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RESEARCH ARTICLE

# Effects of inorganic and organic fertilizers on $CO_2$ and $CH_4$ fluxes from tea plantation soil

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Agricultural practices such as fertilization considerably influence soil greenhouse gas fluxes. However, the effects of fertilization on greenhouse gases fluxes remain unclear in tea soil when soil nitrogen is low. In the present study, soil $CO_2$ and $CH_4$ fluxes under various fertilization treatments in tea soil were investigated during a 50-day period. The experiment consisted of five treatments: no fertilizer (CK), single nitrogen (urea, N), single oilseed rape cake fertilizer (R), nitrogen + cake fertilizer (2:1, NR1), and nitrogen + cake fertilizer (1:2, NR2). The fertilization proportion of NR1 and NR2 was determined by the nitrogen content of nitrogen fertilizer and cake fertilizer. The results revealed that the single application of nitrogen had no significant effect on soil $CO_2$ flux. However, the addition of cake fertilizer significantly increased $CO_2$ emissions through enhanced soil microbial biomass carbon (MBC). Additionally, $CO_2$ emissions were directly proportional to the amount of carbon (C) in the fertilizer. All treatments were minor sinks for $CH_4$ except for the treatment NR1. Specifically, the cumulative $CH_4$ fluxes of NR1 and NR2 were significantly higher than rest of the three treatments, which implies that application of urea and oilseed rape cake reduced the capability of $CH_4$ oxidation in tea soil. Structural equation models indicated that soil $CO_2$ flux is significantly and positively correlated with soil dissolved organic carbon, MBC and soil pH, while mineral nitrogen content was the main factor affecting $CH_4$ flux. Overall, the application of oilseed rape cake increased the oxidation of $CH_4$ and promoted soil C sequestration but inevitably increased the soil $CO_2$ emissions.

**Keywords:** Nitrogenous fertilizer, Oilseed rape cake fertilizer, Greenhouse gases, Microbial metabolisms, Structural equation models

## 1. Introduction

The tea plant (Camellia sinensis), a perennial evergreen woody plant, acts as an important cash crop in tropical and subtropical areas (Yang et al., 2018). It is grown in multiple developing countries such as China, India, Kenya (Wang et al., 2020). The high-quality tea in China is most commonly cultivated in the mountainous regions due to the favorable climate and soil conditions (Yan et al., 2018). The addition of chemical and organic fertilizers can significantly stimulate the tea yield. Chemical fertilizers provide essential nutrients to tea plants and thus improve the bush tea shoot mass and the production of compounds (Mudau et al., 2005; Yang et al., 2014). The addition of organic materials not only maintains soil fertility but also improves soil structure and soil porosity (Kallenbach et al., 2010; Wu et al., 2019). However, fertilization changes community structure of microbes and affects the decomposition of organic matter (Bao et al., 2016; Wei et al., 2019). Furthermore, the addition of fertilizer affects the greenhouse gas (GHG) fluxes from soil (Shimizu et al., 2013; Chen et al., 2017; Liu et al., 2018; Wu et al., 2018).

Carbon dioxide ($CO_2$) and methane ($CH_4$) contribute significantly to global warming, and they are greatly influenced by anthropogenic and agricultural activities (Kallenbach et al., 2010; Shah et al., 2016). The application of organic and inorganic fertilizers highly influence soil $CO_2$ and $CH_4$ emissions (Nyamadzawo et al., 2014; Khan et al., 2017). Many studies have shown that application of chemical fertilizers increases soil $CO_2$ emissions (Shao et al., 2014; Zamanian et al., 2018; Zhang et al., 2019), whereas the effect of nitrogen (N) fertilizer on soil $CH_4$ emissions is not consistent. Kong et al. (2019) observed that the application of N fertilizer improved the soil carbon (C) substrate and benefited the methanogens

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proliferation to improve methanogenic activities and thus promote $CH_4$ emissions. In addition, methane monooxygenase participates in the oxidation process of ammonia ($NH_3$) after using ammonium nitrogen ($NH_4^+$-N), influencing the catalytic oxidation of $CH_4$ (Willison et al., 1995). However, Bodelier and Laanbroek (2004) reported that the application of N fertilizer directly promote the oxidation of $CH_4$ by nitrifying bacteria. Adding straw and green manure to soil are important measures to improve soil organic matter (Wu et al., 2019; Yu et al., 2020). The application of organic fertilizers can promote microbial decomposition activities and root respiration, leading to the increase of the $CO_2$ emission of soil (Qiu et al., 2015; Li et al., 2019). The addition of straw and green manure can improve soil methane production potentials and the abundances of methanogens (Zhou et al., 2020). However, Hoang et al. (2019) found that returning burned straw to the field could reduce seasonal cumulative $CH_4$ emission. Therefore, the results of fertilization types on soil GHG emissions are still controversial, especially the impact of fertilization on $CH_4$ fluxes.

In addition to the single application of chemical or organic fertilizer, the combined application of both is the main measure of agricultural fertilization (Zhou et al., 2019; Qaswar et al., 2020). Different proportions of fertilizers with differences in C/N ratio may affect soil physicochemical properties, and soil $CO_2$ and $CH_4$ emission (Finn et al., 2016; Zhou et al., 2017; Gwon et al., 2019). Fertilizers with low C/N ratio can substantially increase the decomposition of residues and contribute to GHG emissions (Abera et al., 2014; Zhou et al., 2019). But studies have found that adding fertilizers with low C/N ratio can reduce $CH_4$ emissions (Kim et al., 2012). Oilseed rape cake is a low C/N ratio residue, and GHG emission characteristics from soil following combined application of oilseed rape cake and chemical fertilizer is not clear (Raheem et al., 2019). Soil properties had direct or indirect effects on $CO_2$ and $CH_4$ emission. Soil dissolved organic carbon (DOC) is an indicator of the C available to soil microbes, and has close relationship with the respiration and denitrification of heterotrophic microbes (Boyer and Groffman, 1996). Iqbal et al. (2008) observed a positive correlation between DOC and soil $CO_2$ flux, and DOC provided energy to methanogens to promote $CH_4$ production (Zhou et al., 2020). In addition, some studies have shown that soil respiration was positively correlated with soil DOC and soil microbial biomass carbon (MBC) (Ge et al., 2020; Wu et al., 2020). Soil nitrate nitrogen ($NO_3^-$-N) and $NH_4^+$-N not only provides essential nutrients for microbes but also indirectly affects soil microbes and gas emissions. The process of nitrification and denitrification was affected by the soil pH and affected the activity of soil microbes (Sauze et al. 2017; Li et al., 2020). Furthermore, denitrifying intermediates can inhibit methanogenic microorganisms during nitrate reduction (Clarens et al., 1998; Bao et al., 2016). Moreover, $NH_4^+$-N inhibited the oxidation of $CH_4$ by competitive action in upland soils (Schimel, 2000), but Bodelier et al. (2000) found ammonium actually stimulates $CH_4$ oxidation and methanotroph growth in rice-paddy soils. Therefore, clarifying the relationship between soil physicochemical properties and gas flux under different fertilization methods plays an important role in controlling GHG emissions of tea plantations.

Soil respiration is the main flux of C between the atmosphere and soil, and soil C loss can be quantified by soil $CO_2$ and $CH_4$ emission (Khan et al., 2017; Liu et al., 2019). Studies have shown that fertilization can increase soil C sequestration and reduce GHG emissions (Wu et al., 2019). By exploring the emission characteristics of soil $CO_2$ and $CH_4$ in tea plantations, we can understand the soil C sequestration and provide theoretical basis for improving the productivity of tea. In addition, N content of fertilizers is an important factor affecting $CO_2$ and $CH_4$ fluxes. Studies have shown that using low levels of N fertilizers produces low magnitudes of $CO_2$ and $CH_4$ (Shao et al., 2014; Li et al., 2019). In the present, the N concentrations of fertilizers were controlled at a low level, and then explored the $CO_2$ and $CH_4$ emission characteristics of different fertilization methods. We selected the soil of tea plantations in central China for incubation experiment to measure soil $CO_2$ and $CH_4$ fluxes. Organic and inorganic fertilizers were applied in the present study. The specific objectives of this study were to (1) compare the emission pattern and characteristics of $CO_2$ and $CH_4$ in tea plantations soil under different fertilization types and proportions, (2) identify the relationships between soil properties and $CO_2$ and $CH_4$ fluxes, and (3) choose minimal carbon emission fertilization types and proportions and to provide a scientific basis for reducing agricultural pollution in tea plantations. We hypothesized that mixed application of nitrogen and oilseed rape cake fertilizer will increase $CO_2$ and $CH_4$ emissions under the condition of lower nitrogen addition, and soil C content and mineral N content are the main factors affecting $CO_2$ and $CH_4$ emissions.

## 2. Materials and methods

### 2.1. Experimental soil

The surface soil (0～20 cm) in this study was collected from the tea garden of Heshengqiao town (29°02′～30°18′N, 133°31′～144°58′E), Xianning city, Hubei province, China. The region has the characteristics of typical plain-hills area and belongs to the typical subtropical monsoon climate. The annual average temperatures and precipitation are 16.8 °C and 1577 mm, respectively. The red soil in this area can be classified as Ultisols, as well as some Alfisols and Oxisols, on the basis of US soil taxonomy. The field had been under gone tea plantation for more than 10 years. The average elevation of the sampling site is about 35 m, and the surface soil of tea garden was collected from 0～20 cm by the diagonal multipoint mixing. A composite soil sample was made after removing visible organic residues and the small stones. The soil was passed through a 2-mm sieve after air-drying and used for incubation experiments. The properties of the soil were as follows: 45.3% sand, 22.6% silt, 15.7% clay, pH 4.57, bulk density 1.41 g $cm^{-3}$, 17.2 g $kg^{-1}$ total C (TC), 1.04 g $kg^{-1}$ total N (TN), 64.2 mg $kg^{-1}$ $NH_4^+$-N, and 19.1 mg $kg^{-1}$ $NO_3^-$-N.

