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# Biochar and organic substitution improved net ecosystem economic benefit in intensive vegetable production

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## Abstract

Biochar amendment and substituting chemical fertilizers with organic manure (organic substitution) have been widely reported to increase crop production and decrease reactive nitrogen (Nr) loss including nitrous oxide (N<sub>2</sub>O), nitric oxide (NO), and ammonia (NH<sub>3</sub>) emissions, and N runoff and leaching. However, few comprehensive evaluations have been performed on the environmental and economic aspects of biochar amendment or organic substitution. Here, we studied the comprehensive effects of biochar amendment, organic substitution, and biochar amendment combined with organic substitution on crop production, Nr loss, and net ecosystem economic benefit (NEEB) in intensive vegetable production by integrating life-cycle assessment for Nr footprints, empirical models for NH<sub>3</sub> volatilization and N runoff and leaching derived from peer-reviewed publications and validated by the current measurements and direct field measurement for N<sub>2</sub>O and NO emissions during 5 consecutive years of vegetable crop rotations. Five fertilization treatments were applied (SN: synthetic fertilizer application; SNB: SN plus 20 t ha<sup>-1</sup> biochar amendment; SNM: substituting 50% of chemical N fertilizer with organic manure; SNMB: SNM plus 20 t ha<sup>-1</sup> biochar amendment; and CK: no fertilizer or biochar addition). Compared with the SN, the SNB increased vegetable yield (28.4%,  $p < 0.05$ ; interannually varying from -10 to 74.9%) and nitrogen use efficiency (29.2%, interannually varying from -39.7 to 150.4%), and decreased field Nr loss (45.4%,  $p < 0.01$ ; interannually varying from -40.3 to 78.4%), and thus improved NEEB by 7.1%; meanwhile, the SNM increased vegetable yield (11.6%, interannually varying from -5.4 to 27.1%) and nitrogen use efficiency (45.7%,  $p < 0.05$ ; interannually varying from 2.3 to 154%), reduced field Nr loss (34.9%,  $p < 0.01$ ; interannually varying from 8.4–39.0%), and thus improved NEEB by 17.8% ( $p < 0.05$ ) compared to the SN, being  $56.0 \times 10^3$  Chinese Yuan (CNY) ha<sup>-1</sup> crop<sup>-1</sup>. Due to the high foreground Nr loss during organic manure production and high input costs of biochar production, the SNMB decreased the NEEB by 8.0% as compared to the SN. Moreover, the SNB and SNM improved vegetable qualities by increasing protein, soluble sugar, and vitamin C contents while decreasing nitrate content ( $p < 0.05$ ). Therefore, single application of biochar amendment or organic substitution would achieve better NEEB and product quality in vegetable production.

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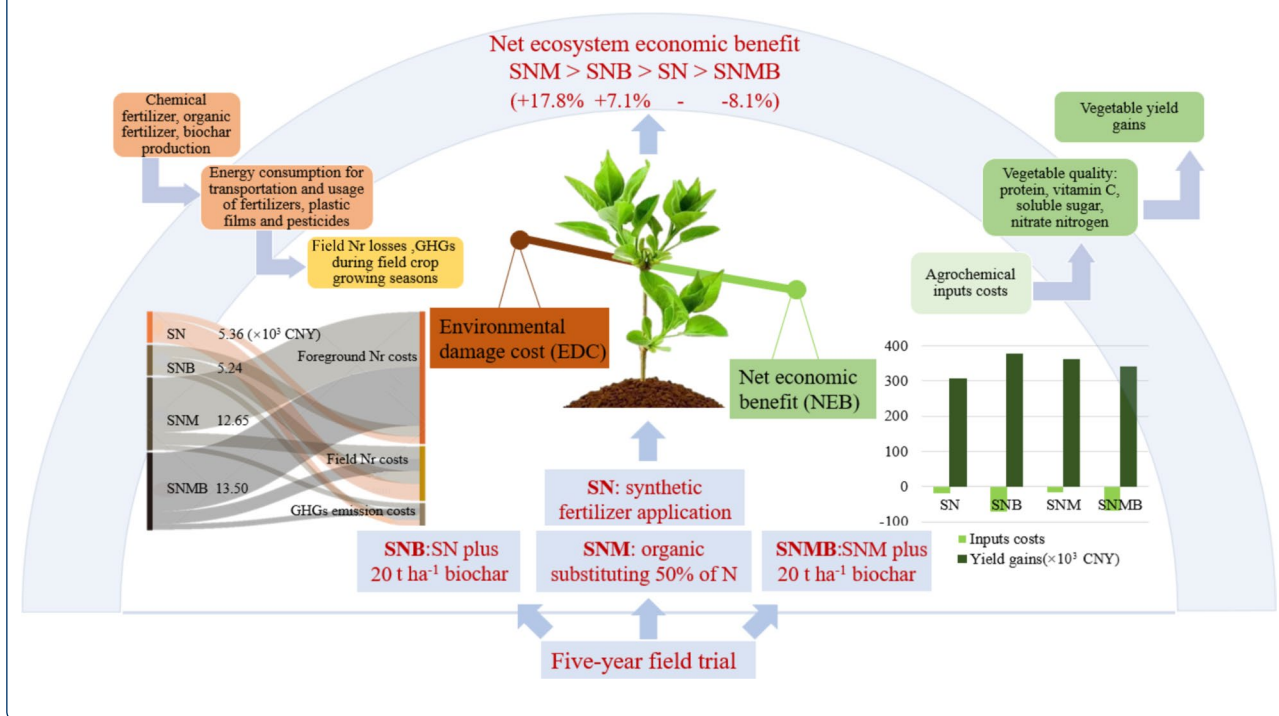
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### Highlights

- Both biochar and organic substitution improved vegetable quality, yield and NEEB.
- Manure production is a hotspot in the foreground Nr loss and N leaching in the field.
- Organic substitution alone produced best NEEB while least in the combined treatment.

**Keywords:** Biochar amendment, Organic substitution, Crop production, Reactive nitrogen, Nitrogen footprint, Net ecosystem economic benefit

### Graphical Abstract



## 1 Introduction

The national vegetable production area in China in 2019 was approximately 20.9 million ha, which accounted for 16.3% of the country’s total arable land (MNR 2021). Vegetable fields receive a high use amount and frequent input of chemical fertilizers and a high multiple cropping index compared to food crop farmland (Zhou et al. 2019), leading to a significant decline in the nitrogen use efficiency (NUE) and soil quality (Mohanty et al. 2020). Reactive nitrogen (Nr) loss in the form of ammonia (NH<sub>3</sub>), nitrogen oxides (NO<sub>x</sub>), and nitrous oxide (N<sub>2</sub>O) accounts for approximately 10% of the nitrogen (N) input, with additional N lost by runoff or leaching in vegetable fields (Tian et al. 2016). All these factors not only aggravate environmental pollution and environmental loss costs (Zhang et al. 2015) but also restrict the sustainable development of the vegetable industry.

As an effective countermeasure, biochar amendment has been widely reported to improve soil quality, NUE and crop yield (Liu et al. 2016; Zhang et al. 2020a, b). Biochar is a stable carbon-rich material produced by the thermochemical transformation of biomass (e.g. crop straw, manure and solid waste) under oxygen-limited or anaerobic conditions (Harter et al. 2016; Osman et al. 2020). Recently, biochar has been extensively studied to determine its ability to enhance nutrient availability in soils (Zhang et al. 2020a, b), promote crop growth (Steinbeiss et al. 2009) and reduce Nr losses (Duan et al. 2018; Xu et al. 2022). Biochar could increase the pH and permeability of the soil (Abel et al. 2013), ease biological and abiotic stresses, and improve microbial activity and biodiversity (Azeem et al. 2020). Although biochar is generally considered to be mostly inert, numerous studies have shown that when applied

to soil, it undergoes changes, such as aging and weathering/maturing over time (Yuan et al. 2019; Zhang et al. 2019). A relatively long-term experiment with an annual assessment would illustrate the actual effect of biochar application in vegetable fields.

Meanwhile, substituting some chemical fertilizer with organic manure (organic substitution) has been widely used to reduce the over-reliance on chemical fertilizers and environmental damage (Cai et al. 2018) although complete organic manure cannot meet the immediate demand for crop nutrients (Xia et al. 2017). Organic substitution can regulate the process of soil N transformation (Liu et al. 2014a, b) and provide exogenous carbon by enhancing microbial activity and increasing soil N and organic carbon fixation (Tang et al. 2019), thereby further improving crop yields and NUE and reducing Nr losses (Gu et al. 2016). Previous studies (Zhou et al. 2019) have found that organic substitution may benefit vegetable production. However, integrated studies of the comprehensive effects and mechanisms of biochar amendment combined with organic substitution in vegetable production are lacking.

