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Impact of nitrogen fertilizer, greenhouse, and crop species on yield-scaled nitrous oxide emission from vegetable crops: A meta-analysis

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ABSTRACT

Vegetable production is recognized as an important anthropogenic source of nitrous oxide (N_2O) emission. An improved understanding of yield-scaled N_2O emission from vegetable production can promote innovation for climate smart cropping. In this study, we performed a meta-analysis to quantify yield-scaled N_2O emission from six types of vegetable crops, to elucidate the effects of greenhouse cultivation and different types of nitrogen (N) fertilizers on yield-scaled N_2O emission from vegetable crops. Significant differences were observed in N_2O emission factor (EF) and area- and yield-scaled N_2O emissions among the six vegetable types. Stem and seed vegetables showed the lowest and highest area- and yield-scaled N_2O emissions, respectively. The average yield of all of the vegetables was significantly higher in greenhouses than in open fields. However, only leafy vegetables were observed to have significantly lower yield-scaled N_2O in greenhouses than in open fields. Emissions of yield-scaled N_2O in response to inorganic N application rate differed among the different vegetable types. The replacement of inorganic N fertilizer with manure significantly reduced yield-scaled N_2O emission from leafy vegetables, but significantly enhanced that from fruit vegetables. Enhanced-efficiency N fertilizer (EENF) significantly increased yield, and significantly reduced area- and yield-scaled N_2O emissions from all of the vegetable types; however, it was less effective for root vegetables and open field cultivation.

1. Introduction

Agricultural nitrogen (N) loss to water and atmosphere via nitrate leaching, NH_3 volatilization, and N_2O emission has caused a cascade of negative impacts on environmental health (Galloway et al., 2008; García-Ayllón, 2017; Riedel et al., 2002). There has been widespread concern during the last three decades over the loss of N from vegetable production areas, especially as N_2O, because of the high application rate of N fertilizer and intensive crop rotation practices (Ju et al., 2006; Rezaei Rashti et al., 2015). The emission of N_2O from global vegetable production areas was estimated at 0.95 Tg N_2O-N yr^{-1} worldwide, which accounts for 24.4% of the global N_2O emissions from agricultural land (Rezaei Rashti et al., 2015). Vegetable production plays an important role in ensuring food availability and safety as well as farmer livelihoods around the world. During the last three decades, harvested areas and production of vegetable crops continuously increased at the rates of 7.0% and 9.5% per year, respectively, because of the increasing consumption and the higher income of vegetable crops over cereal crops (Martellozzo et al., 2014). The mitigation of N_2O emission from vegetable production areas, without affecting crop yield, is critical for the global development of sustainable vegetable production.

Previous field studies have shown that the seasonal N_2O emission from vegetable production areas varies greatly depending on the climate, soil, agronomic practices, and crop species (Haile-Mariam et al., 2008; Pang et al., 2009; Snowdon et al., 2013; De Rosa et al., 2016). Meta-analyses have been performed to determine the effect of temperature, soil properties, greenhouse cultivation, and manure application on N_2O emission from vegetable production areas (Rezaei Rashti et al., 2015; Wang et al., 2018). The results of these analyses showed that the N_2O emission from vegetable crop fields is positively correlated with air temperature, soil moisture, and N application rate but negatively correlated with soil organic carbon content (Rezaei Rashti et al., 2015). Additionally, vegetable crops cultivated in greenhouses show similar N_2O emission factors (EF) but higher levels of seasonal N_2O emission than those cultivated in open fields because of the higher rate of N fertilizer applied in greenhouse cultivation (Wang et al., 2018). Furthermore, manure application does not affect N_2O emission and EF compared with inorganic N fertilizer under similar N application rates

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(Wang et al., 2018). However, the effect of crop species on N_2O emission remains unclear. The edible parts of vegetable crops vary among species. The emission of N_2O in response to N fertilizer may vary among species according to the planting season, crop growth duration, N allocation, and crop management practices (Zhang et al., 2016).

Agronomic practices are known to affect both N_2O emission and vegetable crop yield. For example, synthetic N fertilizer is the main factor that contributes to the increase in N_2O emission from vegetable crops. Application of N fertilizer is essential for the growth of vegetable crops. A high dose of N fertilizer (global average of 220 kg N ha^{-1} per season) is widely applied in vegetable crop production to maximize crop yield, as vegetable crops are more profitable than cereal crops (Martellozzo et al., 2014; Rezaei Rashti et al., 2015). The optimal N application rate for balancing N_2O emission and crop yield is unknown. Greenhouse cultivation is widely used to maintain temperature and enhance vegetable crop yield; however, greenhouse cultivation increases N_2O emission from the soil compared with open field cultivation (Chang et al., 2013; Wang et al., 2018; Yao et al., 2015). The replacement of conventional N fertilizer with enhanced-efficiency N fertilizer (EENF) may enable the reduction of N_2O emission from vegetable cultivation fields; however, the effect of EENF on the yield of vegetable crops can be significantly positive or not obvious compared with conventional N fertilizer (Cheng et al., 2002; Hyatt et al., 2010; Riches et al., 2016). An integrated assessment of yield-scaled N_2O emission, rather than area-scaled N_2O emission, will benefit the trade-off decision making for these agronomy practices (Van Groenigen et al., 2010; Linquist et al., 2012). Many studies have examined the amount and influencing factors of yield-scaled N_2O emission from cereal crops (Linquist et al., 2012; Feng et al., 2013; van Kessel et al., 2013). However, little is known about the yield-scaled N_2O emission from vegetable crops.

In this study, we performed a meta-analysis to: 1) quantitatively summarize the area- and yield-scaled N_2O emissions and N_2O EF of six different types of vegetable crops; 2) investigate the correlation of area- and yield-scaled N_2O emissions with N fertilizer application rates of different vegetable types; and 3) examine the influence of greenhouse cultivation, manure application, and EENF on area- and yield-scaled N_2O emissions.

