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# Management scheme influence and nitrogen addition effects on soil $CO_2$, $CH_4$, and $N_2O$ fluxes in a Moso bamboo plantation

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## Abstract

**Background:** It is still not clear whether the effects of N deposition on soil greenhouse gas (GHG) emissions are influenced by plantation management schemes. A field experiment was conducted to investigate the effects of conventional management (CM) versus intensive management (IM), in combination with simulated N deposition levels of control (ambient N deposition), 30 kg N·ha$^{-1}$·year$^{-1}$ (N30, ambient + 30 kg N·ha$^{-1}$·year$^{-1}$), 60 kg N·ha$^{-1}$·year$^{-1}$ (N60, ambient + 60 kg N·ha$^{-1}$·year$^{-1}$), or 90 kg N·ha$^{-1}$·year$^{-1}$ (N90, ambient + 90 kg N·ha$^{-1}$·year$^{-1}$) on soil $CO_2$, $CH_4$, and $N_2O$ fluxes. For this, 24 plots were set up in a Moso bamboo (*Phyllostachys edulis*) plantation from January 2013 to December 2015. Gas samples were collected monthly from January 2015 to December 2015.

**Results:** Compared with CM, IM significantly increased soil $CO_2$ emissions and their temperature sensitivity ($Q_{10}$) but had no significant effects on soil $CH_4$ uptake or $N_2O$ emissions. In the CM plots, N30 and N60 significantly increased soil $CO_2$ emissions, while N60 and N90 significantly increased soil $N_2O$ emissions. In the IM plots, N30 and N60 significantly increased soil $CO_2$ and $N_2O$ emissions, while N60 and N90 significantly decreased soil $CH_4$ uptake. Overall, in both CM and IM plots, N30 and N60 significantly increased global warming potentials, whereas N90 did not significantly affect global warming potential. However, N addition significantly decreased the $Q_{10}$ value of soil $CO_2$ emissions under IM but not under CM. Soil microbial biomass carbon was significantly and positively correlated with soil $CO_2$ and $N_2O$ emissions but significantly and negatively correlated with soil $CH_4$ uptake.

**Conclusion:** Our results indicate that management scheme effects should be considered when assessing the effect of atmospheric N deposition on GHG emissions in bamboo plantations.

**Keywords:** Greenhouse gases, Management practices, Nitrogen addition, *Phyllostachys edulis*, $Q_{10}$

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## Introduction

Extensive research on soil greenhouse gases (GHGs) has shown that $CO_2$, $CH_4$, and $N_2O$ released from soil significantly contribute to global warming (IPCC 2013; WMO 2019). Atmospheric concentrations of $CO_2$, $CH_4$, and $N_2O$ have increased considerably from 278 ppm, 722 ppb, and 270 ppb in 1750 to 408 ppm, 1869 ppb, and 331 ppb in 2018, respectively (WMO 2019). Forest ecosystems, as an important source of atmospheric $CO_2$ and $N_2O$ and an important sink of $CH_4$ (Liu and Greaver 2009), play a key role in regulating GHG fluxes under global climate change.

Recently, atmospheric N deposition has drastically increased in East and South Asia and is expected to continue to increase (Galloway et al. 2008; Reay et al. 2008; Tian et al. 2016), particularly in subtropical China (Liu et al. 2013), where N deposition has reached 30.9 kg N·ha$^{-1}$·year$^{-1}$ (Xie et al. 2008) and is predicted to reach 50 kg N·ha$^{-1}$·year$^{-1}$ by 2050 (Galloway et al. 2004). Many studies have shown that N deposition can significantly influence forest soil $CO_2$, $CH_4$, and $N_2O$ emissions, including both promotion and inhibition effects (Zhang et al. 2008a; Liu and Greaver 2009; Deng et al. 2020). For example, in temperate forests, the effect of N deposition on soil $CO_2$ emissions includes promotion (Bowden et al. 2004; Zheng et al. 2018) and inhibition (Geng et al. 2017), as well as no effect (Krause et al. 2013; Sun et al. 2014). N deposition reduces (Sitaula et al. 1995; Gulledge et al. 2004; Kim et al. 2012; Krause et al. 2013) or increases (Geng et al. 2017) soil $CH_4$ uptake and accelerates soil $N_2O$ emissions (Venterea et al. 2003; Kim et al. 2012; Krause et al. 2013; Sun et al. 2014; Song et al. 2017a). In tropical forests, N deposition reduces soil $CO_2$ emissions (Mo et al. 2008; Cusack et al. 2011; Tian et al. 2019); enhances (Zhang et al. 2008b; Wang et al. 2014; Tian et al. 2019) or has no effect (Zhang et al. 2008b; Müller et al. 2015; Tang et al. 2018) on soil $N_2O$ emissions; and inhibits or has no effect on soil $CH_4$ uptake (Zhang et al. 2012). N deposition was shown to promote soil $N_2O$ emissions in an N-saturated forest (Xie et al. 2018), while it increased soil $CO_2$ emissions in a bamboo ecosystem (Tu et al. 2013), an evergreen forest (Gao et al. 2014), and a highly P-limited forest (Liu et al. 2019). Additionally, Wang et al. (2015) found that N deposition promoted soil $N_2O$ emissions but reduced soil $CH_4$ uptake in a slash pine plantation. Li et al. (2015) also measured the effects of N deposition in a slash pine plantation and found that soil $CO_2$ and $N_2O$ emissions increased, but soil $CH_4$ uptake was unaffected. These inconsistent results indicate that the effects of N deposition on GHG emissions strongly depend on forest type. Moreover, most studies have only observed the fluxes of one or two GHGs in forest soil under N deposition (Jassal et al. 2010; Kim et al. 2012; Wang et al. 2015; Tian et al. 2019). Studies that simultaneously measure the fluxes of three GHGs in forest soils under increasing N depositions are scarce (Krause et al. 2013; Song et al. 2017a), especially in subtropical plantations (Li et al. 2015; Song et al. 2020).

An increasing number of plantations have been established in recent years to satisfy the increasing global demand for timber products (FAO 2005). As one of the forestry practices that increases productivity, intensive management (IM) is essential for meeting current and future timber needs (McEwan et al. 2020). Several studies have shown that IM significantly increases $CO_2$ emissions (Mori et al. 2017; Yang et al. 2017) but does not affect $CH_4$ or $N_2O$ emissions from forest soils (Mori et al. 2017). Moso bamboo (*Phyllostachys edulis*) plantations are one of the most important types of forests in southern China. Approximately 4.43 million hectares are under Moso bamboo cultivation in this region, comprising 84.02% of the global Moso bamboo forest area (Song et al. 2017b). In recent decades, owing to the high economic and ecological benefits of Moso bamboo, an increasing number of farmers have utilized IM practices to replace conventional management (CM) practices in Moso bamboo plantations, including fertilization, plowing, and weeding understory vegetation (Song et al. 2015). In Moso bamboo plantations, IM has been observed to significantly increase soil $CO_2$ emissions (Liu et al. 2011; Tang et al. 2016), while its effects on soil $N_2O$ and $CH_4$ fluxes remain unknown. Therefore, the effect of IM on soil GHG emissions in Moso bamboo plantations is an empirical gap that needs to be addressed.

Furthermore, Moso bamboo plantations are located in subtropical China where N deposition had increased dramatically in recent years (Liu et al. 2013). Our previous study showed that N deposition increased soil $CO_2$ emissions (Li et al. 2019) and $N_2O$ emissions (Song et al. 2020) but decreased soil $CH_4$ uptake (Song et al. 2020) in Moso bamboo plantations under IM. However, the comprehensive effects of management scheme combined with N deposition on soil GHG fluxes in Moso bamboo plantations remain unclear. Here, we studied the individual and combined effects of N deposition and management scheme on soil $CO_2$, $CH_4$, and $N_2O$ fluxes for one year in a Moso bamboo plantation. We hypothesized that (1) IM increases $CO_2$ emissions but does not affect $N_2O$ emissions or $CH_4$ uptake, because IM can promote soil respiration; (2) N addition promotes $CO_2$ and $N_2O$ emissions but inhibits $CH_4$ uptake under CM, because N addition can promote soil respiration, nitrification and denitrification but inhibit methane oxidation; and (3) IM intensifies the effect of N addition on soil GHG fluxes, because IM can provide more nutriment, especially N.

## Materials and methods

### Study site

The details of the study site were reported previously (Song et al. 2015). Briefly, the site is located in Lin'an

District (30°14′ N, 119°42′ E), Hangzhou City, Zhejiang Province, China, and is characterized by a subtropical monsoon climate with a mean annual temperature of 15.6 °C and a mean annual precipitation of 1420 mm. The soil belongs to the Ferrisols derived from granite (Song et al. 2015). The landscape is hilly, with an elevation range of 100 to 300 m a.s.l. The Moso bamboo plantations were initially established in the late 1970s to replace a native evergreen broadleaf forest, with similar soil type and topography (a southwest slope of approximately 6°). Moso bamboo forests in the study area are divided into CM and IM plantations according to the management scheme to which they are subjected. Conventionally managed plantations are selectively and regularly harvested for bamboo stems and shoots according to demand, with no other management practices in place. In IM plantations, additional management practices such as plowing, weeding by herbicide spray, and fertilization are practiced, in addition to bamboo harvesting as per CM plantations. Specifically, every year in September, fertilizers (67.5 kg N·ha$^{-1}$, 11.8 kg P·ha$^{-1}$, and 74.7 kg K·ha$^{-1}$) are evenly spread on the ground and then plowed to mix with the 30-cm topsoil (Song et al. 2015). Compared with CM plantations, IM plantations have fewer understory species and lower shrub and herbal biomass. Forest stand and soil characteristics at the study site are shown in Table 1 (Song et al. 2015).