### *2.2. Experiment design*

The cake fertilizer used in the experiment was oilseed rape cake, which was dried, crushed, and set aside after 100 mesh sieving. The total C content of rapeseed cake was 446 g $kg^{-1}$, the total N content was 51.2 g $kg^{-1}$, and C/N ratio was 8.71. Urea aqueous solution was used as N fertilizer, instead of granule form. Five treatments were designed in this study: no fertilizer (CK), single nitrogen (urea, N), single cake fertilizer (R), nitrogen + cake fertilizer (2:1, NR1), and nitrogen + cake fertilizer (1:2, NR2), respectively. The N concentrations of all fertilization treatments were limited to 100 mg $kg^{-1}$. The fertilization proportion of NR1 and NR2 was determined by the nitrogen content of nitrogen fertilizer and cake fertilizer. The C contents of R, NR1, and NR2 were 870 mg $kg^{-1}$, 290 mg $kg^{-1}$, and 580 mg $kg^{-1}$, respectively.

A weight of 200 g air-dried soil was placed in a 1000 mL glass bottle. Distilled water was added to moisten the soil, and the soil was preincubated for 10 days in the dark to activate soil microbes. At the end of preincubation, different types and proportions of fertilizer were added to the glass bottles. Three replicates were set for each treatment. At the same time, water content of distilled water was adjusted as 60% for the entire experiment, and the water lost by evaporation was replenished by weighing every 2 days to keep the soil water content constant. Top of the glass bottle was closed by a butyl rubber stopper having two holes. The glass tubes with three valve hose were inserted into holes, which was used to exchange and sample gas. All treatment bottles were incubated aerobically in a biochemical incubator at 25 °C $\pm$ 1.0 °C for 50 days. The incubation bottles consisted of two sets, one set was used to collect gas, and the other one was used to collect soil samples to determine soil DOC, MBC, pH, $NH_4^+$-N, and $NO_3^-$-N.

Gases were sampled from glass bottles each day for the first 7 days, each 2 or 3 days till day 22, and each 5 days till the last day 50. In addition, soil samples of each treatment were destructively sampled at days 1, 3, 7, 13, 22, 41, and 50. Before sampling, the butyl rubber stopper was removed to ensure thorough gas exchange between the ambient air and atmosphere inside each glass bottle. The upper headspace gas sample of the glass bottle was collected as the initial gas concentration and recorded the sampling time. After 2 hours of closure, the gas samples were collected again and stored in a prevacuumed bottle.

### *2.3. Methods for the calculation and determination of gases*

The calculation formula of $CO_2$ and $CH_4$ fluxes of soil greenhouse gases was as follows (Zheng et al., 1998):

$$F = \rho \times \frac{V}{m} \times \frac{dc}{dt} \times \frac{273}{T}$$

Where $F$ is the fluxes of $CO_2$ and $CH_4$ (mg $kg^{-1}$ $h^{-1}$), a positive value represents the emission of this gas from soil to the atmosphere, and a negative value represents the absorption of this gas by the soil. ρ is the density of gas under standard conditions, the density of $CO_2$ and $CH_4$ are 1.98 kg $m^{-3}$, 0.714 kg $m^{-3}$, respectively; $V$ is the glass bottle upper effective space volume ($m^3$); $m$ is the dry weight of soil sample, and the unit is (g); $dc/dt$ is within the unit time gas concentration change; $T$ is the absolute temperature. The concentration of $CO_2$ and $CH_4$ was determined by gas chromatograph (Agilent 7890A, California, USA). Cumulative emissions of $CO_2$ and $CH_4$ were calculated by multiplying the average emission rate of two adjacent gases by the emission time.

### *2.4. Soil analysis*

Soil pH was measured in a 1:2.5 soil: water (w/v) mixture using a pH meter connected with a glass electrode (InsMark$^{TM}$ IS126, Shanghai, China). Soil bulk density was determined using ring sampler weighing method. The particle composition was measured with a laser particle size analyzer (Master-sizer 2000, Malvern, UK). Total C (TC) and total N (TN) were analyzed by elemental analyzer (Vario MACRO Cube, Elementar, Germany). Dissolved organic carbon was extracted with 0.5 mol $L^{-1}$ $K_2SO_4$ and the extracts were measured using a Liqui TOCII analyzer (Elementar, Germany; Jones and Willett, 2006; Wang et al., 2020). Soil microbial biomass carbon was determined by chloroform fumigation-$K_2SO_4$ extraction method(Brookes et al., 1985). The difference between the total C in nonfumigated and fumigated samples was considered as MBC, and the conversion factors was 0.45. Soil was extracted and filtered by 1 mol $L^{-1}$ KCl, and the contents of $NH_4^+$-N and $NO_3^-$-N in the extract were measured by Seal Analytical chemistry AA3 flow analyzer.

### *2.5. Statistical analysis*

Statistical analysis of the data was conducted using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). A one-way analysis of variance and a Duncan multiple comparisons ($P < 0.05$) test were used to assess the significance of differences among different treatments (Liu et al., 2020). All bar graphs and broken line graphs were drawn using Origin 2018. Using the corrplot package in R (v.3.5.2) for pairwise comparisons, and the vegan package in R was used for Mantel tests (Sunagawa et al., 2015; Liu et al., 2019). To understand the relationship between $CO_2$, $CH_4$, and soil properties, we correlated $CO_2$ flux and $CH_4$ flux with soil properties by partial (geographic distance-corrected) Mantel tests. The structural equation modeling (SEM) framework was used to investigate direct and indirect effects of environmental variables on $CO_2$ flux and $CH_4$ flux. The $\chi^2$ values, $P$ values, RMSEA, and AIC were adopted to evaluate the overall goodness of structural equation model fit. SEM was performed by Amos 17.0 software package (Smallwaters Corporation, Chicago, IL, USA).

## 3. Results

### *3.1. Soil $CO_2$ emission flux and cumulative emission*

In all treatments, soil $CO_2$ fluxes showed a gradual decrease in the first 27 days of incubation and finally stay stable (**Figure 1a**). The $CO_2$ fluxes of the CK, NR1, NR2 treatments peaked after a small increase in the first 4 days, and the fluxes of $CO_2$ under four fertilization treatments was higher than those in CK. At the later stage of incubation, $CO_2$ fluxes of each treatment were relatively stable

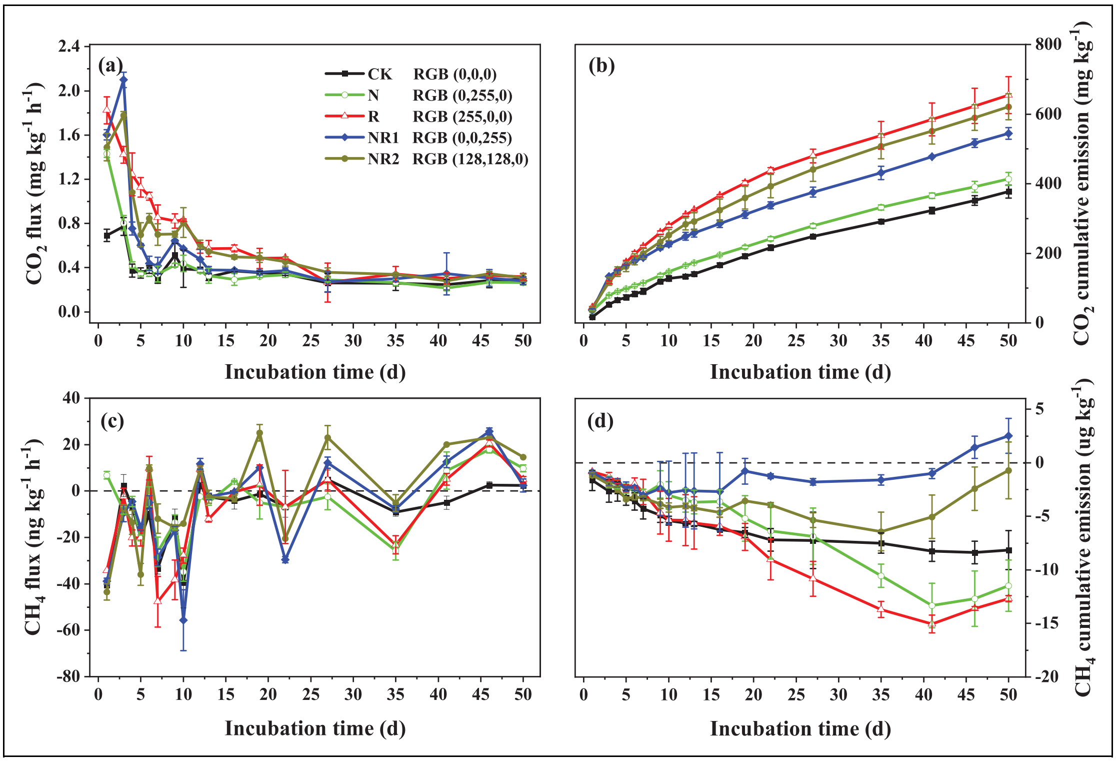

**Figure 1.** $CO_2$ (A) and $CH_4$ (C) fluxes, and cumulative $CO_2$ (B) and $CH_4$ (D) emissions in five different treatments. CK (soil), N (soil + urea), R (soil + rape cake fertilizer), NR1 (soil + urea, rape cake fertilizer (2:1)), NR2 (soil + urea, rape cake fertilizer (1:2)). Error bars represent standard error of the mean ($n$ = 3). DOI: https://doi.org/10.1525/elementa.2021.090.f1

