sum from the other two farms.

Farmer crop management

The farms in Dang Xa were cultivated using small tractors and in Van Noi, hand hoes were used prior to bed forming. In Dang Xa, choy sum was sown on September 15, 2016 and harvested 28 days later, and cabbage (KK cross) was transplanted on September 20, 2016 and harvested 70 days later. In Van Noi, choy sum was sown on 5 October 2016 and harvested 24 days later, and mustard was sown on October 7, 2016, and harvested 23 days later. The mustard and the two choy sum crops were established at densities of 500,000 plants ha^{-1} and cabbage at 30,000 plants ha^{-1}.

Immediately following planting, furrow irrigation was applied until the beds were fully wet. There were no significant rainfall events (>30mm) during the study period. The amounts of nitrogen fertiliser and water supplied across the four farms were 215 kg N ha^{-1} and 0.8 million litres ha^{-1} for choy sum in Dang Xa; 408 kg N ha^{-1} and 1.6 million litres ha^{-1} for cabbage; 110 kg N ha^{-1} and 1.1 million litres ha^{-1} for choy sum in Van Noi; and 105 kg N ha^{-1} and 1.0 million litres ha^{-1} for mustard.

N_2O emission measurements

Nitrous oxide emissions were measured using static non-flow through chambers (diameter 243mm; height 205mm; installed volume of 7.3L). The four round, polyvinyl chloride (PVC) chambers were installed randomly in the centre of raised beds at each farm (**Figure 2**). There were two holes in each chamber lid to insert a syringe needle for sampling and a thermometer to record the temperature at the sampling time. A rubber seal was attached to the cover of the head space to avoid the exchange of gases between the inside and the outside of the chamber during sampling. The chambers remained in place for the entire sample period of September to November 2016 to measure emissions.

Gas samples were taken at critical stages of management activities including soil cultivation, rainfall and/or irrigation, and fertiliser applications in the crop growth period. N_2O samplings were conducted eight times at each farm from September 13 to October 30, 2016. **Table 2** shows the schedule of gas samplings and major farm activities.

Table 2. Gas sampling schedule following farming management events

Date	Choy sum in Dang Xa	Date	Cabbage in Dang Xa
September 13	Gas sampling + pre-tillage	September 19	Gas sampling + pre-tillage
September 15	Tillage + sowing + fertiliser + gas sampling	September 20	Tillage + transplanting + hand watering + gas sampling
September 19	Hand watering + gas sampling	September 23	Furrow irrigation + gas sampling
September 21	Furrow irrigation + gas sampling	September 27	Hand watering + gas sampling
September 27	Nitrogen fertiliser + gas sampling	September 30	Furrow irrigation + gas sampling
September 29	Nitrogen applied + hand water + gas sampling	October 4	Nitrogen applied + hand watering + gas sampling
October 11	Furrow irrigation + gas sampling	October 14	Weeding + dry soil + gas sampling
October 13	No watering + gas sampling	October 20	Urea applied + gas sampling
October 13	Harvesting	November 30	Harvesting
	Mustard in Van Noi		Choy sum in Van Noi
September 28	Gas sampling + pre-tillage	September 28	Gas sampling + pre-tillage
October 7	Tillage + sowing + furrow irrigation + gas sampling	October 5	Tillage + sowing + furrow irrigation + gas sampling
October 11	Furrow irrigation + gas sampling	October 11	Furrow irrigation + gas sampling
October 14	No watering + gas sampling	October 14	No watering + gas sampling
October 21	No watering + gas sampling	October 19	Fertiliser applied + watering + gas sampling
October 21	Watering + fertiliser applied + gas sampling	October 21	Furrow irrigation + gas sampling
October 25	Furrow irrigation + gas sampling	October 25	Fertiliser applied + watering + gas sampling
October 28	No watering + gas sampling	October 28	No watering + gas sampling
October 29	Harvesting	October 30	Harvesting

(A) (B)

Figure 2. Experimental chamber positions at (A) the cabbage and (B) flower choy sum farms (the chamber position designs were identical for the other two farms)

Gas samples were collected between 9am to 2pm at 0, 30, and 45 minutes after the lids were sealed using a 25mL gas-tight syringe (SGE, 25MDR-LL-GT), and introduced into pre-evacuated 5mL Exetainer vials with grey silicon septa (Labco, UK). In addition, the chamber temperature was measured during sampling using a TP 3001 digital thermometer. Gas samples were immediately taken to the Institute of Agriculture and Environment in Hanoi Vietnam for gas analysis.