2. Material and methods

2.1. Data collection

A survey of peer-reviewed studies published before December 2017 was carried out using ISI-Web of Science (www.webofknowledge.com) and Google Scholar (https://scholar.google.com) with the following keywords: 'nitrous oxide,' 'greenhouse gas,' and 'vegetable.' The following four criteria were used to select appropriate studies: (1) studies must be conducted in open field or greenhouse conditions with at least three replications; (2) N_2O fluxes must be measured using the statistic chamber method during the entire growing season; (3) N_2O emission and vegetable yield must be reported for treatments with and without N fertilizer application; and (4) N application rates, crop species, and management options must be similar for manure/EENF and control (CK) treatments. Applying these criteria, a total of 40 studies including 301 comparisons (223 of inorganic N fertilizer, 29 of manure, and 49 of EENF; Table 1) were selected. The experiment sites were distributed among seven countries (Australia, Canada, China, Germany, Japan, Spain, and USA). Detailed information is listed under Supporting Information (Tables S1–S3).

Vegetable species were divided into six categories, according to the edible parts (Pennington and Fisher, 2009): (1) leafy vegetables (lettuce, pak choi, crown daisy, cabbage, Chinese cabbage, spinach, baby bok choy, coriander, amaranth, endive, and tung choy); (2) stem vegetables (broccoli, cauliflower, water convolvulus, celery, asparagus lettuce, and cress); (3) fruit vegetables (tomato, cucumber, and pepper); (4) seed vegetables (green soybean, cowpea, and sweet corn); (5) root vegetables (radish and potato); and (6) bulb vegetables (onion). The planting methods used were classified into two groups: open field and greenhouse. Manure application was divided into two subgroups according to the proportion of organic N (from manure) that replaced inorganic N: $< 1/2$ and $\geq 1/2$. According to action mode, the EENF was classified as nitrification inhibitor (NI) and slow- or control-released fertilizer (S/CRF).

2.2. Data analysis

Five effect sizes, including area-scaled N_2O emission, yield, yield-scaled N_2O emission, EF of N_2O, and N agronomic efficiency (NAE), were analyzed in this meta-analysis. Area-scaled N_2O (kg N_2O-N ha^{-1}) refers to the fertilizer-induced seasonal cumulative N_2O emitted per unit area of the vegetable field. Yield (kg ha^{-1}) is the weight of edible parts harvested from different vegetable crops. Yield-scaled N_2O emission, calculated in terms of carbon dioxide equivalents (g CO_2 eq kg^{-1}), represents seasonal N_2O emission per unit vegetable yield. The N_2O emission was converted into global warming potential (GWP) by multiplying by 298, the 100-year radiative forcing potential coefficients of N_2O to CO_2. The fertilizer-induced area-scaled N_2O, yield, and yield-scaled N_2O were calculated according to the following equation:

$$x_f = x_t - x_c \tag{1}$$

where x_f represents the fertilizer-induced area-scaled N_2O, yield, and yield-scaled N_2O; and x_t and x_c represent the measurements of these three indices for treatment and control, respectively. The background values of area-scaled N_2O, yield, and yield-scaled N_2O were subtracted to examine the net effect of N fertilizer.

The N_2O EF and NAE represent the net N_2O emission and net yield per unit N fertilizer, respectively. They were calculated using Eqs. (2) and (3), respectively:

$$EF = \frac{N_t - N_c}{R} \tag{2}$$

$$NAE = \frac{Y_t - Y_c}{R} \tag{3}$$

In Eq. (2), *EF* represents the emission factor of N_2O emission, and N_t and N_c represent the seasonal cumulative N_2O emission from the N fertilizer treatment and control, respectively. *R* represents the inorganic N application rate in Eqs. (2) and (3). *NAE* in Eq. (3) represents the agronomic efficiency of N fertilizer. Y_t and Y_c in Eq. (3) represent yields of the edible parts of the N fertilizer treatment and control, respectively.

In the present meta-analysis, the mean effect size of all five indices was calculated using a nonparametric weighting function, and the 95% confidence interval (CI) for each index was generated using bootstrapping (Linquist et al., 2012). The mean values of fertilizer-induced area-scaled N_2O emission, EF, yield, NAE, and yield-scaled N_2O emission were calculated as follow:

$$M = \sum (Y_i \times W_i) / \sum (W_i) \tag{4}$$

where Y_i denotes the observation of area-scaled N_2O emission, EF, yield, NAE, and yield-scaled N_2O emission at the ith site, and W_i represents the weight of observations and is equal to the number of replicates performed (n). Thus, this weighting approach assigns more weight to well-replicated field experiments. M is the weighted mean value of each index.

The impact of manure and EENF on area-scaled N_2O emission, EF, yield, NAE, and yield-scaled N_2O emission was calculated by the response ratio (*lnR*) (Hedges et al., 1999.):

$$lnR = ln\left(\frac{X_t}{X_c}\right), \tag{5}$$

where X_t *and* X_c are measurements for the treatment and control,

Table 1
Studies used in this meta-analysis to qualify area-scaled N_2O, yield and yield-scaled N_2O of different vegetables.

ID	Country	Vegetable type	Number of measurements	References	ID	Country	Vegetable type	Numbers of measurement	References
1	China	Fruit	1	Guo et al., 2012	21	China	Fruit, leafy, seed	9	Zhang et al., 2016b
2	China	Fruit	5	Zhang et al., 2015	22	China	Leafy, stem	32	Li, 2015a
3	China	Fruit	1	Nie et al., 2012	23	China	Fruit, leafy, root	23	Qiu, 2011
4	China	Leafy, root, stem	8	Jin et al., 2013	24	China	Leafy, stem	8	Yi, 2013
5	China	Leafy, stem	12	Bi et al., 2017	25	Australia	Leafy, stem	13	Riches et al., 2016
6	China	Leafy	6	Yi et al., 2016	26	Germany	Root	2	Ruser et al., 2001
7	China	Leafy, stem	4	Yu et al., 2012	27	Japan	Leafy	5	Cheng et al., 2002
8	China	Leafy, stem	3	Yu et al., 2008	28	Japan	Leafy	2	Hou and Tsuruta, 2003
9	China	Leafy	5	Zhang et al., 2014	29	Japan	Leafy	3	Cheng et al., 2006
10	China	Fruit, stem	8	Hao et al., 2012	30	Spain	Root	4	Vallejo et al., 2006
11	China	Fruit	4	Li, 2015b	31	Japan	Bulb	5	Toma et al., 2007
12	China	Leafy	3	Deng et al., 2012	32	Canada	Root	4	Burton et al., 2008
13	China	Fruit	2	Lou et al., 2012	33	USA	Root, seed	4	Haile-Mariam et al., 2008
14	China	Fruit, stem	12	Min et al., 2012	34	Spain	Fruit	2	Sánchez-Martín et al., 2008
15	China	Fruit, leafy, root	8	Mu et al., 2013	35	USA	Root	9	Hyatt et al., 2010
16	China	Fruit, stem, seed	3	Yao et al., 2015	36	Spain	Bulb	3	Sanchez-Martin et al., 2010
17	China	Leafy	18	Li et al., 2017	37	Germany	Leafy, stem	6	Pfab et al., 2011
18	China	Fruit, root, seed	3	Yuan et al., 2016	38	Canada	Root	9	Zebarth et al., 2012
19	China	Leafy, seed	16	Yi et al., 2017	39	Canada	Root	6	Gao et al., 2013
20	China	Leafy	28	Zhang et al., 2016a	40	Canada	Root	2	Snowdon et al., 2013

respectively. Only studies that included side-by-side comparisons were selected for the meta-analysis.