## Experimental design and measurements

In November 2012, 24 plots (20 m × 20 m) with a 20-m-wide buffer zone (to avoid disturbing nearby plots) were set up in the Moso bamboo plantations of the study site. According to the N-deposition simulation method reported by Mo et al. (2007) and background atmospheric N deposition data of the site (30.9 kg N·ha$^{-1}$·year$^{-1}$; Xie et al. 2008), the N addition rate was set to equal, double, and triple the local N deposition rate. There were 12 IM plots and 12 CM plots with three replications of four treatment levels: control (ambient N deposition), N30 (low N treatment, ambient + 30 kg N·ha$^{-1}$·year$^{-1}$), N60 (medium N treatment, ambient + 60 kg N·ha$^{-1}$·year$^{-1}$), and N90 (high N treatment, ambient + 90 kg N·ha$^{-1}$·year$^{-1}$) (Song et al. 2015, 2017c). The N source for N-deposition simulation was ammonium nitrate ($NH_4NO_3$; Song et al. 2015). It has been reported that $NH_4^+$ and $NO_3^-$ account for 56.1% and 43.9% of the wet N deposition in China, respectively, and the average $NH_4^+$:$NO_3^-$ ratio was 1.28 (Lei et al. 2016). From January 2013 to December 2015, the amount of $NH_4NO_3$ (Xilong Chemical Co. Ltd., China) corresponding to each N treatment was dissolved in 10 L of water and uniformly sprayed on the forest floor of each N-treated plot in CM and IM plantations once a month (Song et al. 2015). Each control treatment plot was sprayed with 10 L of N-free water to balance the effects of added water.

## Measurement of soil GHG fluxes

Soil $CO_2$, $CH_4$, and $N_2O$ were collected using the static chamber method. The static chamber assembly consists of a permanently mounted base box (40 cm × 40 cm × 10 cm) with a U-shaped groove (5 cm wide and 5 cm deep) at the top and a removable cover box (40 cm × 40 cm × 40 cm). During gas sampling, the cover boxes were placed onto the base boxes and the grooves filled with water to serve as an air seal. A small fan was installed in each chamber to mix the air within the chamber during sampling. The base frame was directly inserted 5 cm into the soil in January 2013. Sampling was conducted between 9:00 am and 10:00 am to minimize the influence of variation. Four samples were taken with a 60-mL plastic syringe attached to a 3-way stopcock every 10 min for 30 min (i.e., at 0, 10, 20, and 30 min). Button thermometers (iButton DS1923; Wdsen Electronic Technology Co. Ltd., China) buried at a depth of 5 cm were used to monitor soil temperature at hourly intervals. GHG concentrations were analyzed after Li et al. (2019) using a gas chromatographer (GC-2014 Shimadzu Corp., Japan) within two days. We collected GHG emission data on a clear day once a month from January to December 2015. Gas fluxes were calculated using the following equation (Li et al. 2019):

$$R = \frac{\Delta c}{\Delta t} \times \rho \times \frac{273}{273 + T} \times \frac{V}{A} \times n \tag{1}$$

where $R$ is gas flux (mg $CO_2$-C·m$^{-2}$·h$^{-1}$ for $CO_2$, μg $CH_4$-C·m$^{-2}$·h$^{-1}$ for $CH_4$, and μg $N_2O$-N·m$^{-2}$·h$^{-1}$ for $N_2O$), $\rho$ is gas density under normal conditions (mg·m$^{-3}$), $V$ is the volume of the static chamber (m$^3$), $A$ is the area that the static chamber covered, $\Delta c/\Delta t$ is the change in gas concentration ($\Delta c$) during a certain time ($\Delta t$), $T$ is air temperature (°C), and $n$ is the coefficient

**Table 1** Forest stand and soil characteristics in the Moso bamboo forests at the study site

| Management Scheme | Stand density (trees·ha$^{-1}$) | DBH (cm) | SBD (g·cm$^{-3}$) | SOC (mg·g$^{-1}$) | TN (mg·g$^{-1}$) | AN (mg·g$^{-1}$) | TP (mg·g$^{-1}$) | AP (mg·g$^{-1}$) | Soil pH |
|---|---|---|---|---|---|---|---|---|---|
| CM | 3106 ± 386a | 10.08 ± 0.38a | 1.06 ± 0.07a | 27.8 ± 0.3a | 0.9 ± 0.03b | 0.06 ± 0.00b | 0.4 ± 0.01a | 0.002 ± 0.000a | 4.53 ± 0.02a |
| IM | 3362 ± 309a | 10.16 ± 0.13a | 0.97 ± 0.07a | 23.7 ± 0.2b | 1.1 ± 0.04a | 0.09 ± 0.00a | 0.5 ± 0.01a | 0.002 ± 0.000a | 4.46 ± 0.01a |

*CM* conventional management; *IM* intensive management; *DBH* diameter at breast height; *SBD* soil bulk density; *SOC* soil organic C; *TN* soil total N; *AN* available N; *TP* soil total P; *AP* available P. Different small letters within columns indicate significant difference at the 0.05 level for converting the masses of $CO_2$, $CH_4$, and $N_2O$ to the masses of C and N (12/44 for $CO_2$, 12/16 for $CH_4$, and 28/44 for $N_2O$).

The following equation was used to calculate cumulative soil $CO_2$, $CH_4$, and $N_2O$ fluxes (Liu et al. 2011):

$$F_g = \sum (R_{i+1} + R_i)/2 \times (t_{i+1} - t_i) \times 24 \times d \tag{2}$$

where $F_g$ is cumulative soil $CO_2$ (kg $CO_2$-C·ha$^{-1}$·year$^{-1}$), $CH_4$ (kg $CH_4$-C·ha$^{-1}$·year$^{-1}$), or $N_2O$ (kg $N_2O$-N·ha$^{-1}$·year$^{-1}$) flux; $R$ is soil $CO_2$ (mg $CO_2$-C·m$^{-2}$·h$^{-1}$), $CH_4$ (mg $CH_4$-C·m$^{-2}$·h$^{-1}$), or $N_2O$ (mg $N_2O$-N·m$^{-2}$·h$^{-1}$) flux determined at each sampling time; $i$ is the sampling number, $t$ is the sampling time, and $d$ is the number of days in each month.

Based on these measurements, an exponential regression model was used to describe the relationship between soil $CO_2$ efflux and soil temperature (Li et al. 2019):

$$Y = \alpha \times e^{kT} \tag{3}$$

where $Y$ is soil $CO_2$ efflux, $T$ is soil temperature at 5-cm depth, and α and k are the model coefficients. Soil $CO_2$ efflux temperature sensitivity ($Q_{10}$) was calculated as in Li et al. (2019):

$$Q_{10} = \alpha \times e^{k(T+10)}/\alpha \times e^{kT} = e^{10k} \tag{4}$$

The Global warming potential (GWP) metric was developed to allow comparisons of the global warming impacts of different gases. The GWP of soil GHG emissions was computed by considering the respective GWP coefficients of $CH_4$ and $N_2O$ using the following equation (Tian et al. 2015):

$$\mathrm{GWP}\left(\mathrm{t\,CO_2eq \cdot ha^{-1}}\right) = F_{CO_2-C} \times \frac{44}{12} + F_{CH_4-C} \times 25 \times \frac{16}{12} + F_{N_2O-N} \times 298 \times \frac{44}{28} \tag{5}$$

where $F_{CO_2-C}$, $F_{CH_4-C}$, and $F_{N_2O-N}$ are the annual fluxes of $CO_2$, $CH_4$, and $N_2O$ respectively based on the masses of C and N; 25 and 298 indicate the radiative forcing of $CH_4$ and $N_2O$, respectively, in terms of a $CO_2$eq unit at a 100-year time horizon (Forster et al. 2007).

### Soil analysis

Ten soil cores (3.5-cm inner diameter) were collected randomly from the topsoil layer (0–20 cm) in each plot in every quarter of 2015. The soil samples were sieved through a 0.15-mm sieve and divided into two portions. One portion was air-dried for measuring soil pH and conducting soil organic carbon (SOC), soil total N (TN), and soil total phosphorus (TP) assays, and the other portion was stored in a refrigerator for measuring soil microbial biomass carbon (MBC), $NH_4^+$, and $NO_3^-$. Briefly, soil pH was measured in a soil:water ratio of 1:2.5 using a pH meter (Li et al. 2016). Soil SOC and TN concentrations were determined using an elemental analyzer (Elementar Vario EL III; Germany). Soil TP was extracted with a Bray-2 solution (Bray 1945) and determined using the molybdate blue colorimetric method. Soil MBC was estimated using the chloroform-fumigation extraction method (Bao 2000). Samples were extracted with a 2-mol·L$^{-1}$ KCl solution, and the concentrations of $NH_4^+$ and $NO_3^-$ were determined using a Dionex ICS 1500 ion chromatographer (Dionex Corp. Atlanta, GA).

