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The combined effects of nitrification inhibitor and biochar incorporation on yield-scaled N_2O emissions from an intensively managed vegetable field in southeastern China

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Abstract. An experiment was conducted to study the influences of nitrification inhibitor (NI) and biochar incorporation on yield-scaled N_2O using the static chamber method and gas chromatography in an intensively managed vegetable field with seven consecutive vegetable crops from 2012 to 2014 in southeastern China. With an equal annual nitrogen (N) application rate (1217 kg N ha^{-1} yr^{-1}), six treatments under three biochar amendment rates – namely, 0 t ha^{-1} (C0), 20 t ha^{-1} (C1) and 40 t ha^{-1} (C2) – with compound fertilizer (CF) or urea mixed with NI of nitrapyrin as chlorinated pyridine (CP) were studied in these field experiments. The results showed that, although there was no significant influence on soil organic carbon (SOC) content or total nitrogen (TN), nitrapyrin could result in a significant increase in soil pH during the experimental period. Nitrapyrin significantly decreased cumulative N_2O emissions by 15.9–32.1 % while increasing vegetable yield by 9.8–41.9 %. Thus, it also decreased yield-scaled N_2O emissions significantly. In addition to the differential responses of the soil pH, biochar amendment significantly increased SOC and TN. Compared with the treatments without biochar addition, the cumulative N_2O emissions showed no significant difference in the CF or the CP group treatments but increased slightly (not significantly) by 7.9–18.3 % in the CP group treatments. Vegetable yield was enhanced by 7.1–49.5 % in the CF group treatments compared with the treatments without biochar amendment, while there was no significant difference in the CP group treatments, and the yield-scaled N_2O emissions were thus decreased significantly. Furthermore, treatments involving with nitrapyrin and biochar incorporation slightly increased yield-scaled N_2O emissions by 9.4 %, on average, compared with CP-C0. Therefore, the application of nitrapyrin could serve as an appropriate practice for increasing vegetable yield and mitigating N_2O emissions in intensively managed vegetable fields and should be further examined in various agroecosystems.

1 Introduction

Nitrous oxide (N_2O) is an important greenhouse gas and also contributes to ozone depletion in the stratosphere (IPCC, 2007; Saggar et al., 2007; Ravishankara et al., 2009). Global N_2O emissions increased from 10 Tg to 12 Tg N_2O-N yr^{-1} between 1900 and 2000 and may reach 16 Tg N_2O-N yr^{-1} by 2050 (Bouwman et al., 2013). The increase in nitrogen (N) fertilizer application in agricultural ecosystems has been recognized as a major source of N_2O, representing approximately 60 % of the global anthropogenic emission rates in 2005 (Smith et al., 2007; Park et al., 2012). Emissions from soils increase markedly following the application of N fertilizers and animal manures for the purpose of increasing crop production (Mosier et al., 1998; Davidson, 2009).

Increasing grain yields is a boundary condition for "greening" Chinese agriculture in light of the increasing food demand in China. The high N fertilizer application rate contributes to high crop yields (Qin et al., 2010) but, inevitably, also to high N_2O emissions (Ding et al., 2007) and nitrate leaching (Li et al., 2007). To minimize the overall greenhouse gas (GHG) impact of agriculture while increasing crop production, the amount of N_2O emitted per unit of crop production (yield-scaled N_2O emissions) needs to be considered (Van Groenigen et al., 2010). The yield-scaled N_2O emissions approach has been suggested as a more comprehensive index to assess N_2O emissions in agricultural ecosystems (Van Groenigen et al., 2010; Grassini and Cassman, 2012). This approach is attractive in view of the need to balance crop production with the mitigation of N_2O emissions from agriculture. Only a few studies have directly addressed yield-scaled emissions in agriculture cropping systems (Halvorson et al., 2010; Wei et al., 2010; Gagnon et al., 2011; Zhou et al., 2014), particularly intensively managed vegetable systems.

Intensively managed vegetable cultivation represents a major source of N_2O emissions in the agricultural sector in China (Zheng et al., 2004; Wang et al., 2011) as a result of the practical characteristics of high N fertilization, intensive irrigation and favorable environmental conditions that are associated with this type of agriculture. Previous studies have shown that annual N fertilizer inputs are extremely high for certain intensively managed vegetable fields (Ju et al., 2006; Xiong et al., 2006; He et al., 2009). These levels are almost 3–4 times the fertilizer levels used for non-vegetable crops in fields where two crops are grown per year (Zheng et al., 2004). As a consequence, N_2O emissions from N fertilizer in vegetable ecosystems represent 20 % (Zheng et al., 2004) or 21.4 % (Wang et al., 2011) of the total emissions from China's farmland.

Alternative practices that could reduce N_2O emissions without necessarily reducing N inputs or crop yields have also been considered, such as nitrification inhibitor (NI) application (Zaman et al., 2009; Ji et al., 2011) and biochar amendment (Zhang et al., 2010; Jia et al., 2012; Wang et al., 2013) in agricultural soils. NIs have been used in the field to improve the efficiency of fertilizers and to reduce both nitrate leaching and denitrification by maintaining the N in the soil as NH_4^+ (Majumdar et al., 2000; Pathak and Nedwell, 2001; Malla et al., 2005; Chen et al., 2010), thus mitigating N_2O emissions and increasing the crop yield from the agricultural ecosystem. A newly developed urea fertilizer mixed with NI of nitrapyrin as chlorinated pyridine (CP) has been used in agricultural ecosystems to mitigate GHG emissions and simultaneously increase crop yield (Ma et al., 2013; Xiong et al., 2013; Zhang et al., 2015). The biochar amendment of soils is currently being considered as a means of mitigating climate change by sequestering carbon (C) while concurrently improving soil properties and functions (Lehmann, 2007; Woolf et al., 2010; Zhang et al., 2012a). However, the effects of biochar amendment induced by biochar addition on N_2O emissions may be either positive or negative depending on the inherent characteristics of biochar, the addition of exogenous N and the soil water regime (Spokas and Reicosky, 2009; Xie et al., 2013; Cayuela et al., 2013, 2014). The soil pH of intensively managed vegetable fields has been found to be much lower than that of other agricultural ecosystems due to the input of large amounts of N. Most likely, this lower soil pH will cause a negative effect if biochar amendment is used to mitigate N_2O emissions because it would affect the activity of N_2O reductase in soil (Cayuela et al., 2014). Overall, based on previous results, both nitrapyrin application and biochar amendment could serve to decrease yield-scaled N_2O emissions in various agricultural ecosystems. As nitrapyrin application and biochar amendment could both significantly affect the soil pH, the combined use of the two practices may have different effects on N transformation processes and NH_3 volatilization and thus affect the N_2O emissions and crop yield in intensively managed vegetable fields (Zhu et al., 2011; Soares et al., 2012; Gong et al., 2013). However, information for investigating the combined effects of nitrapyrin application and biochar amendment incorporation on yield-scaled N_2O in intensively managed vegetable agriculture is limited.

Accordingly, we quantified the effect of nitrapyrin application and biochar amendment incorporation on yield-scaled N_2O emissions in intensively managed vegetable agriculture in southeastern China. The objective of the study was to find appropriate practices for increasing vegetable yield and mitigating N_2O emissions from intensively managed vegetable fields.

2 Materials and methods

2.1 Experiment site and biochar properties

A field experiment was conducted at a suburban site (31°59′ N, 118°51′ E) in Nanjing City, Jiangsu Province, China, from 2012 to 2014. This area has a subtropical monsoon climate with an annual mean rainfall of 1107 mm and an annual mean air temperature of 15.34 °C (Nanjing Meteorology). The selected site had been continuously cultivated conventionally with vegetables for approximately 10 years and is a typical vegetable field. The studied soil was classified as Fimi-Orthic Anthrosols (RGCST, 2001), with a bulk density of $1.2\,g\,cm^{-3}$, a total porosity of 51 %, a clay (< 0.002 mm diameter) fraction of 30.1 %, a silt (0.002–0.02 mm diameter) fraction of 64.7 % and a sand (0.02–2 mm diameter) fraction of 5.2 %. The main properties of this soil are as follows: pH, 5.52; total N, $1.90\,g\,kg^{-1}$; organic carbon, $15.6\,g\,C\,kg^{-1}$; and CEC (cation exchange capacity), $31.2\,cmol\,kg^{-1}$.

