Research Paper

Global warming potential in vegetable production as affected by crop rotation and nitrogen rate[†]

Ju Min¹, Kouping Lu², Haijun Sun³, Longlong Xia¹, Hailin Zhang⁴, and Weiming Shi^{1*}

¹State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China

²School of Environmental and Resource Sciences, Zhejiang A & F University, Lin'an, Hangzhou, Zhejiang, China

³Advanced Analysis and Testing Center, Nanjing Forestry University, Nanjing, China

⁴Oklahoma State University, Department of Plant and Soil Sciences, Stillwater, OK, USA

Correspondence: W. Shi, State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

E-mail: wmsi@issas.ac.cn

[†] This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as an 'Accepted Article', doi: [10.1002/cden.201400785]

Graphical abstract

Optimizing the crop rotation by including legumes could reduce the N₂O emissions by 23.9% and increase the net economic benefit by 32.6%; and the sum of global warming potential could be reduced by 25% or more if fertilizer rates and crop rotations are optimized simultaneously in an intensive vegetable production system.

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Abstract

Greenhouse gas emissions from vegetable production systems contribute to climate change, but the impact of nitrogen (N) rates and crop rotation on global warming potential (GWP) is not well documented. A field experiment was conducted to estimate the sum of GWP (mGWP) and yield-scaled GWP in an intensive vegetable cropping system. The study included the traditional rotation of celery-tomato-lettuce (Rt) and the modified rotation of bur clover-tomato-lettuce (Rm), and each with four fertilizer N options (control, manure-N, optimum and conventional N). The nitrous oxide emission rates were 6.87 and 10.24 kg N ha⁻¹, and the mGWP values were 27.9 and 31.8 MgCO₂-eq ha⁻¹ per year from the optimum and conventional N plots under the traditional rotation, respectively. The change from the traditional to modified rotation reduced N input by 25%, N₂O emissions by 24%, and mGWP by 14% but increased the net economic benefit by 33% under the optimized N application rate in the intensive vegetable cropping system. The trends of yield-scaled GWP from different N rates and vegetable crop rotations were similar to the mGWP. This study proved that optimizing vegetable crop rotation by including legumes and adjusting N application rates simultaneously can reduce global warming potential while maintaining agricultural economic benefit.

Keywords: Fertilizer nitrogen; Greenhouse gas mitigation; Net economic benefit, Nitrous oxide emission

Abbreviations: ANOVA, analysis of variance; **EB**, economic benefit; **ECD**, electron capture detector; **FAO**, Food and Agriculture Organization; **GC**, gas chromatography; **GHG**, greenhouse gas; **GHGI**, **GHG** intensity; **GWP**, global warming potential; **mGWP**, the sum of global warming potential; **NEB**, net EB; **Nmc**, conventional nitrogen; **Nm**, manure-nitrogen; **Nmo**, optimum nitrogen; **NN**, zero-nitrogen control; **NUE**, nitrogen use efficiency; **Rm**, modified rotation of bur clover-tomato-lettuce; **RMB**, renminbi (Chinese currency: yuan); **Rt**, traditional rotation of celery-tomato-lettuce

1. Introduction

Atmospheric nitrous oxide (N₂O), methane (CH₄) and carbon dioxide (CO₂) are the three most potent greenhouse gases (GHGs) that contribute to global warming [1]. Agricultural GHG emissions were

estimated to be 5.1--6.1 Pg CO₂-equivalent (CO₂-eq) in 2005, accounting for 10--12% of total global anthropogenic emissions [2]. The net emission of CO₂-eq from farming activities can potentially be decreased by improving agricultural management to increase soil organic matter content and/or decrease CH₄ and N₂O emissions [3]. In fact, the energy used for irrigation, fuel consumption for field tillage, and application of agrochemicals in crop production systems can also produce large amounts of CO₂-eq which should be taken into consideration in the overall estimation of emission sources contributing to global warming potential (GWP) [4, 5]. Recent studies indicated that agricultural practices, such as fertilization, irrigation, tillage, and crop rotation, significantly contributed to GHG emissions [6--8]. To report GHG emissions per unit area or per unit N applied (e.g., fertilizer-induced N₂O emissions), one option is to assess GHG emissions per unit yield, either termed 'yield-scaled emissions' or 'greenhouse gas intensity' [9]. The yield-based emission or greenhouse gas intensity is calculated by dividing the GWP by the crop yield [10]. The yield-scaled emission is related to agricultural intensification, so efforts should be focused on increasing productivity per unit area instead of expanding agriculture to new farmland [11].

Vegetable and other upland crops are sources of N₂O emissions driven by the fertilizer N applied [12, 13]. In the past two decades (1990--2009), 61% of the world's increase in nitrogen (N) fertilizer production and 52% of the increased N consumption occurred in China. The agricultural N consumption in China was 2.5 times that used in North America and the European Union. China's N fertilizer production is largely using coal generated energy, which produces a greater carbon footprint than other forms of energy such as natural gas [14]. Moreover, Chinese farmers typically have very small farmland per household and often result in over fertilizer application [15].