Obtaining high yield of qualified vegetable products is the primary goal for sustainable vegetable production at minimal environmental damage costs (EDCs) and maximum net economic benefit (NEB). EDCs refer to the costs of degradation of the quality of environmental service functions due to the Nr losses, integratively as N footprint, and greenhouse gases (GHGs) from natural or anthropogenic activities that damage human health and ecosystems (Ying et al. 2017). The net ecosystem economic benefit (NEEB), the difference between the NEB (crop yield benefit minus the costs of agrochemical inputs) and environmental damage cost of crop production, has been widely used to assess the sustainability of development in agricultural production (Liu et al. 2020). In addition to the large amounts of emissions from farmland application, the production and transportation of agrochemical inputs and the associated consumption of energy will indirectly produce Nr and GHGs (Lehmann et al. 2021; Zhang et al. 2013). Therefore, the widely accepted life cycle assessment (LCA) method for Nr release and GHGs should be adopted for comprehensively assessing the EDC (Khoshnevisan et al. 2014) and NEEB in intensive vegetable production.

The objectives of our study were to (1) evaluate the effects of optimal substitution and inter-annual effects on vegetable crop productivity and quality; (2) quantify Nr losses and N footprint using the LCA method; and (3) optimize alternative treatment to improve the feasibility of achieving environmental and economic benefits, including better NEEBs with lower EDCs in intensive vegetable production. Based on the above-mentioned

beneficial consequences of amended biochar and substitution of partial synthesized N fertilizer, we hypothesized that biochar amendment and the suitable organic substitution would result in the best NEEB by improving crop production and reducing the Nr losses and GHG ( $\text{N}_2\text{O}$ ) emissions in a 5-year consecutive vegetable rotation.

## 2 Materials and methods

### 2.1 Experimental site description

The test soil was collected from a typical greenhouse vegetable site in Nanjing, Jiangsu Province ( $32^\circ 01' \text{N}$ ,  $118^\circ 52' \text{E}$ ), Yangtze River Delta Alluvial Plain, China, for a 5-year period from November 2017 to November 2021, which is a typical annual rotation cultivation vegetable system for more than 10 years with an average annual temperature and precipitation of  $17.5^\circ \text{C}$  and 1107 mm. The physical and chemical properties of tested soil are shown in Additional file 1: Table S1.

### 2.2 Experimental design and field management

Five fertilization treatments with three replicates were established as follows: (1) no fertilizer or biochar addition (CK); (2) synthetic fertilizer application (SN); (3) SN plus  $20 \text{ t ha}^{-1}$  biochar amendment (SNB); (4) substituting 50% of chemical N fertilizer with organic manure (SNM); and (5) SNM plus  $20 \text{ t ha}^{-1}$  biochar amendment (SNMB). Biochar was added only once in 2016. Additional file 1: Table S1 presents the properties of the biochar. Both organic and synthetic fertilizers were applied as designed for each treatment before sowing in each crop growing season. The N application rate was  $240 \text{ kg N ha}^{-1} \text{ crop}^{-1}$  as urea; the phosphate (P) application rate was  $120 \text{ kg P ha}^{-1} \text{ crop}^{-1}$  as superphosphate; the potassium (K) application rate was  $240 \text{ kg K ha}^{-1} \text{ crop}^{-1}$  as potassium chloride. The organic manure purchased from Nanjing Mingzhu Fertilizer Co., Ltd was applied at  $120 \text{ kg N ha}^{-1} \text{ crop}^{-1}$  containing 1.1% TN, 0.13% P, 0.83% K and 28.3% organic matter.

Continuous vegetable crop rotations were allocated on adjacent lands. Additional file 1: Table S2 lists the various management dates for the 5-year vegetable cultivation. Vegetable tillage, irrigation and fertilizer application were carried out according to local management practices. The seeds were reasonably sown and mulched to promote seed germination after moderate irrigation. Appropriate irrigation and pesticide spraying were performed during the growing season of vegetables, and plastic greenhouses were installed to ensure the temperature needed for vegetable growth or to withstand adverse weather. There was a short fallow period of about 15–30 days during the vegetable crop rotation. One vegetable crop per year was selected as representative to study the crop yield and Nr losses for 5 consecutive years.

### 2.3 Sample collection and determination

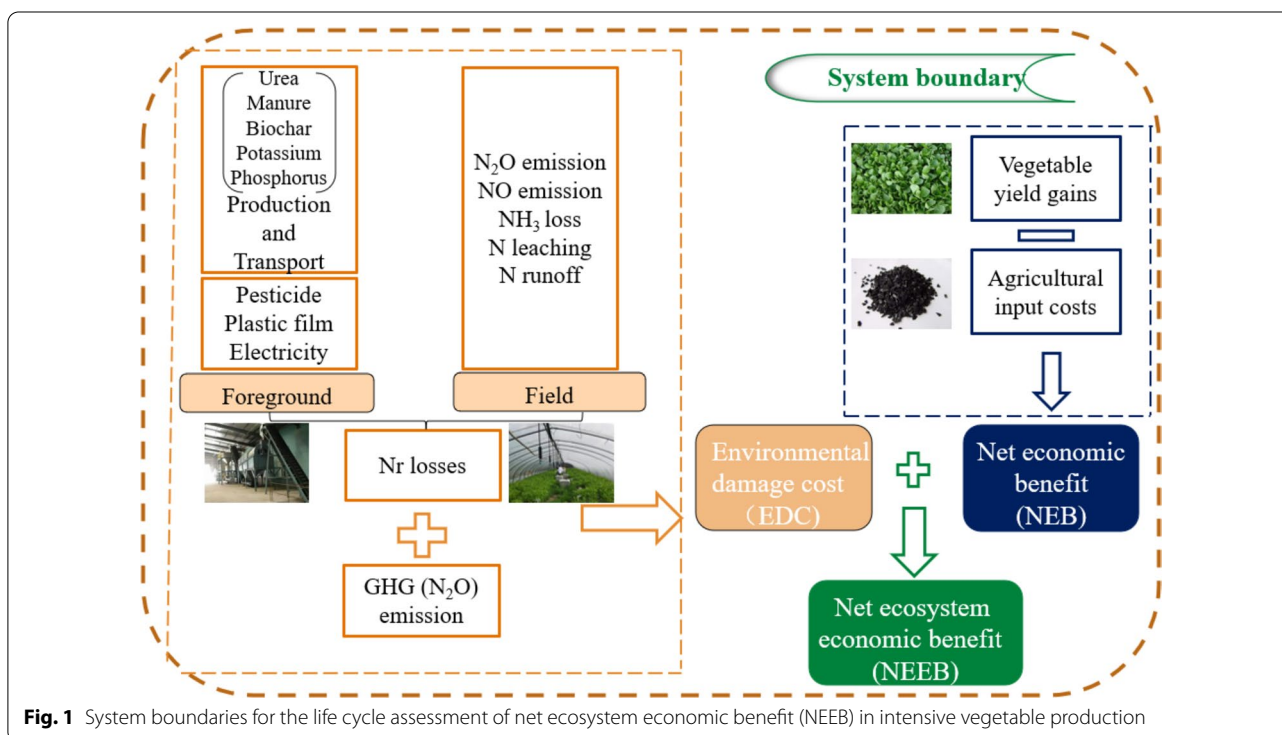
Fresh soil samples were collected from a depth of 0–20 cm. Three replicate samples were removed of debris such as roots and stones and later were divided into two parts, one air-dried and passed through a 2.0 mm sieve to determine soil pH, electrical conductivity (EC) and TN content, and the other to determine soil nitrate nitrogen ( $\text{NO}_3^-$ ), ammonium nitrogen ( $\text{NH}_4^+$ ), dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) contents. Soil TN content was analyzed using an elemental analyzer (Vario EL Cube, Elementar, Germany); soil organic matter (SOC) was determined by the volumetric method using potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ); soil DOC and DON contents were measured using a multiple N/C analyzer (Jena TOC analyzer, Germany) after extraction with distilled water at a soil to water ratio of 1:4 (w:v). Soil pH, EC, temperature, moisture,  $\text{NO}_3^-$  and  $\text{NH}_4^+$  concentrations were measured using methods described in a previous study (Zhang et al. 2020a, b).

After the vegetables were harvested, the yield was calculated based on the total fresh biomass of vegetables in the plot. Samples of fresh vegetables were collected for quality analysis of the protein, vitamin C, soluble sugar and nitrate contents (determined by the standard method of the Quality and Safety Supervision and Testing Center for Agricultural Products and TRANSGENIC Products of the Ministry of Agriculture). The plant samples were first killed at 105 °C and then dried at 70 °C to a

constant weight to calculate the moisture and the weight of dry matter. The N uptake in plants was determined by the Kjeldahl method. The NUE was calculated by the N absorption of each treatment and CK and divided by the amount of N applied.

### 2.4 System boundaries

In this study, the LCA method was used to estimate the N footprint of intensive vegetable production under different fertilizer treatments. The system boundary (Fig. 1) includes the EDC, NEB and NEEB. The EDC consists of N footprint and GHG emissions from agrochemical inputs and energy production. N footprint consists of  $\text{N}_r$  losses in the foreground interface and the field interface throughout the life cycle. The foreground interface includes the fuel and energy consumption due to agrochemical inputs (inorganic and organic fertilizers, biochar, pesticides, and plastic film) as well as farming operations in production and transportation (Hamedani et al. 2019; Zhou et al. 2019). The field interface includes  $\text{N}_2\text{O}$  emissions, NO emissions,  $\text{NH}_3$  volatilization, N leaching and N runoff during field crop growing seasons. Since all the products are sold as fresh vegetables and are not processed, no consideration is given to the loss of greenhouse gases and natural  $\text{N}_r$  during food processing. NEB consists of the benefits of vegetable yield and the costs of agrochemical inputs.