N_2O emission calculation

The nitrous oxide flux rate, F_{N2O} (μg N_2O-N m^{-2} h^{-1}), was calculated using the following equation (Scheer *et al.*, 2014a):

$$F_{N_2O} = \frac{b \times V_{CH} \times MW_{N_2O-N} \times 60 \times 10^6}{A_{CH} \times MV_{corr} \times 10^9}$$

where b is the increase in concentration [ppb/min]; V_{CH} is the volume of the measuring chamber (m^3); MW_{N2O-N} is the molecular weight of N_2O-N [28 g mol^{-1}]; 60 converts minutes to hours and 10^6 converts g to μg; A_{CH} is the basal area of the measuring chamber (m^2); 10^9 converts ppb to mL m^{-3}; and MV_{corr} is the pressure and temperature-corrected molecular volume [m^3 mol^{-1}];

$$MV_{corr} = 0.02241 \times \left(\frac{273.15 + T}{273.15} * \frac{P0}{P1}\right)$$

where MV_{corr} is defined above; T is the air temperature during the measurement (Kelvin); P0 is the air pressure at sea level and P1 is the air pressure at each farm with air pressure at each farm estimated from the height above sea level using a barometric equation; and 0.02241m^3 is the molar volume (Aylward & Findlay, 1974).

Daily N_2O fluxes (g ha^{-1} day^{-1}) from each farm were calculated by averaging the hourly fluxes for each chamber before averaging the four chambers and then multiplying the N_2O emission data by 24 (hours) and 10,000 (m^2). Cumulative autumn season N_2O fluxes (kg N_2O ha^{-1}) for each vegetable farm were calculated by summing the daily N_2O fluxes (kg N_2O-N ha^{-1}) over the measurements of the study period of September to November 2016. Gaps in the dataset due to missing measurement days were filled by linear interpolation between data points.

Total vegetable yields were determined by weighing the total fresh leaves for choy sum and mustard, and the heads for cabbage from each farm when they were harvested.

The emission intensity of each vegetable was calculated as the ratio of cumulative N_2O emissions *1.57 (1.57 is the conversion factor N_2O-N to N_2O based on molar mass) in relation to the fresh yields harvested. Direct N_2O emissions were converted to carbon dioxide equivalents (CO_2-e) within a 100-year horizon by multiplying by a radiative forcing potential equivalent to CO_2 of 298 (IPCC, 2014):

$$\text{Total } CO_2\text{-eGWP} = 298 \times \text{cumulative } N_2O$$

where eGWP refers to the global warming potential in CO_2-equivalent.

Yield-scaled emissions (CO_2-e t^{-1}) were calculated by dividing annual N_2O emissions (CO_2-e ha^{-1} $year^{-1}$) by the fresh yields of each vegetable (ton ha^{-1}) (Wang *et al.*, 2015).

$$\text{Emission intensity (kg tons)} = \frac{\text{Total } CO_2\text{-eGWP (kg ha}^{-1}\text{)}}{\text{Vegetable fresh yields (tons ha}^{-1}\text{)}}$$

Rainfall and its distribution over the study period were collected from the weather station closest to the study communes.

Soil sample collection

Soil samples for evaluation of variations of soil organic carbon, nitrogen availability, and bulk density were collected at two depth levels: 0-15 and 15-30cm at three random sites in each plot. Thirty farms were selected for soil samplings to represent the two communes and different soil types. Soil samples were mixed among the three site samples in order to analyse total organic carbon and nitrogen availability (NH_4^+ and NO_3^-). Moreover, six bulk density soil samples were taken from three holes of each farm at the two soil depth levels, resulting in a total of 180 soil samples for bulk density. The samples were collected at the fallowed soil period prior to the next season when other subsequent crops were planted in order to identify the amount of retaining nitrogen and carbon in the soil.

Data analysis

Fluxes for N_2O were determined from the linear or nonlinear changes of concentrations in a set of four samples taken over the 45-minute sampling period. The Pearson's correlation was used to calculate the correlation coefficient (r) to determine the relationships between the quality of the slope and flux rates. The daily N_2O fluxes were validated if the linear regression value of R^2 was greater than 0.8 to enhance the quality of the flux data.