Due to the relatively high marketable prices of vegetables compared to cereal crops, the land area used for vegetable cultivation in China has rapidly increased to 20.4 million ha by 2012 and accounted for 12.9% of the total planting area [16]. The total N fertilizer used for vegetable production contributed 20% of the national direct N₂O emissions in the 1990s [17]. Fertilizer N strongly impacts N₂O emissions in upland soils [18]. Agricultural N₂O emissions are forecast to increase by 35--60% by 2030 because of increased N fertilizer use and increased animal manure production [19]. Aerobic upland soils, however, contribute little to CH₄ emissions and may even be a sink for CH₄ in some cases [20].

The rates of N fertilizer applied to vegetable fields are typically much higher than on grain crops [21]. As a result, N₂O emissions from intensive vegetable production systems in Southern China on an areal

basis were seven times greater than that from the rice--wheat system on the same soil in the same area [22]. Rational fertilization, irrigation, crop rotation and integrated pest management are needed for the production of high vegetable yields [23--25]. Shang et al. [10] proposed agricultural management strategies to achieve high grain yield and low GHG intensity (GHGI) in a double-rice cropping system using balanced fertilizer management, mid season drainage and crop residue incorporation in the non-rice drained season. Huang et al. [5] pointed out that optimum N management saved roughly half of the fertilizer N compared to conventional agricultural practice, and reduced the net GWP by 51% without significant grain yield loss in a double cropping cereal rotation. Jia et al. [26] found that the net GWP and GHGI were 26--109 Mg (1 Mg = 10^6 g) CO₂-eq ha⁻¹ and 0.17--0.41 kg CO₂-eq ha⁻¹ kg⁻¹ vegetable yield in the intensive vegetable ecosystems, respectively. Recent data showed that N₂O emissions were reduced by 33% with 40% N reduction from local farmers' normal usage in an intensive vegetable system without any yield loss [22]. He et al. [13] also found that using the site-specific N management reduced 27--51% of the N₂O emissions compared to the local farming management in an intensively managed greenhouse tomato cropping system in north China. Moreover, inclusion of leguminous crops within crop rotations reduces the need for external fertilizer N inputs due to biological N fixation [27]. Therefore, rotating appropriate leguminous vegetable crops with vegetable should be a practical measure to reduce N inputs in vegetable production systems. However, it is still unclear to what extent GWP can be reduced following optimum N application in this vegetable cropping system in comparison with the conventional farming practice, and how to mitigate the GHG emissions, and achieve the target vegetable yields and high net economic benefit (NEB) simultaneously.

Therefore, a field experiment was carried out to estimate the sum of GWP (mGWP) and yield-scaled GWP in an intensive vegetable cropping system. The specific objectives of this study were: (1) to monitor the N₂O emissions; (2) to estimate to what extent mGWP and yield-scaled GWP can be reduced by adjusting N rates; and (3) to mitigate the GWP of N₂O emission from the vegetable cropping system by optimizing crop rotation to achieve the target yields and high NEB.

2. Materials and Methods

2.1 Experimental site

A field experiment was conducted in a typical intensive vegetable cropping system at Hudai Town, near

Wuxi, Jiangsu Province, China (31°31'N and 120°06'E) from 24 December 2009 to 20 December 2010. The region has a subtropical humid climate with a mean air temperature of 15.6 °C, and annual mean precipitation of 843 mm with most of the rainfall occurring from July to September (Fig. 1). There was no rainfall input to the field in the plastic covered greenhouses except from July to September when the polyethylene cover was not in use. The soil of the study site was developed from a lacustrine deposit, and was classified as Gleyed-stagnant Anthrosols according to the Food and Agriculture Organization (FAO) soil taxonomy system. The upper layer (0--20 cm) was a silt loam with 7.2% sand, 68.3% silt and 24.5% clay with an initial pH of 6. The soil organic C and total N contents were 27.9 and 1.1 g kg⁻¹, respectively.

2.2 Experimental design

The study included two rotational systems: the traditional rotation of celery-tomato-lettuce (Rt) and the modified rotation of bur clover-tomato-lettuce (Rm). Each rotation had four N options: 1) zero-N control (NN), 2) manure-N (Nm), 3) optimum N (Nmo, manure N as in 2) plus additional N, as recommended by Min et al. [25] and Lu et al. [28]), and 4) conventional N (manure N as in 2) plus the amount of N local farmers use, Nmc). The eight treatments were arranged as a completely randomized block design with three replications and each plot was 2.5 m × 7.5 m. The cultivation and application rates of fertilizers are shown in Table 1. The plots were irrigated three to four times per season with water from a nearby river by a water pump. Mean concentrations of total N in the irrigation water were 3.3, 2.8 and 2.1 mg L⁻¹, respectively, during the celery/bur clover, tomato and lettuce season. The volume of irrigation water was measured using a pool (2 × 4 × 1 m) through which it flowed.