The mean effect size of the response ratio (*RR*) was estimated as follow:

$$RR = \sum (lnR \times W_i)/\sum W_i, \quad (6)$$

where lnR denotes the response ratio in Eq. (5), and W_i denotes the weight in Eq. (4).

The percentage change in each of the five indices was calculated according to the following equation:

$$Change \ \ (\%) = (e^{RR} - 1) \times 100\%, \quad (7)$$

where RR denotes the mean effect size of the response ratio in Eq. (6), and e is the natural base number.

Meta-analysis was performed using MetaWin2.1 software (Rosenberg, 2000). The mean effect sizes were estimated with a random effects model. The 95% CI for each mean effect size was calculated using bootstrapping with 4999 iterations (Rosenberg et al., 2000). Mean effect sizes were considered significantly different when the 95% CIs did not overlap.

3. Results

3.1. Fertilizer-induced area- and yield-scaled N_2O emissions and yield

The mean area-scaled N_2O emission from all vegetables was 3.48 kg N_2O-N ha^{-1} (CI: 2.79–4.29 kg N_2O-N ha^{-1}) (Fig. 1a) of overall vegetables. The mean N_2O emission from different types of vegetables was in the following order: root < stem < fruit < bulb < leafy < seed. The mean EF of all of the vegetables was 1.41% (CI: 1.19–1.64%) (Fig. 1b), which was higher than the default value (1%) reported by the Intergovernmental Panel on Climate Change (IPCC). Significant differences in the N_2O EF were found among the different vegetable types. Stem vegetables showed the lowest EF (0.71%; CI: 0.47–0.98%), which was lower than the IPCC default value. The EFs of fruit (0.91%; CI: 0.65–1.23%) and root (0.94%; CI: 0.54–1.45%) vegetables were similar to the IPCC default value. Those of leafy (1.53%; CI: 1.24–1.85%) and seed (4.88%; CI: 2.88–7.04%) vegetables were higher than the IPCC default value.

The yield and NAE of root, stem, and fruit vegetables were higher than those of leafy and seed vegetables (Fig. 1c, d). The mean yield-scaled N_2O emission from all of the vegetables was 28.2 g CO_2 eq kg^{-1}. Yield-scaled N_2O emission was the highest for seed vegetables (103.6 g CO_2 eq kg^{-1}), followed by fruit (34.3 g CO_2 eq kg^{-1}), leafy (30.3 g CO_2 eq kg^{-1}), and root (8.8 g CO_2 eq kg^{-1}) vegetables, and the lowest for stem vegetables (4.9 g CO_2 eq kg^{-1}).

3.2. Impact of greenhouse on area- and yield-scaled N_2O emissions and yield

The mean area- and yield-scaled N_2O emissions and N_2O EF of all vegetables showed no significant difference between greenhouse and open field cultivation (Fig. 2a, b, e), although the mean yield of all of the vegetables was higher by 135.6% in the greenhouse than in the open field (Fig. 2c). Furthermore, we compared the effect sizes for leafy, stem, and fruit vegetables under greenhouse and open field cultivation; root, bulb, and seed vegetables were excluded from this analysis because most of these vegetables were cultivated using only one system in the selected studies. Greenhouse cultivation significantly reduced area-scaled N_2O emission from leafy vegetables, and significantly increased yield, resulting in a significant reduction in yield-scaled N_2O emission compared with open field cultivation. Greenhouse cultivation significantly increased both area-scaled N_2O emission and yield of stem vegetables but did not affect yield-scaled N_2O emission. In the case of fruit vegetables, greenhouse cultivation increased only the yield; area- and yield-scaled N_2O emissions did not differ between greenhouse and open field cultivation.

3.3. Response of N_2O and yield to inorganic N application rate

Area-scaled N_2O emission showed a significantly positive correlation with the inorganic N application rate (Fig. 3a). Unlike area-scaled N_2O emission, vegetable crop yield did not show a consistent increase with the N application rate (Fig. 3b). The highest yield of all of the vegetables was observed at the application rate of 420 kg N ha^{-1}. The NAE of inorganic N fertilizer decreased with the N application rate (Fig. 3e). A second-degree polynomial function was fitted for the response of yield-scaled N_2O emission to the N application rate. The lowest yield-scaled N_2O emission was observed at the application rate of 187 kg N ha^{-1} for all of the vegetables.

We further analyzed the response of yield-scaled N_2O emission from leafy, stem, root, and fruit vegetables to inorganic N application rate (Fig. 4). A significant correlation was observed between these two variables for leafy, stem, and fruit vegetables, but not for root vegetables. The lowest yield-scaled N_2O emission from fruit vegetables was observed at 198 kg N ha^{-1}, which was close to the value observed for