### Statistical analysis

Data analyses were performed using SPSS 22.0 (SPSS Inc., Chicago, IL, USA) for Windows. One-way analysis of variance (ANOVA) and least significant difference multiple comparisons were used to identify significant differences in $Q_{10}$, GWP, and soil $CO_2$, $CH_4$, and $N_2O$ fluxes. Two-way ANOVA was used to test the significance of the interaction between N addition and management scheme for the variation in soil $CO_2$, $CH_4$, and $N_2O$ fluxes. All data were tested for homogeneity of variance and distribution normality before conducting the ANOVA. In addition, Pearson's correlation analyses between soil characterization and soil $CO_2$, $CH_4$, and $N_2O$ fluxes were conducted.

## Results

### Soil GHG fluxes

The seasonal variation of soil $CO_2$ flux showed the same pattern in all treatments, peaking in summer and reaching a trough in winter (Fig. 1). Compared with CM, IM significantly promoted annual soil $CO_2$ emissions by 7.5%. Compared with the control treatment, N30 and N60 significantly promoted annual soil $CO_2$ emissions by 31.7% and 22.1% in CM plots, and by 34.0% and 20.9% in IM plots, respectively, while N90 had no significant effect on annual soil $CO_2$ emissions in either CM or IM plots (Fig. 1). Management scheme had no significant effect on annual soil $CH_4$ uptake. Compared with the control treatment, N30 had no significant effect on annual soil $CH_4$ uptake in either CM or IM plots, but

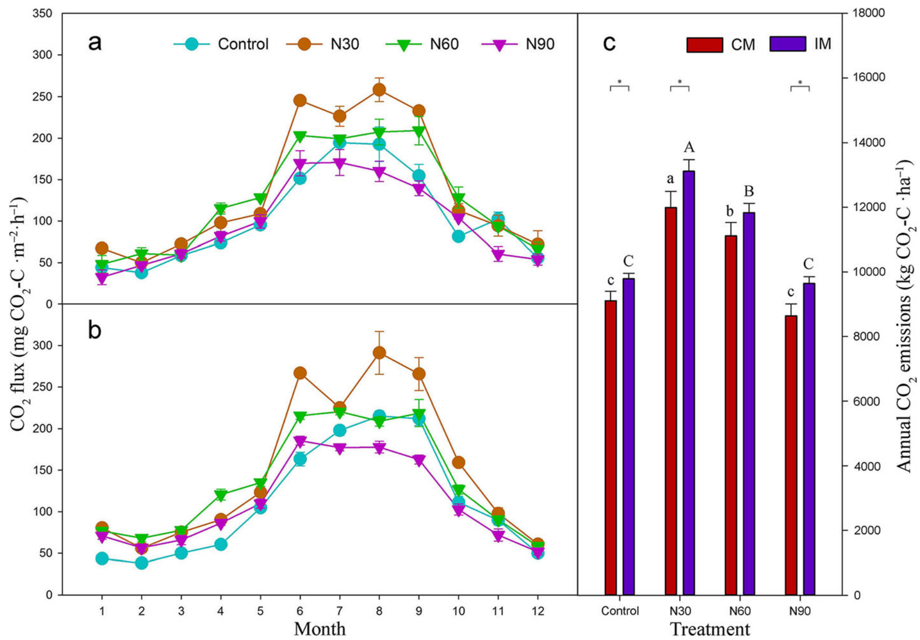


**Fig. 1** Soil $CO_2$ emission rates under different N addition treatments (control, 0 kg N·ha$^{-1}$·year$^{-1}$; N30, 30 kg N·ha$^{-1}$·year$^{-1}$; N60, 60 kg N·ha$^{-1}$·year$^{-1}$; N90, 90 kg N·ha$^{-1}$·year$^{-1}$) in plots under conventional management (CM, **a**) or intensive management (IM, **b**) and annual soil $CO_2$ emissions (**c**) from a Moso bamboo plantation (mean ± standard deviation, $n = 3$). Lowercase letters indicate differences in soil $CO_2$ emissions under different N addition treatments in CM plots ($P < 0.05$). Uppercase letters indicate differences in soil $CO_2$ emissions under different N addition treatments in IM plots ($P < 0.05$). The asterisk indicates differences in soil $CO_2$ emissions between different management schemes under the same N addition treatment ($P < 0.05$)

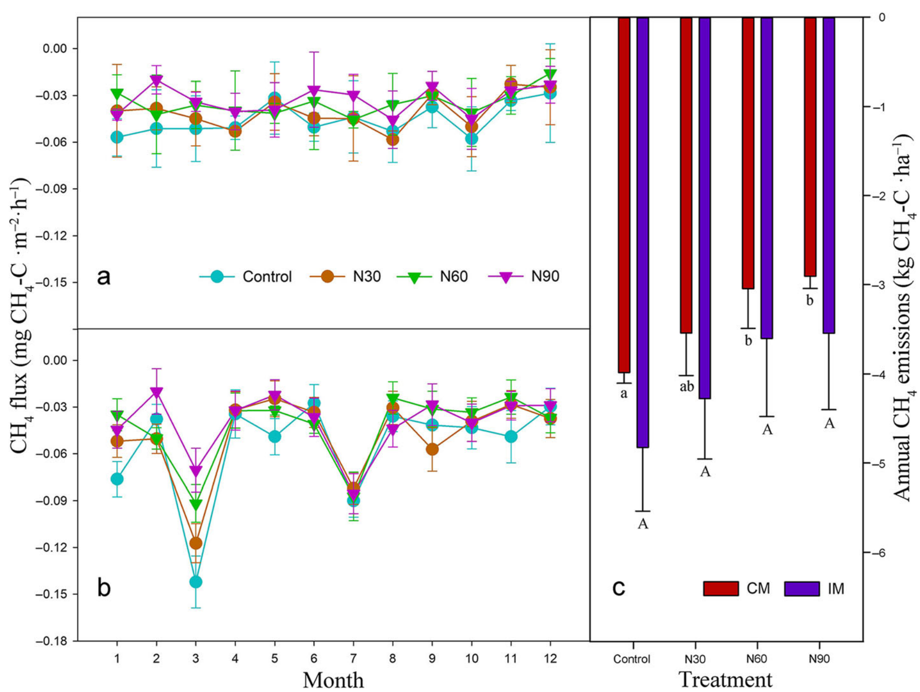


**Fig. 2** Soil $CH_4$ emission rates of different N addition treatments (control, 0 kg N·ha$^{-1}$·year$^{-1}$; N30, 30 kg N·ha$^{-1}$·year$^{-1}$; N60, 60 kg N·ha$^{-1}$·year$^{-1}$; N90, 90 kg N·ha$^{-1}$·year$^{-1}$) in plots under conventional management (CM, **a**) or intensive management (IM, **b**) and annual soil $CH_4$ emissions (**c**) from a Moso bamboo plantation (mean ± standard deviation, $n = 3$). Lowercase letters indicate differences in soil $CH_4$ emissions under different N addition treatments under CM ($P < 0.05$). Uppercase letters indicate differences in soil $CH_4$ emissions under different N addition treatments under IM ($P < 0.05$)

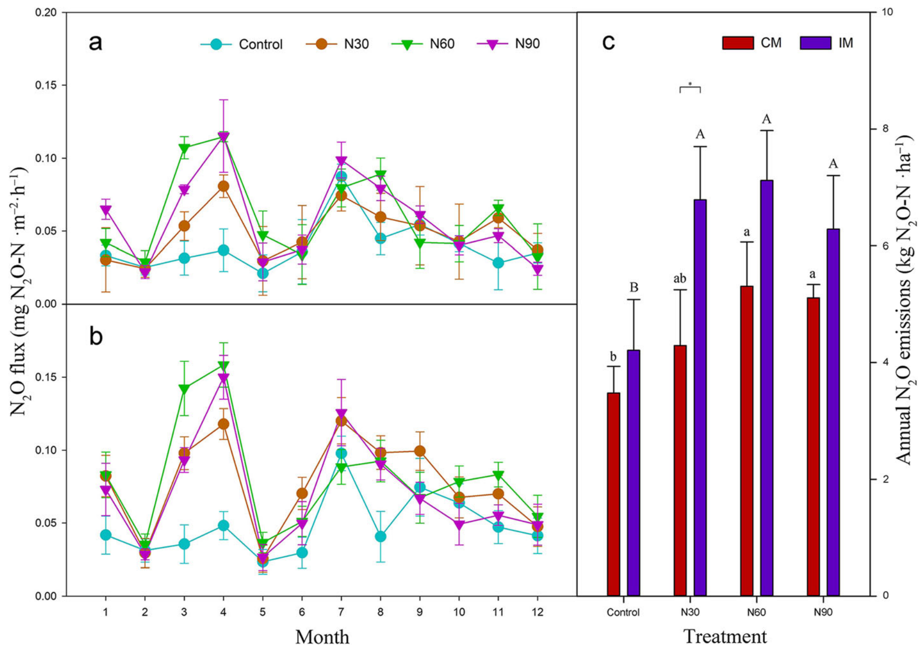


**Fig. 3** Soil $N_2O$ emission rates from plots under different N addition treatments (control, 0 kg N·ha$^{-1}$·year$^{-1}$; N30, 30 kg N·ha$^{-1}$·year$^{-1}$; N60, 60 kg N·ha$^{-1}$·year$^{-1}$; N90, 90 kg N·ha$^{-1}$·year$^{-1}$) under conventional management (CM, **a**) or under intensive management (IM, **b**), and annual soil $N_2O$ emissions (**c**) from a Moso bamboo plantation (mean ± standard deviation, $n = 3$). Lowercase letters indicate differences in soil $N_2O$ emissions from plots under different N addition treatments in CM plots ($P < 0.05$). Uppercase letters indicate differences in soil $N_2O$ emissions from plots under different N addition treatments in IM plots ($P < 0.05$). The asterisk indicates a significant difference in soil $N_2O$ emissions between management schemes with the same N addition treatment ($P < 0.05$)

N60 and N90 significantly inhibited annual soil $CH_4$ uptake by 23.6% and 27.1% in CM plots, respectively (Fig. 2).