For the field experiment, biochar was produced from wheat straw at the Sanli New Energy Company in Henan, China, by pyrolysis and thermal decomposition at 400 °C. The biochar had a carbon content of $467\,g\,C\,kg^{-1}$ and an N content of $5.9\,g\,N\,kg^{-1}$. The initial values of pH, CEC and ash content were 9.4, $24.1\,cmol\,kg^{-1}$ and 20.8 %, respectively.

2.2 Treatments and vegetable management

There were six treatments with the same amount of total N in triplicate for seven consecutive vegetable crops from 12 April 2012 to 12 June 2014 in Nanjing, China. Each plot had an area of $7.5\,m^2$ and measured $3\,m \times 2.5\,m$. Biochar was applied at rates of 0, 20 and $40\,t\,ha^{-1}$ (C0, C1 and C2, respectively) with compound fertilizer (CF) or urea fertilizer mixed with nitrapyrin. All treatments received the same amount of N fertilizer based on local practice during the experimental period. The total N application rate for each treatment was equal – $1217\,kg\,N\,ha^{-1}\,yr^{-1}$ across the experimental period, of which $312.5\,kg\,N\,ha^{-1}$ was applied for amaranth (*Amaranthus mangostanus* L.) and coriander herb (*Coriandrum sativum* L.) and $600\,kg\,N\,ha^{-1}$ was applied for tung choy (*Ipomoea aquatica* Forssk.) and $250\,kg\,N\,ha^{-1}$ for baby bok choy (*Brassica chinensis* L.). Compound fertilizer with an $m(N) : m(P_2O_5) : m(K_2O)$ ratio of 15 : 15 : 15 was used for the CF group treatments, and the N form of the compound fertilizer is ammonium fertilizer, while the corresponding P and K fertilizers were distributed in the form of calcium phosphate and potassium chloride, respectively, in addition to the nitrapyrin urea for the CP group treatments. All fertilization occurred before transplanting and as the base fertilizer for each vegetable crop except for tung choy, which had $312.6\,kg\,N\,ha^{-1}$ as basal fertilization and $287.4\,kg\,N\,ha^{-1}$ as topdressing, following local farmers' practice. Additionally, both P and K fertilizers for the CP group treatments were applied as topdressing for the tung choy growing period as well. Biochar was added once to the vegetable fields before sowing the first vegetable crop (amaranth) on 8 April 2012 and was incorporated into the soil by hand plowing at a depth of 20 cm.

There were seven vegetable crops grown successively during the entire observation period (12 April 2012 to 12 June 2014). Each type of vegetable was seeded by hand and harvested at the appropriate mature stage according to the local farmers' practice. Furthermore, a short fallow period was imposed after fresh biomass was harvested from each vegetable crop. Soon after harvesting each vegetable crop, the field was tilled to a depth of approximately 12–15 cm. A protective plastic film was used to cover the crops according to the growth requirements of each vegetable crop, i.e., from 12 April to 25 May 2012 and 15 March to 12 May 2014 for amaranth and from 20 November 2012 to 24 February 2013 and 5 November 2013 to 14 March 2014 for baby bok choy, as amaranth and baby bok choy require relatively warm weather conditions for growth. All the other management procedures, including crop species, tillage, irrigation and pesticide, followed local farmers' practice and are presented in Table 1.

2.3 Measurements of N_2O fluxes, soil samples and environmental factors

A static opaque chamber method was used to collect air samples from the experimental sites from three replicates for each treatment. Each chamber was made of PVC and consisted of a chamber body ($50 \times 50 \times 50\,cm^3$). The outside of the chamber was coated with sponge and aluminum foil to prevent the effects of high temperatures on the chamber. The chamber was installed on a frame. The frames were inserted 0.1 m deep into the soil in each plot and filled with water to make the chamber gas-tight. Sampling was conducted between 8:30 and 10:30 LT in the morning every other day for 1 week after fertilizer application and then once per week thereafter. Gas fluxes were measured on 121 occasions over the 2-year period. On each sampling occasion, air samples were taken 0, 10, 20 and 30 min after chamber closure. The samples, collected in 20 mL syringes, were returned to the laboratory, and the N_2O was determined on the same day with a gas chromatograph (Agilent 7890A, Agilent Ltd., Shanghai, China) equipped with an electron capture detector (ECD). The carrier gas was argon–methane (5 %) at a flow rate of $40\,mL\,min^{-1}$. The column and ECD temperature were maintained at 40 and 300 °C, respectively. Concentrations of N_2O were quantified by comparing the peak area with those of reference gases (Nanjing Special Gas Factory, Nanjing, China). N_2O fluxes were calculated by using the linear increases in gas concentration with time. The mean flux for one vegetable crop was calculated as the average of all measured fluxes. The measured fluxes were weighted by the interval between two measurements (Xiong et al., 2006). The cumulative seasonal N_2O was calculated as the product of the mean flux and the seasonal duration.

Except for the soil that was analyzed immediately before the experiment in April 2012, another batch of soil samples for each treatment was collected on 12 June 2014 and stored at −20 °C for laboratory analysis. In accordance with Lu (2000), the soil texture was measured using pipette analysis, the total soil organic carbon (SOC) was analyzed by wet digestion with H_2SO_4–$K_2Cr_2O_7$, and the TN (total nitrogen) was determined by semimicro Kjeldahl digestion using Se, $CuSO_4$ and K_2SO_4 as catalysts. The soil pH was measured at a volume ratio of 1 : 2.5 (soil to water ratio) using a PHS−3C mV/pH detector (Shanghai, China). The soil temperature was measured at a depth of 15 cm beneath the collection point when the gas samples were collected.

Simultaneously with the determination of the trace gas fluxes, soil sampling at 0–15 cm depth was conducted for the determination of soil mineral N and soil water content. Soil mineral N was determined at approximately 7–15-day intervals. The soil NH_4^+-N and NO_3^--N were extracted by shaking for 1 h on a rotary shaker with $2\,mol\,L^{-1}$ KCl solution. According to Lu (2000), soil NH_4^+-N and NO_3^--N contents were measured following the two wavelength ultraviolet spectrometry and indophenol blue methods, respectively,

Table 1. Vegetable species and management procedure over the entire experimental period.

Vegetable species	Growth period	Fertilization time	Tillage time	Irrigation time	Pesticide	Greenhouse setting
Amaranth	12 Apr–10 Jul 2012	18 Apr 2012	16 Apr 2012	17 Apr 2012 4 May 2012 8 May 2012 14 May 2012	16 Apr 2012	12 Apr–25 May 2012
Tung choy	11 Jul–19 Nov 2012	10 Jul 2012 7 Sep 2012	9 Jul 2012	10 Jul 2012 25 Jul 2012 15 Aug 2012 18 Sep 2012 25 Sep 2012 8 Oct 2012	9 Jul 2012	
Baby bok choy	2 Nov 2012–27 Mar 2013			9 Dec 2012 29 Dec 2012 15 Jan 2013 1 Feb 2013		20 Nov 2012–24 Feb 2013
Coriander herb	28 Mar–30 Jun 2013	27 Mar 2013	26 Mar 2013	27 Mar 2013 13 Apr2013	26 Mar 2013	
Tung choy	1 Jul–4 Nov 2013	2 Jul 2013 8 Sep 2013	1 Jul 2013	2 Jul 2013 6 Aug 2013 15 Aug 2013 14 Sep 2013	1 Jul 2013	
Baby bok choy	5 Nov 2013–14 Mar 2014	4 Nov 2013	3 Nov 2013	4 Nov 2013 1 Dec 2013 18 Dec 2013		5 Nov 2013–14 Mar 2014
Amaranth	15 Mar–12 Jun 2014	14 Mar 2014	13 Mar 2014	14 Mar 2014 7 Apr 2014 23 Apr 2014	13 Mar 2014	15 Mar–12 May 2014

using an ultraviolet spectrophotometer (HITACHI, U-2900, Japan). The soil moisture content obtained by oven-drying was converted to water-filled pore space (WFPS) using the following equation:

$$\mathrm{WFPS} = \frac{\text{volumetric water content}(\mathrm{cm^3\,cm^{-3}})}{\text{total soil porosity }(\mathrm{cm^3\,cm^{-3}})}. \tag{1}$$

Here, total soil porosity is equal to [1−(soil bulk density ($\mathrm{g\,cm^{-3}}$)/2.65)], with an assumed soil particle density of 2.65 ($\mathrm{g\,cm^{-3}}$). The total soil bulk density was determined by using the cutting ring method from 0 to 10 cm depth according to Lu (2000).