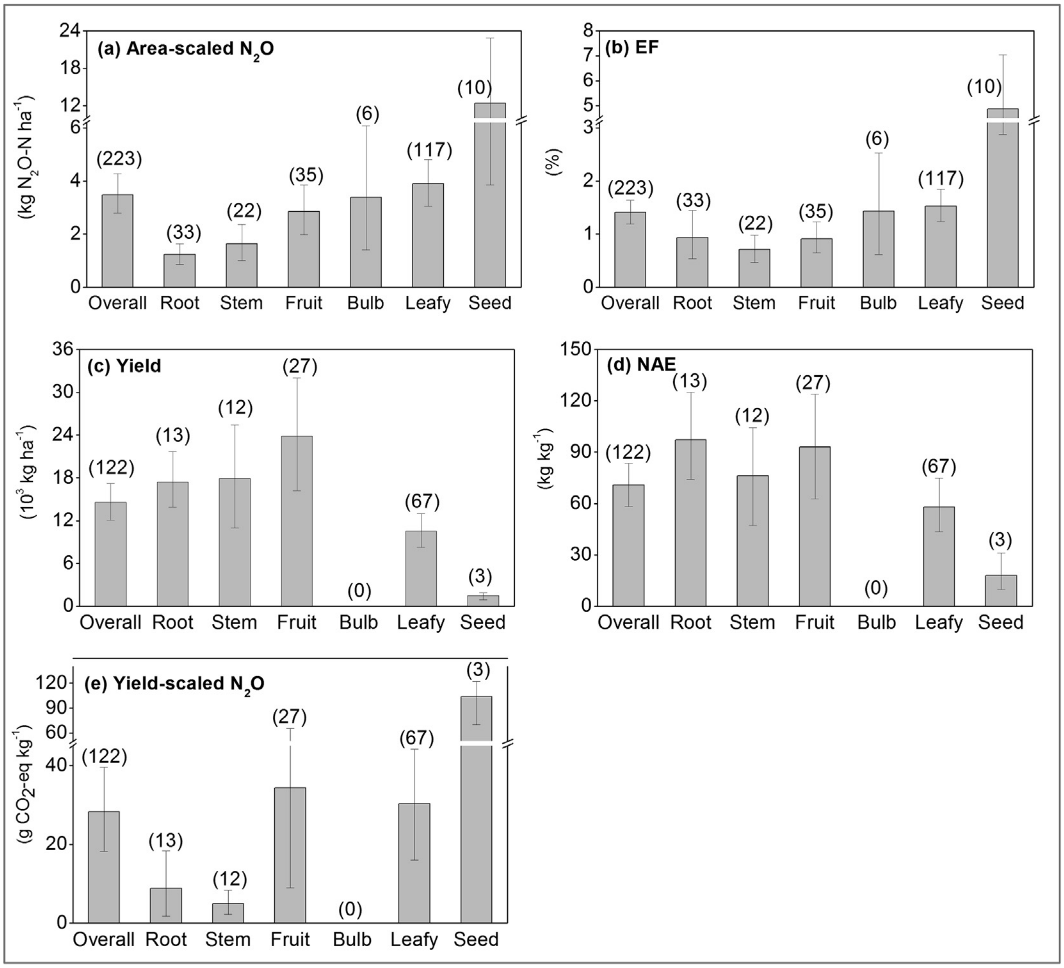

Fig. 1. Fertilizer-induced area-scaled N_2O emission (a), EF (b), yield (c), NAE (d), and yield-scaled N_2O emission (e) of different vegetables. Numbers in parentheses were the amounts of selected measurements. The mean effect sizes were considered significantly different only when the 95%CI did not overlap. The results included only the normal inorganic N fertilizer, such as urea, ammonium sulfate, and ammonium nitrate. Manure and EENF were excluded.

all of the vegetables (Fig. 3). The lowest yield-scaled N_2O emission from leafy vegetables was observed at 9 kg N ha^{-1}, which was much lower than that of fruit vegetables. In the case of stem vegetables, it was difficult to determine an optimal N rate because a linear increase in yield-scaled N_2O emission with the N application rate was observed in the current dataset.

3.4. Impact of manure application on area- and yield-scaled N_2O emissions and yield

The replacement of inorganic N fertilizer with manure significantly increased the vegetable yield and NAE (Fig. 5); however, this did not affect the area- and yield-scaled N_2O emissions from overall vegetables. The effect of manure on N_2O emission and vegetable yield was not dependent on the proportion of manure used to replace the inorganic N fertilizer but was dependent on the vegetable crop species and cultivation method. In the case of fruit vegetables, the increase in area-scaled N_2O (90.3%) due to manure application was higher than the increase in yield (4.7%), resulting in an increase in yield-scaled N_2O emission (81.8%; marginally significant, CI: 1.3–301.2%), compared with inorganic N fertilizer. For leafy vegetables, manure application significantly increased yield (19.3%) and significantly reduced yield-scaled N_2O emission (46.4%). Yield and area- and yield-scaled N_2O emissions from stem vegetables did not differ between application of manure and inorganic N fertilizer. Manure did not affect the area-scaled N_2O emission and EF of all vegetables in open field cultivation, but it significantly increased the area-scaled N_2O emission and EF in greenhouse cultivation.

3.5. Impact of EENF on area- and yield-scaled N_2O emissions and yield

Overall, EENF significantly mitigated area-scaled N_2O emission by 36.1% and increased vegetable yield by 4.1%, compared with normal N fertilizer (Fig. 6). The yield-scaled N_2O emission was mitigated by 37.8%. Both NI and S/CRF significantly reduced the area- and yield-scaled N_2O emissions compared with normal N fertilizer. However, NI was more effective than S/CRF in enhancing vegetable yield. NI significantly increased yield by 5.4%, whereas S/CRF showed no effect on yield. The effect of EENF on various indices depended on the crop species. EENF significantly mitigated area- and yield-scaled N_2O emissions from leafy, stem, and fruit vegetables; but did not affect N_2O emissions and yield of root vegetables. Although EENF significantly mitigated area- and yield-scaled N_2O emissions from vegetable crops both under open field and greenhouse conditions, its effect on vegetable yield differed under the two cultivation systems. EENF significantly increased vegetable yield in the greenhouse but exerted no effect on yield in the open field.