**Table 1.** $CO_2$ and $CH_4$ fluxes under N fertilizer and oilseed rape cake fertilizer. DOI: https://doi.org/10.1525/elementa.2021.090.t1

| | $CO_2$ | | | $CH_4$ | | |
|---|---|---|---|---|---|---|
| Treatment | Variation (mg kg$^{-1}$ h$^{-1}$) | Average (mg kg$^{-1}$ h$^{-1}$) | Cumulative Emission (mg kg$^{-1}$) | Variation (ng kg$^{-1}$ h$^{-1}$) | Average (ng kg$^{-1}$ h$^{-1}$) | Cumulative Emission (μg kg$^{-1}$) |
| CK | 0.25 ~ 0.77 | 0.39 ± 0.04 d | 377 ± 18.3 c | –40.5 ~ 4.86 | –11.2 ± 1.40 a | –8.16 ± 1.83 b |
| N | 0.22 ~ 1.43 | 0.42 ± 0.01 d | 414 ± 18.7 c | –34.8 ~ 17.9 | –4.47 ± 9.37 a | –11.5 ± 2.40 b |
| R | 0.26 ~ 1.82 | 0.75 ± 0.03 a | 654 ± 52.9 a | –47.7 ~ 20.5 | –9.09 ± 7.18 a | –12.7 ± 0.29 b |
| NR1 | 0.27 ~ 2.10 | 0.58 ± 0.01 c | 544 ± 16.9 b | –55.7 ~ 25.7 | –1.49 ± 2.01 a | 2.51 ± 1.63 a |
| NR2 | 0.28 ~ 1.78 | 0.68 ± 0.05 b | 621 ± 37.7 a | –43.5 ~ 25.1 | –2.51 ± 4.48 a | –0.70 ± 2.66 a |

CK (soil), N (soil + urea), R (soil + rape cake fertilizer), NR1 (soil + urea, rape cake fertilizer (2:1)), NR2 (soil + urea, rape cake fertilizer (1:2)). Different letters within a column mean significant difference ($P < 0.05$). Data are means ± *SD* of three independent replicates.

between 0.27 and 0.32 mg kg$^{-1}$ h$^{-1}$. During the incubation, the $CO_2$ fluxes of the N treatment were significantly lower than those in the three treatments with cake fertilizer ($P < 0.05$; **Table 1**). Compared with the control, the treatment with single nitrogen fertilizer had no significant effect on the $CO_2$ emission. The average $CO_2$ fluxes from high to low were, in turn, R > NR2 > NR1 > N > CK. The values were 0.75 ± 0.03, 0.68 ± 0.05, 0.58 ± 0.01, 0.42 ± 0.01, and 0.39 ± 0.04 mg kg$^{-1}$ h$^{-1}$, respectively (**Table 1**).

The cumulative $CO_2$ emission increased gradually in the process of incubation, and it sharply increased in the early stages (**Figure 1b**). In the study period, cumulative $CO_2$ emissions in R, NR2, and NR1 were significantly higher than those in CK ($P < 0.05$; **Table 1**). The R treatment had the highest cumulative emissions of 654 ± 52.9 mg kg$^{-1}$, which is 1.73 times higher than that of the CK treatment (**Table 1**). Cumulative $CO_2$ emission of the CK and N treatment were 377 ± 18.3 mg kg$^{-1}$, 414 ± 18.7 mg kg$^{-1}$ with no significant difference ($P > 0.05$).

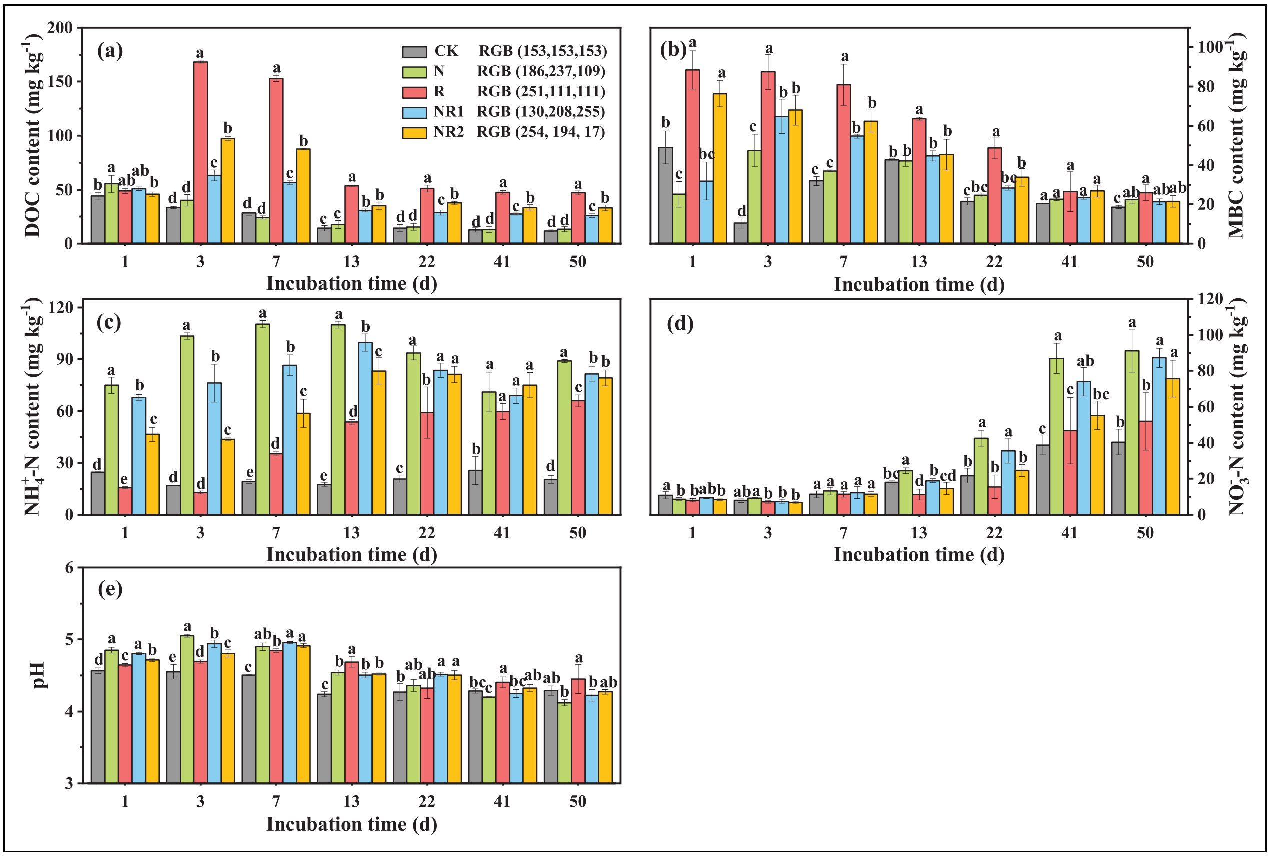

**Figure 2.** Changes in soil DOC contents (A), MBC contents (B), $NH_4^+$-N contents (C), $NO_3^-$-N contents (D) and pH (E) after five different treatments. CK (soil), N (soil + urea), R (soil + rape cake fertilizer), NR1 (soil + urea, rape cake fertilizer (2:1)), NR2 (soil + urea, rape cake fertilizer (1:2)). Data were analyzed by one-way analysis of variance and means were compared by Duncan test. Different letters indicate significant differences ($P < 0.05$) among the different treatments. DOI: https://doi.org/10.1525/elementa.2021.090.f2

### *3.2. Soil $CH_4$ emission flux and cumulative emission*

There were some fluctuations of $CH_4$ fluxes during the whole incubation process. However, the overall trend of $CH_4$ fluxes changed from negative value to positive value, that is, the soil gradually changed from absorbing $CH_4$ to discharging throughout the study stage (**Figure 1c**). At the early stage of incubation, $CH_4$ showed absorption trend in treatments NR2, CK, NR1 and R with absorption values of 43.5 ± 3.49, 40.5 ± 0.32, 38.9 ± 1.32, and 34.3 ± 1.21 ng kg$^{-1}$ h$^{-1}$, respectively. At the end of the incubation, all treatments showed $CH_4$ emissions, and the emissions of NR2, N, R, NR1, and CK were 14.7 ± 2.78, 9.77 ± 1.41, 4.88 ± 1.39, 2.46 ± 2.82, and 2.44 ± 1.44 ng kg$^{-1}$ h$^{-1}$, respectively. During the incubation, there was no significant difference between treatments (**Table 1**).

The soil cumulative $CH_4$ emission of NR2 CK, N and R showed net absorption, and its cumulative emissions at the end of the incubation were –0.70 ± 2.66, –8.16 ± 1.83, −11.5 ± 2.40, and −12.7 ± 0.29 μg kg$^{-1}$, respectively (**Figure 1d**). Among them, the absorption of $CH_4$ by the three treatments (N, R, and NR2) increased first and then decreased. The NR1 treatment switched to net emissions after 41 days, and the final cumulative emissions were 2.51 ± 1.63 μg kg$^{-1}$. The cumulative $CH_4$ emissions in the NR1 and NR2 treatments were significantly higher than that in the CK, N, and R treatments ($P < 0.05$; **Table 1**).