2.4 Estimation of vegetable yields and yield-scaled N_2O emissions

The fresh vegetable yields were measured after each vegetable growth period by weighing all of the aboveground vegetable parts that were grown in each plot.

The yield-scaled N_2O emissions were related to crop yield as in Van Groenigen et al. (2010) and Grassini and Cassman (2012) and were calculated as follows:

$$\text{Yield-scaled } \mathrm{N_2O} \text{ emissions} = \frac{\text{Cumulative } \mathrm{N_2O} \text{ emissions}}{\text{vegetable yield } (\mathrm{kg\,N_2O{-}N\,t^{-1}}\text{ yield})}. \tag{2}$$

2.5 Data processing and statistics

The values presented are given as arithmetic means ± standard error (SE). All figures in this study were plotted in Microsoft Excel 2003. Significant differences in soil temperature and WFPS among different vegetable crops were determined by the nonparametric Kruskal–Wallis test. A two-way ANOVA was used to analyze the effects of nitrapyrin, biochar and their interactions on soil TN, SOC, soil pH, soil mineral N, vegetable yield, N_2O emissions and yield-scaled N_2O emissions throughout the experimental period. A Tukey's multiple range test was used to determine whether significant differences occurred between the treatment means at a significance level of 0.05. All statistical analyses were performed using JMP, version 7.0 (SAS Institute, USA, 2007).

3 Results

3.1 Soil properties and soil microclimate

Nitrapyrin had no significant influence on soil TN or SOC during the experimental period. However, significant increases in soil TN were observed in treatments with biochar amendments (Table 2, $p < 0.001$). Compared with the treatments without biochar amendments, soil TN was increased by 81.5–99.3 and 44.8–63.2 % for the CF and CP group

Table 2. Influence of biochar amendment on soil total nitrogen (TN), soil organic carbon (SOC) and soil pH in six different treatments over the entire experimental period. Values represent means ± SD ($n = 3$).

Treatments	TN		SOC		pH
	($g\,N\,kg^{-1}$)	($t\,N\,ha^{-1}$)	($g\,C\,kg^{-1}$)	($t\,C\,ha^{-1}$)	
T0	1.9	4.56	15.6	37.44	5.52
CF-C0	1.46 ± 0.03 d	3.52 ± 0.08	12.7 ± 0.6 c	30.4 ± 0.81	5.27 ± 0.08 c
CP-C0	1.74 ± 0.12 c	4.2 ± 0.29	12.8 ± 0.8 c	30.79 ± 1.96	6.24 ± 0.08 a
CF-C1	2.65 ± 0.02 b	6.38 ± 0.03	21.8 ± 0.2 b	50.74 ± 0.47	3.64 ± 0.04 d
CP-C1	2.52 ± 0.16 b	6.05 ± 0.4	23.2 ± 0.3 a	55.7 ± 0.33	5.79 ± 0.05 b
CF-C2	2.91 ± 0.05 a	6.96 ± 0.11	23.5 ± 0.3 a	56.3 ± 0.62	3.68 ± 0.06 d
CP-C2	2.84 ± 0.12 a	6.83 ± 0.29	23.1 ± 0.9 a	55.52 ± 2.13	5.26 ± 0.08 c
P	***		***		***

T0 provides the initial soil condition prior to the experiments; CF – compound fertilizer; CP – chlorinated pyridine, a mixture of urea and nitrapyrin; C0 – biochar $0\,t\,ha^{-1}$; C1 – biochar $20\,t\,ha^{-1}$; C2 – biochar $40\,t\,ha^{-1}$. The increased SOC and TN in the whole soil horizon were calculated according to a depth of 20 cm topsoil. Means ± SD with different letters in the same column indicate significant differences between treatments according to Tukey's multiple range test ($p < 0.05$).
*** $p < 0.001$. P value: the index of differences between the control group and the experimental group. If $p < 0.05$ and $p < 0.01$, significant differences exist between the control group and the experimental group.

treatments, respectively. Similar to soil TN, SOC increased significantly in the treatments with biochar amendment (Table 2, $p < 0.001$). SOC was enhanced by 66.9–85.1 and 80.4–81.3 % for the CF and CP group treatments, respectively, compared with the treatments without biochar amendment. Moreover, nitrapyrin increased soil pH significantly by 0.97–2.15 units compared with the treatments without nitrapyrin ($p < 0.001$), and biochar amendment significantly decreased soil pH by 1.59–1.63 and 0.45–0.98 units for the CF and CP group treatments (Table 2, $p < 0.001$), respectively. Significant interactions between nitrapyrin and biochar were observed to affect soil TN ($p < 0.05$) and soil pH ($p < 0.001$) throughout the intensive vegetable experimental period.

No statistical differences in WFPS and soil temperature were detected among all the treatments over the whole experimental period (data not shown). Dynamic variation in soil temperature was detected with seasonal change of outside temperature although plastic film was sometimes put in place in low-temperature seasons in the vegetable field. As shown in Figure 1a and 1b, significant differences were found between different vegetable crops, with high temperature in the summer and low temperature in the winter season ($p < 0.001$). Moreover, soil WFPS rates ranged from 31.9 to 76.0 % across all the experimental period. No significant differences in WFPS rates were detected among vegetable crops (Fig. 1c).

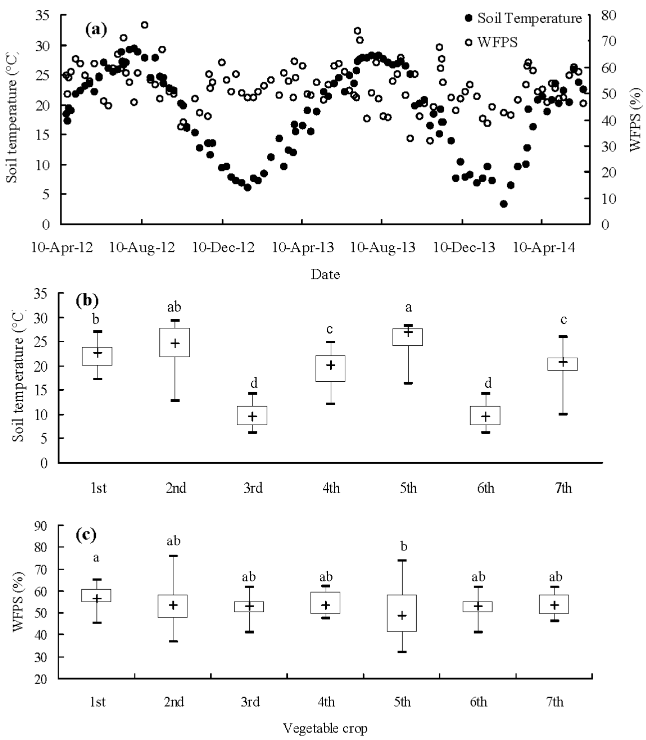

Figure 1. Dynamics of soil temperature (T) and WFPS across the experimental period **(a)**. Box plots for soil temperature **(b)** and WFPS **(c)** in different vegetable crops. The first to seventh mean different vegetable crops in rotation across the experimental period. Different letters indicate significant difference among all treatment medians ($p < 0.05$). The plus mark in the box represents the medians of all data.