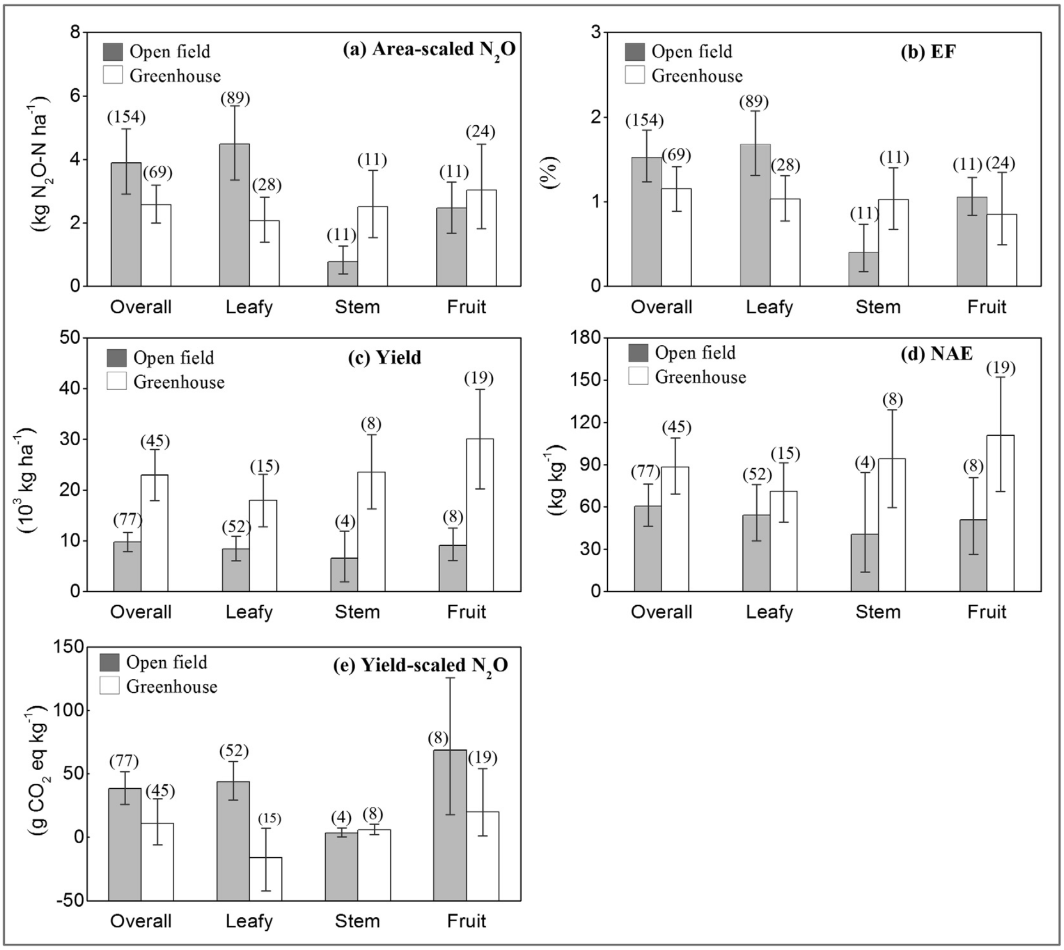

Fig. 2. Impact of greenhouse cultivation on area-scaled N_2O emission (a), EF (b), vegetable yield (c), NAE (d), and yield-scaled N_2O emission (e) of different vegetables.

4. Discussion

4.1. Fertilizer-induced N_2O emission indices of vegetable crops

The EF and yield-scaled N_2O emission are two important indices for the evaluation of climate-smart cropping practices. According to a previous meta-analysis, the global average EF (0.94%; CI: 0.89–0.99%) of vegetable crops is similar to the IPCC default value (1%) (Rezaei Rashti et al., 2015). However, the results of this study showed that the mean EF of all vegetables was 1.41% (CI: 1.19–1.64%) (Fig. 1b), which was higher than the IPCC default value. We believe that our results are more reliable, as our dataset was more comprehensive (n = 223) than that of Rezaei Rashti et al. (2015) (n = 90). The mean N_2O EF in this analysis was higher than that of cereal crops (Gerber et al., 2016,) because of the higher input of N fertilizer in vegetable production as compared to cereal crops (Diao et al., 2013; Porter et al., 2017).

The average yield-scaled N_2O emission of all vegetables was 28.2 g CO_2 eq kg^{-1}, which was lower than the global yield-scaled greenhouse gas emissions of cereal crops (166 g CO_2 eq kg^{-1}, 185 g CO_2 eq kg^{-1}, and 662 g CO_2 eq kg^{-1} for wheat, maize, and rice, respectively) (Linquist et al., 2012). However, it should be noted that the yield of vegetable crops was measured on a wet weight basis, while that of cereal crops was measured on the basis of dry weight. The water content of most vegetable crops is greater than 80%. Thus, if the water content is deducted from yield, the yield-scaled N_2O emission from vegetable crops is comparable to that of wheat and maize. The results of the current study further showed that the N_2O EF and yield-scaled N_2O were highly dependent on the type of vegetable crops (Fig. 1), suggesting that the discrepancy in N_2O EF among different species of vegetable crops must be considered for regional or global estimation. Variance in the N_2O EF and yield-scaled N_2O was attributed to the difference in the amount of N input, N uptake, irrigation, and environmental factors during growth duration among vegetable species (Thompson et al., 2007; Thorup-Kristensen, 2006; Ti et al., 2015). Seed vegetables showed much higher EF and yield-scaled N_2O than other types of vegetable crops (Fig. 1). Seed vegetables that were commonly used in the analyzed dataset were sweet corn and green soybean, which are usually planted in the summer. High temperature, along with abundant N supply, resulting from high N fertilizer application and additional atmospheric N_2 fixation, stimulates N_2O emission from these crops (Zhang et al., 2016; Yi et al., 2017).

4.2. Impact of greenhouse cultivation on N_2O emission and yield of vegetable crops

Our results showed that the yield of vegetable crops was significantly higher in the greenhouse than in the open field (Fig. 2). This was likely attributable to the higher N application rate, more favorable growing conditions, and longer growing season in the greenhouse than in the open field (Nagasaki, 2009; Shinohara, 2011). However, greenhouse cultivation did not affect the area- and yield-scaled N_2O emissions and EF of all of the vegetables compared with open field cultivation (Fig. 2), possibly because greenhouse cultivation exerted both positive and negative effects on N_2O emission from soil compared with open field cultivation. Relatively higher N application rates and the greenhouse effect have been shown to stimulate N_2O production in the