The dynamics of annual soil $N_2O$ emission rates were not significantly affected by management scheme, but N addition caused $N_2O$ emission rates to peak from March to April (Fig. 3). In CM plots, compared with the control treatment, N30 did not significantly affect annual soil $N_2O$ emissions, while N60 and N90 significantly promoted annual soil $N_2O$ emissions by 52.7% and 47.0%, respectively (Fig. 3). On the contrary, in IM plots, compared with control treatment, N30, N60, and N90 significantly promoted annual soil $N_2O$ emissions by 61.3%, 69.2%, and 49.3%, respectively. Two-way ANOVA showed that N addition or management scheme independently had significant effects on soil $CO_2$ emissions, $CH_4$ uptake, and $N_2O$ emissions, but the interactions between them did not (Table S1).

The $Q_{10}$ value of soil $CO_2$ efflux varied from 1.89 to 2.37 under the different treatments combining management scheme and N addition (Table S2). IM significantly increased the $Q_{10}$ value by 11.3% relative to that in CM when no N was added. N addition had no significant effect on the $Q_{10}$ value in CM plots but significantly decreased the $Q_{10}$ value in IM plots (Table S2). Furthermore, the significantly higher $Q_{10}$ value in IM than in CM plots under no N addition treatments decreased under both N60 and N90 treatments (Table S2).

Soil $CO_2$ flux was significantly and positively correlated with soil MBC and TP concentrations but significantly and negatively correlated with soil SOC and TN concentrations, and C/N ratio ($P < 0.05$, Table 2). Soil $CH_4$ flux significantly and negatively correlated with soil MBC, TP, and $NH_4^+$ concentrations ($P < 0.05$, Table 2). Soil $N_2O$ flux was significantly and positively correlated

**Table 2** Pearson correlation coefficients between soil physicochemical properties and $CO_2$, $CH_4$, and $N_2O$ fluxes

| | MBC | SOC | TN | TP | C/N | pH | $NO_3^-$ | $NH_4^+$ |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ fluxes | 0.430$^{**}$ | −0.814$^{**}$ | −0.606$^{**}$ | 0.529$^{**}$ | −0.291$^{*}$ | 0.261 | −0.035 | 0.200 |
| $CH_4$ fluxes | −0.374$^{**}$ | −0.065 | − 0.247 | −0.325$^{*}$ | 0.144 | −0.082 | − 0.114 | −0.290$^{*}$ |
| $N_2O$ fluxes | 0.334$^{**}$ | −0.172 | 0.267 | 0.092 | −0.409$^{**}$ | −0.237$^{*}$ | 0.621$^{**}$ | 0.178 |

*MBC* soil microbial biomass carbon; *SOC* soil organic carbon content; *TN* total nitrogen; *TP* total phosphorus. ** $P < 0.01$, * $P < 0.05$

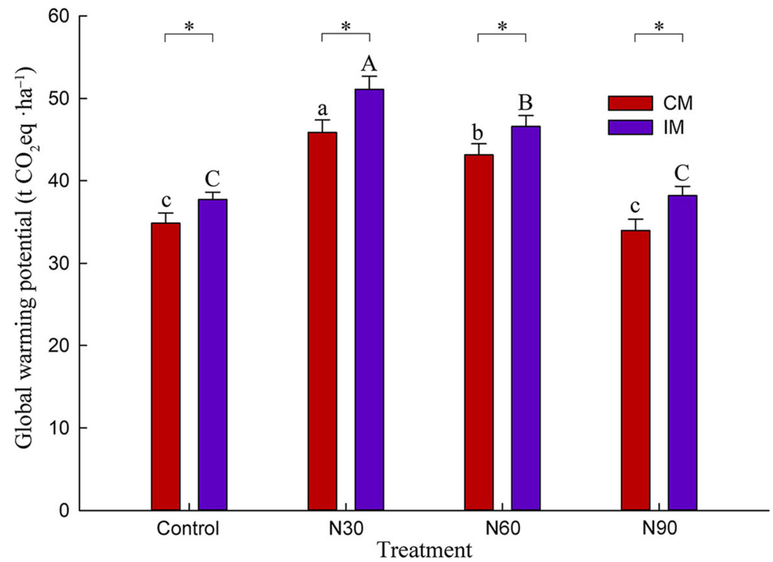


**Fig. 4** Annual global warming potential (GWP) of soil greenhouse gas emissions ($CO_2$, $CH_4$, and $N_2O$) in *Phyllostachys edulis* plantations (mean ± standard deviation, $n = 3$). Lowercase letters indicate differences in GWP under different N addition treatments in CM plots ($P < 0.05$). Uppercase letters indicate differences in GWP under different N addition treatments in IM plots ($P < 0.05$). The asterisk indicates differences in GWP under different management schemes within the same N addition treatment ($P < 0.05$)

with soil MBC and $NO_3^-$ concentrations and negatively correlated with C/N ratio and pH ($P < 0.05$, Table 2).

### Annual GWP of soil GHG fluxes

Annual GWP owing to soil $CO_2$, $CH_4$, and $N_2O$ emissions was 34.88 ± 1.19 t $CO_2$eq·ha$^{-1}$ in the Moso bamboo plantations under CM and without N addition (Fig. 4). Compared with CM, IM significantly increased the annual GWP by 7.98%. Furthermore, compared with the control treatment, N30 and N60 significantly increased the annual GWP by 31.5% and 23.7% in CM plots, and by 35.6% and 23.6% in IM plots, respectively, while N90 had no significant impact on the annual GWP under either CM or IM treatments.

## Discussion

### Effect of management scheme on soil $CO_2$, $CH_4$, and $N_2O$ emissions

We observed that the mean annual soil $CO_2$, $CH_4$, and $N_2O$ emission rates in control plots under CM were 9106.09 ± 297.15 kg $CO_2$-C·ha$^{-1}$, − 3.98 ± 0.12 kg $CH_4$-C·ha$^{-1}$, and 3.48 ± 0.46 kg $N_2O$-N·ha$^{-1}$, respectively (Table S3). Our study showed that the mean annual soil $CO_2$ emission rate in the Moso bamboo forest was higher than that of boreal forests (3220 ± 310 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$), temperate coniferous forests (6810 ± 950 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$), deciduous forests (6470 ± 510 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$; Raich and Schlesinger 1992), subtropical bitter bamboo (*Pleioblastus amarus*) (4280 ± 110 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$; Tu et al. 2013), and Chinese fir (*Cunninghamia lanceolata*) forests (6637.36 ± 581.24 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$; Wang et al. 2018); however, it was lower than the corresponding rate in subtropical evergreen broad-leaved (11,509.09 ± 463.64 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$; Liu et al. 2011) and tropical moist forests (12,600 ± 570 kg $CO_2$-C·ha$^{-1}$·year$^{-1}$; Raich and Schlesinger 1992). The mean annual soil $CH_4$ emission rate in this study was similar to that in mid-subtropical nature forests (− 4.13 ± 0.44 kg $CH_4$-C·ha$^{-1}$·year$^{-1}$; Chen et al. 2014) but lower than that in typical tropical montane rainforests (− 1.93 ± 0.15 kg $CH_4$-C·ha$^{-1}$·year$^{-1}$; Yang et al. 2018), evergreen broad-leaved forests (− 1.90 kg $CH_4$-C·ha$^{-1}$·year$^{-1}$; Fang et al. 2009), larch plantations (− 0.54 kg $CH_4$-C·ha$^{-1}$·year$^{-1}$; Kim et al. 2012), and Korean pine forests (− 0.05 kg $CH_4$-C·ha$^{-1}$·year$^{-1}$; Song et al. 2017a). The mean annual soil $N_2O$ emission rate in this study was higher than that of typical tropical montane rainforests (1.67 ± 0.04 kg $N_2O$-N·ha$^{-1}$·year$^{-1}$; Yang et al. 2018), larch (*Larix kaempferi*) plantations (1.13 kg $N_2O$-N·ha$^{-1}$·year$^{-1}$; Kim et al. 2012), and Korean pine (*Pinus koraiensis*) forests (1.11 kg $N_2O$-N·ha$^{-1}$·year$^{-1}$; Song et al. 2017a) but was lower than that of evergreen broad-leaved forests (6.00 kg $N_2O$-N·ha$^{-1}$·year$^{-1}$; Fang et al. 2009) and three subtropical forests (6.40 ± 2.41 kg $N_2O$-N·ha$^{-1}$·year$^{-1}$; Tang et al. 2006). Overall, compared with other subtropical forests, bamboo forest soils under CM showed lower $CO_2$, $CH_4$, and $N_2O$ emission rates, which have a significant positive effect in decreasing the GWP of soil GHG emissions.