### *3.3. Changes in soil properties*

Throughout the study stage, the contents of DOC and MBC in the R treatment were significantly higher than other treatments (**Figure 2a** and b). At the end of the incubation, DOC content in the R, NR2, NR1, and N treatments was 2.91, 1.66, 1.21, and 0.12 times higher than the CK treatment, respectively. Compared with the treatment with single N fertilizer, the average content of DOC in R, NR2, NR1 treatment was significantly increased ($P < 0.05$; **Table 2**). The content of MBC treated by fertilization showed a trend of decreasing gradually with the development of incubation time (**Figure 2b**). In the whole incubation, the average MBC content of each treatment was R > NR2 > NR1 > N > CK from high to low (**Table 2**).

The $NH_4^+$-N content of the N treatment was the highest in the incubation process (**Figure 2c**). Moreover, the average contents of $NH_4^+$-N in each treatment (N, NR1, NR2, R, CK) were 94.4 ± 4.28, 81.1 ± 0.42, 67.9 ± 1.21, 41.5 ± 3.74, and 20.7 ± 1.87 mg kg$^{-1}$, respectively and there were significant differences among the treatments ($P < 0.05$; **Table 2**). The trend of $NO_3^-$-N content in soil gradually increased with time, especially in N and NR1 treatments(**Figure 2d**). The average contents of $NO_3^-$-N in the treatment of N and NR1 were significantly higher than the treatment of R ($P < 0.05$; **Table 2**). In addition,

**Table 2.** The changes of the pH value and the content of DOC, MBC, $NH_4^+$-N, and $NO_3^-$-N in five different treatments. DOI: https://doi.org/10.1525/elementa.2021.090.t2

| Treatment | DOC (mg $kg^{-1}$) | | MBC (mg $kg^{-1}$) | | $NH_4^+$-N (mg $kg^{-1}$) | | $NO_3^-$-N (mg $kg^{-1}$) | | pH | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Variation | Average | Variation | Average | Variation | Average | Variation | Average | Variation | Average |
| CK | 11.9 ~ 43.9 | 20.3 ± 3.23$^e$ | 10.5 ~ 48.9 | 26.2 ± 1.42$^d$ | 16.8 ~ 25.6 | 20.7 ± 1.87$^e$ | 7.94 ~ 40.4 | 21.3 ± 2.20$^{bc}$ | 4.24 ~ 4.57 | 4.37 ± 0.04$^b$ |
| N | 12.9 ~ 55.5 | 25.6 ± 0.76$^d$ | 22.4 ~ 47.5 | 30.8 ± 4.74$^{cd}$ | 71.1 ~ 110.4 | 94.4 ± 4.28$^a$ | 8.72 ~ 91.2 | 40.8 ± 0.74$^a$ | 4.12 ~ 5.05 | 4.62 ± 0.08$^a$ |
| R | 47.0 ~ 168 | 83.2 ± 3.61$^a$ | 25.9 ~ 88.5 | 57.9 ± 3.01$^a$ | 12.9 ~ 65.9 | 41.5 ± 3.74$^d$ | 7.15 ~ 51.9 | 18.1 ± 7.54$^c$ | 4.32 ~ 4.85 | 4.58 ± 0.03$^a$ |
| NR1 | 26.2 ~ 63.2 | 40.5 ± 1.00$^c$ | 21.4 ~ 64.8 | 35.8 ± 3.35$^c$ | 67.9 ~ 99.7 | 81.1 ± 0.42$^b$ | 7.49 ~ 87.2 | 34.9 ± 1.69$^a$ | 4.22 ~ 4.96 | 4.60 ± 0.01$^a$ |
| NR2 | 33.1 ~ 97.3 | 52.9 ± 1.39$^b$ | 21.5 ~ 76.4 | 45.1 ± 1.70$^b$ | 43.7 ~ 83.2 | 67.9 ± 1.21$^c$ | 6.86 ~ 75.6 | 26.6 ± 3.99$^b$ | 4.27 ~ 4.91 | 4.59 ± 0.03$^a$ |

CK (soil), N (soil + urea), R (soil + rape cake fertilizer), NR1 (soil + urea, rape cake fertilizer (2:1)), NR2 (soil + urea, rape cake fertilizer (1:2)). Different letters within a column mean significant difference ($P < 0.05$). Data are means ± *SD* of three independent replicates.

the average $NO_3^-$-N content of the R treatment was the lowest, which was 18.1 ± 7.54 mg $kg^{-1}$.

The change of soil pH value with time under different treatments was shown in **Figure 2e**. Soil pH value in each treatment varied within the range of 4.12–5.05. The average pH value of the four fertilization treatments was significantly higher than the CK treatment (**Table 2**). At the end of incubation, compared with CK, the pH value of R treatment increased by 0.01 units, while the pH value of N, NR1, and NR2 treatment decreased by 0.21, 0.06, and 0.04 units, respectively.

### *3.4. The relationship between soil $CO_2$, $CH_4$ flux and soil properties*

According to the correlation results between soil properties, pH showed a correlation with $NO_3^-$-N ($r = -0.8$), DOC ($r = 0.73$), and MBC ($r = 0.67$), while $NO_3^-$-N had a negative correlation with DOC ($r = -0.66$) and MBC ($r = -0.68$), and DOC had a positive correlation with MBC ($r = 0.73$; **Figure 3**). Correlation results can be used to determine collinear problems among factors and construct structural equation models. To understand the relationship between $CO_2$, $CH_4$, and soil properties, we correlated $CO_2$ flux and $CH_4$ flux with soil properties by partial (geographic distance-corrected) Mantel tests. Overall, DOC and MBC had the strongest correlations with $CO_2$ flux, followed by $NO_3^-$-N and pH. The correlation between $CH_4$ flux and $NO_3^-$-N was the strongest, while DOC was not significantly correlated (**Figure 3**).

The effects of different fertilization treatments showed a reasonable fit to our hypothesized causal relationships, as shown by the properties of the SEM ($\chi^2 = 7.04$, $P = 0.42$, RMSEA = 0.01, AIC = 35.0, **Figure 4a**; $\chi^2 = 3.80$, $P = 0.70$, RMSEA = 0.00, AIC = 33.8, **Figure 4c**). $NH_4^+$-N exerted an indirect negative effect on $CO_2$ flux and $CH_4$ flux, as shown by $CO_2$ (–0.14) and $CH_4$ (–0.16) release, and $NO_3^-$-N showed a negative control on $CO_2$ (–0.15) and $CH_4$ (–0.32), respectively. The emission for both $CO_2$ and $CH_4$ was positively affected by DOC. The MBC showed a direct effect on $CO_2$ (+0.43) and $CH_4$ (+0.21) emission, respectively. And pH mainly exerted a positive control on $CO_2$ release (+0.63) and $CH_4$ formation (+0.32) (**Figure 4b** and d).

## 4. Discussion

The trend of $CO_2$ emissions under different fertilization types was consistent, but there were significant differences among treatments. The $CO_2$ fluxes showed a gradual decline during the whole incubation period (**Figure 1a**), which was consistent with the content of MBC (**Figure 2b**). Previous studies have reported that soil $CO_2$ emission was affected by multiple factors, including organic matter content (Iqbal et al., 2008), microbial activities (Sauze et al., 2017), and different fertilization treatments (Nyamadzawo et al., 2014). However, for indoor cultivated soil without vegetation cover, microbial respiration in soil was the main way of $CO_2$ emission (Zhang et al., 2016). Therefore, with the available C and N sources of microbes gradually reduced, the $CO_2$ emission rate slowed down and finally stabilized, which was coincident with the study

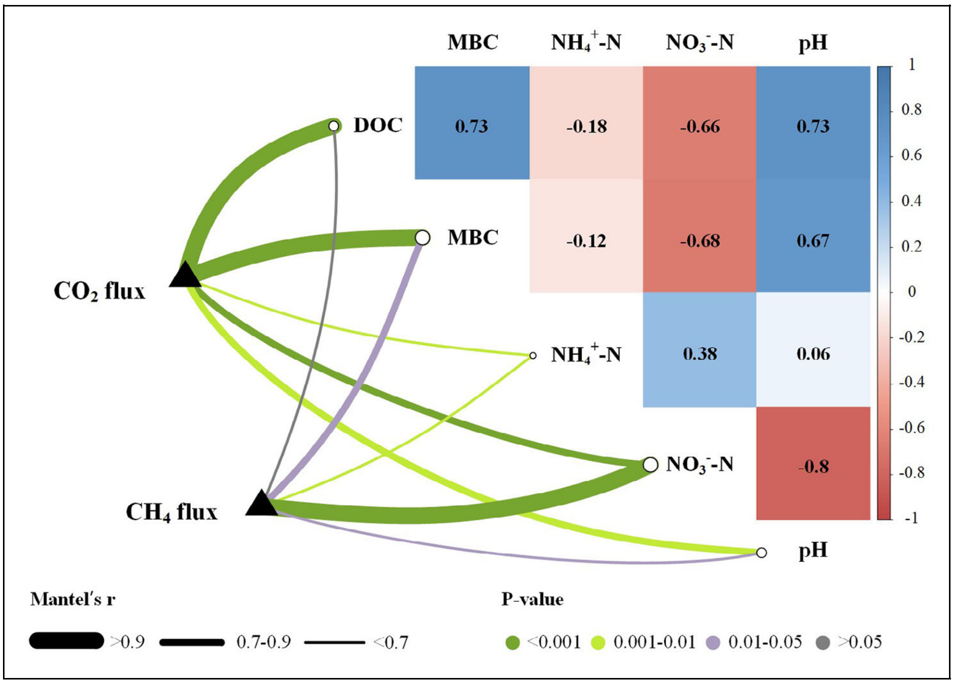

**Figure 3.** Environmental drivers of $CO_2$ and $CH_4$ fluxes. Pairwise comparisons of physicochemical property are shown, with a color gradient denoting Spearman's correlation coefficients. $CO_2$ flux and $CH_4$ flux were related to each environmental factor by partial (geographic distance-corrected) Mantel tests. Edge width corresponds to the Mantel's *r* statistic for the corresponding distance correlations, and edge color denotes the statistical significance based on 9,999 permutations. DOI: https://doi.org/10.1525/elementa.2021.090.f3