Data were analysed using SPSS to derive descriptive statistics, namely frequencies, percentages, and means of fertiliser, irrigation, and tillage associated with N_2O emissions. ANOVA and the Student-Newman-Keuls test were used to determine the differences at statistically significant levels ($P< 0.05$) in N_2O emissions and nitrogen amounts from the different vegetable farms. Emission data were checked to ensure it conformed to a normal distribution.

Results

Temperature and rainfall

The four study farms received only total 126 mm of rainfall with a significant amount of rainfall (63mm) on September 26, 2016 during the gas emission sampling period from August 13 to October 30, 2016 and the air temperature ranged from 20°C to 30°C (**Figure 3**). The low rainfall indicated that most of the water was supplied by irrigation. The air temperature during the study period did not limit N_2O emissions.

Soil characteristics

Both the top and deep soils were mostly sandy and silt texture with very low to low levels of organic matter and low to fair levels of nitrogen availability, indicating limited water and nutrient holding capacities and low basic soil fertility. The organic matter content was found to be in the range of 0.23% to 0.82%. Total nitrogen varied from 7 to 21 $mgkg^{-1}$ for NO_3^- and from 1.44 to 4.51 $mg\ kg^{-1}$ for NH_4^+ (**Table 3**). The low levels of nitrogen availability were due to a decline at the pre-plant stage over the transition of the growing season under dry soil conditions and no fertilizer applications. Water filled soil porosity was quite high as there were sufficient water supplies over the season. This facilitated N_2O fluxes as these conditions were favourable for active organisms in producing N_2O emissions.

Daily N2O emissions

Figure 4 shows the wide variation in daily N_2O emissions across the four crops. The highest

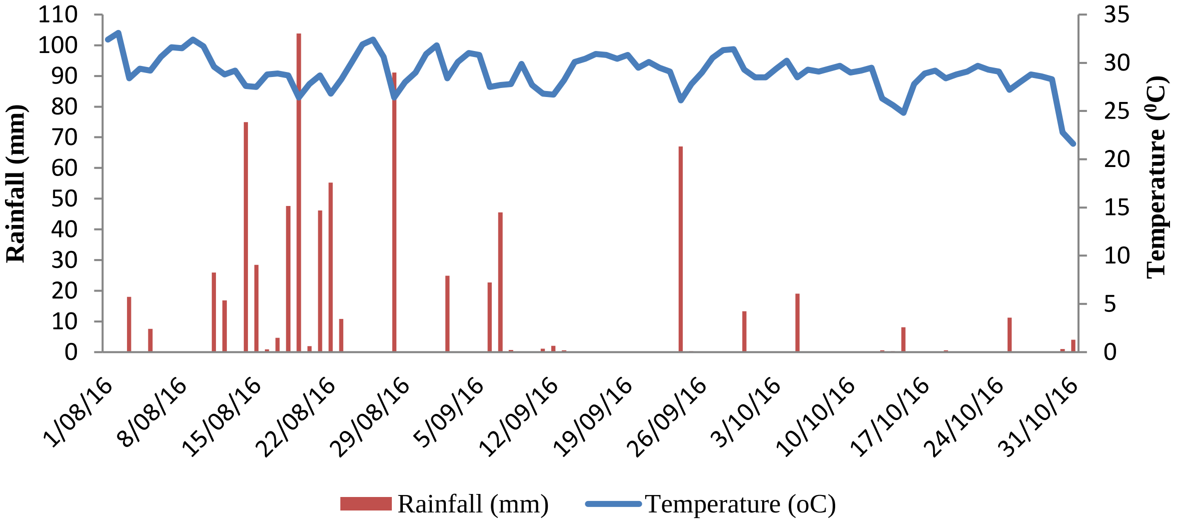

Figure 3. Daily rainfall and temperature at the study sites over gas measurement period