2.3 Field management

The greenhouses were covered with polyethylene film from January to July and October to December (Fig. 1). Chicken manure, 120 kg P₂O₅ ha⁻¹ and 150 kg K₂O ha⁻¹ were applied as basal fertilizer, and urea-N was broadcast both as a basal and top-dressing fertilizer (Table 1). The basal fertilizers were mechanically mixed into 0-15 cm depth of soil, and each top-dress was spread evenly by hand on the soil surface and incorporated into the soil by irrigation. Celery and bur clover were directly sown and the seeding rates were 4.5 and 45 kg ha⁻¹, respectively, and seedlings of tomato and lettuce were transplanted into each plot at the beginning of their respective growing seasons. A

granular insecticide (carbofuran) was applied at the beginning of each vegetable growing season. Glyphosate was sprayed on the soil at the beginning and end of each vegetable growing season to control weeds. Insecticide and fungicide (a mixture of chlorantraniliprole and carbendazol) were sprayed weekly during the growing periods.

2.4 N₂O emission and yield measurements

N₂O emissions were measured manually from 24 December 2009 to 17 December 2010 using the opaque closed chamber technique described by Xing et al. [29]. Each static chamber covered an area of 0.6 × 0.7 m and its height could be adjusted from 0.6 to 1.2 m depending on the height of the plants. N₂O flux was measured in triplicate, usually once per week throughout each crop growth period. Measurements were made more frequently after fertilization and irrigation. Boxes were kept on the plants continuously for 1 h during the daytime (9:00--10:00 am) on the sampling days. Four samples at 15 min intervals were analyzed for N₂O by gas chromatography (GC) (HP 5890 II) with an electron capture detector (ECD) and N as the carrier gas. Details for the GC-ECD method were described by Zheng et al. [30]. Chamber temperature, outside air temperature and soil temperature were measured at the same time as N₂O measurements. Cumulative seasonal N₂O emissions were calculated from the individual fluxes and the time between the measurements.

Fruits or harvestable parts of vegetables were picked and weighed from a 5.0 m × 1.5 m area in the middle of each plot at the appropriate harvest time.

2.5 Calculation of mGWP and yield-scaled GWP

The overall impact was defined as the sum of the warming forces of all GHGs based on the 100-year global warming potentials [31]. The mGWP is analogous to the carbon footprint including the main emission sources. The mGWP from the intensive vegetable cropping systems was calculated using the following equation:

$$\text{mGWP (kg CO}_2\text{-eq ha}^{-1}\text{ year}^{-1}) = \text{N}_2\text{O}_{\text{GWP}} + \text{Fertilizer}_{\text{GWP}} + \text{Power}_{\text{GWP}} + \text{Fuel}_{\text{GWP}} + \text{Pesticide}_{\text{GWP}} \quad (1)$$

The calculations of N₂O_{GWP}, fertilizer_{GWP}, power_{GWP}, fuel_{GWP} and pesticide_{GWP} were described by Huang et al. [5].

The yield-scaled GWP was calculated by dividing mGWP by yield:

$$\text{Yield-scaled GWP (kg CO}_2\text{-eq Mg}^{-1}\text{ year}^{-1}\text{ vegetable)} = \text{mGWP/vegetable yield} \quad (2)$$

2.6 NEB

From an economic perspective, NEB can provide a scientific basis for formulating policies to guide farmers adopting eco-friendly approaches of N input rates and crop rotation patterns. The NEB was calculated by the following equation:

$$\text{NEB (RMB ha}^{-1} \text{ year}^{-1}) = \text{Economic benefit (EB)}_{\text{yield}} \text{ (RMB ha}^{-1} \text{ year}^{-1}) - \text{EB}_{\text{production cost}} \text{ (RMB ha}^{-1} \text{ year}^{-1}) - \text{EB}_{\text{mGWP}} \text{ (RMB ha}^{-1} \text{ year}^{-1}) \quad (3)$$

where:

$$\text{EB}_{\text{yield}} = \sum (\text{seasonal vegetable yield (kg ha}^{-1}) \times v \text{ (RMB kg}^{-1}) \quad (4)$$

where v is the vegetable price, and average prices of 1.0, 1.5, 2.0 and 3.0 RMB kg⁻¹ for celery, lettuce, tomato and bur clover, respectively, were used [16].

$$\text{EB}_{\text{production cost}} = \sum (\text{Production cost (h ha}^{-1}/\text{L ha}^{-1} \text{ per kg/ha)} \times p \text{ (RMB h}^{-1}/\text{RMB L}^{-1} \text{ per RMB kg}^{-1})] \quad (5)$$

where p is the recent price of each production cost, and prices of 1.0 RMB h⁻¹, 7.59 RMB L⁻¹, 18 RMB kg⁻¹, 25 RMB kg⁻¹, 40 RMB kg⁻¹, 4.36 RMB kg⁻¹, 8.0 RMB kg⁻¹, 7.0 RMB kg⁻¹, 40/60 RMB kg⁻¹ for power (h ha⁻¹), fuel (L ha⁻¹), polythene film (kg ha⁻¹), pesticide (kg ha⁻¹), manure-N (kg ha⁻¹), urea-N (kg ha⁻¹), P₂O₅ (kg ha⁻¹), K₂O (kg ha⁻¹), celery/bur clover seed (kg ha⁻¹), respectively, were used [16].