We found that IM significantly increased annual $CO_2$ emissions, which partially supports our first hypothesis and was consistent with the results of Liu et al. (2011) in

Moso bamboo forests. However, some studies indicate that the state box method using linear fitting will cause an underestimation of soil $CO_2$ efflux (Wang 2005; Luo and Zhou, 2006). Therefore, the real soil $CO_2$ efflux may be greater in the Moso bamboo plantation. Soil $CO_2$ efflux mainly comprises root respiration and microbial respiration (Coleman 1973). IM practices, such as fertilization, stimulate root respiration (Jassal et al. 2010; Mori et al. 2013; Tang et al. 2016). Concomitantly, ploughing disaggregates soil and releases protected SOC (Sainju et al. 2008; Li et al. 2013; Tivet et al. 2013), which provides more substrate for microbial respiration, and the decomposition of protected SOC can increase soil $CO_2$ emissions. Meanwhile, fertilization increases soil MBC by providing abundant nutrients for microbial growth (Li et al. 2016) and accelerates the decomposition of organic matter by heterotrophic microorganisms (Cleveland et al. 2002; Ilstedt et al. 2003), resulting in a decrease in SOC concentration (Ma et al. 2011) and promotion of soil $CO_2$ emissions (Tu et al. 2013). We observed that soil $CO_2$ flux was significantly and positively correlated with soil MBC and significantly and negatively correlated with SOC (Table 2). IM had no significant effect on annual $CH_4$ uptake or $N_2O$ emissions, which partially supports our first hypothesis regarding the fluxes of these two gases, i.e., IM does not affect soil $N_2O$ emissions or $CH_4$ uptake. Previous studies have also shown that management does not affect soil $CH_4$ uptake or $N_2O$ emissions (Whalen and Reeburgh 2000; Jassal et al. 2010; Zhang et al. 2015). The response of soil $N_2O$ emissions to external environmental factors and the influence on soil $CH_4$ uptake were determined to be the major reasons for the differences observed in soil GHG emissions (Yan et al. 2014). Some studies found that applying N fertilizer could stimulate soil $N_2O$ emissions in farmland soil (Jäger et al. 2013) and vineyard soil (Tatti et al. 2012). However, compared with CM, IM did not significantly increased soil $N_2O$ emissions (Fig. 3), which may be attributed to infrequent fertilization (once a year).

The $Q_{10}$ value reflects the temperature dependence of soil $CO_2$ efflux, calculated from a series of soil $CO_2$ efflux measurements over a time period while soil temperature changes (Rey et al. 2002; Ma et al. 2014). The $Q_{10}$ value of the soil $CO_2$ efflux in plantations under CM is 2.13, which is close to the $Q_{10}$ value of Moso bamboo forests in the Wanmulin Natural Reserve (2.08; Wang et al. 2011) and the average $Q_{10}$ of bamboo forests in China (2.10; Song et al. 2014). Compared with CM, IM significantly increased the $Q_{10}$ of soil $CO_2$ efflux (Table S2). Tang et al. (2016) observed the same result and concluded that the main reason might be the increase in $Q_{10}$ of soil microbial respiration. In the present study and the previous study on the same site, IM significantly increased soil MBC (Table S4; Li et al. 2016). Moreover, a significant positive correlation between soil $CO_2$ flux and soil MBC was found in this study (Table 2), which supports the conclusion of Tang et al. (2016). Li et al. (2020) have found that root respiration does not affect $Q_{10}$ of soil $CO_2$ efflux in forest ecosystems.

Compared with CM, IM significantly increased the annual GWP in Moso bamboo plantations (Fig. 4), which can be mainly attributed to the increase in $CO_2$ emissions (Table S5). The results suggest that IM induces greater GHG emissions from soils than CM did, although IM may enhance the productivity of Moso bamboo plantations (Zhou et al. 2010). Therefore, the C benefits of IM to Moso bamboo plantations need further comprehensive evaluation, especially in the scenarios of increasing atmospheric N deposition.

### Effect of N addition on soil $CO_2$, $CH_4$, and $N_2O$ fluxes

In this study, N addition enhanced $CO_2$ emissions in both CM and IM plots, which partially supports our second hypothesis, i.e., N addition promotes $CO_2$ emissions. Tu et al. (2009) observed that simulated N deposition promoted soil $CO_2$ emission in a bitter bamboo plantation. Some short-term simulated N deposition studies have also shown similar results (Madritch and Hunter 2003; Mo et al. 2005; Song et al. 2007). Soil $CO_2$ emissions are related to above-ground biomass, litter mass, underground root biomass, and soil biological factors (e.g., microorganisms and animals) (Zhang et al. 2008a). Our previous studies showed that N input increased the amount of leaf litter (Zhang et al. 2017), decomposition of leaf litter (Song et al. 2015), fine root litter (Song et al. 2017c), and soil microbial biomass (Li et al. 2016) in the current study site, all of which contributed to oxidizing organic C to $CO_2$ (Steudler et al. 1991; Emmett 1999), thus increasing $CO_2$ emissions. In this study, soil MBC significantly and positively correlated with $CO_2$ flux (Table 2), which supports the conclusion that N addition increased soil $CO_2$ emissions by increasing MBC. However, Li et al. (2017) found that the $CO_2$ emissions of the Moso bamboo forest soil did not change after N addition ($40\ kg\ N{\cdot}ha^{-1}$, $KNO_3$) in their incubation experiment, which was different from our experimental results. This difference may be owing to the difference in N source, the external environment of the experiment, and the processing time.

N addition significantly inhibited soil $CH_4$ uptake in CM, which supports our second hypothesis, i.e., N addition decreases $CH_4$ uptake in CM. Similar results have been observed in a Douglas fir stand (Jassal et al. 2011) and a young Japanese larch plantation (Kim et al. 2012). Soil $CH_4$ uptake rate is usually negatively correlated with soil $NH_4^+$ concentration (Zhang et al. 2012), as was observed in this study (Table 2). The inhibitory effect of $NH_4^+$ on soil $CH_4$ oxidation can be attributed to the production of the intermediates, hydroxylamine and $NO_2^-$, during the nitrification of $NH_4^+$, which likely inhibits the activity of methane-oxidizing bacteria, thereby extending the inhibition time (Nyerges and Stein 2009). Further, low pH can reduce the activity of methane-oxidizing bacteria (Semenov et al. 2004), because soil acidification may increase the concentration of $Al^{3+}$ in the forest soil solution, while $Al^{3+}$ ions have an obvious toxic effect on $CH_4$-oxidizing bacteria (Nanba and King 2000; Tamai et al. 2007).

In this study, N addition (N60 and N90) significantly increased $N_2O$ emissions, which partially supports our second hypothesis, i.e., N addition increases soil $N_2O$ emissions. Similar results were observed in a young Japanese larch forest (Kim et al. 2012) and in incubated Moso bamboo forest soil (Li et al. 2017). N input can increase soil N availability, nitrification, and denitrification and, thus increase $N_2O$ emissions (Repo et al. 2009). N addition decreased soil pH significantly (Table S4), while $NO_2^-$ may have induced aerobic denitrification in acidic soils (Mørkved et al. 2007), thereby increasing $N_2O$ emissions. A significant negative correlation between soil pH and soil $N_2O$ flux was found in this study (Table 2). N addition increased soil total N content and, thus decreased the soil C/N ratio (Li et al. 2019), which is beneficial for the proportion of external N input converted to $N_2O$ (Zhang et al. 2008a). Similarly, a significant negative correlation between soil C/N ratio and soil $N_2O$ flux was found in this study (Table 2).

N addition had no effect on $Q_{10}$ of soil $CO_2$ efflux relative to that in the control treatment in plots under CM but significantly decreased $Q_{10}$ value in IM plots (Table S2). Similar results have been reported by Mo et al. (2007), who found three-year high-N addition (150 kg N·ha$^{-1}$·year$^{-1}$) reduced $Q_{10}$ values in a mature tropical forest. Tu et al. (2013) also observed that N addition decreased $Q_{10}$ of soil $CO_2$ efflux in a bamboo ecosystem in southwestern China. Karhu et al. (2014) suggested that microbial community responses increase the temperature sensitivity of soil heterotrophic respiration. Our previous studies have shown that, although N addition significantly increased soil MBC, it also decreased soil pH (Li et al. 2016), which might result in microbial activity being inhibited by soil acidity (Kunito et al. 2016). This, in turn, may hamper the microbial community responses, whereby the microbial community has no effect on the temperature sensitivity of soil $CO_2$ efflux. Furthermore, our previous studies have shown that increases in soil MBC are inhibited when N addition exceeds 60 kg N·ha$^{-1}$·yr$^{-1}$ (Li et al. 2016). We suspect that N input from N addition and N fertilizer in IM treatments inhibited any increase in soil MBC and even reduced soil MBC. This might be why N addition did not affect the temperature sensitivity of soil $CO_2$ efflux under CM, yet it reduced the $Q_{10}$ value in the plots under IM.