**Fig. 1** System boundaries for the life cycle assessment of net ecosystem economic benefit (NEEB) in intensive vegetable production

## 2.5 Field monitoring and analysis of Nr losses and GHGs

Gas emissions were collected by the static opaque chamber method every 2 days between 8:00 and 10:00 a.m. for 2 weeks after fertilization and every other week thereafter. Samples were measured with a gas chromatograph (Agilent 7890A, Agilent Ltd., Shanghai, China) and a NO<sub>x</sub> analyzer Thermo Model 42i (Thermo Environmental Instruments Inc., Franklin, MA, USA) for N<sub>2</sub>O and NO concentrations, respectively (Zhou et al. 2019). Details of the sampling measurements are given in our previous publications (Fan et al. 2017; Zhou et al. 2019). The emission fluxes of each gas were obtained from the slope of a linear regression of the gas volume ratio of each sample group against the corresponding sampling time, and the cumulative annual emissions were calculated from the average flux weighted by the time interval. The calculation formula of gas emission flux is as follows:

$$F = \rho \times \frac{V}{A} \times \frac{\Delta C}{\Delta t} \times \frac{273}{273 + T} \quad (1)$$

where  $F$  represents the N<sub>2</sub>O and NO emission fluxes ( $\mu\text{g N m}^{-2} \text{ h}^{-1}$ );  $\rho$  represents the density of N<sub>2</sub>O-N and NO-N under standard conditions, which have values of 1.25 g L<sup>-1</sup> and 0.625 g L<sup>-1</sup>, respectively;  $V$  is the volume of the sampling box (m<sup>3</sup>);  $A$  is the surface area of soil in the sampling base (m<sup>2</sup>);  $\frac{\Delta C}{\Delta t}$  represents the emission rate of gases (the units of N<sub>2</sub>O and NO are nL L<sup>-1</sup> h<sup>-1</sup> or ppbv h<sup>-1</sup>) and the coefficient of the linear regression equation performed between the gas concentration of four or two samples collected each time in each plot, and time, and  $T$  is the temperature in the sampling box (°C).

The empirical models used for the calculation of NH<sub>3</sub> volatilization, N leaching, N runoff and the change ratio

of NH<sub>3</sub> volatilization in organic and inorganic fertilizers (Additional file 2: A1) are shown below from 17 peer-reviewed publications on vegetable production in China (Zhou et al. 2019). The change ratio of NH<sub>3</sub> volatilization with biochar addition (Additional file 3: A2) is shown below from 17 peer-reviewed publications on vegetable production. We selected one season to determine the NH<sub>3</sub> volatilization of vegetable crops for model validation (Additional file 1: Fig. S1). The change ratios of the combined application of organic and inorganic matter and biochar addition were consistent with the measured change ratios in our study, indicating that our estimation model was reasonable. Therefore, the measured change ratios of the combined application of the three factors were used to estimate NH<sub>3</sub> volatilization throughout the test period. Among them, the measured value was lower than the model estimated value, which may be due to the low temperature and low TN content in the measurement season, which slows NH<sub>3</sub> volatilization. The change ratio of N leaching and N runoff under biochar addition and organic substitution was determined based on a meta-analysis of data from 141 references (Madaline et al. 2021), which is consistent with the result of our empirical model. Due to the lack of N runoff and N leaching loss data for the SNMB, we adopted the average value of the two single treatments to represent the combined treatment. All selected studies met the following criteria. First, NH<sub>3</sub> volatilization was measured by the micrometeorological or dynamic chamber method, and N leaching and N runoff were measured by the suction cap or lysimeter method. Second, the means and sample sizes of the control and treatment plots were clarified. Third, the amount of N application, the replacement ratio of organic fertilizer and the amount of biochar addition were clarified.

$$\text{NH}_3 \text{ volatilization} = 9.18 \ln(\text{N rate}) - 42.6 \left( R^2 = 0.67; n = 34; P < 0.01 \right) \quad (2)$$

$$\text{CR}_{\text{M NH}_3}(\%) = -151.87\text{Rs}_M^2 + 152.7\text{Rs}_M - 16.20 \left( R^2 = 0.69; n = 12; P < 0.05 \right) \quad (3)$$

$$\text{CR}_{\text{B NH}_3}(\%) = 21.82\text{Rs}_B^2 - 74.199\text{Rs}_B + 70.351 \left( R^2 = 0.70; n = 31; P < 0.01 \right) \quad (4)$$

$$\text{CR}_{\text{MB NH}_3}(\%) = \text{NH}_3 \text{ volatilization} \times (1 - 0.05) \quad (n = 50; \text{SD} = 1.4; P < 0.01) \quad (5)$$

$$\text{N}_{\text{leaching}} = 77.2 \ln(\text{N rate}) - 407.53 \left( R^2 = 0.45; n = 38; P < 0.01 \right) \quad (6)$$

$$N_{M \text{ leaching}} = N_{\text{leaching}} \times (1 - 0.29) \quad (n = 61; SE = 4.7; P < 0.01) \tag{7}$$

$$N_{B \text{ leaching}} = N_{\text{leaching}} \times (1 - 0.37) \quad (n = 80; SE = 2.8; P < 0.01) \tag{8}$$

$$N_{MB \text{ leaching}} = N_{\text{leaching}} \times (1 - 0.33) \tag{9}$$

$$N_{\text{runoff}} = 15.79 \ln(N \text{ rate}) - 78.09 \quad (R^2 = 0.43; n = 33; P < 0.01) \tag{10}$$

$$N_{M \text{ runoff}} = N_{\text{runoff}} \times (1 - 0.29) \quad (n = 61; SE = 4.7; P < 0.01) \tag{11}$$

$$N_{B \text{ runoff}} = N_{\text{runoff}} \times (1 - 0.37) \quad (n = 80; SE = 2.8; P < 0.01) \tag{12}$$

$$N_{MB \text{ runoff}} = N_{\text{runoff}} \times (1 - 0.33) \tag{13}$$

where the N rate denotes the application rate of N fertilizer;  $CR_{M \text{ NH}_3}$ ,  $CR_{B \text{ NH}_3}$  and  $CR_{MB \text{ NH}_3}$  denote the relative change rates of soil  $\text{NH}_3$  volatilization in the SNM, SNB, and SNMB, respectively;  $Rs_M$  denotes the ratio of replacing chemical fertilizer with organic manure;  $Rs_B$  denotes the ratio of added biochar;  $N_{M \text{ leaching}}$ ,  $N_{B \text{ leaching}}$  and  $N_{MB \text{ leaching}}$  denote N leaching in the SNM, SNB, and SNMB, respectively; and  $N_{M \text{ runoff}}$ ,  $N_{B \text{ runoff}}$  and  $N_{MB \text{ runoff}}$  denote N runoff in the SNM, SNB, and SNMB, respectively.

### 2.6 EDC and NEEB

In this study, the NEEB, NEB and the EDC of each treatment were estimated as follows:

$$NEB = \sum_{a=1}^b (Y_a \times P_a) - \sum_{m=1}^n (R_m \times P_m) \tag{14}$$

where  $Y_a$  ( $\text{kg ha}^{-1}$ ) represents the yield of vegetable “a”;  $P_a$  ( $\text{¥ kg}^{-1}$ ) represents the market price of vegetable “a”;  $R_m$  ( $\text{kg ha}^{-1}$ ) represents the use of agrochemical inputs and energy “m”; and  $P_m$  ( $\text{kg}^{-1}$ ) represents the actual purchase prices of agrochemical inputs and energy “m”. The detailed price is shown in Additional file 1: Table S3.