$$\text{EB}_{\text{mGWP}} = \text{mGWP (kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1} \text{ per area)} \times c \times m \quad (6)$$

where c is the international carbon price, and m is the exchange rate of EUR to RMB. The latest exchange rate of 8.39 and the average carbon price of 17.13 € t⁻¹ CO₂-eq [32] were adopted.

2.7 Statistical Analyses

SPSS 16.0 (SPSS Ver. 16.0 for Windows, SPSS, Chicago, IL, USA) was used for statistical analysis of the data. The effects of the crop rotation and nitrogen rate on the N₂O emission and fresh vegetable yield were evaluated using two-way analysis of variance (ANOVA).

3. Results

3.1 Yield and agronomic nitrogen use efficiency (NUE)

The marketable yields of each growing season were recorded for both rotations (Rt and Rm) (Fig. 2). The treatments that received additional N produced more vegetable than the control (NN), but there

were no significant differences in yields between Nmo and Nmc treatments of the two rotations. However, the yields of the Nm treatments were 70.7--87.2% lower than those of Nmo and Nmc treatments probably due to inadequate N. The average marketable yields from the Nmo and Nmc plots were 92.8 and 89.5 Mg ha⁻¹ for celery, and 72.1 and 75.5 Mg ha⁻¹ for bur clover, respectively; and the agronomic NUE were 112 and 88 kg fresh vegetable kg⁻¹ N for celery, and 230 and 208 kg fresh vegetable kg⁻¹ N for bur clover, respectively (Fig. 2).

3.2 N₂O emissions

The highest N₂O emission for each crop of Rt and Rm were 448, 1094 and 621 µg N m⁻² h⁻¹ for celery, tomato and lettuce, respectively, and 166, 857 and 532 µg N m⁻² h⁻¹ for bur clover, tomato and lettuce, respectively, in the Nmc-treated soil. The peak emission values in the Nmo treatment of Rt and Rm rotation were 18--46% and 18--45% lower than those of Nmc, respectively (Fig. 3). All treatments that received N had more N₂O emissions than the control (NN), and pulse N₂O emissions were mainly observed after irrigation and fertilization.

The emission rates of celery growing season were 17 and 32% lower than that of the bur clover season in Nmo and Nmc treatments, respectively (Table 2). Two-way ANOVA analyses indicated that the annual N₂O emissions and annual yield were significantly affected by crop rotation patterns, nitrogen rates and their interactions (Table 3). The highest annual cumulative emission rate (10.24 kg N ha⁻¹) was observed in RtNmc-treated soil which had received 1690 kg N ha⁻¹, and the RmNmc was 18% lower than the RtNmc treatment in annual cumulative emission rate with N application rate of 1260 kg N ha⁻¹ (Table 2). Relative to the Nmc treatment, the Nmo treatment of Rt and Rm received 17 and 16% less N input and decreased the annual N₂O emissions by an average of 33 and 38%, respectively (Table 2). Taking the N₂O emission from the NN treatment as the background emission, the fertilizer-induced N₂O emission factors for RtNmo, RtNmc, RmNmo and RmNmc were 0.39, 0.52, 0.37 and 0.56% of the N input, respectively. Similarly the manure-induced N₂O emissions accounted for 0.42--0.43% of the N applied.

3.3 mGWP and yield-scaled GWP

In this study, field management included irrigation (power), tillage (fuel), utilization of the polythene film, and pest prevention and control (insecticide and fungicide) (Table 4); fertilizer input

included nitrogen, phosphorus, and potassium. The total equivalent carbon emission rates were 31.16 and 26.53 Mg ha⁻¹ in the Nmc treatment from Rt and Rm, respectively. The contribution from manufacturing of fertilizer dominated the mGWP, accounting for 42--48% of the mGWP in Nmc and Nmo treatments from the two rotations (Fig. 4). The N₂O emission, power consumption for irrigation, fuel consumption for tillage, polythene film consumption for warming and pesticide production accounted for 10--15, 4--5, 1--2, 18--20 and 16--21% of the mGWP in Nmc and Nmo treatments of the two vegetable rotations (Fig. 4). Since pesticide use was a major field management, the equivalent carbon emission rate of bur clover season was 16% lower than that of celery season (Table 4) due to higher pesticide usage for celery.