The GWP of a GHG is a measure of how much energy the emissions of 1 kg of a gas will absorb over a given period of time relative to that absorbed by the emissions of 1 kg of $CO_2$ (Tian et al. 2015). The larger the GWP, the more that a given gas warms the Earth compared with $CO_2$ over that time period. Moderate N addition significantly increased annual GWP of soil GHG fluxes in both CM and IM plots, which is mainly attributed to the increase in annual soil $CO_2$ emissions. Annual soil $CH_4$ uptake and $N_2O$ emissions did not significantly affect annual GWP. The reason was that the GWP values of $CH_4$ and $N_2O$ were much larger than that of $CO_2$ (25 and 298 times, respectively), but the annual soil $CH_4$ uptake and $N_2O$ emissions were only 0.12‰–0.18‰ and 0.16‰–0.31‰ of the annual $CO_2$ emissions, respectively.

In addition, IM enhanced soil $CO_2$ and $N_2O$ emissions under low N addition (N30), which partly supports our third hypothesis, i.e., IM promotes soil $CO_2$ and $N_2O$ emissions under N addition. The finding that IM provided more N input may be why IM significantly increased soil $CO_2$ and $N_2O$ emissions under low N addition. IM did not affect soil $CH_4$ uptake under N addition, which was consistent with the effect on plots without N addition, but it did not support our third hypothesis that IM inhibits soil $CH_4$ uptake under N addition. This may due to the combination of IM and N addition offsetting the inhibitory effect of N addition on soil $CH_4$ uptake. In summary, IM significantly increased GWP under low N addition owing to the main contribution of $CO_2$ emissions to GWP.

## Conclusion

Compared with CM, IM significantly increased the GWP of soil GHG emissions and sensitivity of soil $CO_2$ efflux to soil temperature ($Q_{10}$), mainly owing to an increase in soil $CO_2$ emissions. Nitrogen deposition (≤60 kg N·ha$^{-1}$·year$^{-1}$) significantly increased soil $CO_2$ and $N_2O$ emissions but inhibited $CH_4$ uptake, which resulted in a significant increase in GWP. However, N addition (> 60 kg N·ha$^{-1}$·year$^{-1}$) decreased all soil $CO_2$ and $N_2O$ emissions and $CH_4$ uptake. Concomitantly, the $Q_{10}$ value of soil $CO_2$ efflux was significantly reduced after N addition in plots under IM, which indicates that N addition might mitigate the effect of future climate warming on soil $CO_2$ efflux in intensively managed Moso bamboo plantations. Soil MBC correlated significantly and positively with soil $CO_2$ and $N_2O$ fluxes but correlated negatively with soil $CH_4$ fluxes, indicating that soil microbes have a strong influence on soil GHG emissions. These results demonstrate that management scheme and N application influenced the GWP of the Moso bamboo plantation ecosystem under study.

## Supplementary Information

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**Additional file 1: Table S1.** Two-way ANOVA of the effects of nitrogen (N) addition and management scheme on soil $CO_2$, $CH_4$, and $N_2O$ fluxes in a Moso bamboo forest. **Table S2** Sensitivities of soil $CO_2$ efflux to soil temperature ($Q_{10}$) at a depth of 5 cm. **Table S3** Annual soil $CO_2$, $N_2O$ and $CH_4$ emissions calculated in different treatment plots. **Table S4** Soil physicochemical properties under different treatments (mean ± standard error, $n = 12$). **Table S5** $CO_2$ emission, $N_2O$ emission and $CH_4$ uptake contribution to GWP in different treatment plots.

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#### Authors' contributions

Xinzhang Song and Changhui Peng designed research, Junbo Zhang and Quan Li performed research, collected and analyzed data; All authors discussed the results and revised the manuscript. The author(s) read and approved the final manuscript.

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#### Availability of data and materials

The datasets used and/or analyzed in this study are available from the corresponding author on request.

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

Not applicable.

#### Competing interests

All authors have no conflict of interest.

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#### References

Bao SD (2000) Soil and agricultural chemistry analysis, 3rd edn. Chinese Agriculture Press, Beijing

Bowden RD, Davidson E, Savaga K, Arabia C, Steudler P (2004) Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest soils at the Harvard Forest. Forest Ecol Manag 196:43–56

Bray HR (1945) Soil-plant relations: II. Balanced fertilizer use through soil tests for potassium and phosphoru. Soil Sci 60:463–474

Chen CQ, Yang ZJ, Liu XF, Wu JJ, Huang YM (2014) Responses of $CH_4$ uptake rates to simulated N deposition in a nature forest in mid-subtropical China. Acta Ecol Sin 34:2498–2508 (in Chinese)

Cleveland C, Townsend A, Schmidt S (2002) Phosphorus limitation of microbial processes in moist tropical forests: evidence from short-term laboratory incubations and field studies. Ecosystems 5:680–691

Coleman DC (1973) Compartmental analysis of "total soil respiration": an exploratory study. Oikos 24:361–366

Cusack DF, Silver WL, Torn MS, McDowell WH (2011) Effects of nitrogen additions on above- and belowground carbon dynamics in two tropical forests. Biogeochemistry 104:203–225

Deng L, Huang CB, Kim DG, Shangguan ZP, Wang KB, Song XZ, Peng CH (2020) Soil GHG fluxes are altered by N deposition: new data indicate lower N stimulation of the $N_2O$ flux and greater stimulation of the calculated C pools. Glob Chang Biol 26:2613–2629

Emmett BA (1999) The impact of nitrogen on forest soils and feedbacks on tree growth. Water Air Soil Poll 116:65–74

Fang YT, Gundersen P, Zhang W, Zhou GY, Christiansen JR, Mo JM, Dong SF, Zhang T (2009) Soil-atmosphere exchange of $N_2O$, $CO_2$ and $CH_4$ along a slope of an evergreen broad-leaved forest in southern China. Plant Soil 319: 37–48

FAO (2005) Proceedings FAO advisory committee on paper and wood products. Food and Agricultural Organisation of the United Nations: Forty-sixth Session, Vancouver

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Dorland RV (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S (ed) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, UK, pp 130–234

Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner GP, Cleveland CC, Green PA, Holland EA, Karl DM, Michaels AF, Porter JH, Townsend AR, Vörösmarty CJ (2004) Nitrogen cycles: past, present and future. Biogeochemistry 70:153–226

Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320:889–892

Gao Q, Hasselquist NJ, Palmroth S, Zheng ZM, You WH (2014) Short-term response of soil respiration to nitrogen fertilization in a subtropical evergreen forest. Soil Biol Biochem 76:297–300

Geng J, Cheng SL, Fang HJ, Yu GR, Li XY, Si GY, He S, Yu GX (2017) Soil nitrate accumulation explains the nonlinear responses of soil $CO_2$ and $CH_4$ fluxes to nitrogen addition in a temperate needle-broadleaved mixed forest. Ecol Indic 79:28–36

Gulledge J, Hrywna Y, Cavanaugh C, Steudler PA (2004) Effects of long-term nitrogen fertilization on the uptake kinetics of atmospheric methane in temperate forest soils. FEMS Microbiol Ecol 49:389–400

Ilstedt U, Giesler R, Nordgren A, Malmer A (2003) Changes in soil chemical and microbial properties after a wildfire in a tropical rainforest in Sabah, Malaysia. Soil Biol Biochem 35:1071–1078

IPCC (2013) Climate change 2013: the physical science basis. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, UK and New York https://boris.unibe.ch/id/eprin t/71452. Accessed 15 October 2020

Jäger N, Duffner A, Ludwig B, Flessa H (2013) Effect of fertilization history on short-term emission of $CO_2$ and $N_2O$ after the application of different N fertilizers – a laboratory study. Arch Agron Soil Sci 59:161–171

Jassal RS, Black TA, Roy R, Ethier G (2011) Effect of nitrogen fertilization on soil $CH_4$, and $N_2O$ fluxes, and soil and bole respiration. Geoderma 162:182–186

Jassal RS, Black TA, Trofymow JA, Roy R, Nesic Z (2010) Soil $CO_2$ and $N_2O$ flux dynamics in a nitrogen-fertilized Pacific Northwest Douglas-fir stand. Geoderma 157:118–125

Karhu K, Auffret MD, Dungait JAJ, Hopkins DW, Prosser JI, Singh BK, Subke JA, Wookey PA, Agren GI, Sebastia MT, Gouriveau F, Bergkvist G, Meir P, Nottingham AT, Salinas N, Hartley IP (2014) Temperature sensitivity of soil respiration rates enhanced by microbial community response. Nature 513: 81–84

