



Factors Influencing N₂O Emissions from Vegetable Crops and Comparison with Other Food Crops: A Meta-Analysis

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Abstract

The use of nitrogen fertilisers to increase crop productivity increases global nitrous oxide (n₂o) emissions. This study used a meta-analysis technique to evaluate the influence of nitrogen fertilisers (rates and types) and other factors (soil organic carbon, soil nitrogen and ph) on n₂o emissions from vegetable crops, which were then compared to emissions from three other food crops. A total of 176 field measurements on n₂o emissions for vegetable crops were collected from 33 peer-reviewed papers and 168 measurements for potato, corn and wheat crops were collected from 38 peer-reviewed papers. Vegetable crops produced higher n₂o emissions than wheat and potato crops. The average amount of nitrogen fertiliser application for vegetable crops was 287 kg n ha⁻¹, resulting in average cumulative n₂o emissions of 4.52 kg n₂o-n ha⁻¹. Nitrogen rates of over 200 kg ha⁻¹ applied for vegetable crops were strongly, positively associated with n₂o emissions. The impact of inorganic nitrogen fertilisers on n₂o emissions was significantly higher than organic nitrogen fertilisers. Further studies should include more factors driving n₂o emissions such as soil moisture, soil tillage, soil temperature and soil types to assess their overall impacts on n₂o emissions and help develop mitigation options.

Keywords: N₂O Emissions, Vegetable Crops, Nitrogen Fertilisers, N₂O Emission Factors.

Introduction

Atmospheric n₂o concentration has been increasing at an annual rate of 0.26% from 1750 to 2006 (ipcc, 2007; stavi & lal, 2013) with the concentration of 324 ppb in 2011 being 20% higher than the level in the pre-industrial period prior to 1750 (ipcc, 2014). nitrous oxide is a powerful greenhouse gas with a global warming potential over 100 years which is 298 times larger than co₂ and is a strong [ozone depleting](#) substance (ipcc, 2007).

Agricultural production, including the use of fertiliser, irrigation practices and tillage cultivation are responsible for 60% of total global nitrous oxide emissions (ciais, *et al.*, 2014). nitrogen fertiliser rates, nitrogen

source, crop species, crop rotation and tillage, residue management, ph, soil water content and soil temperature can all influence n₂o emissions (halvorson, del grosso, & reule, 2008; snyder, bruulsema, jensen, & fixen, 2009a; stehfest & bouwman, 2006). Of these, nitrogen fertiliser rate is the most influential factor driving n₂o fluxes (hoben, gehl, millar, grace, & robertson, 2011; rashti, wang, moody, chen, & ghadiri, 2015). Previous studies have shown that agricultural soils are responsible for approximately 50% of the total global n₂o anthropogenic emissions (shcherbak, millar, & robertson, 2014). nitrogen fertiliser rate is the best single predictor of n₂o emissions from agricultural soils as it accounts for 80%

of the N_2O emissions from Chinese vegetable fields (Diao, et al., 2013; Yan, et al., 2014), which constitute 50% of global vegetable production (Wang, et al., 2018).

Inorganic and organic fertilisers are commonly used to improve the growth and yields of vegetable crops. The amount and form of available nitrogen in inorganic and organic fertilisers largely accounts for differences in N_2O emissions resulting from their application (Asgedom, Tenuta, Flaten, Gao, & Kebreab, 2014; Charles, et al., 2017; Shcherbak, et al., 2014; Zhou, et al., 2017). However, the effects of fertiliser types on N_2O emissions from vegetable production are not known for specific regions and crops (Wang, et al., 2018).

Several studies have reviewed N_2O emissions in vegetable cropping systems and influencing factors using multivariate regressions (Liu, Qin, Zou, Guo, & Gao, 2013; Rashti, et al., 2015; Wang, Xiong, & Yan, 2011; Wang, et al., 2018). While Wang, et al., (2011; 2018) and Liu, et al. (2013) collected data on N_2O emissions from Chinese vegetable fields, Liu, et al. (2013) and Rashti, et al. (2015) compared N_2O emissions from vegetables in greenhouses and open-air fields. In this study, a larger gas measurement dataset on N_2O emissions was collected from papers published on global vegetable fields and three other food crops (corn, potato and wheat).