Relative to the Rt, the Rm decreased the equivalent carbon emission rates by 14 and 15% in Nmo and Nmc treatment, respectively (Fig. 4), and the yield-scaled GWP were also decreased by 8% in Nmo, and by 7% in Nmc treatment (Table 5). The yield-scaled GWP across all treatments ranged from 114 to 166 kg CO₂-eq Mg⁻¹ year⁻¹ vegetable and followed the order of NN > Nmc > Nm > Nmo (Table 5). Compared with the control (NN), N application (Nm, Nmo and Nmc) increased the annual mGWP, but decreased annual yield-scaled GWP by 11--28% (Table 5).

4. Discussion

4.1 Yield and agronomic NUE

The average marketable yields from the Nmo and Nmc plots in Rm were 22 and 16% lower than that of Rt, respectively (Fig. 2). The agronomic NUE for bur clover doubled that of celery in the Nmo-treated soil (Fig. 2), which could be attributed to the lower N input of 150 kg N ha⁻¹ for bur clover as compared to the N rate of 500 kg N ha⁻¹ for celery. The agronomic NUE values for the vegetables were relatively high compared to values of 9.0--22.2 kg grain kg⁻¹ N in a rice--wheat rotation reported elsewhere [34], because the fresh vegetable yield at 204--226 Mg ha⁻¹ (Fig. 2) was much higher than the grain yield of 14.4 Mg ha⁻¹ described by Ma et al. [34].

High N application rate is one of the characteristics of intensive vegetable production in China. The present study showed no significant difference ($p < 0.05$) of vegetable yields (fresh weight) under the fertilizer N rates of 1410 and 1690 kg N ha⁻¹ year⁻¹ (RtNmo and RtNmc treatments with organic source N, Fig. 2) in celery-tomato-lettuce rotation (Rt), and under the fertilizer N rates of 1060 and 1260 kg N ha⁻¹ year⁻¹ (RmNmo and RmNmc treatments with organic source N, Fig. 2) in bur

clover-tomato-lettuce rotation (Rm). Decreasing the N rate by 16% (Nmo) from the conventional N application rates (Nmc) did not result in yield losses, which is consistent with previous studies [25]. This suggests that the conventional practice substantially over-applies N fertilizers. Excessive N fertilizers are generally applied based on farmers' experience without considering the environmental consequences for vegetable production. To reduce the over-application of N fertilizers in intensive vegetable cropping systems, some recently developed techniques such as site-specific nitrogen management can be used to improve N fertilizer recommendation as reported by He et al. [23]. Moreover, the interaction of fertilization and water management is very important in the vegetable field, and the split application of water and N fertilizer according to vegetable requirements at any growth phase and the application of the fertilizer close to the roots can increase the NUE and reduce N loss to the environment [35].

4.2 N₂O emissions

Under the different N rates, most of the pulse N₂O emissions occurred after the irrigation and fertilization, which is consistent with previous studies [13, 36]; there were several emission peaks from 29 July to 11 September (Fig. 3), which could be triggered by heavy rainfall alone during the open-periods (the polyethylene-cover was not in use from 22 July to 12 October, Fig. 1). Cumulative N₂O emissions ranged from 8.44 to 10.24 kg N₂O-N ha⁻¹ year⁻¹ under the conventional N rate treatment of the two rotations (Table 2). N₂O emissions were comparable to previous reports [13, 24, 37]. The annual N₂O emission was decreased by 24% (from 6.87 to 5.23 kg N ha⁻¹) when celery-tomato-lettuce rotation (Rt) was changed to bur clover-tomato-lettuce rotation (Rm) under the optimum N management (Table 2) due to less N demand of bur clover (only one-third of that of celery). Chirinda et al. [27] pointed out that biological N fixation of legumes could potentially lead to increased N₂O emissions from the crop. Carter and Ambus [38] found, in a study with grass-clover mixtures grown in a ¹⁵N₂-enriched atmosphere, that only 2% of the total N₂O emitted from the sward came from recently fixed N. In this study, the N fertilizer application rates may be the dominated factors for N₂O emissions rather than the N fixed from the atmosphere by bur clover. N₂O emissions usually increase linearly or exponentially with increasing N application rates, so the reduction of N rate to an optimum level could substantially reduce N₂O emissions in cropping systems [13]. The annual N₂O emission of the conventional practice (1690 kg N ha⁻¹ year⁻¹) with Rt was decreased by 33% when it was changed

to the optimum N management ($1410 \text{ kg N ha}^{-1} \text{ year}^{-1}$).

The N_2O emission ratios have been reported to be 0.27--0.30% [23] and 0.72% [37] of applied N. The N_2O emission ratio ranged from 0.52 to 0.56% under the conventional N rate treatment of the two vegetable rotations (Table 2) in this study, which is in the Intergovernmental Panel on Climate Change, IPCC, range of 0.25--2.25% [1] and was also consistent with our previous measurement [22]. Assuming $10.24 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ to be representative for these greenhouse systems in China with a total area of 20.4 million ha [16], the total N_2O emissions from conventional rotation greenhouse are about $208 \times 10^6 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$. If the modified rotation (Rm) is used, the total N_2O emissions would be reduced by $102 \times 10^6 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$, which is similar to that reported by Wang et al. [24].