3.2 Dynamics of N_2O fluxes and soil NH_4^+-N and NO_3^--N content

The dynamics of N_2O fluxes from all the treatments across the seven vegetable growth crops are shown in Fig. 2. The pattern of these fluxes was relatively consistent and was sporadic and pulse-like. N_2O fluxes showed a similar trend dur-

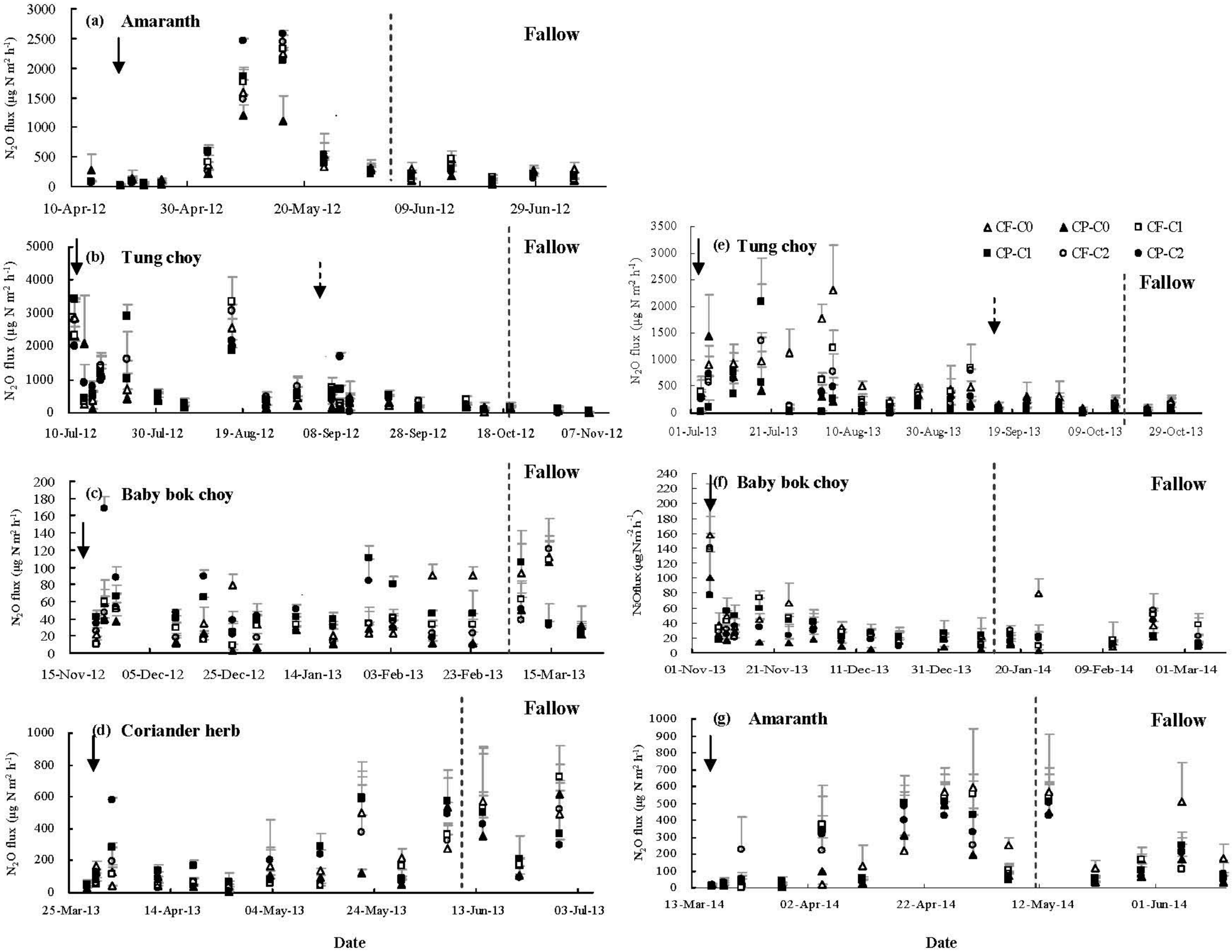

Figure 2. Dynamics of soil N_2O emission fluxes under different treatments in vegetable fields with seven consecutive vegetable crops from 2012 to 2014 in southeastern China. The solid and dashed arrows indicate basal fertilization and topdressing, respectively. The dashed vertical line in each subfigure separates the vegetable growing and fallow periods. The bars indicate the standard error of the mean (+ SE) for the three replicates of each treatment. See Table 2 for treatment codes.

ing the same period in both years. Following basal fertilization, tillage and irrigation, N_2O emissions ranging from 17 to 3406 $\mu g\,N\,m^{-2}\,h^{-1}$ were observed in all treatments across the experimental period. N_2O emissions primarily occurred with the increase in soil temperature during the summer, from May to October. However, as shown in Fig. 2d and 2g, no significant N_2O peaks were found in certain vegetable crops to which basal or topdressing fertilization was added because of the low soil temperature after fertilization in the vegetable field.

Soil NH_4^+-N and NO_3^--N contents ranged from 58.0–413.9 to 36.4–279.1 $mg\,N\,kg^{-1}$ across the growth period of the seven vegetable crops, as shown in Figs. 3 and 4, respectively. The fertilization events considerably increased soil mineral N ($NO_3^- + NH_4^+$) content. As the nitrapyrin limited the nitrification process, significantly higher soil NH_4^+-N contents were observed for the treatments with nitrapyrin compared to the treatments with compound fertilizer at the same N rate (Fig. 3). In contrast to the NH_4^+-N, a significantly lower content of soil NO_3^--N was observed in the plots treated with nitrapyrin (Fig. 4). In addition, biochar increased the soil NH_4^+-N content, while it decreased the soil NO_3^--N contents throughout the intensive vegetable growth period, but not significantly (Figs. 3, 4).

3.3 Cumulative N_2O emissions, vegetable yield and yield-scaled N_2O emissions

The cumulative N_2O emissions for each treatment across the entire experimental period are shown in Table 3a. These emissions varied widely among different crops during the individual vegetable crop-growing season. Additionally, the cumulative N_2O emissions showed significant differences among all the treatments. The greatest N_2O-N flux