This chapter focuses on the relationship between nitrogen rate, types of fertilisers within N_2O emission measurements in field vegetable experiments and type of four crops (vegetables, maize, wheat and potato) and N_2O emissions from 2010 to 2017, and aims to: (1) evaluate the relationships between N_2O emissions and crop management practices including the use of nitrogen fertilisers (rates and types), vegetable species and soil properties including soil organic carbon, soil nitrogen and pH that are likely to influence N_2O emissions and (2) compare the N_2O emissions of vegetables and other common food crops.

Materials and Methods

Data Collection

Data on N_2O emissions from vegetable fields published in peer-reviewed journals from 2000 to 2017 was collected and categorised according to: (1) N_2O emissions measured in field conditions during the entire [growing seasons](#) of vegetable crops; and (2) N_2O emissions assessed in treatments both with and without [N fertiliser application](#), as well as different nitrogen fertiliser types.

Only field studies were included, and nitrous oxide emissions from pot, incubation and greenhouse studies were excluded. The emissions from treatments with inhibitors, polymer-coated urea and fallow season (without crops) were also excluded as they are mitigation options. Two studies which have extremely high nitrogen fertiliser application rates and N_2O emissions due to local farmer application of high nitrogen rates (Jia, Sun, Kong, Yan, & Xiong, 2012) and (Mei, et al., 2011) were also excluded. As a result, the collected dataset on vegetable crops consisted of 176 field observations from 33 published studies from six countries including Australia, China, Germany, Japan, Scotland and the United States. The dataset and sources are provided in Appendix 1. The dataset on corn, potato and wheat crops was collected from a total of 38 published studies with 168 observations on N_2O emissions. The dataset and sources are provided in the Appendix.

N_2O emissions in this study refer to the cumulative N_2O emissions (seasonal or yearly N_2O emissions). One observation in the statistical analysis was defined as one dataset of N_2O emissions. The information in each study included N_2O emissions, observation days, fertiliser amount and types, vegetable species, soil organic carbon, total soil nitrogen and soil pH.

Data Calculation and Statistical Analysis

The aim of this analysis was to investigate the relationships between N_2O emissions and nitrogen fertiliser rates and types. To increase statistical power in the analysis, some of the data were re-grouped. First, fertiliser rate was

split as follows: (0, 1 - 200 kg ha⁻¹, 201 - 300 kg ha⁻¹, 301 - 500 kg ha⁻¹, 501 - 1000 kg ha⁻¹ and >1000 kg ha⁻¹). Second, fertiliser type was categorised into four types: inorganic nitrogen fertiliser (compound npk fertiliser nitrogen, nitrate, ammonia, calcium ammonium nitrate and urea), organic fertiliser (dung and urine of human and animals, chicken manure and pig manure) and combination of inorganic and organic fertiliser, and no fertiliser.

Anova and pairwise comparison using lsd were used to determine the different rates and types of nitrogen fertilizers impacting on n₂o emissions, then the linear mixed effects model was used to determine any significant main effects or interactions variables including fertiliser rates, types, soil organic carbon, soil nitrogen, soil ph and observation days. This model also accounts for other unknown variables such as sample sizes, different soil textures and soil water content influencing the n₂o emissions on vegetable crops. This model used country as a random effect. We could only collect mean of n₂o emissions in treatments of experiments from the selected studies and standard deviations for each n₂o emission mean are not usually available for inclusion in statistical analysis. Therefore, means and standard deviations were calculated from each group including fertiliser types and rates in each study. Nitrogen fertiliser rates were regrouped into three levels: 1<200 kg n ha⁻¹, 201-500 kg n ha⁻¹ and > 500 kg n ha⁻¹. All the statistical analysis was performed using r statistical software

(version 4.3.4). Mixed-effects meta-regression was carried out on the raw means using the 'metafor' package in r.

The data observations from the original n₂o emissions were not normally distributed when the residual distribution was tested using qq norm plot. Therefore, the original observations were transformed into log-transformed n₂o emissions for the statistical analysis.