4.3 mGWP and yield-scaled GWP

In terms of field managements, fertilization and N_2O emissions, the mGWP were mainly attributed to fertilizer input under the conventional N application rate of Rt and Rm (Fig. 4), and N fertilizer manufacturing accounted for 91--93% of the fertilizer induced GWP, which was consistent with Jia et al. [26]. The CH_4 emissions only accounted for 0.4--2.0% of the net GWP in the intensive vegetable system [26] while CH_4 emissions dominated the net GWP for the rice--wheat rotation in the same region due to the prolonged anaerobic condition [34]. The equivalent carbon emission from polythene film production, pesticide production and N_2O emissions accounted for 15--18, 16--18 and 15% of the mGWP (Fig. 4), which were the second important emission source.

One strategy to limit GWP is to reduce the greenhouse gas emissions generated from N fertilizer production by optimizing N application rates based on crop N demand [39]. Being a leguminous vegetable crop with a lower N fertilizer requirement of 210 kg N ha^{-1} , or about one-third of the N applied to celery, bur clover can meet the demand for the optimum yield (Fig. 2). According to this study, changing the current conventional cropping system (celery-tomato-lettuce) to bur clover-tomato-lettuce cropping system can reduce 24% of the N_2O emissions and 14% of the mGWP (Tables 2 and 5), whereas increase of 28% in vegetable yield and 33% of the NEB under the optimized N application rate (Nmo) (Table 6). Nmo which decreased the N application by 16% resulted in 33% reduction in N_2O emissions without any yield loss, 14% decrease in the mGWP due to less energy consumption for fertilizer manufacturing and transporting, and a 6% increase in the net economic

benefit relative to the conventional N application rate (N_{mc}) under the celery-tomato-lettuce rotation (Tables 2, 4, 5 and 6). Based on vegetable yields, mGWP and yield-scaled GWP, the optimized N application rate (N_{mo}) should be used to simultaneously achieve better vegetable yield and alleviate climatic impacts of greenhouse vegetable production. N_2O emissions can also be reduced by using nitrification inhibitors [40], polymer coated controlled release fertilizers [41] or site-specific N management as compared to traditional management practices [23].

5. Conclusion

The modified rotation including legume reduced mGWP. 50% of the emission was from N fertilizer manufacturing, and the sum of polythene film production, pesticide production, and N_2O emissions from the field accounted for the other 50%. The change from the traditional rotation of R_t to R_m reduced N inputs by 25%, N_2O emissions by 24%, and mGWP by 14% but increased the NEB by 33% under the optimized N application rate in this intensive vegetable cropping system. Compared with the conventional N application rate, the optimized N application rate with 17% less N input maintained the targeted yields and significantly reduce N_2O emissions, and consequently reduced 14% of the mGWP, and increased 6% NEB for the celery-tomato-lettuce rotation. This finding strongly suggests that an effective strategy to reduce GWP is to encourage farmers applying the appropriate amount of fertilizer and including legume in vegetable crop rotations.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (31201686), the Jiangsu Agriculture Science and Technology Innovation Fund (JASTIF, CX(14)2050), and the Chinese Academy Sciences Innovation Program (grant no. ISSASIP1115).

The authors have declared no conflict of interest.

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Table 1 Cultivation and fertilization in the intensive vegetable field

Vegetation	Growth period (mm/dd/yy)	Fertilization (kg N ha ⁻¹)				TN from IW ^b (kg N ha ⁻¹)
		NN	Nm	Nmo	Nmc	
Bur clover	12/24/09--03/30/10	0	70	70 + 150 ^a	70 + 190 ^a	2.6
Celery	12/24/09--03/30/10	0	70	70 + 500	70 + 620	2.6
Tomato	04/15/10--07/25/10	0	70	70 + 280	70 + 370	3.1
Lettuce	09/17/10--12/20/10	0	70	70 + 420	70 + 490	1.3

All treatments received 150 kg K₂O ha⁻¹ and 120 kg P₂O₅ ha⁻¹ as basal fertilizer each season.

^aManure (poultry litter)-N plus urea-N. Manure and 50% of the urea-N were applied as basal fertilizer, the other 50% of the urea-N was split into two equal top-dresses in each season.

^bTN from IW, total nitrogen from irrigation water, all treatments received the same TN from IW in the same growth season.

Table 2 Annual N₂O emission rates and emission factors in soils treated with N fertilizers of two vegetable rotations.