The EDC is defined mainly as the damage costs caused by the foreground and field Nr losses to the ecosystem and human health and  $\text{N}_2\text{O}$  as a GHG to climate warming, and is evaluated by the following equation.

$$EDC = \sum_{i=1}^n N r_i A \times P_i + N_2OA \times P_{N_2O} \tag{15}$$

$$NEEB = NEB - EDC \tag{16}$$

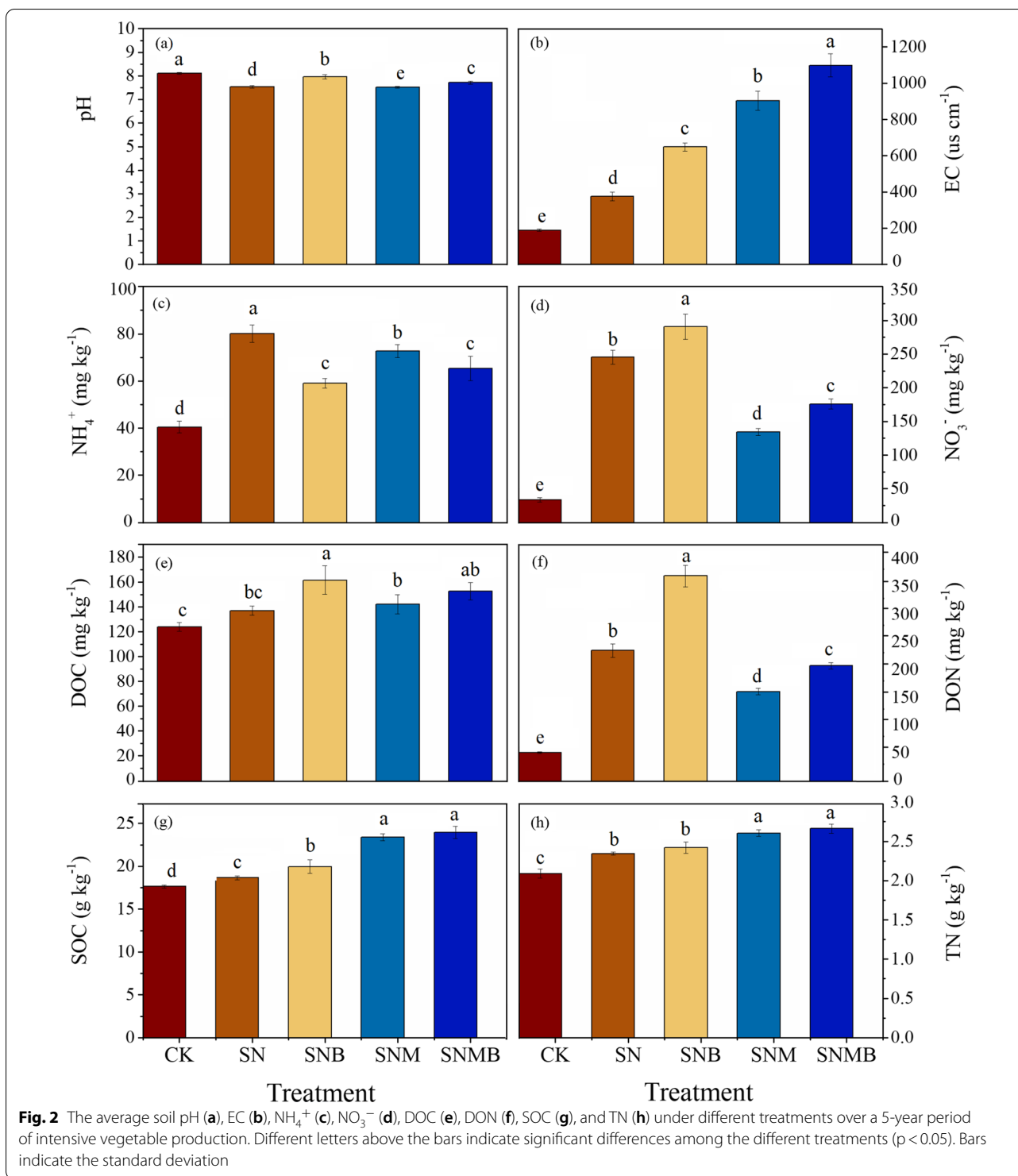
where  $N r_i A$  ( $\text{kg N ha}^{-1}$ ) represents the total emission of reactive nitrogen “i”;  $P_i$  ( $\text{¥ kg}^{-1} \text{ N}$ ) represents the cost of environmental damage per unit mass of reactive nitrogen “i”;  $N_2OA$  ( $\text{kg N ha}^{-1}$ ) represents greenhouse gas emissions ( $\text{N}_2\text{O}$ ); and  $P_{N_2O}$  ( $\text{¥ kg}^{-1} \text{ N}$ ) represents the greenhouse effect caused by greenhouse gas emissions (expressed in international trading prices). Detailed EDCs are shown in Additional file 1: Table S3.

### 2.7 Uncertainty analysis

Considering that the foreground Nr loss parameters were obtained from our published articles and the emission factors were extracted from those widely used studies, we should recognize the inaccuracy of the results caused by the uncertainty of the evaluation criteria in this study. A separate empirical model was established using corrected  $R^2$  values to limit the uncertainty, and the relevant parameters cited have been given their standard errors. Still, the variations can be large due to differences in seasons, crop species, and unit damage prices. Furthermore, biochar relies heavily on the empirical analysis of market participants and researchers due to differences in feedstock and preparation processes and prices (Sun and Huang 2020; Hao and Tian 2020). Therefore, the overall effects of biochar amendment and organic substitution on the ecosystem may have been underestimated or overestimated to some extent.

### 2.8 Data analysis and statistics

Data calculation and statistical analyses were performed by Microsoft Excel and SPSS (IBM Co., Armonk, NY, USA) and visualized by Origin (Version 9.0, USA) and R software. One-way ANOVAs were performed to analyze the responses of crop production and Nr losses to the different treatments and inter-annual variation. Two-factor ANOVAs were performed to evaluate the interaction between the treatment and year. The Tukey test was used for multiple comparisons of whether the difference between the means of each variable was significant ( $p < 0.05$ ).

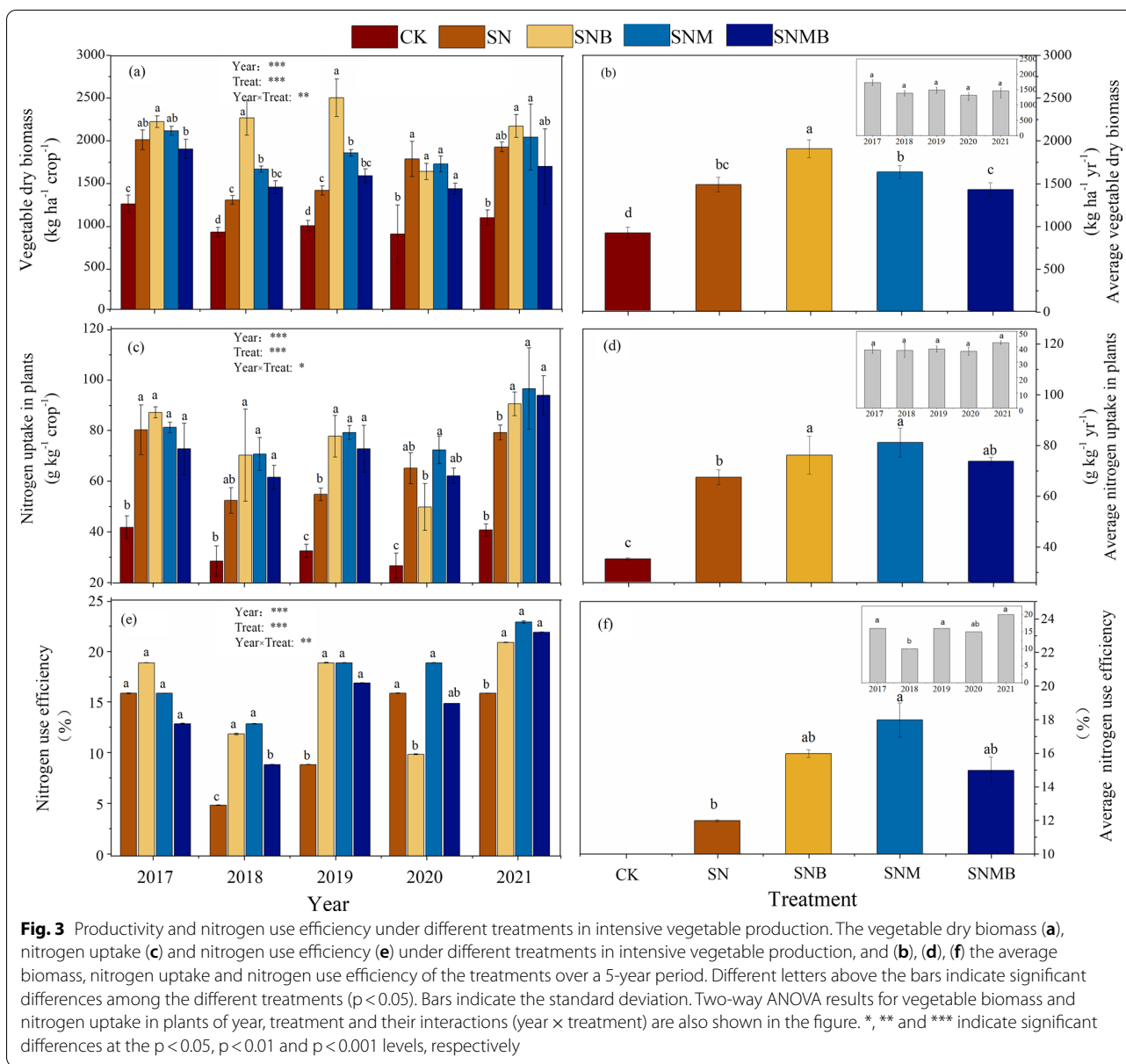


### 3 Results

#### 3.1 Soil physical and chemical properties

As shown in Fig. 2, compared with the SN, the SNB increased the pH (5.8%,  $p < 0.01$ ), the contents of DON (57.3%,  $p < 0.05$ ) and  $\text{NO}_3^-$ -N (18.3%,  $p < 0.05$ ); the