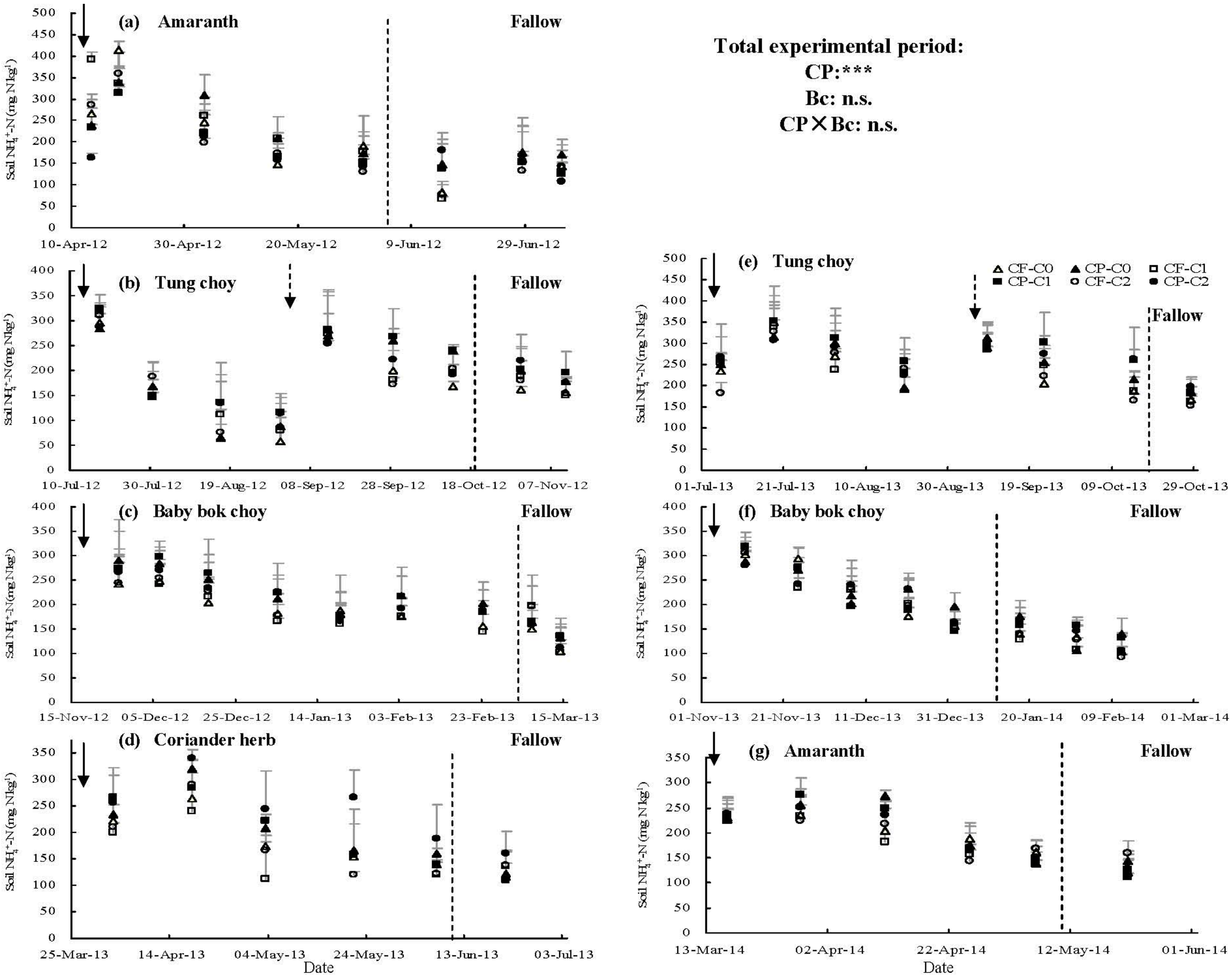

Figure 3. Dynamics of the soil NH_4^+-N concentrations within the 0–15 cm of soil under different treatments in vegetable fields with seven consecutive vegetable crops from 2012 to 2014 in southeastern China. The solid and dashed arrows indicate basal fertilization and topdressing, respectively. The dashed vertical line in each subfigure separates different vegetable growth periods. The bars indicate the standard error of the mean (+ SE) for the three replicates of each treatment. See Table 2 for treatment codes. *** $p < 0.001$; n.s. – not significant.

was observed in the CF-C0 treatment ($54.6 \pm 1.5\,kg\,N\,ha^{-1}$), whereas the lowest flux was in the CP-C0 treatment ($37.1 \pm 4.4\,kg\,N\,ha^{-1}$). As shown in Tables 3a and 4, significant decreases in the cumulative N_2O emissions were detected in the treatments with nitrapyrin ($p < 0.001$). The decreases ranged from 15.9 to 32.1 % compared with the treatments without nitrapyrin application ($p < 0.001$). In contrast, biochar amendment had no significant influence on cumulative N_2O emissions in both CF and CP group treatments (Table 4). However, as shown in Table 3a, slight increases in the cumulative N_2O emissions were observed. These increases were 7.9 and 18.3 % for CP-C1 and CP-C2, respectively, but were not significant compared with CP-C0, which also indicated that the biochar amendment rates would not result in a significant difference in the cumulative N_2O emissions. Furthermore, no significant interaction between nitrapyrin and biochar amendment was observed to affect the cumulative N_2O emissions throughout the intensively managed vegetable experimental period (Table 4).

Table 3b shows details of the fresh weight for each vegetable crop. The highest fresh weight yield for the seven consecutive vegetable crops was $535.4 \pm 16.7\,t\,ha^{-1}$ for CP-C1, an increase of 71.7 % compared with CF-C0. Both nitrapyrin application ($p < 0.001$) and biochar amendment ($p < 0.05$) significantly increased the yield in the intensively managed vegetable system across the experimental period (Table 4). As shown in Table 3b, nitrapyrin significantly increased vegetable yield compared with the treatments without nitrapyrin. In addition, the vegetable yield was significantly enhanced by 9.8–41.9 % with the increase of the biochar amendment rates in CF group treatments (Table 3b). However, a decrease in vegetable yield was observed in the CP-C2 treat-

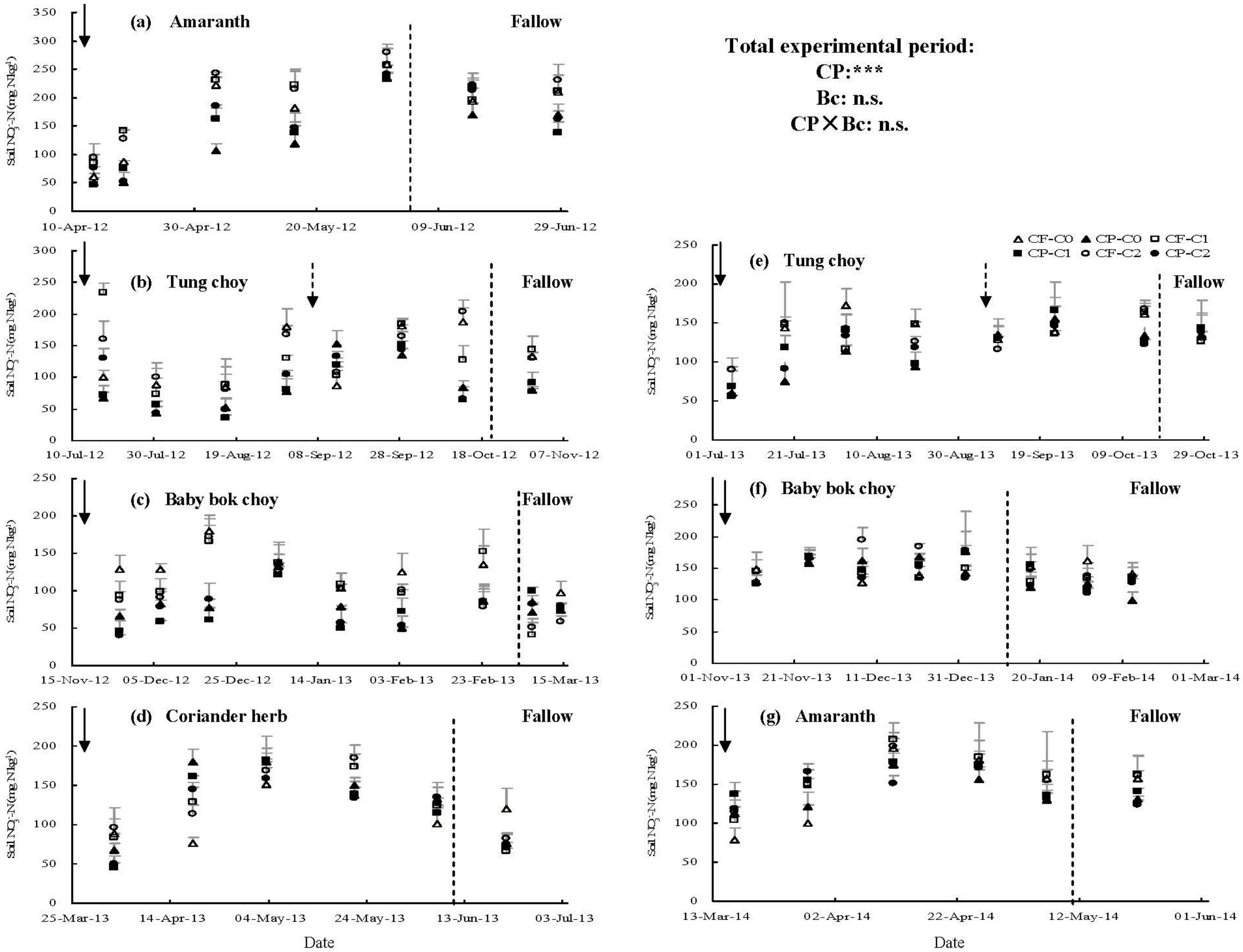

Figure 4. Dynamics of the soil NO_3^--N concentrations within the 0–15 cm of soil under different treatments in vegetable fields with seven consecutive vegetable crops from 2012 to 2014 in southeastern China. The solid and dashed arrows indicate basal fertilization and topdressing, respectively. The dashed vertical line in each subfigure separates different vegetable growth periods. The bars indicate the standard error of the mean (+ SE) for the three replicates of each treatment. See Table 2 for treatment codes. *** $p < 0.001$; n.s. – not significant.

ment compared with CP-C0. Moreover, significant interactions between nitrapyrin and biochar amendment were observed to affect vegetable yield throughout the intensive vegetable experimental period (Table 4, $p < 0.05$).