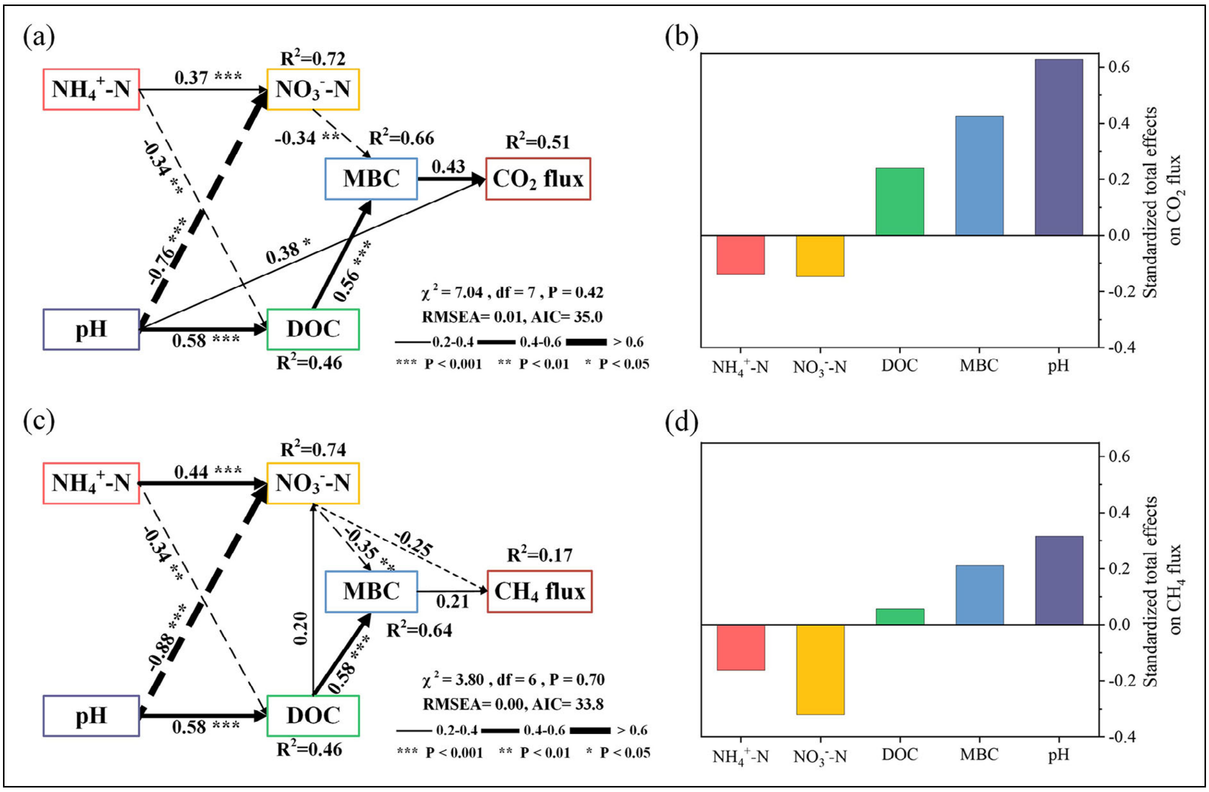

**Figure 4.** The structural equation model (SEM) showing the effects of $NH_4^+$-N, $NO_3^-$-N, microbial biomass C (MBC), dissolved organic C (DOC), and pH on $CO_2$ (A) and $CH_4$ (C) fluxes. Standardized total effects of soil $NH_4^+$-N, $NO_3^-$-N, MBC, DOC, and pH on $CO_2$ (B) and $CH_4$ (D) fluxes as revealed by SEM. The width of the arrows indicates the strength of the standardized path coefficient. Solid lines represent positive path coefficients and dashed lines represent negative path coefficients. $R^2$ values represent the proportion of the variance explained for each endogenous variable. DOI: https://doi.org/10.1525/elementa.2021.090.f4

result of Senbayram et al. (2019). Compared to the CK treatment, single application of N fertilizer had no significant effect on soil $CO_2$ flux (**Table 1**). This result indicated that the addition of organic matter was the main source of $CO_2$ production (Singh et al., 1999). In addition, organic carbon as the substrate of soil respiration could provide available C and N for microbial decomposition (Witt et al., 2000; Qiu et al., 2015; Shah et al., 2016), and organic materials such as straw and cake fertilizer applied into the soil are conducive to the formation of soil aggregates and increase the soil porosity and promote the diffusion of $CO_2$ (Kallenbach et al., 2010). This was also the reason why $CO_2$ emission of three cake fertilizer treatments was higher than the N treatment (**Table 1**).

Among them, the $CO_2$ emission of single cake fertilizer treatment was higher than that of nitrogen fertilizer and cake fertilizer mixed treatment (**Figure 1b**). This could be due to the lower C/N ratio of oilseed rape cake (8.71) which is conducive for high respiration and ultimately $CO_2$ emissions (Kim et al., 2012; Raheem et al., 2019). In addition, specific C/N ratio is required for microbial activities to meet their nutritional requirements, and the addition of the residue with a low C/N ratio in this study made the N content a factor not limiting microbial activity (Finn et al., 2016; Wei et al., 2019). Therefore, the C content of fertilizer was an important factor affecting $CO_2$ emission in this study. The C content in R treatment was the highest, which provided more C sources for soil microbial activities. This was also supported by the result of $CO_2$ emission that was positively affected by DOC and MBC, as revealed by SEM (**Figure 4b**). As an indicator of microbial available C, DOC can indirectly affect soil respiration by influencing microbial activity and MBC (Boyer and Groffman, 1996; Wu et al., 2020). A previous study has shown that the abundance of soil phototrophs increased most at higher soil pH, promoting the production of $CO_2$ (Sauze et al., 2017). This is consistent with the results of the structural equation model that $CO_2$ was positively affected by pH (**Figure 4b**). In addition, $CO_2$-C is considered to be the sole C source promoting the autotrophic growth of nitrifiers (Xia et al., 2011; Zhang et al., 2019). Soil pH can indirectly affect soil $CO_2$ emissions by affecting soil nitrification rate (Li et al., 2020).

$CH_4$ fluxes mainly remained negative and low during the study period(**Figure 1c**). Our finding was similar to other research results from cultivated land (Li et al., 2019) and grassland (Shimizu et al., 2013). The main reason is that the experiment was carried out under the condition of aerobic, and $CH_4$ can be oxidized by methanotroph, so it is not conducive to the production of $CH_4$ (Zhou et al., 2020). However, $CH_4$ emissions do exist during the whole incubation process (**Figure 1c**). This could be due to uneven distribution of soil particles and water leading to the formation of anaerobic microzone, resulting in $CH_4$ emissions (Kong et al., 2019). Moreover, Hurkuck et al. (2012) observed that in addition to microbial activity, organic compounds such as lignin and pectin showed substantial release of $CH_4$. The cumulative emissions of $CH_4$ from each treatment in a short period of 50 days were mainly concentrated in negative values (**Figure 1d**), which can be considered that the soil of the tea garden is the net absorption sink of $CH_4$ in a short time and be similar to farmland (Jacinthe and Lal, 2005).

There was no significant difference between the $CH_4$ fluxes among treatments. However, the cumulative $CH_4$ fluxes in two treatments that mixed application of N fertilizer and cake fertilizer (NR1, NR2) were significantly higher than the other three (CK, N, R; **Table 1**). The R treatment showed the highest $CH_4$ absorption; it is possible that more abundant C sources were provided to methanotroph than other treatments (Wang et al., 2019; Zhou et al., 2020). However, compared with the N treatment, NR1 and NR2 reduced $CH_4$ absorption (**Figure 1d**), and previous studies have reported that $NH_4^+$-N has a similar molecular shape and size to $CH_4$, and $NH_4^+$-N can be used as a substrate for methanotroph to inhibit the absorption of $CH_4$ (Bedard and Knowles, 1989; Schimel, 2000). This is consistent with the results that the $NH_4^+$-N content of NR1 and NR2 was higher in incubation (**Figure 2c**). In addition, $NH_4^+$-N produces $NO_2^-$ in the oxidation process, which may poison methanotroph in a short time and inhibit the oxidation of $CH_4$ (Dunfield and Knowles, 1995). Although the N treatment had the highest $NH_4^+$-N content, there is no C source for microorganisms to carry out oxidation activities. This explains why NR1 absorbed the least $CH_4$ in this result (**Figure 1d**). The input of oilseed rape cake provided available C sources for methanogen and methanotroph (Seghers et al., 2005), but the input of nitrogen affected microbial activities and indirectly affected $CH_4$ emission (**Figure 4c**). The N treatment had the highest $NO_3^-$-N content, and its cumulative $CH_4$ emissions were lower than the control treatment (**Table 2**; **Figure 1d**). Some studies have found that nitrate has an inhibitory effect on $CH_4$ production (Lu et al., 2000). On the one hand, denitrification intermediates ($NO_2^-$, NO, $N_2O$) from nitrate reduction can inhibit methanogens (Clarens et al. 1998; Liu et al., 2017). On the other hand, $CH_4$ emission is reduced when nitrate reducers are more competitive than methanogens for common substrates (Bao et al., 2016). This was shown by the $NO_3^-$-N, which indicated a negative effect for $CH_4$ as revealed by structural equation models (**Figure 4d**).