Kim YS, Imori M, Watanabe M, Hatano R, Yi MJ, Koike T (2012) Simulated nitrogen inputs influence methane and nitrous oxide fluxes from a young larch plantation in northern Japan. Atmos Environ 46:36–44

Krause K, Niklaus PA, Schleppi P (2013) Soil-atmosphere fluxes of the greenhouse gases $CO_2$, $CH_4$ and $N_2O$ in a mountain spruce forest subjected to long-term N addition and to tree girdling. Agric For Meteorol 181:61–68

Kunito T, Isomura I, Sumi H, Park H, Toda H, Otsuka S, Nagaoka K, Saeki K, Senoo K (2016) Aluminum and acidity suppress microbial activity and biomass in acidic forest soils. Soil Biol Biochem 97:23–30

Lei L, Zhang XY, Wang SQ, Lu XH, Ouyang XY, Hong YG (2016) A review of spatial variation of inorganic nitrogen (N) wet deposition in China. PLoS One 11:e0146051

Li JQ, Pendall E, Dijkstra FA, Nie M (2020) Root effects on the temperature sensitivity of soil respiration depend on climatic condition and ecosystem type. Soil Till Res 199:104574

Li Q, Song XZ, Chang SX, Peng CH, Xiao WF, Zhang JB, Xiang WH, Li Y, Wang WF (2019) Nitrogen depositions increase soil respiration and decrease temperature sensitivity in a Moso bamboo forest. Agr For Meteorol 268:48–54

Li Q, Song XZ, Gu HH, Gao F (2016) Nitrogen deposition and management practices increase soil microbial biomass carbon but decrease diversity in Moso bamboo plantations. Sci Rep 6:28235

Li XY, Cheng SL, Fang HJ, Yu GR, Dang XS, Xu MJ, Wang L, Si GY, Geng J, He S (2015) The contrasting effects of deposited $NH_4^+$ and $NO_3^-$ on soil $CO_2$, $CH_4$ and $N_2O$ fluxes in a subtropical plantation, southern China. Ecol Eng 85:317–327

Li YF, Zhang JJ, Chang SX, Jiang PK, Zhou GM, Fu SL, Yan ER, Wu JS, Lin L (2013) Long-term intensive management effects on soil organic carbon pools and chemical composition in Moso bamboo (*Phyllostachys pubescens*) forests in subtropical China. Forest Ecol Manag 303:121–130

Li ZZ, Zhang L, Deng BL, Liu YQ, Kong FQ, Huang GX, Zou Q, Liu Q, Guo XM, Fu YQ, Niu DK, Siemann E (2017) Effects of moso bamboo (*Phyllostachys edulis*) invasions on soil nitrogen cycles depend on invasion stage and warming. Environ Sci Pollut Res 24:24989–24999

Liu HM, Zhou GY, Bai SH, Song JJ, Shang YJ, He M, Wang XH, Zheng ZM (2019) Differential response of soil respiration to nitrogen and phosphorus addition in a highly phosphorus-limited subtropical forest, China. Forest Ecol Manag 448:499–508

Liu J, Jiang PK, Wang HL, Zhou GM, Wu JS, Yang F, Qian XB (2011) Seasonal soil $CO_2$ flux dynamics after land use change from a natural forest to Moso bamboo plantations in subtropical China. Forest Ecol Manag 262:1131–1137

Liu LL, Greaver TL (2009) A review of nitrogen enrichment effects on three biogenic GHGs: the $CO_2$ sink may be largely offset by stimulated $N_2O$ and $CH_4$ emission. Ecol Lett 12:1103–1117

Liu XJ, Zhang Y, Han WX, Tang A, Shen JL, Cui ZL, Vitousek P, Erisman JW, Goulding K, Christie P (2013) Enhanced nitrogen deposition over China. Nature 494:459–462

Luo YQ, Zhou XH (2006) Soil respiration and the environment. Higher Education Press, Beijing

Ma SJ, Li ZC, Wang G, Liu RJ, Fu MY, Zhou BZ (2011) Effects of intensive and extensive management on soil active organic carbon in bamboo forests of China. Chin J Plant Ecol 35:551–557 (in Chinese)

Ma YC, Piao SL, Sun ZZ, Lin X, Wang T, Yue C, Yang Y (2014) Stand ages regulate the response of soil respiration to temperature in a *Larix principis-rupprechtii* plantation. Agric For Meteorol 184:179–187

Madritch MD, Hunter MD (2003) Intraspecific litter diversity and nitrogen deposition affect nutrient dynamics and soil respiration. Oecologia 136:124–128

McEwan A, Marchi E, Spinelli R, Brink M (2020) Past, present and future of industrial plantation forestry and implication on future timber harvesting technology. J For Res 31:339–351

Mo JM, Brown S, Xue JH, Fang YT, Li ZA, Li DJ, Dong SF (2007) Response of nutrient dynamics of decomposing pine (*Pinus massoniana*) needles to simulated N deposition in a disturbed and a rehabilitated forest in tropical China. Ecol Res 22:649–658

Mo JM, Fang YT, Xu GL, Li DJ, Xue JH (2005) The short-term responses of soil $CO_2$ emission and $CH_4$ uptake to simulated N deposition in nursery and forests of Dinghushan in subtropical China. Acta Ecol Sin 25:682–690 (in Chinese)

Mo JM, Zhang W, Zhu WX, Gundersen P, Fang YT, Li DJ, Wang H (2008) Nitrogen addition reduces soil respiration in a mature tropical forest in southern China. Glob Chang Biol 14:403–412

Mori T, Imai N, Yokoyama D, Mukai M, Kitayama K (2017) Effects of selective logging and application of phosphorus and nitrogen on fluxes of $CO_2$, $CH_4$ and $N_2O$ in lowland tropical rainforests of Borneo. J Trop For Sci 29:248–256

Mori T, Ohta S, Ishizuka S, Konda R, Wicaksono A, Heriyanto J, Hamotani Y, Gobara Y, Kawabata C, Kuwashima K, Nakayama Y, Hardjono A (2013) Soil greenhouse gas fluxes and C stocks as affected by phosphorus addition in a newly established *Acacia mangium* plantation in Indonesia. Forest Ecol Manag 310:643–651

Mørkved PT, Dorsch P, Bakken LR (2007) The $N_2O$ product ratio of nitrification and its dependence on long-term changes in soil pH. Soil Biol Biochem 39:2048–2057

Müller AK, Matson AL, Corre MD, Veldkamp E (2015) Soil $N_2O$ fluxes along an elevation gradient of tropical montane forests under experimental nitrogen and phosphorus addition. Front Earth Sci 3:66

Nanba K, King GM (2000) Response of atmospheric methane consumption by Maine forest soils to exogenous aluminum salts. Appl Environ Microbiol 66:3674–3679

Nyerges G, Stein LY (2009) Ammonia cometabolism and product inhibition vary considerably among species of methanotrophic bacteria. FEMS Microbiol Lett 297:131–136

Raich JW, Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus B 44:81–99

Reay DS, Dentener F, Smith P, Grace J, Feely RA (2008) Global nitrogen deposition and carbon sinks. Nat Geosci 1:430–437

Repo ME, Susiluoto S, Lind SE, Jokinen S, Elsakov V, Biasi C, Virtanen T, Martikainen PJ (2009) Large $N_2O$ emissions from cryoturbated peat soil in tundra. Nat Geosci 2:189–192

Rey A, Pegoraro E, Tedeschi V, De Parri I, Jarvis PG, Valentini R (2002) Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. Glob Chang Biol 8:851–866

Sainju UM, Jabro JD, Stevens WB (2008) Soil carbon dioxide emission and carbon content as affected by irrigation, tillage, cropping system, and nitrogen fertilization. J Environ Qual 37:98–106

Semenov VM, Kravchenko IK, Kuznetsova TV, Semenova NA, Bykova SA, Dulov LE, Gal'chenko VF, Pardini G, Gispert M, Boeckx P, van Cleemput O (2004) Seasonal dynamics of atmospheric methane oxidation in gray forest soils. Microbiology 73:356–362

Sitaula BK, Bakken LR, Abrahamsen G (1995) $CH_4$ uptake by temperate forest soil: effect of N input and soil acidification. Soil Biol Biochem 27:871–880

Song L, Tian P, Zhang JB, Jin GZ (2017a) Effects of three years of simulated nitrogen deposition on soil nitrogen dynamics and greenhouse gas emissions in a Korean pine plantation of Northeast China. Sci Total Environ 609:1301–1311

Song XG, Hu TX, Xian JR, Xiao CL, Liu WT (2007) Soil respiration and its response to simulated nitrogen deposition in evergreen broad-leaved forest, Southwest Sichuan. J Soil Water Conserv 21:168–172 (in Chinese)

Song XZ, Chen XF, Zhou GM, Jiang H, Peng CH (2017b) Observed high and persistent carbon uptake by Moso bamboo forests and its response to environmental drivers. Agr For Meteorol 247:467–475

Song XZ, Li Q, Gu HH (2017c) Effect of nitrogen deposition and management practices on fine root decomposition in Moso bamboo plantations. Plant Soil 410:207–215