SNM and SNMB increased the SOC (25.4 and 28.4%, respectively;  $p < 0.01$ ) and TN (11.2 and 13.6%, respectively;  $p < 0.05$ ), thus all improving the soil quality (Additional file 1: Fig. S2a). In the SNB, the content of  $\text{NO}_3^-$ -N (158.1–433.1  $\text{mg kg}^{-1}$ ) was 116.3% ( $p < 0.01$ )

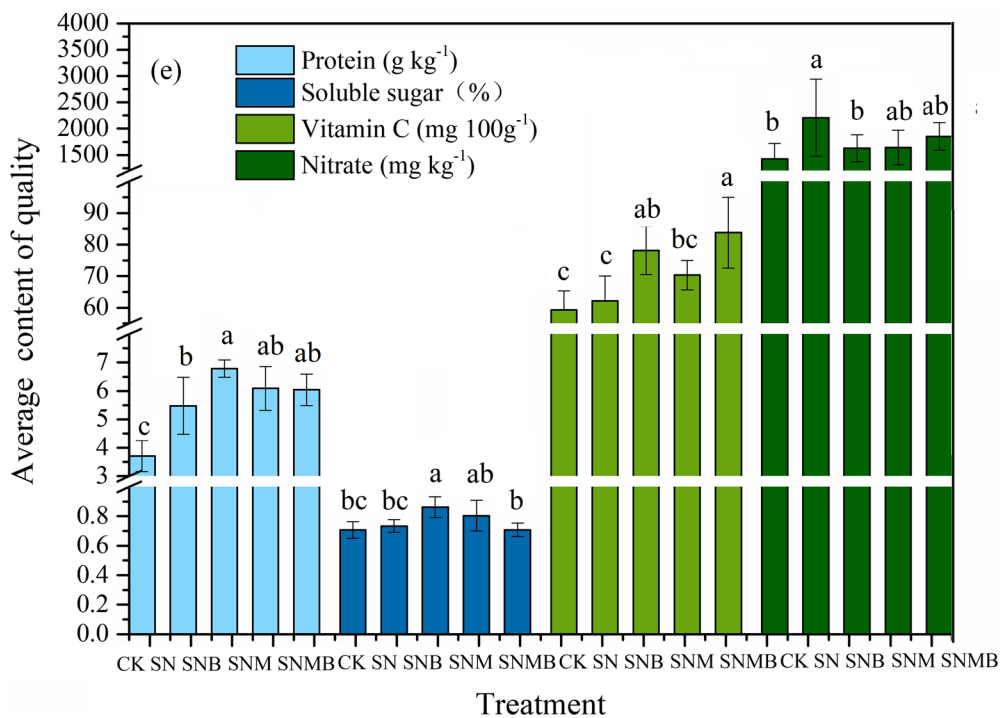
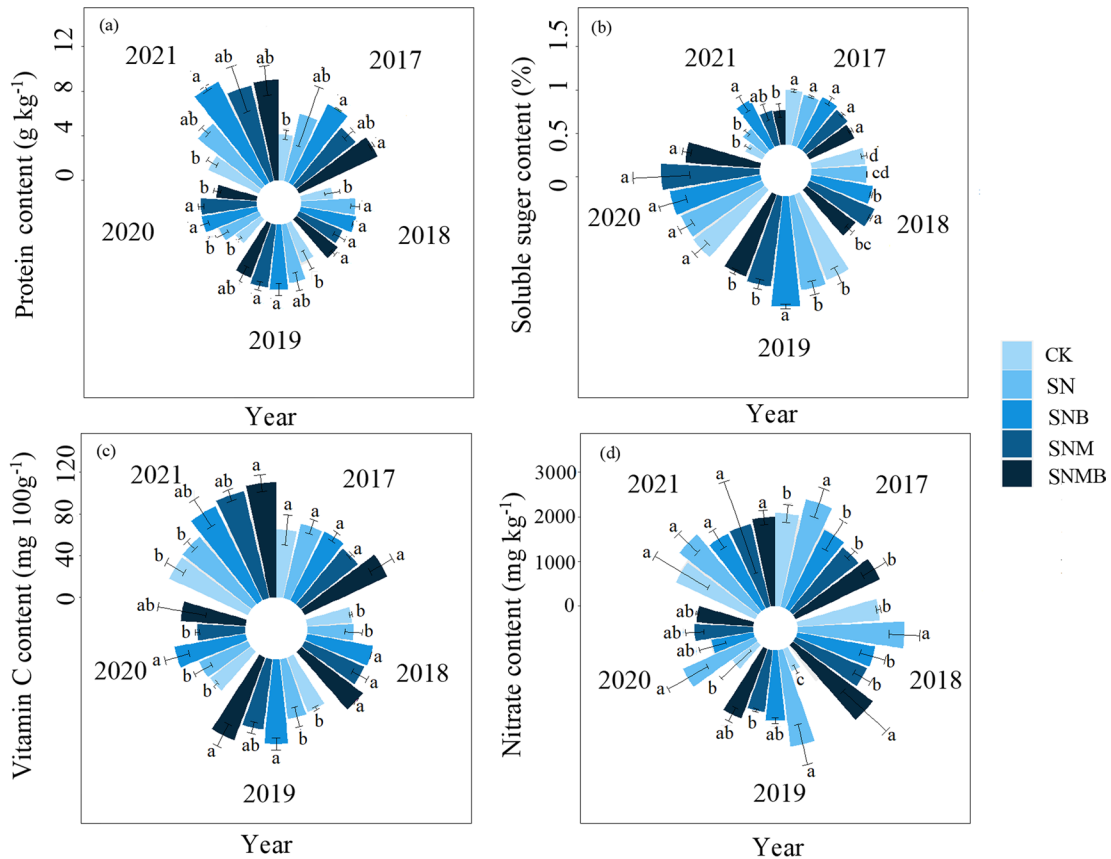


and 65.4% ( $p < 0.01$ ) higher than that in the SNM (29.9–237.9  $\text{mg kg}^{-1}$ ) and SNMB (63.0–256.9  $\text{mg kg}^{-1}$ ), respectively, while the content of  $\text{NH}_4^+\text{-N}$  (46.9–71.0  $\text{mg kg}^{-1}$ ) was decreased by 18.8% ( $p < 0.05$ ) and 9.7%, respectively. Therefore, biochar amendment had a positive effect on the transformation of N to a state that is more easily absorbed and utilized by crops, and the effect is better than that of the SNMB. The inter-annual variation trends of soil physical and chemical properties in all treatments were basically similar, although the soil  $\text{NO}_3^-\text{-N}$  showed a decreasing trend for 4 consecutive years (Additional file 1: Table S4).

### 3.2 Crop productivity and quality

Across the five seasons, the largest vegetable yield was from the SNB, which was 1.3 times greater than that from the SN (Fig. 3a). The average vegetable yields varied at 1020.0–2149.6  $\text{kg ha}^{-1} \text{crop}^{-1}$  for all treatments (Fig. 3b). On average, the SNB and the SNM increased the vegetable yield by 28.4% ( $p < 0.05$ ; interannually varying from – 10 to 74.9%) and 11.6% (interannually varying from – 5.4 to 27.1%) while the SNMB decreased the vegetable yield by 4.4% (interannually varying from – 12.3 to 19.7%) compared with the SN. After biochar amendment, the vegetable yields showed an increasing





**Fig. 4** Quality (protein, soluble sugar, vitamin C, and nitrate) of vegetables under different treatments and years in intensive vegetable production. Different letters above the bars indicate significant differences among the different treatments at  $p < 0.05$ . Bars indicate the standard deviation (mean  $\pm$  SD,  $n = 3$ )

trend from 2017 to 2019, at 2.21 t ha<sup>-1</sup>, 2.26 t ha<sup>-1</sup>, and 2.49 t ha<sup>-1</sup>, although the effect of biochar gradually decreased after approximately 4 to 5 years of observation.

Compared with the SN (66.4 kg ha<sup>-1</sup> crop<sup>-1</sup>), the SNM (80.0 kg ha<sup>-1</sup> crop<sup>-1</sup>) increased the N uptake by 20.5% ( $p < 0.05$ ; interannually varying from 1.1 to 44.5%), while the SNB (75.1 kg ha<sup>-1</sup> crop<sup>-1</sup>) and SNMB (72.6 kg ha<sup>-1</sup> crop<sup>-1</sup>) increased the N uptake by an average of 13.1% and 9.5%, respectively (Fig. 3c, d). The SNM and SNB improved the NUE by an average of 45.7% ( $p < 0.05$ ; interannually varying from 2.3 to 154%) and 29.2% (interannually varying from -39.7 to 150.4%) compared to the SN (Fig. 3e, f).