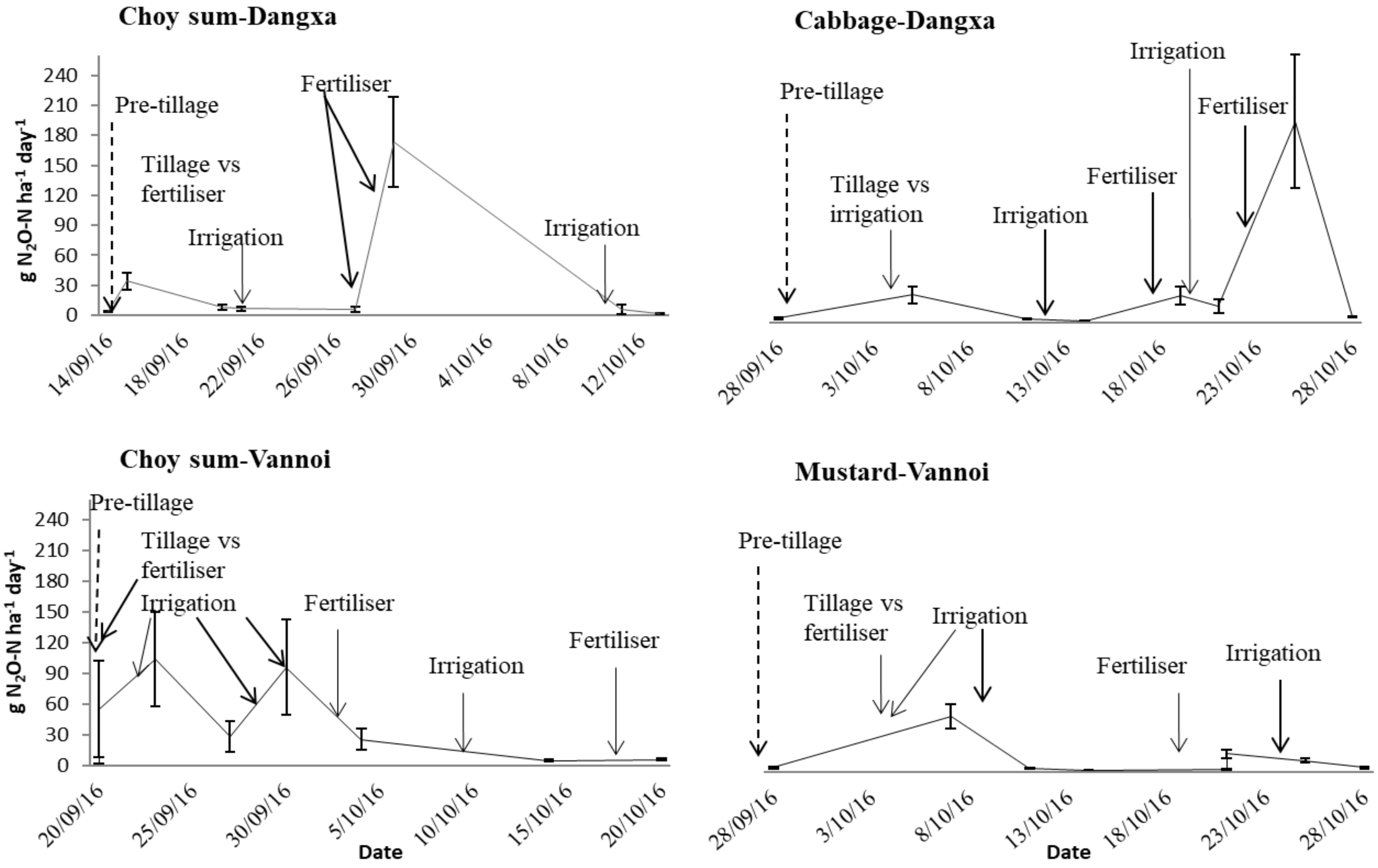

Figure 4. Daily nitrous oxide emissions on each vegetable farm over the autumn season, Hanoi

Note: The error bars indicate standard error (n=4).

Table 3. Soil characteristics of the vegetable farms in Van Noi and Dang Xa

Commune	Deep level (cm)	SOC (%)	NH_4^+ (mg kg^{-1})	NO_3- (mg kg^{-1})	Bulk density	WFSP (%)
Dang Xa	0-15	0.82 ± 0.08	4.21 ± 0.96	19.21 ± 1.58	1.42 ± 0.01	0.83 ± 0.01
	15-30	0.39 ± 0.11	4.51 ± 0.39	7.43 ± 4.38	1.47 ± 0.01	0.87 ± 0.02
Van Noi	0-15	0.51 ± 0.03	1.82 ± 0.55	20.55 ± 6.77	1.50 ± 0.13	0.82 ± 0.03
	15-30	0.23 ± 0.02	1.44 ± 0.45	7.00 ± 1.50	1.63 ± 0.01	0.86 ± 0.02

Note: SOC: Soil organic carbon; WFSP: Water filled space porosity; average values ± standard error.