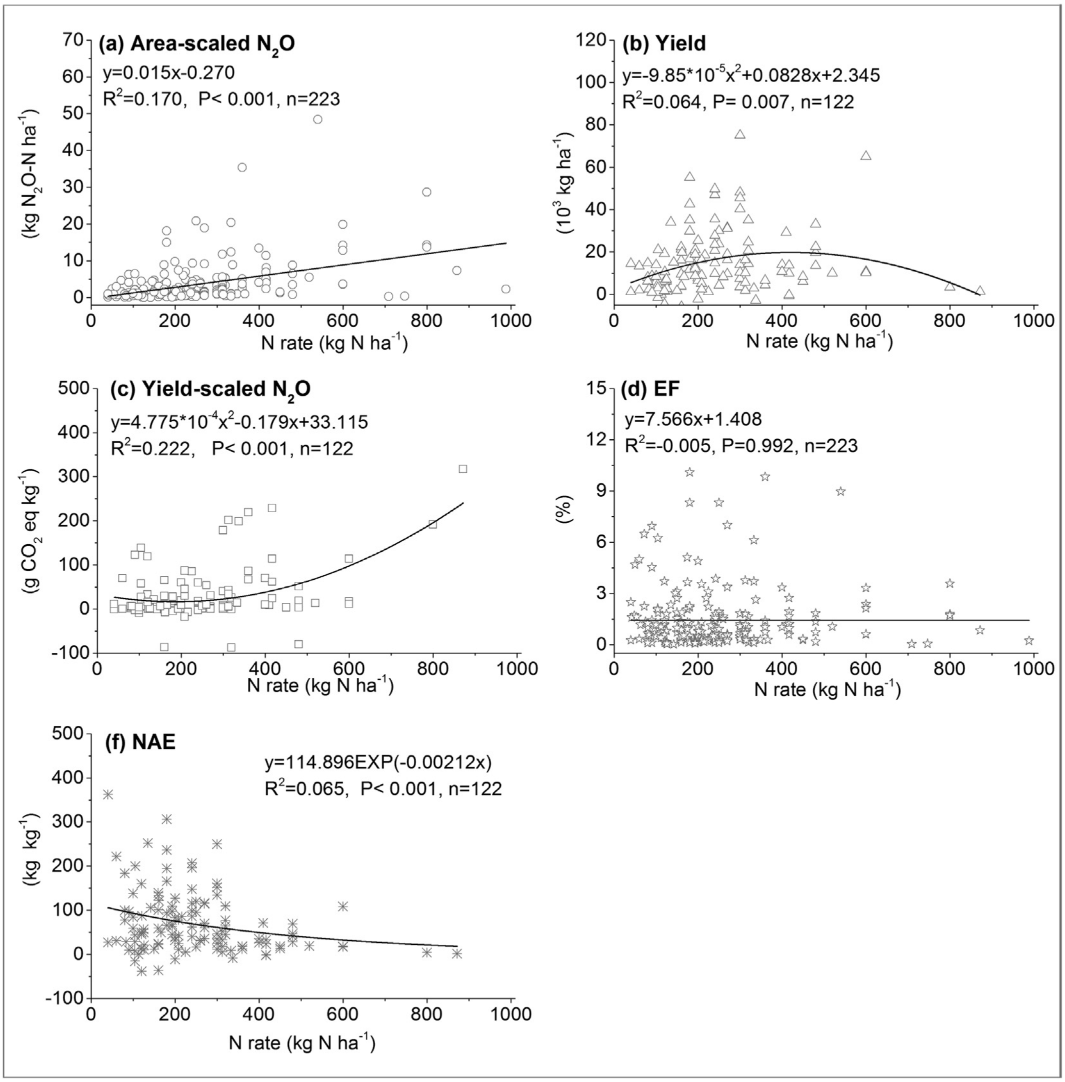

Fig. 3. Response of area-scaled N_2O (a), yield (b), yield-scaled N_2O (c), EF (d) and NAE (e) to inorganic N application rates for all vegetables.

soil (Liu et al., 2013; Yao et al., 2015). In contrast, more favorable growing conditions in the greenhouse promote crop growth and N absorption, thus facilitating the competition for N between crops and microbes (Shinohara, 2011). Additionally, intensive irrigation in greenhouse cultivation increases the migration of NO_3^- from surface soil to deep soil, and increases the loss of NO_3^- via leaching, which may reduce N_2O production (Lou et al., 2012). These effects likely balance each other.

However, yield-scaled N_2O emission from leafy vegetables was significantly reduced in the greenhouse than in the open field. The average growth duration of leafy vegetables was comparable under the open field (76 days) and greenhouse (79 days) systems, whereas the average N application rate was lower in the greenhouse (202 kg N ha^{-1}) than in the open field (253 kg N ha^{-1}). Lower N application rates and more favorable environmental conditions in the greenhouse possibly increase the N uptake by leafy vegetables and reduce yield-scaled N_2O emission compared with that of open field conditions (Liu et al., 2013; Ti et al., 2015).

4.3. Impact of inorganic N fertilizer and manure application on N_2O emission and yield of vegetable crops

Inorganic N fertilizer is the dominant source of N for crop growth and N_2O production. Our results showed that the optimal N application rate for balancing N_2O emission and yield was 187 kg N ha^{-1} for all of the vegetables (Fig. 3), which was comparable with the recommended rate for cereal crops (135–211 kg N ha^{-1}) (Van Groenigen et al., 2010; Hoben et al., 2011; Gao and Bian, 2017). The optimal N rate for leafy vegetables was much lower than that of fruit vegetables (Fig. 4). This was possibly because the root depth of leafy vegetables is shallower than that of fruit vegetables (Greenwood et al., 1982; Şimşek et al., 2005). The N uptake ability of leafy vegetables may be weaker than that of fruit vegetables.

Manure application did not affect area- and yield-scaled N_2O emissions from vegetable crops (Fig. 5). Manure provides abundant organic carbon for soil microbes and increases the O_2 consumption of microbial respiration, thus leading to anaerobic soil conditions that prompt the total reduction of N_2O to N_2 through denitrification (Vallejo et al., 2006; Sanchez-Martin et al., 2010). However, this positive effect of manure on reducing N_2O emission is affected by agronomic practices. Sanchez-Martin et al. (2010) reported that frequent irrigation could remove the dissolved organic carbon (DOC) from the upper soil, thus weakening the effect of manure on denitrification. Surface application of manure can stimulate N_2O emission compared to incorporation into the soil (Porter et al., 2017). Furthermore, our results showed that manure significantly reduced the yield-scaled N_2O emission of leafy vegetables but increased the area- and yield-scaled N_2O emissions from fruit vegetables (Fig. 5). This was possibly because of the difference in