It is worth noting that the results of $CO_2$ and $CH_4$ emissions in this experiment were obtained by using tea plantation soil under indoor incubation conditions rather in the presence of tea plants. The uptake of soil nutrients by tea plants, root exudates, water and climatic factors can affect the soil $CO_2$ and $CH_4$ emissions under planting conditions (Xiang et al., 2008; Kechavarzi et al., 2010; Du et al., 2020). Besides, the soil sampled from tea plant field was disturbed in terms of grinding and adding treatments, and thus soil organic matter become more vulnerable to the decomposition increasing the amount of substrate for microorganisms and affecting greenhouse gas emission (Six et al., 2000). Therefore, filed studies are necessary to deeply and systematically exploration of influencing rules and mechanisms pertinent to GHGs from tea plant soils.

## 5. Conclusions

The application of urea and oilseed rape cake fertilizer showed a significant difference for the $CO_2$ and $CH_4$ fluxes from tea plantation soil. The single application of N fertilizer had no significant impact on soil $CO_2$ emissions. However, the addition of cake fertilizer significantly increased soil MBC content and $CO_2$ emissions, especially the treatment of single cake fertilizer showed the highest emissions. The C content of fertilizer was positively proportional to the $CO_2$ emissions of soil. The cumulative emissions of $CH_4$ from each treatment were mainly concentrated in negative values, which can be considered that the soil of the tea garden is the net absorption and sink of $CH_4$ in a short time. Mixed application of N fertilizer and cake fertilizer reduced the soil absorption of $CH_4$. It is likely that $NH_4^+$-N was involved in microbial oxidation activity and inhibited the absorption of $CH_4$. In addition, soil pH, MBC, and DOC were the main factors affecting $CO_2$ fluxes, while $CH_4$ fluxes were mainly affected by mineral nitrogen contents. In conclusion, under the condition of low nitrogen addition, the single application of cake fertilizer increased the $CO_2$ emission but increased the oxidation of $CH_4$ and promoted soil C sequestration. The mixed application of urea and oilseed rape cake fertilizer reduced the emission of $CO_2$ but also increased $CH_4$ emissions. These results are helpful to further understand the $CO_2$ and $CH_4$ emission processes in tea plantation soil and provide potential strategies to reduce $CO_2$ and $CH_4$ emissions and improve soil C sequestration through improved fertilization management.

### Data accessibility statement

All data generated or analyzed during this study are included in this article, and the underlying data are presented in the supplemental material.

### Supplemental files

The supplemental files for this article can be found as follows:

Data 1-$CO_2$ emission.xlsx
Data 2-$CH_4$ emission.xlsx
Data 3-Soil property.xlsx

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### Competing interests

The authors have no competing interests to declare.

### Author contributions

SL and SZ contributed equally to this work.

Contributed to conception and design: SL, SZ, LF.

Contributed to acquisition of data: SL, SZ, GS, MS, WJ, YC, CD.

Contributed to analysis and interpretation of data: SL, SZ, GS, LF.

Drafted and/or revised the article: SZ, GS, MS, WJ, YC, CD.

Approved the submitted version for publication: All authors.

### References

**Abera, G, Wolde-Meskel, E, Bakken, LR**. 2014. Unexpected high decomposition of legume residues in dry season soils from tropical coffee plantations and crop lands. *Agronomy for Sustainable Development* **34**(3): 667–676. DOI: http://dx.doi.org/10.1007/s13593-013-0172-7.

**Bao, Q, Huang, Y, Wang, F, Nie, S, Nicol, GW, Yao, H, Ding, L**. 2016. Effect of nitrogen fertilizer and/or rice straw amendment on methanogenic archaeal communities and methane production from a rice paddy soil. *Applied Microbiology and Biotechnology* **100**(13): 5989–5998. DOI: http://dx.doi.org/10.1007/s00253-016-7377-z.

**Bedard, C, Knowles, R**. 1989. Physiology, biochemistry, and specific inhibitors of $CH_4$, $NH_4^+$, and CO oxidation by methanotrophs and nitrifiers. *Microbiological Review* **53**(1): 68–84. DOI: http://dx.doi.org/10.1128/mmbr.53.1.68-84.1989.

**Bodelier, PLE, Laanbroek, HJ**. 2004. Nitrogen as a regulatory factor of methane oxidation in soils and sediments. *FEMS Microbiology Ecology* **47**(3): 265–277. DOI: http://dx.doi.org/10.1016/s0168-6496(03)00304-0.

**Bodelier, PLE, Roslev, P, Henckel, T, Frenzel, P**. 2000. Stimulation by ammonium-based fertilizers of methane oxidation in soil around rice roots. *Nature* **403**(6768): 421–424. DOI: http://dx.doi.org/10.1038/35000193.

**Boyer, JN, Groffman, PM**. 1996. Bioavailability of water extractable organic carbon fractions in forest and agricultural soil profiles. *Soil Biology & Biochemistry* **28**(6): 783–790. DOI: http://dx.doi.org/10.1016/0038-0717(96)00015-6.

**Brookes, PC, Landman, A, Pruden, G, Jenkinson, DS**. 1985. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology & Biochemistry* **17**(6): 837–842. DOI: http://dx.doi.org/10.1016/0038-0717(85)90144-0.

**Chen, D, Li, Y, Wang, C, Fu, X, Liu, X, Shen, J, Wang, Y, Xiao, R, Liu, DL, Wu, J**. 2017. Measurement and modeling of nitrous and nitric oxide emissions from a tea field in subtropical central China. *Nutrient Cycling in Agroecosystems* **107**(2): 157–173. DOI: http://dx.doi.org/10.1007/s10705-017-9826-1.

**Clarens, M, Bernet, N, Delgenes, JP, Moletta, R**. 1998. Effects of nitrogen oxides and denitrification by Pseudomonas stutzeri on acetotrophic methanogenesis by Methanosarcina mazei. *FEMS Microbiology Ecology* **25**(3): 271–276. DOI: http://dx.doi.org/10.1016/s0168-6496(98)00008-7.

**Du, L, Zhu, Z, Qi, Y, Zou, D, Zhang, G, Zeng, X, Ge, T, Wu, J, Xiao, Z**. 2020. Effects of different stoichiometric ratios on mineralisation of root exudates and its priming effect in paddy soil. *The Science of the Total Environment* **743**: 140808–140808. DOI: http://dx.doi.org/10.1016/j.scitotenv.2020.140808.

**Dunfield, P, Knowles, R**. 1995. Kinetics of inhibition of methane oxidation by nitrate, nitrite, and ammonium in a humisol. *Applied and Environmental Microbiology* **61**(8): 3129–3135. DOI: http://dx.doi.org/10.1128/aem.61.8.3129-3135.1995.

**Finn, D, Page, K, Catton, K, Kienzle, M, Robertson, F, Armstrong, R, Dalal, R**. 2016. Ecological stoichiometry controls the transformation and retention of plant-derived organic matter to humus in response to nitrogen fertilisation. *Soil Biology & Biochemistry* **99**: 117–127. DOI: http://dx.doi.org/10.1016/j.soilbio.2016.05.006.

**Ge, X, Cao, Y, Zhou, B, Xiao, W, Tian, X, Li, MH**. 2020. Combined application of biochar and N increased temperature sensitivity of soil respiration but still decreased the soil $CO_2$ emissions in moso bamboo plantations. *Science of the Total Environment* **730**: 139003. DOI: http://dx.doi.org/10.1016/j.scitotenv.2020.139003.

**Gwon, HS, Khan, MI, Yoon, YE, Lee, YB, Kim, PJ, Hwang, HY**. 2019. Unexpected higher decomposition of soil organic matter during cold fallow season in temperate rice paddy. *Soil & Tillage Research* **192**: 250–257. DOI: http://dx.doi.org/10.1016/j.still.2018.11.009.

**Hoang, TTH, Do, DT, Tran, TTG, Ho, TD, Rehman, HU**. 2019. Incorporation of rice straw mitigates $CH_4$ and $N_2O$ emissions in water saving paddy fields of Central Vietnam. *Archives of Agronomy and Soil Science* **65**(1): 113–124. DOI: http://dx.doi.org/10.1080/03650340.2018.1487553.

**Hurkuck, M, Althoff, F, Jungkunst, HF, Jugold, A, Keppler, F**. 2012. Release of methane from aerobic soil: an indication of a novel chemical natural process? *Chemosphere* **86**(6): 684–689. DOI: http://dx.doi.org/10.1016/j.chemosphere.2011.11.024.

**Iqbal, J, Hu, RG, Du, LJ, Lan, L, Shan, L, Tao, C, Leilei, R**. 2008. Differences in soil $CO_2$ flux between different land use types in mid-subtropical China. *Soil Biology & Biochemistry* **40**(9): 2324–2333. DOI: http://dx.doi.org/10.1016/j.soilbio.2008.05.010.

**Jacinthe, PA, Lal, R**. 2005. Labile carbon and methane uptake as affected by tillage intensity in a Mollisol. *Soil & Tillage Research* **80**(1-2): 35–45. DOI: http://dx.doi.org/10.1016/j.still.2004.02.018.