N_2O emissions were observed immediately after soil cultivation for the mustard and cabbage crops. The peaks of daily N_2O emissions occurred at the second top dressing of fertiliser application for both choy sum crops.

Different farm activities appeared to drive the fluctuations in mean daily N_2O emissions over the autumn season. The daily average emissions of the four vegetable farms after the second fertiliser application increased almost 20 times higher than before fertilisation (3.46 to 58.49 g N_2O-N ha^{-1}) and increased 14 times after tillage, watering, and the first fertiliser application (3.46 to 42.03 g N_2O-N ha^{-1}). Thus, N_2O fluxes increased with tillage cultivation, irrigation practices, and fertiliser applications while emissions were low when none of these management activities were taking place.

Seasonal N2O emissions and emission intensity

There were no statistically significant differences in the daily and seasonal N_2O emissions across the four vegetables, although there were great variations. Daily emissions ranged from 12.15 to 40.08 g N_2O-N ha^{-1} while cumulative seasonal emissions ranged from 1.13 to 8.45 kg N_2O-N ha^{-1} (**Table 4**).

Emission intensity, which refers to the ratio of kilograms of carbon dioxide equivalent emissions per ton of fresh vegetable yield, varied greatly across the four vegetable farms. The choy sum in Van Noi had the highest emission intensity of 215 kg CO_2-e ton^{-1}, which was 63% higher than the choy sum and 36% higher than the cabbage in Dang Xa. The emission intensity of mustard was only 37 kg CO_2-e ton^{-1}, the lowest emission intensity among the four crops (**Table 4**).

Discussion

Peak N_2O emissions on the two choy sum farms occurred when the second top dressings of urea were applied. The largest N_2O emissions in the mustard and cabbage farms were observed at early planting coinciding with soil tillage and basal fertiliser applications. Liu *et al.* (2013) reported similar peaks in N_2O emissions in vegetable crops in China due to fertiliser application, irrigation, and tillage. Higher emissions were also associated with soil tillage, fertiliser application, and irrigation across the four study farms (**Figure 4**). These observations are consistent with other studies reporting positive correlations between greenhouse gas emissions and nitrogen fertiliser, irrigation, and crop residues (Liu *et al.*, 2013; Tongwane *et al.*, 2016), because these practices create favourable conditions for denitrification (IPCC, 2007; Varvel & Wilhelm, 2008; Baldock *et al.*, 2012; Jia *et al.*, 2012a; Li, 2013; Yan *et al.*, 2014; Rashti *et al.*, 2015b).

While the daily and cumulative N_2O emissions in the four vegetable farms were not statistically significantly different, they ranged from 12.2 to 40.1 g N_2O-N ha^{-1} day^{-1}. They were higher than the daily emissions from a broccoli farm in sub-tropical Australia of 1 to 3 g N_2O-N ha^{-1} (Scheer *et al.*, 2014b) and much lower than the daily emissions from a choy sum farm in China of 366 g N_2O-N ha^{-1} day^{-1} (Jia *et al.*, 2012a).

The average global daily emissions from vegetable crops is 57.8 g N_2O-N ha^{-1} day^{-1} and ranges from 3.3 to 703.3 g N_2O-N ha^{-1} day^{-1} (Liu *et al.*, 2013). The wide range of global daily emissions can mainly be explained by significant differences in fertiliser management. In this

Table 4. Daily and autumn season N_2O emissions and emission intensities at the four vegetable farms