Table 3c shows that the yield-scaled N_2O emissions, which were related to the cumulative N_2O emissions and the fresh-weight yield, ranged from 0.074 ± 0.004 to 0.175 ± 0.017 kg N_2O-N t^{-1} yield over the entire experimental period. The lowest value of yield-scaled N_2O emissions was 0.074 ± 0.004 kg N_2O-N t^{-1} yield for CP-C0, that is, the treatment with nitrapyrin application and without biochar amendment. As shown in Table 4, both nitrapyrin application ($p < 0.001$) and biochar amendment ($p < 0.05$) significantly decreased the yield-scaled N_2O emissions during the entire experimental period. Furthermore, significant interactions between nitrapyrin and biochar were observed to affect yield-scaled N_2O emissions throughout the experimental period (Table 4, $p < 0.05$).

4 Discussion

4.1 Effects of nitrapyrin as nitrification inhibitor on N_2O emissions and vegetable yield

N_2O emissions are directly related to the amount of mineral N available in the soil. A two-way ANOVA indicated that seasonal N_2O emissions during the vegetable-growing periods were significantly affected by nitrapyrin application (Table 4, $p < 0.001$), in agreement with previous results (Ma et al., 2013; Xiong et al., 2013; Zhang et al., 2015). Different types of NI that were effective in reducing N_2O have been reported by previous studies (Xu et al., 2000; Boeckx et al., 2005; Zaman et al., 2008, 2009; Zaman and Blenner-

Table 3. Cumulative N_2O emissions, vegetable yield and yield-scaled N_2O emissions under different treatments over the entire experimental period.

Treatments	Amaranth	Tung choy	Baby bok choy	Coriander herb	Tung choy	Baby bok choy	Amaranth	Total rotation
	18 Apr–10 Jul 2012 (41/83)	11 Jul–19 Nov 2012 (100/131)	20 Nov 2012–27 Mar 2013 (98/127)	28 Mar–30 Jun 2013 (62/94)	1 Jul–4 Nov 2013 (106/126)	5 Nov 2013–14 Mar 2014 (67/129)	15 Mar–12 Jun 2014 (58/89)	18 Apr–12 Jun 2014 (779)
(a) Cumulative N_2O emissions ($kg\,N\,ha^{-1}$)								
CF-C0	9 ± 0.8 a	17.7 ± 0.9 ab	1.1 ± 0.7 a	4.1 ± 1.2 a	16.5 ± 2.8 a	0.8 ± 0.2 ab	5.3 ± 0.3 a	54.6 ± 1.5 a
CP-C0	6.7 ± 1.2 d	15.6 ± 1.2 b	0.8 ± 0.1 b	2.7 ± 0.5 a	6.5 ± 1.4 c	0.6 ± 0.1 c	3.8 ± 1.6 a	37.1 ± 4.4 d
CF-C1	9.3 ± 0.5 ab	21.3 ± 4.0 a	1.1 ± 0.1 ab	4.4 ± 0.7 a	11.4 ± 3.8 b	0.9 ± 0.2 a	4.8 ± 1.6 a	52.6 ± 10.2 ab
CP-C1	8.3 ± 0.6 c	16.1 ± 0.4 b	0.9 ± 0.2 ab	3.9 ± 1.9 a	9.6 ± 2.3 bc	0.7 ± 0.1 abc	4.7 ± 1.6 a	43.9 ± 5.8 bcd
CF-C2	9.4 ± 0.7 bc	20.7 ± 1.7 a	0.9 ± 0.2 ab	3.6 ± 0.7 a	8.8 ± 2.2 bc	0.7 ± 0.1 abc	4.2 ± 0.6 a	47.3 ± 2.4 abc
CP-C2	8.6 ± 0.9 b	15.7 ± 2.2 b	0.9 ± 0.1 ab	3.1 ± 0.4 a	7.6 ± 0.6 bc	0.6 ± 0.1 bc	3.9 ± 0.8 a	39.8 ± 3.5 cd
(b) Vegetable yield ($t\,ha^{-1}$)								
CF-C0	11.1 ± 1.8 c	83.1 ± 12.4 c	10.2 ± 3.6 d	18.6 ± 1 bc	132.5 ± 6 b	44.9 ± 4.6 a	11.5 ± 4.4 c	311.8 ± 23.8 d
CP-C0	19.8 ± 0.4 a	140.5 ± 11.9 a	58.9 ± 5.7 b	24.7 ± 4.1 b	163.6 ± 16.3 a	47.2 ± 9.3 a	45.5 ± 2 a	500.3 ± 34.9 a
CF-C1	19.3 ± 1.4 ab	95.2 ± 3.9 c	39 ± 8.1 c	25.8 ± 5.2 b	131.9 ± 14.1 b	49.9 ± 6.1 a	16.1 ± 4.4 c	377.2 ± 23.4 c
CP-C1	23.3 ± 0.9 a	123.7 ± 12.6 ab	81 ± 6.5 a	24.9 ± 3.2 b	177.2 ± 14.5 a	61.6 ± 13.2 a	43.7 ± 6.8 ab	535.4 ± 16.7 a
CF-C2	14.6 ± 5.7 bc	128.9 ± 6.8 ab	57.8 ± 11.4 b	12.6 ± 2.6 c	172.2 ± 4.9 a	43.1 ± 17.3 a	17 ± 9.3 c	446.2 ± 36.1 b
CP-C2	19.5 ± 2.9 ab	120.7 ± 7.2 b	62.1 ± 13.4 b	35.3 ± 8.5 a	161.4 ± 9.7 a	56.7 ± 9.4 a	33.9 ± 6.5 b	489.7 ± 12.7 ab
(c) Yield-scaled N_2O emissions ($kg\,N_2O-N\,t^{-1}$ yield)								
CF-C0	0.814 ± 0.082 a	0.216 ± 0.031 a	0.135 ± 0.105 a	0.218 ± 0.062 ab	0.125 ± 0.026 a	0.019 ± 0.005 a	0.516 ± 0.207 a	0.175 ± 0.017 a
CP-C0	0.338 ± 0.051 c	0.112 ± 0.005 c	0.014 ± 0.002 b	0.131 ± 0.101 b	0.041 ± 0.011 c	0.012 ± 0.004 a	0.084 ± 0.032 c	0.074 ± 0.004 d
CF-C1	0.475 ± 0.027 bc	0.225 ± 0.048 a	0.029 ± 0.01 b	0.176 ± 0.057 ab	0.085 ± 0.035 b	0.017 ± 0.005 a	0.302 ± 0.07 b	0.139 ± 0.027 b
CP-C1	0.337 ± 0.022 c	0.131 ± 0.011 bc	0.029 ± 0.002 b	0.167 ± 0.089 ab	0.054 ± 0.011 bc	0.012 ± 0.027 a	0.114 ± 0.051 bc	0.081 ± 0.009 cd
CF-C2	0.659 ± 0.317 ab	0.161 ± 0.009 b	0.016 ± 0.001 b	0.293 ± 0.083 a	0.051 ± 0.013 bc	0.019 ± 0.011 a	0.302 ± 0.154 b	0.106 ± 0.009 c
CP-C2	0.417 ± 0.065 bc	0.131 ± 0.025 bc	0.015 ± 0.006 b	0.089 ± 0.019 b	0.047 ± 0.005 c	0.011 ± 0.004 a	0.019 ± 0.019 bc	0.081 ± 0.008 cd

See Table 2 for treatment codes. The total range of observation dates includes sampling that occurred during vegetable planting or at other periods. The values indicate mean ± SD. Data in the brackets indicate the vegetable growing days/total days including the following fallow period for each vegetable crop in rotation. Different letters indicate a significant difference between treatments ($p < 0.05$).