Results and Discussion

Impacts of Nitrogen Fertiliser Rates on N₂O Emissions

The n₂o emissions had a positive linear relationship with n fertiliser rates (p<001). Nitrogen application rate could only explain 32% of the n₂o emissions, probably due to variability in the dataset of 176 observations (figure 1). similar meta-analyses using regression models have shown that nitrogen rate can explain from 36% of the n₂o emissions (in greenhouses) to 41% (open fields) (liu, et al., 2013), 42% (rashti, et al., 2015) and 52% (wang, et al., 2011).

The slightly lower level of nitrogen predictability in this study could be due to the range of types of nitrogen fertilisers (bouwman, boumans, & batjes, 2002), soil water-filled pore space and temperature (he, jiang, chen, zhang, & su, 2009), tillage and soil properties (wang, et al., 2011) or simply the wide range in nitrogen application rate (table 1).

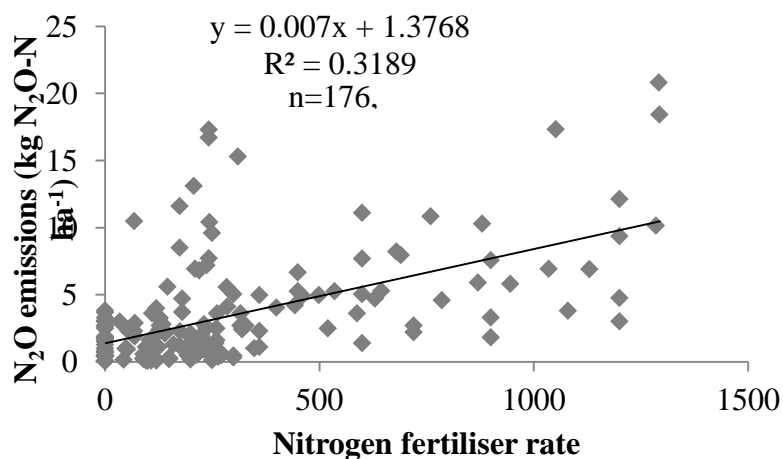


Figure 1: Linear relationship between seasonal N₂o emissions and nitrogen fertiliser application in vegetable fields, with 176 observations

A group of nitrogen rates from 1 kg to 200 kg ha⁻¹ for vegetable crops did not produce differences in n₂o emissions compared with non-nitrogen fertiliser treatments. At nitrogen

rates from 201 to 500 kg ha⁻¹, n₂o emissions increased significantly and the highest n₂o emissions were observed in the nitrogen rate group of 1000–1300 kg ha⁻¹.

Table 1: Nitrous oxide emission for different nitrogen fertiliser amounts

Nitrogen Amount (Kg Ha ⁻¹)	Number Of Observations	Mean N ₂ O Emissions (Kg Ha ⁻¹)
0	30	1.4 (0.21) A
1-200	59	1.9 (0.30) A
201-300	34	3.9 (0.78) B
301-500	17	4.0 (0.79) Bc
501<1000	20	5.6 (0.64) Cd
>1000	10	10.3 (0.49) D
Average		4.52

Note: Means which are significantly different (p<0.05) are indicated by different letters. Standard errors of the mean are in brackets

The average n₂o emission in the meta-analysis was 4.52 kg n₂o-n ha⁻¹ at an average nitrogen rate of 287 kg n ha⁻¹. the average global nitrogen application rate for vegetables was 220 kg n ha⁻¹ season⁻¹ (rashti, et al., 2015). In china, nitrogen fertiliser rates for vegetable crops range from 300 to 700 kg ha⁻¹ season⁻¹ (li & wang, 2007). the rates for cabbage in china were even higher, ranging from 300 to 900 kg n ha⁻¹ season⁻¹ (chen, et al., 2004). The average cumulative n₂o emission in Chinese vegetable systems was 3.91 kg n₂o-n ha⁻¹ (wang, et al., 2018).