Treatment	Seasonal emission rate (kg N ha ⁻¹)				Annual emission rate (kg N ha ⁻¹)		^b Ef of total applied N (%)	^c Ef of applied synthetic N (%)
	Celery/Bur clover	Tomato	Lettuce		(kg N ha ⁻¹)	^a Annual N rate (kg ha ⁻¹)		
RtNN	^d 0.33 ± 0.31 ± 0.76 ± 1.40 ±					0 + 7	--	--
	0.2b	0.1c	0.1c	0.4c				
RtNm	0.42 ± 0.58 ± 1.29 ± 2.29 ±					210 + 7	0.42	--
	0.1b	0.3c	0.2c	0.6c				
RtNmo	1.20 ± 1.62 ± 4.04 ± 6.87 ±					1410 + 7	0.39	0.38
	0.2a	0.3b	0.2b	0.7b				
RtNmc	1.50 ± 2.92 ± 5.82 ± 10.24 ±					1690 + 7	0.52	0.54
	0.6a	0.2a	0.6a	1.4a				
RmNN	0.30 ± 0.32 ± 0.72 ± 1.35 ±					0 + 7	--	--

	0.1b		0.1c		0.1d		0.3d				
RmNm	0.43	±	0.57	±	1.25	±	2.25	±	210 + 7	0.43	--
	0.1b		0.2c		0.1c		0.4c				
RmNmo	1.00	±	1.42	±	2.81	±	5.23	±	1060 + 7	0.37	0.35
	0.3a		0.1b		0.2b		0.6b				
RmNmc	1.02	±	2.57	±	4.85	±	8.44	±	1260 + 7	0.56	0.59
	0.1a		0.4a		0.2a		0.7a				

^a Fertilizer-N plus the annual total nitrogen from irrigation water.

^b Emission factor induced by total applied N from synthetic fertilizer and manure.

^c Emission factor induced by applied N from synthetic fertilizer.

^d Mean ± SD ($n = 3$), values within the same column followed by the same letter denotes no significant difference according to Tukey's multiple-comparison test at the 5% level.

Table 3 Two-way ANOVA for the effects of the crop rotation (R) and nitrogen rate (N) on the annual N₂O emission and annual yield.

Factor	df	Annual N ₂ O emissions (kg N ha ⁻¹)			Annual yield (Mg ha ⁻¹)		
		SS	F	P	SS	F	P
R	1	4.67	39.95	<0.001	201.84	31.71	<0.001
N	3	241.79	689.08	<0.001	87987	4607.80	<0.001
R × N	3	4.23	12.05	<0.001	381709	19.96	<0.001
Model	7	250.69			88570		
Error	14	1.64			89.11		

df, degree of freedom.

Table 4 Contributions to carbon emission equivalents from field management and fertilizer applications in an intensive vegetable system.

Crop	Fieldmanagement				Fieldmanagement				Fertilizer(kgCO ₂ -eq ha ⁻¹ area) ^b					
					(kgCO ₂ -eq ha ⁻¹ area) ^a									
	Pow	Fuel	Polythe	Pest	Pow	Fu	Polyt	Pest	N	N	N	N	P ₂	K
rotation	(ha ⁻¹)	(L ha ⁻¹)	(kg ha ⁻¹)	(kg ha ⁻¹)	er	el	hene	icid	N	N	N	m	O	O
							film	e			mo	c	5	
Celer y	450	22.5	575	76	439	89	1593	136 8	0	79 1	49 41	59 37	18 1	1 4 7
Tom ato	450	22.5	575	97	439	89	1593	174 6	0	79 1	311 5	38 62	18 1	1 4 7
Lettu ce	360	22.5	575	109	351	89	1593	196 2	0	79 1	42 77	48 58	18 1	1 4 7
Rt (C-T- L)	1260	67.5	1725	282	122 9	26 7	4779	507 6	0	23 73	12 33 3	14 65 7	54 3	4 4 1
Bur clover	450	22.5	575	64	439	89	1593	115 2	0	79 1	20 36	23 68	1 8 1	1 4 7
Tomat o	450	22.5	575	97	439	89	1593	174 6	0	79 1	311 5	38 62	1 8 1	1 4 7
Lettuc e	360	22.5	575	109	351	89	1593	196 2	0	79 1	42 77	48 58	1 8 1	1 4 7
Rm (B-T- L)	126 0	67.5	1725	270	122 9	26 7	4779	486 0	0	23 73	94 28	110 88	5 4 3	4 4 1

^a The carbon emission coefficient was 1.30 [kgCO₂-eq (kW h)⁻¹] for power, 3.94 (kgCO₂-eq L⁻¹) for fuel, 2.77 (kgCO₂-eq kg⁻¹) for polythene film, and 18.0 (kgCO₂-eq kg⁻¹) for pesticides (herbicide, insecticide and fungicide) used [5,14].

^b The carbon emission coefficient was 8.3 (kgCO₂-eq kg⁻¹) for urea-N, 11.3 (kgCO₂-eq kg⁻¹) for manure-N, 1.51 (kgCO₂-eq L⁻¹) for P₂O₅, and 0.98 (kgCO₂-eq kg⁻¹) for K₂O [5,14, 33].