Compared with the SNM and SNMB, the contents of the protein and soluble sugar were increased by 13.4% and 18.1%, 6.7% and 17.8%, while the nitrate content was decreased by 7% and 13% under the SNB, respectively (Fig. 4a–d). The average product contents of protein, soluble sugar, and vitamin C over the 5 years under the SNB were increased by 22.6%, 25.9%, and 28.8%, respectively as compared to the SN ( $p < 0.05$ ), while the corresponding values were insignificantly increased by 11.1%, 12.6%, and 13.8% under the SNM (Fig. 4e). Compared to the SN, the content of nitrate under the SNB was lower by 27.2% ( $p < 0.05$ ) while the value was 25.7% for the SNM. Hence, biochar amendment is the optimal fertilization for improving crop quality (Additional file 1: Fig. S2b).

### 3.3 N footprint and EDC

During the whole vegetable rotation period, the dynamic changes in N<sub>2</sub>O fluxes were varying with soil temperature and soil water-filled porosity (Additional file 1: Fig. S3a). N<sub>2</sub>O emissions were higher under 65–80% WHC and 30 °C than those under 60% WHC and 25 °C. For the first 3 years from 2017 to 2019, N<sub>2</sub>O fluxes ranged from 9.66 to 2890.26 μg N m<sup>-2</sup> h<sup>-1</sup>, and its peak was detected within 1 week after fertilization (Additional file 1: Fig. S3c), with the largest N<sub>2</sub>O flux occurring in the SN (on average 1787.73 μg N m<sup>-2</sup> h<sup>-1</sup>) which was 57.4% higher than the biochar amendment and 53.6% higher than the

organic substitution ( $p < 0.01$ ). For the next 2 years during 2020 and 2021, the largest N<sub>2</sub>O flux became on average 2036.92 μg N m<sup>-2</sup> h<sup>-1</sup> and occurred for the SNB.

The NO fluxes presented similar seasonal dynamics to those of N<sub>2</sub>O fluxes (Additional file 1: Fig. S3b). Cumulative N<sub>2</sub>O emissions varied from 0.20 to 3.76 kg N ha<sup>-1</sup> crop<sup>-1</sup> and the cumulative NO emissions ranged from 0.04 to 0.45 kg N ha<sup>-1</sup> crop<sup>-1</sup> across all (Table 1). Compared with the SN, the organic substitution reduced N<sub>2</sub>O emissions and NO emissions by 18.9–27.4% and 35.9–39.5% ( $p < 0.05$ ), respectively, and no significant differences occurred among these treatments. The SNB increased NH<sub>3</sub> volatilization by 13.3% and 6.3%, but decreased N leaching and N runoff by 5.9–11.2% compared with the organic substitution.

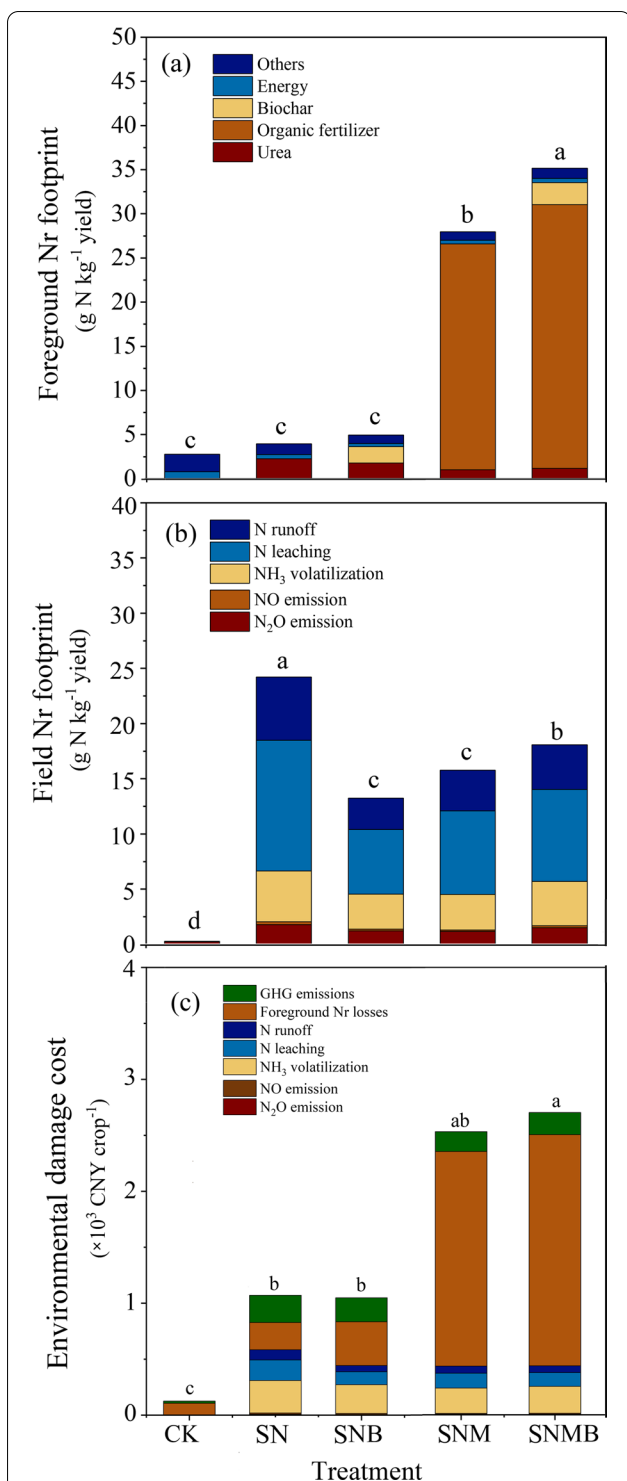
The foreground interface N footprint ranged from 2.8 to 35.1 g N kg<sup>-1</sup> yield (Fig. 5a). The production and transport of organic manure dominated the foreground interface N footprint by 84.9–91.4%, which eventually led to an increase in the foreground N footprint under the SNM (28.0 g N kg<sup>-1</sup> yield) and SNMB (35.1 g N kg<sup>-1</sup> yield) compared with the SNB (4.9 g N kg<sup>-1</sup> yield) ( $p < 0.01$ ). The field N footprint ranged from 0.3 to 24.2 g N kg<sup>-1</sup> yield (Fig. 5b). N leaching dominated the N footprint, accounting for an average of 46.8%, whereas NH<sub>3</sub> volatilization and N runoff were secondary contributors. Compared with the SN, the SNB, SNM, and SNMB reduced the field N<sub>r</sub> loss by 45.4%, 34.9% and 25.3% ( $p < 0.01$ ; interannually varying from -40.3 to 78.4%, 8.4 to 39.0% and -22.0 to 49.5%, respectively). When considering the foreground interface and the field interface together, the SNB (18.2 g N kg<sup>-1</sup> yield) reduced the N footprint by 58.4 and 65.8% compared with the SNM (43.7 g N kg<sup>-1</sup> yield) and SNMB (53.2 g N kg<sup>-1</sup> yield) ( $p < 0.01$ ), respectively.

The EDC associated with N<sub>r</sub> losses and GHG emissions ranged from 0.16 × 10<sup>3</sup> CNY ha<sup>-1</sup> crop<sup>-1</sup> for CK to 2.75 × 10<sup>3</sup> CNY ha<sup>-1</sup> crop<sup>-1</sup> for the SNMB (Fig. 5c). Foreground N<sub>r</sub> losses were the main contributor to EDC in the organic substitution, with an average of 74.8%, resulting in EDC increasing by 130% in the SNM (2.57 × 10<sup>3</sup> CNY ha<sup>-1</sup> crop<sup>-1</sup>) and 145% in the SNMB (2.75 × 10<sup>3</sup> CNY ha<sup>-1</sup> crop<sup>-1</sup>) compared to the SN

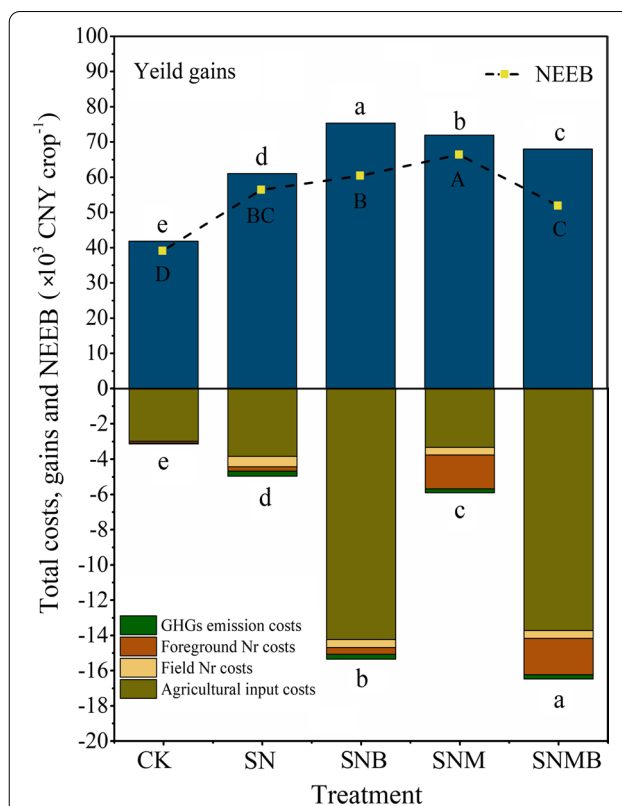
**Table 1** Five-year cumulative field N<sub>r</sub> losses (kg N ha<sup>-1</sup> crop<sup>-1</sup>) under different treatments averaged across 5 years of 2017–2021 in intensive vegetable production