**Jones, DL, Willett, VB**. 2006. Experimental evaluation of methods to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil. *Soil Biology & Biochemistry* **38**(5): 991–999. DOI: http://dx.doi.org/10.1016/j.soilbio.2005.08.012.

**Kallenbach, CM, Rolston, DE, Horwath, WR**. 2010. Cover cropping affects soil $N_2O$ and $CO_2$ emissions differently depending on type of irrigation. *Agriculture Ecosystems & Environment* **137**(3–4): 251–260. DOI: http://dx.doi.org/10.1016/j.agee.2010.02.010.

**Kechavarzi, C, Dawson, Q, Bartlett, M, Leeds-Harrison, PB**. 2010. The role of soil moisture, temperature and nutrient amendment on $CO_2$ efflux from agricultural peat soil microcosms. *Geoderma* **154**(3–4): 203–210. DOI: http://dx.doi.org/10.1016/j.geoderma.2009.02.018.

**Khan, A, Tan, DKY, Munsif, F, Afridi, MZ, Shah, F, Wei, F, Fahad, S, Zhou, R**. 2017. Nitrogen nutrition in cotton and control strategies for greenhouse gas emissions: A review. *Environmental Science and Pollution Research* **24**(30): 23471–23487. DOI: http://dx.doi.org/10.1007/s11356-017-0131-y.

**Kim, SY, Gutierrez, J, Kim, PJ**. 2012. Considering winter cover crop selection as green manure to control methane emission during rice cultivation in paddy soil. *Agriculture Ecosystems & Environment* **161**: 130–136. DOI: http://dx.doi.org/10.1016/j.agee.2012.07.026.

**Kong, DL, Li, SQ, Jin, YG, Wu, S, Chen, J, Hu, T, Wang, H, Liu, S, Zou, J**. 2019. Linking methane emissions to methanogenic and methanotrophic communities under different fertilization strategies in rice paddies. *Geoderma* **347**: 233–243. DOI: http://dx.doi.org/10.1016/j.geoderma.2019.04.008.

**Li, N, Kumar, P, Lai, LM, Abagandura, GO, Kumar, S, Nleya, T, Sieverding, HL, Stone, JJ, Gibbons, W**. 2019. Response of soil greenhouse gas fluxes and soil properties to nitrogen fertilizer rates under Camelina and Carinata nonfood oilseed crops. *BioEnergy Research* **12**(3): 524–535. DOI: http://dx.doi.org/10.1007/s12155-019-09987-4.

**Li, Z, Zeng, Z, Tian, D, Wang, J, Fu, Z, Zhang, F, Zhang, R, Chen, W, Luo, Y, Niu, S**. 2020. Global patterns and controlling factors of soil nitrification rate. *Global Change Biology* **00**: 1–11. DOI: http://dx.doi.org/10.1111/gcb.15119.

**Liu, H, Ding, Y, Zhang, Q, Liu, X, Xu, J, Li, Y, Di, H**. 2018. Heterotrophic nitrification and denitrification are the main sources of nitrous oxide in two paddy soils. *Plant and Soil* **445**(1–2): 39–53. DOI: http://dx.doi.org/10.1007/s11104-018-3860-x.

**Liu, H, Wu, X, Li, Z, Wang, Q, Liu, D, Liu, G**. 2017. Responses of soil methanogens, methanotrophs, and methane fluxes to land-use conversion and fertilization in a hilly red soil region of southern China. *Environmental Science and Pollution Research International* **24**(9): 8731–8743. DOI: http://dx.doi.org/10.1007/s11356-017-8628-y.

**Liu, J, Li, N, Zhang, W, Wei, X, Tsang, D, Sun, Y, Luo, X, Bao, Z, Zheng, W, Wang, J, Xu, G, Hou, L, Chen, Y, Feng, Y**. 2019. Thallium contamination in farmlands and common vegetables in a pyrite mining city and potential health risks. *Environmental Pollution* **248**: 906–915. DOI: http://dx.doi.org/10.1016/j.envpol.2019.02.092.

**Liu, J, Wei, X, Zhou, Y, Tsang, D, Bao, Z, Yin, M, Lippold, H, Yuan, W, Wang, J, Feng, Y, Chen, D**. 2020. Thallium contamination, health risk assessment and source apportionment in common vegetables. *Science of the Total Environment* **703**: 135547. DOI: http://dx.doi.org/10.1016/j.scitotenv. 2019.135547.

**Liu, J, Zang, H, Xu, H, Zhang, K, Jiang, Y, Hu, Y, Zeng, Z**. 2019. Methane emission and soil microbial communities in early rice paddy as influenced by urea-N fertilization. *Plant and Soil* **445**(1–2): 85–100. DOI: http://dx.doi.org/10.1007/s11104-019-04091-0.

**Lu, YH, Wassmann, R, Neue, HU, Huang, CY**. 2000. Atmospheric pollutants and trace gasses - Dissolved organic carbon and methane emissions from a rice paddy fertilized with ammonium and nitrate. *Journal of Environmental Quality* **29**(6): 1733–1740. DOI: http://dx.doi.org/10.2134/jeq2000.00472425002900060002x.

**Mudau, NF, Soundy, P, du Toit, ES**. 2005. Plant growth and development of bush tea as affected by nitrogen, phosphorus, and potassium nutrition. *Hortscience* **40**(6): 1898–1901. DOI: http://dx.doi.org/10.21273/hortsci.40.6.1898.

**Nyamadzawo, G, Wuta, M, Nyamangara, J, Smith, JL, Rees, RM**. 2014. Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management. *Nutrient Cycling in Agroecosystems* **100**(2): 161–175. DOI: http://dx.doi.org/10.1007/s10705-014-9634-9.

**Qaswar, M, Jing, H, Ahmed, W, Li, D, Liu, S, Lu, Z, Cai, A, Lisheng, L, Yongmei, X, Jusheng, G, Huimin, Z**. 2020. Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. *Soil & Tillage Research* **198**, 104569. DOI: http://dx.doi.org/10.1016/j.still.2019.104569.

**Qiu, QY, Wu, LF, Ouyang, Z, Li, BB, Xu, YY, Wu, SS, Gregorich, EG**. 2015. Effects of plant-derived dissolved organic matter (DOM) on soil $CO_2$ and $N_2O$ emissions and soil carbon and nitrogen sequestrations. *Applied Soil Ecology* **96**: 122–130. DOI: http://dx.doi.org/10.1016/j.apsoil.2015.07.016.

**Raheem, A, Zhang, J, Huang, J, Jiane, Y, Siddik, MA, Deng, A, Gao, J, Zhang, W**. 2019. Greenhouse gas emissions from a rice-rice-green manure cropping system in South China. *Geoderma* **353**: 331–339. DOI: http://dx.doi.org/10.1016/j.geoderma.2019.07.007.

**Sauze, J, Ogee, J, Maron, PA, Crouzet, O, Nowak, V, Wohl, S, Kaisermann, A, Jones, SP, Wingate, L**. 2017. The interaction of soil phototrophs and fungi with pH and their impact on soil $CO_2$, $CO^{18}O$ and OCS exchange. *Soil Biology and Biochemistry* **115**: 371–382. DOI: http://dx.doi.org/10.1016/j.soilbio.2017.09.009.

**Schimel, J**. 2000. Global change: Rice, microbes and methane. *Nature* **403**(6768): 375–377. DOI: http://dx.doi.org/10.1038/35000325.

**Seghers, D, Siciliano, SD, Top, EM, Verstraete, W**. 2005. Combined effect of fertilizer and herbicide applications on the abundance, community structure and performance of the soil methanotrophic community. *Soil Biology and Biochemistry* **37**(2): 187–193. DOI: http://dx.doi.org/10.1016/j.soilbio.2004.05.025.

**Senbayram, M, Saygan, EP, Chen, R, Aydemir, S, Kaya, C, Wu, D, Bladogatskaya, E**. 2019. Effect of biochar origin and soil type on the greenhouse gas emission and the bacterial community structure in N fertilised acidic sandy and alkaline clay soil. *Science of the Total Environment* **660**: 69–79. DOI: http://dx.doi.org/10.1016/j.scitotenv.2018.12.300.

**Shah, A, Lamers, M, Streck, T**. 2016. $N_2O$ and $CO_2$ emissions from South German arable soil after amendment of manures and composts. *Environmental Earth Sciences* **75**(5). DOI: http://dx.doi.org/10.1007/s12665-015-5126-8.

**Shao, R, Deng, L, Yang, QH, Shangguan, ZP**. 2014. Nitrogen fertilization increase soil carbon dioxide efflux of winter wheat field: A case study in Northwest China. *Soil & Tillage Research* **143**: 164–171. DOI: http://dx.doi.org/10.1016/j.still.2014.07.003.

**Shimizu, M, Hatano, R, Arita, T, Kouda, Y, Mori, A, Matsuura, S, Niimi, M, Jin, T, Desyatkin, AR, Kawamura, O, Hojita, M, Miyata, A**. 2013. The effect of fertilizer and manure application on $CH_4$ and $N_2O$ emissions from managed grasslands in Japan. *Soil Science and Plant Nutrition* **59**(1): 69–86. DOI: http://dx.doi.org/10.1080/00380768.2012.733926.

**Singh, S, Singh, JS, Kashyap, AK**. 1999. Methane flux from irrigated rice fields in relation to crop growth and N-fertilization. *Soil Biology & Biochemistry* **31**(9): 1219–1228. DOI: http://dx.doi.org/10.1016/s0038-0717(99)00027-9.