These results are consistent with previous studies that n₂o emissions are strongly correlated with nitrogen fertiliser application rates (shcherbak, et al., 2014; yan, et al., 2014). the meta-analysis showed that nitrogen fertiliser application to vegetables in china

would increase the annual n₂o emissions by 97% (liu, et al., 2013). n₂o emission rates have a linear response to increased nitrogen fertiliser rates at less than or meeting crop requirements (halvorson, et al., 2008) but increase exponentially when exceeding nitrogen fertiliser for crop requirements (over 220 kg crop⁻¹ season⁻¹) (shcherbak, et al., 2014; snyder, bruulsema, jensen, & fixen, 2009b).

Impacts of Fertiliser Types on N₂O Emissions

Nitrogen fertiliser type in the meta-analysis had a significant impact on n₂o emissions. Inorganic fertilisers alone and inorganic plus organic fertilisers for vegetable crops produced significantly higher n₂o emissions than either organic fertilisers or no fertiliser application (figure 2).

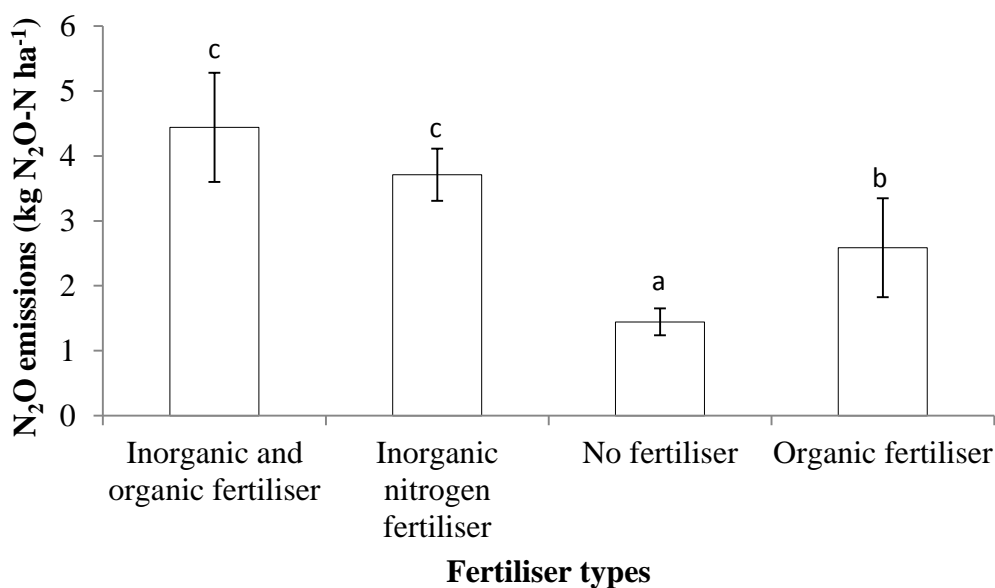


Figure 2: Impacts of nitrogen fertiliser types on n₂o emissions in vegetable crops

Note: means which are significantly different ($p < 0.05$) are indicated by different letters, and the error bars indicate standard errors. Organic fertiliser refers to fertilisers made by plant- or animal-based materials while inorganic fertiliser means it is manufactured or extracted from minerals or synthetic chemicals.

This finding was consistent with the results from a review study, showing that n₂o emissions were highest for the mix of organic and inorganic nitrogen fertilisers (3.5 kg n₂o-n ha⁻¹ yr⁻¹), the second highest for inorganic fertilisers (3.0 kg n₂o-n ha⁻¹ yr⁻¹) and the lowest for solid organic fertilisers (1.7 kg n₂o-n ha⁻¹ yr⁻¹) (de rosa, et al., 2016). a six-year study in five grassland areas in japan showed that mineral fertilisers had higher n₂o emission factors than manures (shimizu, et al., 2013). However, the finding was inconsistent with a study which concluded that 30% higher n₂o emissions were associated with organic fertilisers compared with inorganic fertilisers alone for all crops in china (zhou, et al., 2017). Meng, et al. (2005) reported that the application of manures in the 12-year period did not result in greater n₂o emissions compared with inorganic fertilisers. a review study (stehfest & bouwman, 2006) on n₂o emissions concluded there were no significant effects of fertiliser type on n₂o emissions, rather the amount of nitrogen application

was the significant factor. a recent meta-analysis confirmed that different nitrogen fertilisers with the same nitrogen rates did not affect n₂o emissions in greenhouse vegetable systems (wang, et al., 2018).