Treatment	Cumulative N <sub>2</sub> O	Cumulative NO	NH <sub>3</sub> volatilization	N leaching	N runoff
CK	1.18 ± 0.09e	0.22 ± 0.24d	–	–	–
SN	14.91 ± 0.30a	2.23 ± 0.15a	38.55	98.95	48.1
SNB	13.19 ± 0.32b	1.66 ± 0.13b	34.00	62.85	30.55
SNM	10.83 ± 0.27d	1.35 ± 0.06c	30.00	70.75	34.4
SNMB	12.09 ± 0.28c	1.43 ± 0.18c	32.00	66.80	32.45

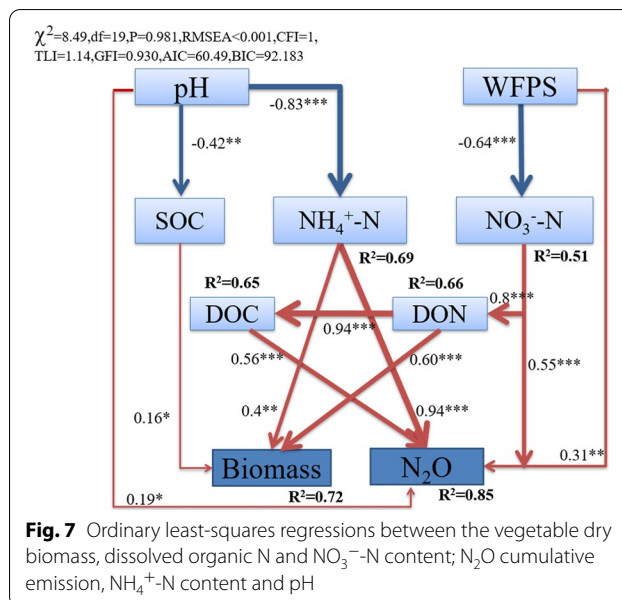
Mean ± SE, the lowercase letters represent significant differences according to the Tukey's multiple range test ( $p < 0.05$ )



**Fig. 5** Contributions of different sources to the foreground N footprint (a), field N footprint (b), and environmental damage costs (c) under different treatments in intensive vegetable production. Others refer to the manufacture and transport of potassium, phosphorus, insecticides and plastic film. Energy refers to fuel and electricity consumption. The lowercase letters represent significant differences according to Tukey's multiple range test ( $p < 0.05$ )



**Fig. 6** Vegetable yield gains, NEEB, total costs incurred by GHG emissions, N releases, and inputs under different treatments in intensive vegetable production. The lowercase letters represent significant differences in total costs, gains and uppercase letters represent NEEB ( $p < 0.05$ )



**Fig. 7** Ordinary least-squares regressions between the vegetable dry biomass, dissolved organic N and NO<sub>3</sub><sup>-</sup>-N content; N<sub>2</sub>O cumulative emission, NH<sub>4</sub><sup>+</sup>-N content and pH

( $p < 0.01$ ). In contrast, field Nr losses were the main contributor to EDC under the SNB at 40.1%, and the EDC of SNB ( $1.11 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup>) was 1.28% lower than that under the SN.

### 3.4 NEEB

The NEEB is comprised of yield gains minus agrochemical input costs and EDCs (Fig. 6). The NEEBs of four fertilization treatments ranged from  $51.6 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup> to  $66.0 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup>, 33.2–70.7% higher than that of the CK ( $38.6 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup>). Among them, the SNM achieved the optimal NEEB ( $66.0 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup>) and increased by 17.8% ( $p < 0.01$ ) compared to the SN ( $56.1 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup>). The NEEB of the SNB ( $60.0 \times 10^3$  CNY ha<sup>-1</sup> crop<sup>-1</sup>) was 7.1% higher than that of the SN, but 10.0% lower than that of the SNM, mainly due to the cost of agrochemical inputs. The SNMB decreased the NEEB by 14.1% compared to the SNB ( $p < 0.05$ ), and even an 8% decrease compared to the SN.

## 4 Discussion

### 4.1 Crop production and NUE as affected by biochar and organic substitution

The findings showed that N fertilizer significantly increased vegetable yields and N uptake compared with the plots without N fertilizer, which was consistent with the results reported by previous studies (Zhang et al. 2011). Among the different treatments for adding N fertilizer, biochar amendment significantly increased crop production and N uptake, serving as the optimal fertilization treatment (Fig. 3), which supported the findings of previous meta-analyses (Jeffery et al. 2011). The contents of soil DON and NO<sub>3</sub><sup>-</sup>-N, which proved to be important factors limiting vegetable yield (Fig. 7), were improved in the SNB, whereas the soil pH and SOC were not affected, indicating that the increase in vegetable yield with biochar is unlikely to be a result of the lime effect. We found that vegetable growth and N assimilation were enhanced by the low NH<sub>4</sub><sup>+</sup>/NO<sub>3</sub><sup>-</sup> ratio (Fig. 2), which supported the previous observations (Hu et al. 2021). In biochar-amended soils, due to its higher surface area and porosity, the higher N bioavailability promoted soil microbial activity (Agegnehu et al. 2016) and accelerated nutrient cycling, further increasing crop productivity and NUE (Bailey et al. 2011). However, soils with biochar amended for more than 4 years failed to improve the N bioavailability or soil nitrification. Organic substitution dramatically increased NUE and N uptake compared with traditional N management, which was consistent with the previous report (Zhang et al. 2020a, b). Reasonably, the rapid supply of N by chemical fertilizers early in the crop growing season and a continuous supply of N can

promote crop growth at the later stage due to the long-lasting effect of organic manures (Liang et al. 2019).

We also observed the improvement of vegetable qualities by biochar amendment in this study. The SNB significantly increased the contents of soluble protein, vitamin C, and soluble sugar in vegetables and significantly reduced the nitrate content compared with the SN (Fig. 4e). Probably due to the slow-release effect of the porous structure of biochar on the adsorption of fertilizer nutrients (Lehmann et al. 2003), biochar amendment may facilitate the proper supply of N and the conversion rate of NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup>, avoiding the accumulation of plant NO<sub>3</sub><sup>-</sup>. Moreover, biochar may improve the quality by promoting the synthesis of related enzymes in the plant (Liu et al. 2014a, b) with its abundant trace elements (Additional file 1: Table S1). The SNM improved vegetable quality to some extent without significant differences as compared to the SN (Fig. 4e). Organic fertilizers improved SOC and soil structure (Fig. 2g), and enhanced the performance of microorganisms related to soil aggregate structure, thus promoting the production of aggregates and reducing the amount of NH<sub>4</sub><sup>+</sup> converted to NO<sub>3</sub><sup>-</sup> (Luan et al. 2019). However, the alteration of soil microbial and enzyme activities by biochar amendment and organic substitution should be further clarified for improving vegetable qualities.

### 4.2 N footprint and EDC as affected by biochar and organic substitution

Different fertilization treatments significantly increased the N footprint in vegetable production (Fig. 5). When considering the Nr losses caused by the foreground and field interfaces, the total Nr loss range of each treatment during the experimental period was 3.1–85.2 kg N ha<sup>-1</sup> crop<sup>-1</sup>, which was much larger than that in other farmland ecosystems, mainly due to the frequent large amount of N input.

The foreground N footprint of organic manure substitution increased significantly by approximately five to eight times that of the other fertilization treatments, because of the large amount of NH<sub>3</sub> volatilization in the production process of organic manure. This finding is generally consistent with meta-analyses showing that NH<sub>3</sub> volatilization dominates Nr losses during the process of producing organic manure (Hou et al. 2015). Conversely, biochar amendment greatly reduced the N footprint, which was not significantly different from the CK and SN. Thus, the preparation of biochar using pyrolytic coking and carbon-rich plant waste of raw materials would serve as a green sustainable development measure that can alleviate the Nr losses in vegetable production.

The results of the field interface also showed that fertilization significantly increased the N footprint, which is consistent with previous studies (Cui et al. 2013; Zhou et al. 2019). First, the high N cycling pattern leads to serious N leaching in vegetable systems. Second, a multiple cropping index and frequent irrigation lead to a significant ratio of  $\text{NH}_3$  volatilization and N runoff (Xia et al. 2016). Meanwhile, this study confirmed that biochar amendment and organic substitution significantly reduced the N footprint, and the differences among them were not significant. Not surprisingly, there was a negative correlation between the N footprint and NUE in the field (Cui et al. 2013). Biochar or organic manure promotes microbial activity with the increase of available carbon supplies (Mandal et al. 2016), facilitates the conversion and fixation of mineral N into organic N and DON, and reduces the leaching of N (Fig. 7) (Zhou et al. 2019). The direct application of biochar to soil may be an effective method of increasing soil C and N storage (Tan et al. 2018).