Table 4. Two-way ANOVA for the effects of nitrapyrin (CP) and biochar (Bc) on the cumulative N_2O emissions, vegetable yield and yield-scaled N_2O emissions over the entire experimental period.

Factors	DF	Cumulative N_2O emissions			Vegetable yield			Yield-scaled N_2O emissions		
		SS	*F*	*P*	SS	*F*	*P*	SS	*F*	*P*
CP	1	570.09	19.29	< 0.001	76 098.8	111.36	< 0.001	0.0171	78.04	< 0.001
Bc	2	66.28	1.21	0.3577	12 977.7	9.58	< 0.05	0.0029	6.63	< 0.05
CP × Bc	2	86.83	1.47	0.2687	17 542.7	12.95	< 0.05	0.0044	10.13	< 0.05
Model	5	723.21	4.89		10 6619.4	31.48		0.0244	22.31	
Error	12	354.67			8126.9			0.0026		

DF – degrees of freedom; SS – sum of squares; *F* – ratio of mean squares of two independent samples; *P* – index of differences between the control group and the experimental group. If $p < 0.05$ and $p < 0.001$, significant differences exists between the control group and the experimental group.

hassett, 2010). Nitrapyrin could efficiently inhibit the activity of the ammonia oxidase, reduce the abundance of the *nirK* gene in vegetable soil, and thus inhibit the nitrification process while regulating the NH_4^+ and NO_3^- content of soil (Figs. 3, 4) , which is highly related to mitigating N_2O emissions (Di et al., 2009, 2014). Moreover, nitrapyrin application in vegetable soil resulted in a significant increase in soil pH but an insignificant increase in soil TN and SOC across the seven consecutive vegetable growing periods (Table 2, $p < 0.001$). The pH increase effect may have been a result of the production of hydroxyl (OH^-) ions during urea hydrolysis (De Boer and Kowalchuk, 2011). Similarly, Zaman et al. (2008) have reported a low rise in soil pH after applying Agrotain-treated urea to pasture soil. A laboratory incubation of DCD decomposition also showed a soil pH increase with the addition of urine with or without dicyandiamide (DCD) (Singh et al., 2008). Zhu et al. (2011) reported a negative correlation between soil pH and N_2O emission rate in vegetable soils, which may indicate that the increasing of soil pH is another factor mitigating N_2O emissions.

A previous study has shown that N fertilizers combined with NI, such as DCD and 3,4-dimethylpyrazole phosphate (DMPP), may improve the yield and quality of agricultural and horticultural crops (Pasda et al., 2001). Similarly, nitrapyrin produced a significant increase in vegetable yield in our study across the experimental period (Tables 3b and 4, $p < 0.001$). Possible explanations for higher crop yields obtained with NH_4^+-containing fertilizers supplemented with nitrapyrin (Fig. 3) include the reduction of N losses by leaching and volatilization and the improved bioavailability of N and N uptake of the crops (O'Connor et al., 2012) in the vegetable soil. Ma et al. (2013) reported that two types of NIs (nitrapyrin and DCD) increased average wheat yield by 9.7 % under conventional and no-till practices during the winter wheat-growing season. In addition, since nitrapyrin could significantly increase soil pH, the uptake rates of the inorganic N would increase due to the increasing effect of nitrapyrin on soil pH in vegetable fields (Jampeetong et al., 2013). Moreover, Zhang et al. (2015) find that nitrapyrin significantly increased vegetable yield by 12.6 % in an intensively managed vegetable field, which may due to CP being beneficial for the growth and N assimilation of the crops (Liu et al., 2013).

4.2 Effects of biochar on N_2O emissions and vegetable yield

As shown in Tables 3a and 4, biochar had no significant influence on cumulative N_2O during the experimental period. Decreases in the net emissions of N_2O from certain agricultural ecosystems as a result of soil amendment with biochar have been well documented by previous studies (Cayuela et al., 2014; Felber et al., 2014). Additionally, a meta-analysis of 30 papers (published from 2007 to 2013) by Cayuela et al. (2014) found that soil N_2O emissions, which were affected by biochar characteristics, soil characteristics and N fertilizer type, were reduced by 54 % in both laboratory and field studies. However, biochar amendment had no significant influence on cumulative N_2O emissions during the experimental period and even slightly increased cumulative N_2O by 7.9–18.3 % in the CP group treatments (Tables 3a, 4). Thus, the mitigating effect of biochar amendment on N_2O emissions did not work in the intensively managed vegetable field in this study, which is in consistent with previous short-term laboratory incubation results in acidic soils (Yuan and Xu, 2011; Wang et al., 2014). This finding may firstly be due to the decrease in soil pH in the treatments amended with biochar (Table 2). In contrast with the significant increase in soil pH due to the liming effect of biochar generally reported in previous studies (Biederman and Harpole, 2012; Zhang et al., 2010), soil pH decreased significantly in the plots amended with biochar (Table 2, $p < 0.001$). With such a high amount of N fertilization application, biochar may lose the buffering effects of soil pH changes. Luo et al. (2011) reported that biochar with low pyrolysis temperature had more water-extractable organic carbon. Although considered to be stable in soil, biochar brings an extra carbon source for heterotrophic nitrification processes, which may also cause an increase in the

H^+ content due to nitrification processes in the soil (Schmidt, 1982; De Boer and Kowalchuk, 2001; Wrage et al., 2001) and thus decrease the soil pH significantly. In addition, the decrease in soil pH may, most likely, be attributed to the weathering effect of biochar after 2 years of incorporation into fields (Jones et al., 2012; Spokas, 2013), particularly in intensively managed vegetable fields. Yao et al. (2010) reported that the pH of biochar samples decreased from 8.4 to 7.5, primarily due to the loss of base cations through leaching and probable carbonation during the weathering process; biochar offers the practical benefits of high N fertilization input and may also be weathered more easily in vegetable soils. Cayuela et al. (2014) also reported that the effectiveness of biochar application on mitigating N_2O emissions was significant in neutral and alkaline soils but not in acidic soils with pH < 5, which is probably due to the fact that low soil pH may adversely affect the activity of N_2O reductase in vegetable fields (Liu et al., 2010). The decrease in soil pH may also increase the heterotrophic nitrification rate, which may cause the increase of N_2O emissions in vegetable fields (Zhu et al., 2011), though heterotrophic nitrification is generally considered to be a minor source of N_2O (Anderson et al., 1993). Moreover, vegetable fields have a high amount of N input and one may expect ammonia oxidation and linked nitrifier denitrification (ND), important processes generating N_2O (Wrage et al., 2001; Huang et al., 2014). Sánchez-García et al. (2014) found that biochar increased the cumulative N_2O emissions in the soil when ammonia oxidation and the linked ND were the major processes generating N_2O emissions, whereas it decreased N_2O emissions in the soil when denitrification was the main pathway leading to N_2O emissions under the same experimental conditions.