Nitrate, ammonium or urea in inorganic nitrogen fertiliser can release or mineralise rapidly, increasing soil nitrogen availability and n₂o emissions (aguilera, lassaletta, sanz-cobena, garnier, & vallejo, 2013; kaiser & r. ruser, 2000; sánchez-martín, arce, benito, garcia-torres, & vallejo, 2008). in contrast, nitrogen from organic fertilisers such as compost, manure and crop residues is released more slowly under immobilisation (cassman, dobermann, & walters, 2002), increased soil moisture and soil carbon favourable for microbial activities, further increasing n₂o emissions (aguilera, et al., 2013; kaiser & r. ruser, 2000; sánchez-martín, et al., 2008). therefore, fertiliser form has an impact on n₂o emissions.

Combined Factors Affecting N₂O Emissions

The results of the mixed-effect regression model confirmed a significant relationship between n₂o emissions and nitrogen fertiliser application rate in vegetable crops. other factors including fertiliser types, soil organic carbon, soil nitrogen and soil ph did not influence n₂o emissions (table 2).

Table 2: Statistical results for all soil properties and management factors on n₂o emissions in the mixed-effect model regression analysis (log-transformed data)

Factor	Number Of Observations	Coefficient	95% Confidence Intervals		P Value
			Lower	Upper	
Fertiliser Type					
Inorganic Nitrogen Fertiliser	91	1.41	-0.93	3.76	0.24
Inorganic And Organic Fertiliser	39	-0.17	-0.64	0.30	0.48
Organic Fertiliser	13	-0.13	-0.66	0.40	0.64
Nitrogen Fertiliser Rates (Kg Ha ⁻¹)					
1-200	59	1.41	-0.93	3.76	0.24
200-500	53	0.44	0.01	0.87	0.04*
>500	31	0.89	0.42	1.36	0.0002***
Soil Organic Carbon	140	0.02	-0.02	0.06	0.40
Soil Nitrogen	133	-0.36	-1.06	0.34	0.32
Ph	138	-0.10	-0.36	0.17	0.48

Note: Significance Levels: *** At P<0.001; * At P<0.05

Although fertiliser type significantly affected n₂o emissions in assessing pair parameter relationships (figure 2), it did not affect n₂o emissions using the mixed-effect model to combine other factors driving n₂o emissions (table 2). This suggests that the interaction among factors also plays a role in influencing emissions. In addition, exclusion of studies in the meta-regression, due to lack of replication may also influence the results.

N₂O Emissions from Vegetables Compared To Other Food Crops

Vegetable crops produced significantly higher n₂o emissions than potato and wheat crops (p<0.01), primarily due to nitrogen fertiliser

rates (figure 3). For example, the amount of nitrogen applied for vegetables was double that applied to potato and wheat crops (351 kg ha⁻¹ compared to 159 and 167 kg ha⁻¹, respectively). In china, vegetable crops can produce n₂o emissions seven times higher than rice or wheat production from the same area and soils (min, shi, xing, powlson, & zhu, 2012). vegetable cropping soils had the highest n₂o emission fluxes (6.5 kg n₂o-n ha⁻¹ year⁻¹) compared to wheat (4.8 kg n₂o-n ha⁻¹ year⁻¹) and corn (2.9 kg n₂o-n ha⁻¹ year⁻¹) under various soil management regimes in the united states (mummey, smith, & bluhm, 1998).