The EDC caused by the intermediate product of nitrification and denitrification could not be ignored, although the emission of  $\text{N}_2\text{O}$  and NO accounted for a very small proportion of the  $\text{N}_r$  losses at the field interface (Henckel and Conrad 1998). In the present study, biochar amendment and organic substitution were found to mitigate  $\text{N}_r$  losses by altering  $\text{NH}_4^+$  and DOC and thereby affected emissions during nitrification (Fig. 7).  $\text{NH}_4^+$  was concentrated in the reduced soil layer and susceptible to slow diffusion to the soil surface (Kapoor et al. 2008). In addition, readily decomposable organic carbon sources were both C and N substrates for nitrification (Zhou et al. 2019). Biochar amendment reduced soil N effectiveness for  $\text{N}_2\text{O}$  production and promoted the further reduction of  $\text{N}_2\text{O}$  to  $\text{N}_2$  in denitrification with increased electron transfer (Xu et al. 2022). However, biochar amendment increased nitrification associated  $\text{N}_2\text{O}$  emissions 2–3 years after fertilization, which is consistent with findings by Edwards et al. (2018), but reduced cumulative  $\text{N}_2\text{O}$  emissions compared with the SN throughout the 5 years experimental period (Table 1).

#### 4.3 NEEB as affected by biochar and organic substitution

Assessments of NEEBs, which show the relationship between agronomic productivity and environmental sustainability, can provide a scientific basis for improving agronomic management in terms of costs and encourage farmers to adopt management that benefits C (Zhang et al. 2015). Previous studies have reported the effects of biochar amendment (Li et al. 2015) and organic manure (Zhou et al. 2019) on crop yields and NEEBs, although little attention has been focused on the influence of different coordinated application treatments, which directly

affect farmers' motivation. Combining the economic and environmental costs, the SNM generated the highest NEEBs in the current study. This was attributed to the reduced cost of agrochemical inputs due to organic farming. This result represents a substantial change and encourages farmers to adopt a rational strategy of combining organic and inorganic fertilizers. However, it is worth noting that the SNM caused a significantly higher EDC than the other treatments due to the excessive loss of  $\text{N}_r$  in the early composting process, which emphasizes that reducing the foreground N footprint of the compost production process should be the focus of developing mitigation measurements. Studies have pointed out that  $\text{NH}_3$  volatilization can be attenuated by adopting appropriate organic management measures, such as processing organic waste before incorporation to produce biochar (Khan et al. 2013; Tang et al. 2019; Yao et al. 2018). On the one hand, converting agricultural organic waste into organic manure is a resource-saving approach that can reduce the pressure of environmental pollution to some extent (Zhou et al. 2019); on the other hand, it can improve soil quality and soil environment and reduce global warming (Zhang et al. 2020a, b). It should be noted that the SNMB reduced the NEEBs of the ecosystem compared with the SN and did not achieve the expected results and its disadvantages were highlighted; therefore, it is not recommended.

Although not significantly different in NEEB from the SN, the SNB may still be an appropriate agricultural approach for providing high productivity and environmental benefits in vegetable systems. First, nutrients and trace elements from biochar replenish soil fertility, provide space for microorganisms to survive and reproduce, and improve the structure and abundance of microbial communities (Ducey et al. 2013). Second, the nutrients in biochar are mainly in organic form with the slow nutrient release, which ensures nutrient availability throughout the growing season and improves carbon and nitrogen retention (Xiang et al. 2017). Although biochar is an environmentally friendly soil amendment with high adoption potential for farmers, few studies have performed comprehensive analyses to support this claim (Håring et al. 2017). Our study showed that the impact of biochar addition on the NEEBs was not significant compared to that of the SN mainly because biochar application is not competitive with other alternatives for soil amendment due to labor and purchase costs, which is consistent with previous studies (Petelina et al. 2014). Even with significant increases in vegetable productivity after biochar application, production and usage on small and medium-sized farms remain a significant challenge (Strassburg et al. 2016). This study suggests that possible low-cost options include modifying the preparation process to

produce biochar at low cost, using biochar in low quantities (depending on whether productivity increases as a result), or using biochar for more beneficial land uses.

However, the SNMB reduced the NEEBs compared to the SN, mainly due to the EDC of organic compost and agrochemical inputs of biochar were too large to cover the yield gains.

#### 4.4 Inter-annual effects of biochar and organic substitution

Generally, biochar amendment can sequester carbon and reduce Nr emissions; the temporal evolution pattern of biochar in situ cannot be ignored. Studies have reported that after many years of application, biochar loses the ability to increase crop yields and reduce Nr losses (Aller et al. 2018) and may even reduce soil microbial activity or abundance (Ameloot et al. 2014), while others have found that aged biochar could still improve soil fertility and promote crop growth (Qin et al. 2016). Through temperature and precipitation changes, anthropogenic tillage and microbial activities can lead to physical fragmentation or chemical oxidation after mixing biochar into the soil, which decreases its effectiveness in storing carbon in the subsurface, but improves soil fertility and reduces pollutants (Wang et al. 2020). The properties of biochar, such as pH, ash, and functional groups, changed with aging due to constant exposure (Aller et al. 2018). Therefore, relatively long-term observations may indicate changes in the effectiveness of our treatments. This is confirmed by our findings that vegetable yield decreased in the 4th to the 5th year of the trial period in the SNB and SNMB and the production effect of the SNMB was lower than the effect of both alone and sometimes even lower than the SN. The long-term high C/N of biochar and organic application stimulated microbial colonization, which led to N fixation in the soil, which is not beneficial for the current crop utilization and growth.

In addition, the Nr losses of the biochar amendment strategies significantly increased in the 4th to 5th years (Additional file 1: Fig. S3), resulting in a lower overall effect of SNMB in reducing field Nr losses ( $N_2O$ , NO,  $NH_3$ ) than the SNM. This ultimately leads to a decrease in the NEEBs of the SNMB is thus not recommended, probably because the long-term tillage of the soil reduced the electron transfer ability and led to the loss of the ability to reduce  $N_2O$  (Yuan et al. 2019), which is not conducive to the stability of the combined dispensing. Although the aging effect of biochar negated the initially observed effects on Nr losses, we cannot conclude that biochar is inevitably losing its capacity for mitigating soil

Nr losses due to the large interannual variations observed (Fig. 5). It should be noted that the beneficial effects of biochar on soil properties by providing more favorable conditions for microbial growth are long lasting, and the focus should be on a comprehensive assessment of the long-term effects of biochar applications in various agroecosystems.

## 5 Conclusions

Our 5-year observations demonstrate that the SNM and SNB improved crop yield, quality, and NUE by reducing Nr losses and promoting SOC sequestration, and they ultimately increased the NEEBs compared to the SN, while the SNM produced the best NEEB. However, the SNMB reduced the NEEBs compared to the SN mainly because of the high costs of agrochemical inputs from biochar and EDC from manure production. Overall, the SNM is a win–win approach that not only provides substantial economic benefits to farmers but also has a low upfront cost. The expected NEEBs can be improved by optimizing the biochar production process and organic manure substituting rates. The combined effects of fertilizer, biochar and organic manure need to be further explored in various geographic settings and ecosystem types.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s42773-022-00168-9>.

**Additional file 1: Table S1.** The properties of soil and biochar; **Table S2.** Cultivation and fertilization management practices in intensive vegetable production from 2017–2021 at Nanjing, China; **Table S3.** Components of NEB ( $103 \text{ CNY ha}^{-1} \text{ 5yr}^{-1}$ ) and EDC ( $103 \text{ CNY ha}^{-1} \text{ 5yr}^{-1}$ ) under different strategies in intensive vegetable production; **Table S4.** Soil physical and chemical properties under different treatments in intensive vegetable production; **Fig S1.**  $NH_3$  fluxes and cumulative  $NH_3$  emissions during the first vegetable crop season in 2020; **Fig S2.** The evaluation system of soil quality (WFPS, DOC, DON, SOC, TN,  $N_2O$ ) and crop quality (Biomass, N content, Protein, Soluble sugar, Vitamin C, Nitrate) under different treatments in intensive vegetable production; **Fig S3.** Temporal variation of mean soil temperature, WFPS, (a) NO fluxes (b) and  $N_2O$  fluxes (c) during the experimental period. Error bars indicate the standard error of the mean of each treatment.

**Additional file 2: Supplement A1.** The 17 peer-reviewed publications on vegetable production in China to derive the calculation of  $NH_3$  volatilization, N leaching, N runoff parameters and the change ratio of  $NH_3$  volatilization in organic and inorganic fertilizers used for the current study's empirical models.

**Additional file 3: Supplement A2.** The 17 peer-reviewed publications on vegetable production to derive the change ratio of  $NH_3$  volatilization with biochar addition used for the current study's empirical models.

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### Author contributions

RB: conceptualization, software, writing; QZ: supervision, software; LZ: lab measurement; XX: methodology; XZ: data analysis; YD: project administration; XY: conceptualization, supervision; ZX: funding acquisition, supervision, conceptualization, writing and revision. All authors read and approved the final manuscript.

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### Availability of data and materials

Data has been included as additional files and will be made available on reasonable request.

### Declarations

### Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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