Table 5 Annual N₂O emissions and mGWP and yield-scaled GWP over the annual cycle of two vegetable rotations

Treatment	mGWP ^a		Yield (fresh weight) (Mg ha ⁻¹) ^b		Yield-scaled GWP ^c	
	Rt	Rm	Rt	Rm	Rt	Rm
N0	12.0 ± 0.2d	11.8 ± 0.1d	73 ± 10c	74.5 ± 9c	166 ± 20a	159 ± 17a
Nm	15.8 ± 0.3c	15.5 ± 0.2c	121 ± 14b	122.9 ± 9b	131 ± 13b	127 ± 8b
Nmo	27.9 ± 0.3b	24.0 ± 0.3b	226 ± 9a	209.8 ± 8a	123 ± 3b	114 ± 3b
Nmc	31.8 ± 0.7a	27.2 ± 0.3a	215 ± 13a	204.3 ± 6a	148 ± 6ab	133 ± 2b

^a mGWP (MgCO₂-eq ha⁻¹ yr⁻¹ area) = N₂O_{GWP} + fertilizer_{GWP} + power_{GWP} + fuel_{GWP} + pesticide_{GWP} + polythene film_{GWP}.

^b Mean ± SD (*n* = 3), values within the same column followed by the same letter denotes no significant difference according to Tukey's multiple-comparison test at the 5% level.

^c Yield-scaled GWP (kgCO₂-eq Mg⁻¹ year⁻¹ vegetable) = mGWP/vegetable yield.

Table 6 Effects of N application rates and vegetable rotations on EB and NEB

Treatment	EB _{yield}		EB _{production cost}		EB _{mGWP}		NEB	
	(RMB ha ⁻¹ year ⁻¹)		(RMB ha ⁻¹ year ⁻¹)		(RMB ha ⁻¹ year ⁻¹)		(RMB ha ⁻¹ year ⁻¹) ^a	
	Rt	Rm	Rt	Rm	Rt	Rm	Rt	Rm
N0	156 500	220 600	46 127	48 302	1725	1691	108 648	170 607
Nm	261 900	361 900	54 527	56 702	2268	2234	205 105	302 964
Nmo	489 150	628 100	59 759	60 408	4007	3449	425 384	564 243
Nmc	463 350	609 950	60 980	61 280	4568	3903	397 802	544 767

^a NEB (RMB ha⁻¹ year⁻¹) = EB_{yield} (RMB ha⁻¹ year⁻¹) -- EB_{production cost} (RMB ha⁻¹ year⁻¹) -- EB_{mGWP} (RMB ha⁻¹ year⁻¹).

Fig. 1 The precipitation, air temperature and soil temperature of the study site. The open-field (polyethylene-cover was not in use) periods were from July 22 to October 12, 2010.

Fig. 2 The marketable yields and agronomic NUE in Rt and bur Rm. See Table 1 for the treatment codes. The agronomic NUE was calculated as the difference in fresh vegetable yield between the N treated and no N plots and normalized to the N fertilizer rate (denoted with the lines). Bars represent the SD of means, with three replicates per treatment. The same letter denotes no significant difference according to Tukey's multiple-comparison test at the 5% level.

Fig. 3 Seasonal variation of N₂O emissions from soils in an intensive vegetable production system. + indicates timing of irrigation. Arrows denote the timing of application of fertilizers. Data points represent the mean ($n = 3$).

Fig. 4 The contributions of field management and fertilizer inputs to estimated GWP in the intensive vegetable system. The same letter denotes no significant difference according to Tukey's multiple-comparison test at the 5% level.

Fig. 1 The precipitation, air temperature and soil temperature of the study site. The open-field (the polyethylene-cover was not in use) periods were from July 22 to October 12 in 2010.

Fig. 2 The marketable yields and agronomic nitrogen use efficiency (NUE) in celery-tomato-lettuce rotation (Rt) and bur clover-tomato-lettuce rotation (Rm). See Table 1 for the treatment codes. The agronomic NUE was calculated as the difference in fresh vegetable yield between the N treated and no N plots and normalized to the N fertilizer rate (denoted with the lines). Bars represent the SD of means, with three replicates per treatment. The same letter denotes no significant difference according to Tukey's multiple-comparison test at the 5% level.

Fig. 3 Seasonal variation of nitrous oxide (N_2O) emissions from soils in an intensive vegetable production system. + indicates timing of irrigation. Arrows denote the timing of application of fertilizers. Data points represent the mean ($n = 3$).

Fig. 4 The contributions of field management and fertilizer inputs to estimated global warming potentials (GWP) in the intensive vegetable system. The same letter denotes no significant difference according to Tukey's multiple-comparison test at the 5% level.

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Author/s:

Min, J;Lu, K;Sun, H;Xia, L;Zhang, H;Shi, W

Title:

Global Warming Potential in an Intensive Vegetable Cropping System as Affected by Crop Rotation and Nitrogen Rate

Date:

2016-07-01

Citation:

Min, J., Lu, K., Sun, H., Xia, L., Zhang, H. & Shi, W. (2016). Global Warming Potential in an Intensive Vegetable Cropping System as Affected by Crop Rotation and Nitrogen Rate. Clean - Soil, Air, Water, 44 (7), pp.766-774. <https://doi.org/10.1002/clen.201400785>.

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