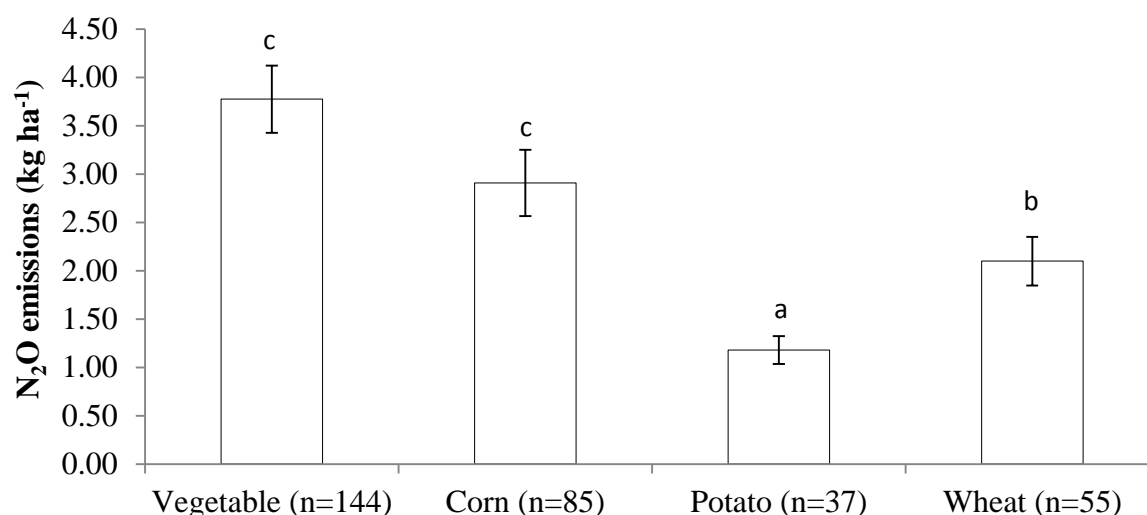


Figure 3: impacts of plant crops on seasonal N₂O emissions

Note: Means which are significantly different ($p < 0.05$) are indicated by different letters, the error bars indicate standard errors and n is the number of observations.

Irrigation and nitrogen inputs are commonly higher in intensive vegetable production compared to broad acre crops and this commonly leads to higher n₂o emissions (min, *et al.*, 2012). a recent meta-analysis on chinese vegetables also reported that average n₂o emissions were higher compared to other crops due to higher inputs of nitrogen fertilisers (wang, *et al.*, 2018). for example, the average nitrogen application rate for vegetable production in china of 388 kg n ha⁻¹ is 1.81 times higher than for cereal production (wu, *et al.*, 2016). the higher nitrogen fertiliser inputs for vegetables compared to cereal crops are due to various factors including lower root densities and nutrient absorption capacities (brumm & schenk, 1993), higher available soil moistures and higher yield expectations compared to cereals, potentially leading to higher n₂o emissions due to increased nutrient availability and microbial activities (lin, iqbal, hu, & feng, 2010). Although n₂o emissions produced from vegetable crops were higher per square meter than crops such as corn, potato and wheat, these crops contribute more n₂o emissions due to the large areas planted. the global areas planted are 10 million ha of to vegetables, 191 million ha of maize, 19 million ha of potato and 215 million ha of wheat (fao, 2017).

Seventy percent of the data observations on n₂o emissions for global vegetable production are from studies in china, and china accounts for more than half of the world's vegetable production (wang, *et al.*, 2018). Therefore, this meta-analysis is largely affected by studies in china. In addition, this meta-analysis did not include other factors in the mixed-effect regression models which can also influence n₂o emissions such as soil moisture (rainfall and irrigation), soil tillage, and soil temperature and soil types.

Conclusions

This meta-analysis study for vegetables worldwide with data collected from n₂o emission studies on vegetable production systems during 2010 to 2017 indicated nitrogen rates of over 200 kg ha⁻¹ applied for vegetable crops were strongly, positively associated with n₂o emissions. The higher n₂o emissions from inorganic fertilisers than from organic fertilisers suggest opportunities to reduce n₂o emissions by encouraging use of organic fertilisers. Compared to corn, wheat and potato crops, vegetable crops produced higher n₂o emissions than wheat and potato crops per hectare. However, the total areas planted to each crop need to be considered in estimating the total n₂o emissions for each crop. In addition, other factors affecting n₂o emissions including soil moisture, soil tillage,

soil temperature and soil types, which could not be included in this study, should be considered to assess overall impacts on N_2O emissions.

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