**Six, J, Elliott, ET, Paustian, K**. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology & Biochemistry* **32**(14): 2099–2103. DOI: http://dx.doi.org/10.1016/s0038-0717(00)00179-6.

**Sunagawa, S, Coelho, LP, Chaffron, S, Kultima, JR, Labadie, K, Salazar, G, Djahanschiri, B, Zeller, G, Mende, DR, Alberti, A, Cornejo-Castillo, FM, Costea, PI, Cruaud, C, d'Ovidio, F, Engelen, S, Ferrera, I, Gasol, JM, Guidi, L, Hildebrand, F, Kokoszka, F, Lepoivre, C, Lima-Mendez, G, Poulain, J, Poulos, BT, Royo-Llonch, M, Sarmento, H, Vieira-Silva, S, Dimier, C, Picheral, M, Searson, S, Kandels-Lewis, S, Oceans, T, Bowler, C, de Vargas, C, Gorsky, G, Grimsley, N, Hingamp, P, Iudicone, D, Jaillon, O, Not, F, Ogata, H, Pesant, S, Speich, S, Stemmann, L, Sullivan, MB, Weissenbach, J, Wincker, P, Karsenti, E, Raes, J, Acinas, SG, Bork, P**. 2015. Structure and function of the global ocean microbiome. *Science* **348**(6237), 1261359. DOI: http://dx.doi.org/10.1126/science.1261359.

**Wang, C, Shen, J, Liu, J, Qin, H, Yuan, Q, Fan, F, Hu, Y, Wang, J, Wei, W, Li, Y, Wu, J**. 2019. Microbial mechanisms in the reduction of CH4 emission from double rice cropping system amended by biochar: A four-year study. *Soil Biology and Biochemistry* **135**: 251–263. DOI: http://dx.doi.org/10.1016/j.soilbio.2019.05.012.

**Wang, J, She, J, Zhou, Y, Tsang, D, Beiyuan, J, Xiao, T, Dong, X, Chen, Y, Liu, J, Yin, M, Wang, L**. 2020. Microbial insights into the biogeochemical features of thallium occurrence: A case study from polluted river sediments. *Science of the Total Environment* **739**: 139957.

**Wang, Z, Geng, Y, Liang, T**. 2020. Optimization of reduced chemical fertilizer use in tea gardens based on the assessment of related environmental and economic benefits. *Science of the Total Environment* **713**: 136439. DOI: http://dx.doi.org/10.1016/j.scitotenv.2019.136439.

**Wei, X, Razavi, BS, Hu, Y, Xu, X, Zhu, Z, Liu, Y, Kuzyakov, Y, Li, Y, Wu, J, Ge, T**. 2019. C/P stoichiometry of dying rice root defines the spatial distribution and dynamics of enzyme activities in root-detritusphere. *Biology and Fertility of Soils* **55**(3): 251–263. DOI: http://dx.doi.org/10.1007/s00374-019-01345-y.

**Willison, TW, Webster, CP, Goulding, KWT, Powlson, DS**. 1995. Methane oxidation in temperate soils: Effects of land use and the chemical form of nitrogen fertilizer. *Chemosphere* **30**(3): 539–546. DOI: http://dx.doi.org/10.1016/0045-6535(94)00416-r.

**Witt, C, Cassman, KG, Olk, DC, Biker, U, Liboon, SP, Samson, MI, Ottow, JCG**. 2000. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant and Soil* **225**(1–2): 263–278. DOI: http://dx.doi.org/10.1023/a:1026594118145.

**Wu, L, Zhang, W, Wei, W, He, Z, Kuzyakov, Y, Bol, R, Hu, R**. 2019. Soil organic matter priming and carbon balance after straw addition is regulated by long-term fertilization. *Soil Biology & Biochemistry* **135**: 383–391. DOI: http://dx.doi.org/10.1016/j.soilbio.2019.06.003.

**Wu, X, Wang, F, Li, T, Fu, B, Lv, Y, Liu, G**. 2020. Nitrogen additions increase $N_2O$ emissions but reduce soil respiration and $CH_4$ uptake during freeze–thaw cycles in an alpine meadow. *Geoderma* **363**, 114157. DOI: http://dx.doi.org/10.1016/j.geoderma.2019.114157.

**Wu, Y, Li, Y, Fu, X, Shen, J, Chen, D, Wang, Y, Liu, X, Xiao, R, Wei, W, Wu, J**. 2018. Effect of controlled-release fertilizer on $N_2O$ emissions and tea yield from a tea field in subtropical central China. *Environmental Science and Pollution Research International* **25**(25): 25580–25590. DOI: http://dx.doi.org/10.1007/s11356-018-2646-2.

**Xia, W, Zhang, C, Zeng, X, Feng, Y, Weng, J, Lin, X, Zhu, J, Xiong, Z, Xu, J, Cai, Z, Jia, Z**. 2011. Autotrophic growth of nitrifying community in an agricultural soil. *ISME Journal* **5**(7): 1226–1236. DOI: http://dx.doi.org/10.1038/ismej.2011.5.

**Xiang, SR, Doyle, A, Holden, PA, Schimel, JP**. 2008. Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils. *Soil Biology & Biochemistry* **40**(9): 2281–2289. DOI: http://dx.doi.org/10.1016/j.soilbio.2008.05.004.

**Yan, P, Shen, C, Fan, L, Li, X, Zhang, L, Zhang, L, Han, W**. 2018. Tea planting affects soil acidification and nitrogen and phosphorus distribution in soil. *Agriculture Ecosystems & Environment* **254**: 20–25. DOI: http://dx.doi.org/10.1016/j.agee.2017.11.015.

**Yang, T, Li, H, Hu, X, Li, J, Hu, J, Liu, R, Deng, ZY**. 2014. Effects of fertilizing with N, p, se, and zn on regulating the element and functional component contents and antioxidant activity of tea leaves planted in red soil. *Journal of Agricultural and Food Chemistry* **62**(17): 3823–3830. DOI: http://dx.doi.org/10.1021/jf5004286.

**Yang, X-D, Ni, K, Shi, Y-Z, Yi, X-Y, Zhang, Q-F, Fang, L, Ma, LF, Ruan, J**. 2018. Effects of long-term nitrogen application on soil acidification and solution chemistry of a tea plantation in China. *Agriculture Ecosystems & Environment* **252**: 74–82. DOI: http://dx.doi.org/10.1016/j.agee.2017.10.004.

**Yu, QG, Hu, X, Ma, JW, Ye, J, Sun, WC, Wang, Q, Lin, H**. 2020. Effects of long-term organic material applications on soil carbon and nitrogen fractions in paddy fields. *Soil & Tillage Research* **196**: 7. DOI: http://dx.doi.org/10.1016/j.still.2019.104483.

**Zamanian, K, Zarebanadkouki, M, Kuzyakov, Y**. 2018. Nitrogen fertilization raises $CO_2$ efflux from inorganic carbon: A global assessment. *Global Change Biology* **24**(7): 2810–2817. DOI: http://dx.doi.org/10.1111/gcb.14148.

**Zhang, J, Peng, C, Zhu, Q, Xue, W, Shen, Y, Yang, YZ, Shi, GH, Shi, SW, Wang, M**. 2016. Temperature sensitivity of soil carbon dioxide and nitrous oxide emissions in mountain forest and meadow ecosystems in China. *Atmospheric Environment* **142**: 340–350. DOI: http://dx.doi.org/10.1016/j.atmosenv.2016.08.011.

**Zhang, LH, Shao, HB, Wang, BC, Zhang, LW, Qin, XC**. 2019. Effects of nitrogen and phosphorus on the production of carbon dioxide and nitrous oxide in salt-affected soils under different vegetation communities. *Atmospheric Environment* **204**: 78–88. DOI: http://dx.doi.org/10.1016/j.atmosenv.2019.02.024.

**Zhang, Q, Li, Y, He, Y, Liu, H, Dumont, MG, Brookes, PC, Xu, J**. 2019. Nitrosospira cluster 3-like bacterial ammonia oxidizers and Nitrospira-like nitrite oxidizers dominate nitrification activity in acidic terrace paddy soils. *Soil Biology and Biochemistry* **131**: 229–237. DOI: http://dx.doi.org/10.1016/j.soilbio.2019.01.006.

**Zheng, XH, Wang, MX, Wang, YS, Shen, RX, Li, J, Heyer, J, Kogge, M, Laotu, L, Jisheng, J**. 1998. Comparison of manual and automatic methods for measurement of methane emission from rice paddy fields. *Advances in Atmospheric Sciences* **15**(4): 569–579. DOI: http://dx.doi.org/10.1007/s00376-998-0033-5.

**Zhou, G, Cao, W, Bai, J, Xu, C, Zeng, N, Gao, S, Rees, RM**. 2019. Non-additive responses of soil C and N to rice straw and hairy vetch (Vicia villosa Roth L.) mixtures in a paddy soil. *Plant and Soil* **436**(1–2): 229–244. DOI: http://dx.doi.org/10.1007/s11104-018-03926-6.

**Zhou, GP, Gao, SJ, Xu, CX, Dou, FG, Shimizu, KY, Cao, W**. 2020. Rational utilization of leguminous green manure to mitigate methane emissions by influencing methanogenic and methanotrophic communities. *Geoderma* **361**: 12. DOI: http://dx.doi.org/10.1016/j.geoderma.2019.114071.

**Zhou, ZH, Wang, CK, Jin, Y**. 2017. Stoichiometric responses of soil microflora to nutrient additions for two temperate forest soils. *Biology and Fertility of Soils* **53**(4): 397–406. DOI: http://dx.doi.org/10.1007/s00374-017-1188-y.

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