Biochar amendment significantly increased SOC and soil TN (Table 2, $p < 0.001$) and thus significantly improved vegetable yield compared with the treatments that received no biochar addition (Table 4, $p < 0.05$), which agrees well with the previously reported benefit of adding biochar to soils (Major et al., 2010; Jia et al., 2012). In addition, vegetable yield was significantly increased with the increase of biochar amendment rates in the CF group treatments, which is in agreement with previous results (Zhang et al., 2010). In our study, SOC increased significantly by 66.9–85.1 % in the treatments amended with biochar over the experimental period (Table 2, $p < 0.001$). This result is consistent with the finding that average SOC increased by 61 % due to biochar addition, reported in a meta-analysis by Biederman and Harpole (2012). Biochar amendment significantly increased SOC, most likely due to its inert recalcitrant C component, which can contribute to soil carbon sequestration, at least over periods of decades to millions of years (Kuzyakov et al., 2009, 2014; Lehmann et al., 2011). Additionally, biochar amendment also significantly increased soil TN (Table 2, $p < 0.001$), which is consistent with a previous study in a rice paddy (Zhang et al., 2012b). Most likely, this difference in soil TN is probably due to the release of N in soil from the biochar (Singh et al., 2010; Schouten et al., 2012). The N content of the biochar used in our experiment was 5.9 $g\,N\,kg^{-1}$, and this potential N source may also have increased the soil TN. Additionally, the amendment of biochar would offer a further opportunity to achieve N fertilizer savings in vegetable soil, which may result in an increase in soil TN due to the mineral N absorption effects of biochar, as seen in comparison with treatments without biochar amendment in an intensively managed vegetable field (Ding et al., 2010). Furthermore, the vegetable yield enhancement effect of biochar may also be associated with increases in root exudation in the plots amended with biochar (Gregory, 2006). Biochar amendment in agricultural soil may stimulate microbial activity, resulting in nutrient release (Steinbeiss et al., 2009), reducing nutrient leaching (Laird et al., 2010), and improving crop nutrient availability and plant N uptake (Saarnio et al., 2013) in the intensively managed vegetable field. Moreover, as shown in Table 3b, a significant difference in vegetable yield among the treatments was found under different biochar application rates with compound N fertilization (CF-C0, CF-C1 and CF-C2), in agreement with the results reported by Jeffery et al. (2011), although the plots amended with biochar showed a significantly lower soil pH (Table 2, $p < 0.001$).

4.3 The combined effects of nitrapyrin and biochar incorporation on yield-scaled N_2O emissions

Analyzing N_2O emissions on a yield basis provides interesting information for estimating the environmental impacts of intensive agricultural production systems. As shown in Table 3c, yield-scaled N_2O emissions ranged from 0.074 ± 0.004 to 0.175 ± 0.017 $kg\,N_2O\text{-}N\,t^{-1}$ yield, much lower than the values previously reported (Van Groenigen et al., 2010; Ma et al., 2013). Ordinarily, vegetable crops require higher N application rates than staple food crops such as rice, wheat and maize (Li and Wang, 2007). Moreover, the leafy vegetables in this study differed from other crops, and all aboveground portions of the vegetable plants were considered as the yield, resulting in low values of yield-scaled N_2O in our vegetable field.

Overall, nitrapyrin significantly decreased yield-scaled N_2O emissions across the experimental period (Tables 3c and 4, $p < 0.001$), contributing to the N_2O-reducing and vegetable-increasing effects of nitrapyrin in intensively managed vegetable field. Our results indicate that the yield-scaled N_2O emissions were minimal in the CP-C0 treatment (0.074 ± 0.004 $kg\,N_2O\text{-}N\,t^{-1}$ yield). This treatment showed the lowest cumulative N_2O emissions (37.1 ± 4.4 $kg\,N\,ha^{-1}$) and the second-highest vegetable yield (500.3 ± 34.9 $t\,ha^{-1}$). Under the application of equal amounts of N, nitrapyrin application was a more efficient way to reduce the yield-scaled N_2O emissions in our case. This approach may significantly improve vegetable yield while causing a decrease in N_2O emissions and, thus, improved agronomic N use efficiency

(NUE) in intensively managed vegetable agriculture (Li et al., 2007; Asing et al., 2008). Overall, nitrapyrin application without biochar amendment (CP-C0) can serve as an appropriate way of mitigating N_2O emissions while increasing vegetable yield in intensively managed vegetable agriculture.

Although biochar amendment did not significantly decrease the cumulative N_2O emissions, it significantly decreased the yield-scaled N_2O emissions across the experimental period (Table 3c, Table 4, $p < 0.05$), mainly due to the increasing effect of biochar on vegetable yield. Obvious interactions in yield-scaled N_2O emissions were observed between nitrapyrin and biochar addition (Table 4, $p < 0.05$). However, no significant interactions between nitrapyrin and biochar were observed in N_2O emissions in the current study. Treatments with nitrapyrin and biochar incorporation slightly increased the cumulative N_2O by 7.9–18.3 %, but not significantly (Tables 3a and 4), which indicated that biochar might be able to diminish the mitigating effect of nitrapyrin, namely, the effect of inhibiting the nitrification process in vegetable soil (Figs. 3, 4). Vegetable soil in our study is acidic due to large N applications in which biochar increases the heterotrophic nitrification rate in the treatments with both nitrapyrin and biochar (CP-C1 and CP-C2). Therefore, the treatments involving nitrapyrin and biochar had higher cumulative N_2O emissions compared with the CP-C0 treatment in vegetable fields. Additionally, with such a low soil pH, the denitrification process and the ND process may also become the major contributors to the N_2O pool (Zhu et al., 2011, 2013). Although biochar had no significant effect on soil mineral N content, it decreased the soil NH_4^+-N content and increased the soil NO_3^--N content in the treatments amended with biochar in both the CF and the CP group (Figs. 3, 4), which may simultaneously increase the NO_2^- content in the vegetable soil and thus increase the cumulative N_2O emissions linked with other N_2O-generating processes in the vegetable field across the experimental period. Moreover, Di et al. (2014) reported that DCD was highly effective in inhibiting the growth of ammonia-oxidizing bacteria (AOB) communities and reducing N_2O emissions under high soil moisture, whereas Yanai et al. (2007) found that, when the soils were rewetted at 83 % WFPS, the suppressive effects of charcoal addition on N_2O emissions were not observed. Thus, biochar addition diminished the mitigation effect of nitrapyrin on the cumulative N_2O emissions in vegetable soil under the high WFPS condition that was due to frequent irrigations (Fig. 1).

Significant interactions in yield were observed, though no significant differences in vegetable yield were found among different combinations of nitrapyrin and biochar (CP-C0, CP-C1 and CP-C2 (Table 3b)), indicating that the biochar incorporation rate did not increase vegetable yield when combined with nitrapyrin application. Most likely, the vegetable yields were relatively high compared with other ecosystems, although both nitrapyrin and biochar separately can significantly increase vegetable yield, which may also explain the fact that increasing biochar amendment rates did not result in a significant increase in vegetable yield across the experimental period (Table 3b). Since we did not measure the individual N transformation processes or the microbes in vegetable soil responding to N_2O emissions and vegetable yield, the combined effects of nitrapyrin and biochar incorporation on N_2O emissions and vegetable yield in intensively managed vegetable fields need further study.

5 Conclusions

Yield-scaled N_2O emissions were significantly affected by both nitrapyrin application and biochar amendment in intensively managed vegetable agriculture. Throughout the experimental period, although significant influences on soil TN and SOC were not found, nitrapyrin application significantly increased soil pH and vegetable yield while significantly decreasing the cumulative N_2O emissions in the intensively managed vegetable field, therefore causing a significant decrease in yield-scaled N_2O emissions over the experimental period. Moreover, biochar amendment significantly increased soil TN, SOC and vegetable yield but had no significant influence on the cumulative N_2O emissions, whereas this amendment significantly decreased soil pH and yield-scaled N_2O emissions. Nitrapyrin and biochar incorporation into vegetable soil slightly increased yield-scaled N_2O emissions during the experimental period. Yield gains were the most important factor for lower yield-scale N_2O emissions in our case compared with previous studies. Overall, taking environmental and economic benefits into consideration, nitrapyrin application in the vegetable field was the best procedure for reducing the yield-scaled N_2O emissions. The long-term combined effects of nitrapyrin application and biochar amendment on and their underlying mechanisms for N transformation processes in intensively managed vegetable agriculture should be further studied.

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