Song XZ, Peng CH, Ciais P, Li Q, Xiang WH, Xiao WF, Zhou GM, Deng L (2020) Nitrogen addition increased $CO_2$ uptake more than non-$CO_2$ greenhouse gases emissions in a Moso bamboo forest. Sci Adv 6:eaaw5790

Song XZ, Peng CH, Zhao ZY, Zhang ZT, Guo BH, Wang WF, Jiang H, Zhu QA (2014) Quantification of soil respiration in forest ecosystems across China. Atmos Environ 94:546–551

Song XZ, Zhou GM, Gu HH, Qi LH (2015) Management practices amplify the effects of N deposition on leaf litter decomposition of the Moso bamboo forest. Plant Soil 395:391–400

Steudler PA, Melillo JM, Bowden RD, Castro MS, Lugo AE (1991) The effects of natural and human disturbances on soil nitrogen dynamics and trace gas fluxes in a Puerto Rican wet forest. Biotropica 23:356–363

Sun LY, Li L, Chen ZZ, Wang JY, Xiong ZQ (2014) Combined effects of nitrogen deposition and biochar application on emissions of $N_2O$, $CO_2$ and $NH_3$ from agricultural and forest soils. Soil Sci Plant Nutr 60:254–265

Tamai N, Takenaka C, Ishizuka S (2007) Water-soluble Al inhibits methane oxidation at atmospheric concentration levels in Japanese forest soil. Soil Biol Biochem 39:1730–1736

Tang WG, Chen DX, Phillips OL, Liu X, Zhou Z, Li YD, Xi D, Zhu FF, Fang JY, Zhang LM, Lin MX, Wu JH, Fang YT (2018) Effects of long-term increased N deposition on tropical montane forest soil $N_2$ and $N_2O$ emissions. Soil Biol Biochem 126:194–203

Tang XL, Fan SH, Qi LH, Guan FY, Du MY, Zhang H (2016) Soil respiration and net ecosystem production in relation to intensive management in Moso bamboo forests. Catena 137:219–228

Tang XL, Liu SG, Zhou GY, Zhang DQ, Zhou CY (2006) Soil-atmospheric exchange of $CO_2$, $CH_4$, and $N_2O$ in three subtropical forest ecosystems in southern China. Glob Chang Biol 12:546–560

Tatti E, Goyer C, Zebarth BJ, Viti C, Giovannetti L, Burton DL (2012) Short-term effects of mineral and organic fertilizer on denitrifiers, nitrous oxide emissions and denitrification in long-term amended vineyard soils. Soil Sci Soc Am J 77:113–122

Tian HQ, Chen GS, Lu CQ, Xu XF, Hayes DJ, Ren W, Pan SF, Huntzinger DN, Wofsy SC (2015) North American terrestrial $CO_2$ uptake largely offset by $CH_4$ and $N_2O$ emissions: toward a full accounting of the greenhouse gas budget. Clim Chang 129:413–426

Tian HQ, Chen GS, Lu CQ, Xu XF, Ren W, Zhang B, Banger K, Tao B, Pan SF, Liu ML, Zhang C, Bruhwiler L, Wofsy S (2016) Global methane and nitrous oxide emissions from terrestrial ecosystems due to multiple environmental changes. EHS 1:1–20

Tian J, Dungait JAJ, Lu XK, Yang YF, Hartley LP, Zhang W, Mo JM, Yu GR, Zhou JZ, Kuzyakov Y (2019) Long-term nitrogen addition modifies microbial composition and functions for slow carbon cycling and increased sequestration in tropical forest soil. Glob Chang Biol 25:3267–3281

Tivet F, Sá JCD, Lal R, Briedis C, Borszowskei PR, Santos JBD, Farias A, Eurich G, Hartman DDC, Junior MN, Bouzinac S, Séguy L (2013) Aggregate C depletion by plowing and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. Soil Till Res 126:203–218

Tu LH, Hu TX, Huang LH, Li RH, Dai HZ, Luo SH, Xiang YB (2009) Response of soil respiration to simulated nitrogen deposition in *Pleioblastus amarus* forest, rainy area of West China. Chin J Plant Ecol 33:728–738 (in Chinese)

Tu LH, Hu TX, Zhang J, Li XW, Hu HL, Liu L, Xiao YL (2013) Nitrogen addition stimulates different components of soil respiration in a subtropical bamboo ecosystem. Soil Biol Biochem 58:255–264

Venterea RT, Groffman PM, Verchot LV, Magill AH, Aber JD, Steudler PA (2003) Nitrogen oxide gas emissions from temperate forest soils receiving long-term nitrogen inputs. Glob Chang Biol 9:346–357

Wang C, Yang ZJ, Chen GS, Fan YX, Liu Q, Tian H (2011) Characteristics of soil respiration in *Phyllostachys edulis* forest in Wanmulin natural reserve and related affecting factors. Chin J Appl Ecol 22:1212–1218 (in Chinese)

Wang FM, Li J, Wang XL, Zhang W, Zou B, Neher DA, Li ZA (2015) Nitrogen and phosphorus addition impact soil $N_2O$ emission in a secondary tropical forest of South China. Sci Rep-UK 4:5615

Wang YH (2005) Chamber method measurement of greenhouse gas emissions from typical terrestrial ecosystems of China: method research, application and results discussion. Dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences

Wang YS, Cheng SL, Fang HJ, Yu GR, Xu MJ, Dang XS, Li LS, Wang L (2014) Simulated nitrogen deposition reduces $CH_4$ uptake and increases $N_2O$ emission from a subtropical plantation forest soil in southern China. PLoS One 9:e93571

Wang YX, Zhu XD, Bai SB, Zhu TT, Qiu WT, You YJ, Wu MJ, Berninger F, Sun ZB, Zhang H, Zhang XH (2018) Effects of forest regeneration practices on the flux of soil $CO_2$ after clear-cutting in subtropical China. J Environ Manag 212: 332–339

Whalen SC, Reeburgh WS (2000) Effect of nitrogen fertilization on atmospheric methane oxidation in boreal forest soils. Chemosphere-Glob Chang Sci 2: 151–155

WMO (2019) WMO greenhouse gas bulletin (GHG bulletin) - the state of greenhouse gases in the atmosphere based on global observations through 2018. World Meteorological Organization

Xie DN, Si GY, Zhang T, Mulder J, Duan L (2018) Nitrogen deposition increases $N_2O$ emission from an N-saturated subtropical forest in Southwest China. Environ Pollut 243:1818–1824

Xie YX, Zhang SL, Zhao X, Xiong ZQ, Xing GX (2008) Seasonal variation patterns of $NH_4^+$-N/$NO_3^-$-N $\delta^{15}NH_4^+$ value in rainwater in Yangtze river delta. Chin J Appl Ecol 19:2035–2041 (in Chinese)

Yan JH, Zhang W, Wang KY, Qin F, Wang WT, Dai HT, Li PX (2014) Responses of $CO_2$, $N_2O$ and $CH_4$ fluxes between atmosphere and forest soil to changes in multiple environmental conditions. Glob Chang Biol 20:300–312

Yang H, Liu SR, Li YD, Xu H (2018) Diurnal variations and gap effects of soil $CO_2$, $N_2O$ and $CH_4$ fluxes in a typical tropical montane rainforest in Hainan Island, China. Ecol Res 33:379–392

Yang M, Li YF, Li YC, Chang SX, Yue T, Fu WJ, Jiang PK, Zhou GM (2017) Effects of inorganic and organic fertilizers on soil $CO_2$ efflux and labile organic carbon pools in an intensively managed Moso bamboo (*Phyllostachys pubescens*) plantation in subtropical China. Commun Soil Sci Plan 48:332–344

Zhang JB, Lv JH, Li Q, Ying YQ, Peng CH, Song XZ (2017) Effects of nitrogen deposition and management practices on leaf litterfall and N and P return in a Moso bamboo forest. Biogeochemistry 134:115–124

Zhang W, Mo JM, Fang YT, Lu XK, Wang H (2008a) Effects of nitrogen deposition on the greenhouse gas fluxes from forest soils. Acta Ecol Sin 28:2309–2319 (in Chinese)

Zhang W, Mo JM, Yu GR, Fang YT, Li DJ, Lu XK, Wang H (2008b) Emissions of nitrous oxide from three tropical forests in southern China in response to simulated nitrogen deposition. Plant Soil 306:221–236

Zhang W, Zhu XM, Liu L, Fu SL, Chen H, Huang J, Lu XK, Liu ZF, Mo JM (2012) Large difference of inhibitive effect of nitrogen deposition on soil methane oxidation between plantations with N-fixing tree species and non-N-fixing tree species. J Geophys Res-Biogeo 117:G00N16

Zhang YF, Sheng J, Wang ZC, Chen LG, Zheng JC (2015) Nitrous oxide and methane emissions from a Chinese wheat-rice cropping system under different tillage practices during the wheat-growing season. Soil Till Res 146: 261–269

Zheng S, Biao HF, Quan Q, Xu L, Chen Z, He NP (2018) Effect of nitrogen and acid deposition on soil respiration in a temperate forest in China. Geoderma 329:82–90

Zhou GM, Jiang PK, Xu QF (2010) Carbon fixing and transition in the ecosystem of bamboo stands. Science Press, Beijing