Commune	Crop	Daily N_2O emissions ($g\ N_2O\text{-}N\ ha^{-1}$) (n = 4)	Seasonal N_2O emissions ($kg\ N_2O\text{-}N\ ha^{-1}$) (n = 32)	Fresh yield ($tons\ ha^{-1}$)	Emission intensity ($kg\ CO_2\text{-}e\ ton^{-1}$)
Dang Xa	Choy sum	29.98 ± 8.2	4.25 ± 0.37	15.00	132.56
	Cabbage	40.08 ± 21.0	8.45 ± 0.08	43.24	91.43
Van Noi	Choy sum	31.80 ± 10.3	5.76 ± 0.44	12.50	215.59
	Mustard	12.15 ± 2.8	1.13 ± 0.05	14.29	37.00
P		> 0.05	> 0.05		

Note: Emission columns are mean ± standard error of the mean, P> 0.05 indicates no significant difference between vegetables.

study, crops received fertiliser at rates from 105 to 408 kg N ha^{-1} while many vegetable systems summarised by Liu *et al.* (2013) and the study by Jia *et al.* (2012a) had extremely high nitrogen inputs of over 1000 kg ha^{-1} $year^{-1}$. The lower emissions from the study by Scheer *et al.* (2014b) were due to the application of only 120 kg N ha^{-1} for the broccoli crop.

In this study, the seasonal emissions in cabbage were 8.45 kg N_2O-N ha^{-1} with a nitrogen application rate of 408 kg ha^{-1} (**Table 5**). For the same vegetable, the seasonal N_2O emissions were only 0.65 kg ha^{-1} with a nitrogen fertiliser rate of 225 kg ha^{-1} in Japan (Cheng *et al.*, 2002) and 6.30 kg ha^{-1} with a nitrogen fertiliser rate of 450 kg ha^{-1} in China (Cao *et al.*, 2006). These results indicated that high N_2O emissions are strongly associated with nitrogen application rates in intensive vegetable production.

The N_2O derived emissions intensity varied among the types of vegetables. Although it had the highest seasonal N_2O emissions, cabbage had a lower than average emission intensity compared to choy sum: 94.43 vs. 123.56 kg $CO_{2\text{-}e}$ ton^{-1} in Dang Xa and 215.59 kg $CO_{2\text{-}e}$ ton^{-1} in Van Noi because the crop also produced the highest yields. These are similar emission intensity values compared to other agricultural crops such as vegetables (170 to 410 kg CO_2-e ton^{-1}) (Jia *et al.*, 2012b), wheat (265 kg CO_2 -e ton^{-1}), and maize (230 kg CO_2- e ton^{-1}), but much lower than rice (947 kg CO_2 -e ton^{-1}) (Wang *et al.*, 2015). While using fertilizers and irrigation increased N_2O emissions, they also increased vegetable yields. The Australian processing tomato and baby leaf spinach crops are well placed with very low emission intensities due to the use of drip irrigation and low chemical fertilizer applications (Montagu *et al.*, 2017).

Conclusion

This study provides the first field data on N_2O emissions from vegetable cropping systems in Vietnam and is also one of the few studies globally to report N_2O fluxes using direct field measurements. Mean daily N_2O emissions ranged from 12.15 to 40.08 g N_2O-N ha^{-1}. Autumn N_2O emissions ranged from 1.13 to 8.45 kg N_2O-N ha^{-1} across the four leafy vegetable crops in Hanoi Vietnam. Emission intensities varied among the types of vegetables from 37 kg CO_2-e ton^{-1} (mustard) to 215 kg CO_2-e ton^{-1} (choy sum). This indicated that the crop management practices need to be designed to increase crop yields but reduce emissions. Overuse of nitrogen fertilisers and furrow irrigation are likely to increase N_2O emissions. This study was limited to field gas measurements in one autumn crop season. Gas measurements over multiple seasons and crop rotations should be conducted to confirm the results and better understand the annual dynamics of N_2O emissions in Vietnam.

The study results can help improve nitrogen fertiliser management practices through the recommendation that farmers should comply strictly with nitrogen recommendations for individual vegetables to reduce greenhouse gas

Table 5. Fertiliser use and seasonal N_2O emissions of the four vegetables in the autumn season at the four farms

Commune	Crop	Total amount of N (kg ha^{-1})	Seasonal N_2O emissions (kg N_2O-N ha^{-1})
Dang Xa	Choy sum	215	4.24
	Cabbage	408	8.45
Van Noi	Mustard	110	5.76
	Choy sum	105	1.13

emissions associated with commercial vegetable production in peri-urban Hanoi, Vietnam.

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