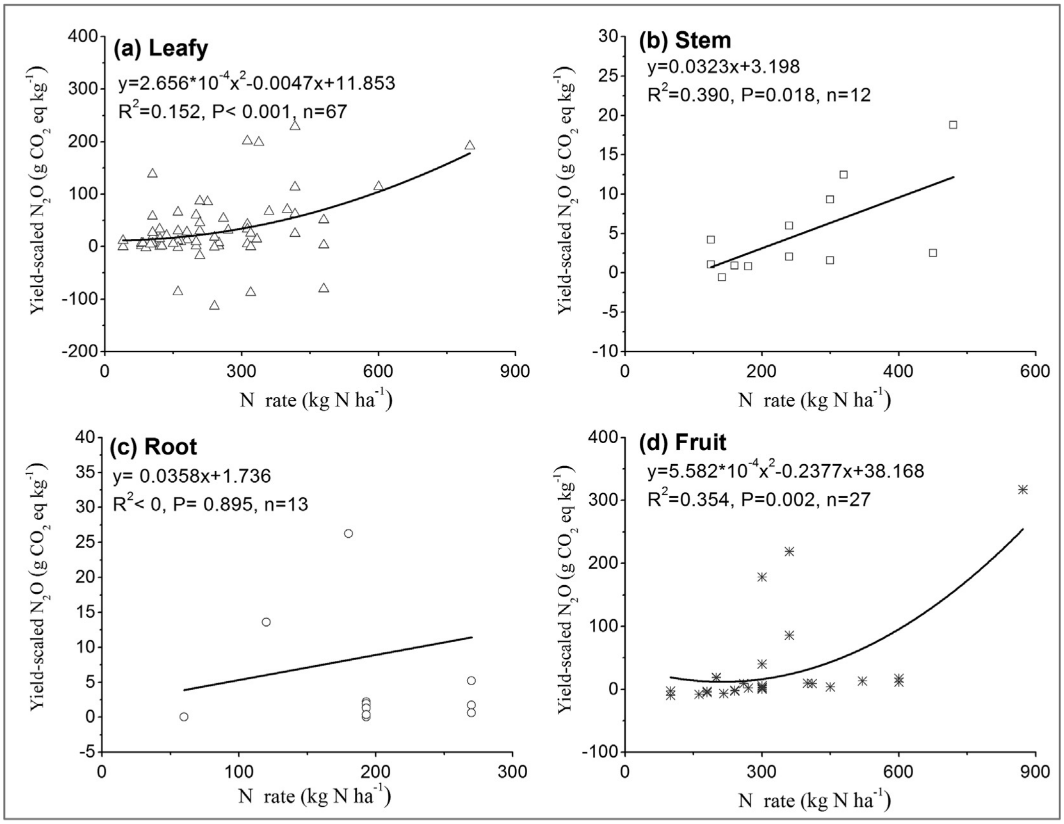

Fig. 4. Response of yield-scaled N_2O to inorganic N application rates for leafy, stem, root, and fruit vegetables.

N application rates. In our analysis, the average N application rate was 450 kg N ha^{-1} for fruit vegetables and 218 kg N ha^{-1} for leafy vegetables. Manure has been reported to stimulate the N_2O emission under high N application rate because of the low C/N ratio in soil, but to inhibit N_2O emission under low N application rate (Porter et al., 2017). Therefore, agronomic practices should be adjusted for manure to maximize yield and environmental benefits.

4.4. Impact of EENF on N_2O emission and yield of vegetable crops

The effect size of EENF on N_2O emission and yield in this study was similar to that reported for cereal crops in previous studies (Akiyama et al., 2010; Abalos et al., 2014; Feng et al., 2016). NI was more effective than S/CRF on the yield of vegetable crops (Fig. 6). This was possibly because of the difference in the pathway regulating the

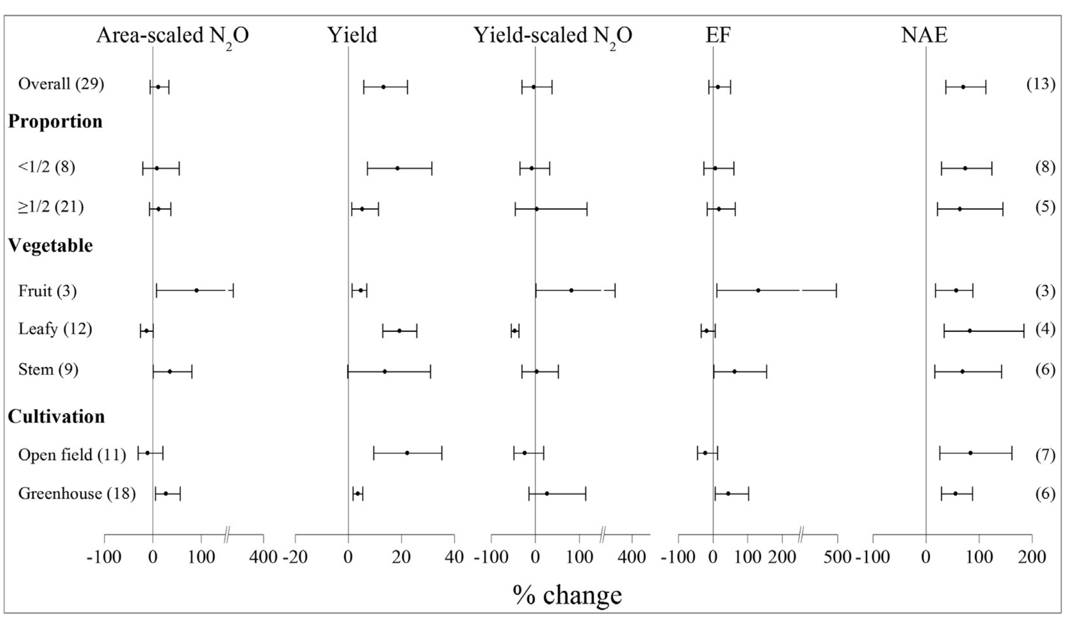

Fig. 5. Impact of manure on area-scaled N_2O, yield, yield-scaled N_2O, EF, and NAE. Numbers in the left parentheses were the amounts of area-scaled N_2O and EF; and the numbers in the right parentheses were the amounts of yield, yield-scaled N_2O and NAE. The mean effect sizes were considered significantly different only when the 95%CI did not overlap.

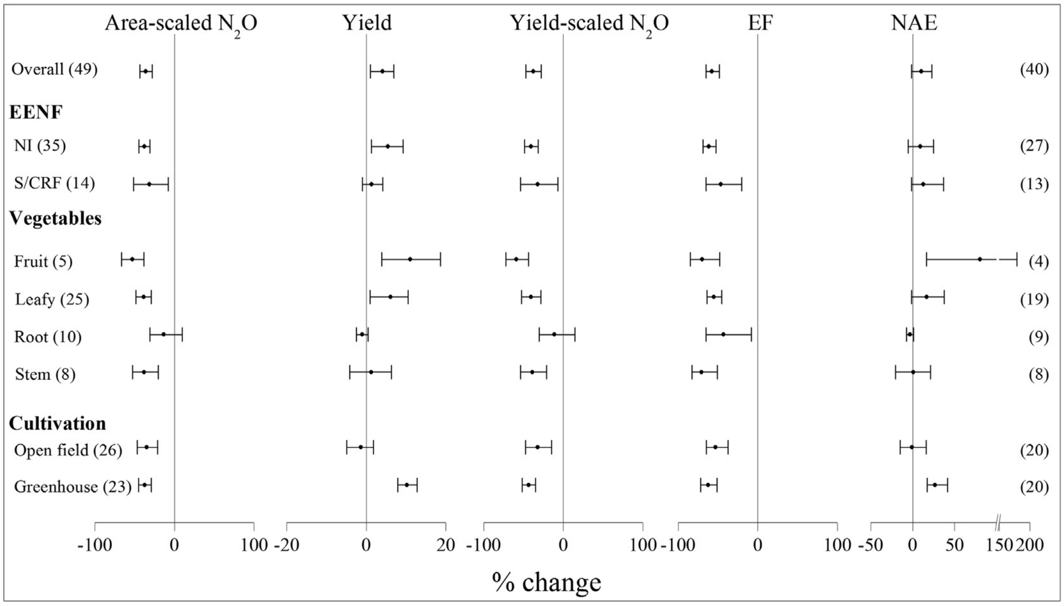

Fig. 6. Impact of EENF on area-scaled N_2O, yield, yield-scaled N_2O, EF, and NAE.

transformation of N fertilizer of these two EENFs. NI prevents the oxidation of NH_4^+ to NO_3^- by repressing the activity of nitrifiers in soil, while S/CRF reduces N release to better match crop demand through coating or chemical modification of fertilizer (Chien et al., 2009). Field experiments on cereal and forage crops have shown that the performance of S/CRF is less stable than that of NI, as it was difficult to precisely match N release from S/CRF with crop uptake in field conditions (Abalos et al., 2014; Feng et al., 2016). The regulation of N release by S/CRF is highly dependent on rainfall, soil properties, and fertilizer application method (Golden et al., 2011; Uchida et al., 2012; Halvorson et al., 2014).

In this study, EENF more effectively mitigated area- and yield-scaled N_2O emissions from leafy, stem, and fruit vegetables than from root vegetables (Fig. 6). This was possibly because the average growth duration of root vegetables (145 days) is approximately twice as long as that of leafy (66 days) and stem (67 days) vegetables. Approximately 90% of the comparisons for root vegetables used S/CRF as EENF in the selected studies. Previous studies have reported that 80% of the N in S/CRF is released within 30–60 days (Cahill et al., 2010; Golden et al., 2011). Therefore, S/CRF cannot regulate N release throughout the growth season for root vegetables. For fruit vegetables, the growth duration (141 days) was similar to that of root vegetables, and all of the fruit vegetables used NI as EENF in the selected studies. The half-life of NI was up to 231 days when applied at 19.5 kg ha^{-1} and at a temperature of 10 °C (Kelliher et al., 2008); these parameters were comparable to the NI application rate (15–150 kg ha^{-1}) and mean annual temperature (11.5 °C) in the selected studies. Thus, NI rather than S/CRF is recommend for the vegetable crops with long growing seasons.

The effect size of EENF on vegetable crop yield was affected by the cultivation method (Fig. 6). EENF significantly increased the yield of vegetable crops cultivated in the greenhouse but did not affect that of vegetable crops cultivated in open fields. EENF only delayed the release or transformation of N applied to soil. The effect of EENF on vegetable crop yield depended on the rate of crop growth and synchronization of N release with crop demand. Favorable environmental conditions prompted growth and N absorption of vegetables in the greenhouse compared with in the open field (Shinohara, 2011), thus strengthening the effect of EENF on vegetable crop yield. Additionally, rainfall in the open field may weaken the effect of EENF on N release and transformation in soil (Hyatt et al., 2010), thus disturbing the synchronization of N release with crop demand and weakening the effect of EENF on vegetable crop yield.

4.5. Study limitations

Vegetable crop yield and N_2O emission are affected by several agricultural practices, such as fertilizer application, irrigation, and crop rotation (Sanchez-Martin et al., 2010; Pang et al., 2009; Porter et al., 2017). In the current study, we only assessed the effects of greenhouse cultivation and three types of N fertilizer (inorganic N fertilizer, manure, and EENF) on yield-scaled N_2O emission because of the limited number of studies. Additionally, we were unable to compare the N use efficiency of vegetable crops under different agricultural practices, as there were insufficient studies reporting N uptake in vegetable plants. The evaluation of N use efficiency should provide additional evidence to elucidate the pathways by which agricultural practices affect the competition for N between vegetables and soil microbes (Van Groenigen et al., 2010). Vegetable crops comprise diverse species, are rotated more intensively, require higher N input, and generate higher income than cereal crops. However, the number of studies focusing on N_2O emission from vegetables is far lower than that of cereal crops. More field experiments are needed to measure the N_2O emission from different vegetable species and under different agricultural practices. With increasing data availability, it is important to analyze the mechanisms controlling N transformation and allocation in vegetable fields. In addition, future studies should aim to perform an integrated assessment on N loss (including NO_3^- leaching, N_2O emission, and NH_3 volatilization) and to identify the optimal agricultural practices achieving high-yield with less N loss.

5. Conclusions

The N_2O EF of vegetables showed significant differences among the six vegetable types, suggesting that the regional or global estimation should consider the discrepancy among different vegetable species. The average yield of all of the vegetables was significantly higher in the greenhouse than that in the open field. Only leafy vegetables showed significantly lower area- and yield-scaled N_2O emissions in the greenhouse as compared to the open field. A significant correlation was observed between yield-scaled N_2O emission and inorganic N application rate. The lowest yield-scaled N_2O emission for all of the vegetables was observed at an application rate of 187 kg N ha^{-1}. The replacement of inorganic N fertilizer with manure significantly reduced yield-scaled N_2O emission only from leafy vegetables. Additionally, EENF significantly mitigated area-scaled N_2O emission and increased crop yield, resulting in a significant reduction in yield-scaled N_2O emission compared with normal N fertilizer.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.02.001.

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