



HAL
open science

Nitrogen addition increased CO₂ uptake more than non-CO₂ greenhouse gases emissions in a Moso bamboo forest

Xinzhang Song, Changhui Peng, Philippe Ciais, Quan Li, Wenhua Xiang, Wenfa Xiao, Guomo Zhou, Lei Deng

► To cite this version:

Xinzhang Song, Changhui Peng, Philippe Ciais, Quan Li, Wenhua Xiang, et al.. Nitrogen addition increased CO₂ uptake more than non-CO₂ greenhouse gases emissions in a Moso bamboo forest. *Science Advances*, 2020, 6 (12), <10.1126/sciadv.aaw5790>. <hal-04233639>

HAL Id: hal-04233639

<https://hal.science/hal-04233639v1>

Submitted on 9 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

ECOLOGY

Nitrogen addition increased CO₂ uptake more than non-CO₂ greenhouse gases emissions in a Moso bamboo forest

Xinzhang Song^{1*}, Changhui Peng^{2,3}, Philippe Ciais⁴, Quan Li¹, Wenhua Xiang⁵, Wenfa Xiao⁶, Guomo Zhou¹, Lei Deng³

Atmospheric nitrogen (N) deposition affects the greenhouse gas (GHG) balance of ecosystems through the net atmospheric CO₂ exchange and the emission of non-CO₂ GHGs (CH₄ and N₂O). We quantified the effects of N deposition on biomass increment, soil organic carbon (SOC), and N₂O and CH₄ fluxes and, ultimately, the net GHG budget at ecosystem level of a Moso bamboo forest in China. Nitrogen addition significantly increased woody biomass increment and SOC decomposition, increased N₂O emission, and reduced soil CH₄ uptake. Despite higher N₂O and CH₄ fluxes, the ecosystem remained a net GHG sink of 26.8 to 29.4 megagrams of CO₂ equivalent hectare⁻¹ year⁻¹ after 4 years of N addition against 22.7 hectare⁻¹ year⁻¹ without N addition. The total net carbon benefits induced by atmospheric N deposition at current rates of 30 kilograms of N hectare⁻¹ year⁻¹ over Moso bamboo forests across China were estimated to be of 23.8 teragrams of CO₂ equivalent year⁻¹.

INTRODUCTION

Atmospheric nitrogen (N) deposition is considered to be a driver of increasing carbon (C) storage in woody biomass, particularly in N-limited temperate and boreal forests in North America and Europe (1–3). However, there is still debate on the impact of N deposition on the greenhouse gas (GHG) balance of tropical forests, which have abundant available soil N and a much leakier N cycle than temperate forests (4, 5). The tree growth and C storage in woody biomass were not found to significantly respond atmospheric N deposition in temperate forests across Europe and northeastern United States (6, 7). Similar results were also observed in P-limited Hawaiian tropical forests growing on soil of 4.1 million years (8). However, Frey *et al.* (9) demonstrated that N addition increased soil C accumulation largely due to a suppression of organic matter decomposition rather than enhanced C inputs via litterfall and root production. These results suggest that the responses of forest C sequestration to N addition are variable depending on background limitation, changes in the nutrient use efficiency of plants and decomposers, and limitation of other nutrients such as phosphorus (P) (10, 11). Few studies on N deposition effects have focused on tropical and subtropical regions compared with boreal and temperate regions (12).

Methane (CH₄) and nitrous oxide (N₂O) are the important GHGs that contribute to more than one-quarter of anthropogenic global warming, and their emissions partly offset terrestrial CO₂ uptake at the global scale (13, 14). It has been reported that the emissions of CH₄ and N₂O from terrestrial ecosystems offset 73% of the land CO₂

sink over the North American continent (15). Forest soils are a sink for CH₄, but this sink may have decreased by 77% from 1988 to 2015 (16). Humid tropical forest soils have higher background N₂O losses than temperate forest soils and are the largest source of N₂O across natural ecosystems (12). Nitrogen addition was reported to increase CH₄ and N₂O production and inhibit CH₄ consumption in recent studies, which may shift the net GHG balance toward a source of CO₂ equivalents (CO₂eqs) and could offset 53 to 76% of increased C sequestration induced by N deposition across terrestrial ecosystems (14).

This study focuses on Moso bamboo (*Phyllostachys edulis*), a widely planted species in East and Southeast Asia, covering 4.43 Mha in subtropical China (17). Moso bamboo has extremely fast growth rates (completing height and diameter growth within 2 months after shoot emergence) and a strong regeneration ability (alternating high and low new bamboo recruitment years). The site studied is intensively managed with one-third of the aboveground biomass being removed by thinning each 2 years, thus leaving tree cohorts younger than 4 years. The residence time of most harvested bamboo products, such as bamboo flooring and bamboo furniture, is larger than 20 years (18, 19). Management practices include fertilization, ploughing, and weeding. Therefore, Moso bamboo forests can always grow and remove CO₂ from the atmosphere; at steady state, their net ecosystem exchange is equal to harvest, and the standing biomass carbon stock remains constant. The net CO₂ sink of the system formed by bamboo forests and their wood products thus depends mainly on the lifetime and accumulation in wood products and waste. Our 5-year observation using eddy covariance measurements found that the mean annual net C sequestration in both trees and soil was 6.03 Mg C ha⁻¹ (17). Over a 30-year time period, the carbon stock of the system including plantation and its products pool is 246 metric tons (t) C ha⁻¹, higher than the 200 t C ha⁻¹ of Chinese fir (*Cunninghamia lanceolata*), another fast growing tree in China (19).

The regions where Moso bamboo mainly distributes are today subject to much higher N deposition rates of 30 kg N ha⁻¹ year⁻¹ (20) than Western European (8 to 11 kg) and United States (4 to 5 kg) (21). Moreover, N deposition is predicted to increase by 50 to 100% by 2030 relative to the year 2000 and could reach up to 50 kg N ha⁻¹

¹State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Hangzhou 311300, China. ²Institute of Environment Sciences, Department of Biology Sciences, University of Quebec at Montreal, Case Postale 8888, Succursale Centre-Ville, Montreal H3C3P8, Canada. ³State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, China. ⁴Laboratoire des Sciences du Climat et de l'Environnement, CEA CNRS UVSQ, Gif-sur-Yvette 91191, France. ⁵Faculty of Life Science and Technology, Central South University of Forestry and Technology, Changsha 410004, China. ⁶Key Laboratory of Forest Ecology and Environment, State Forestry Administration, Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing 100091, China.

*Corresponding author. Email: songxinzhang@gmail.com

year⁻¹ by 2050 in China (22, 23). It was shown that N deposition significantly increased P uptake (24), photosynthetic capacity (25), decomposition rates of leaf litter (26) and fine roots (27), loss of dissolved organic carbon (DOC) (28), and soil microbial biomass (29) in bamboo forests. However, how N deposition affects ecosystem productivity, soil carbon storage, soil uptake of CH₄ and soil N₂O emissions, and thus the net GHG balance remains to be quantified. In this study, we performed a 4-year field experiment at three N addition levels of 30, 60, and 90 kg N ha⁻¹ year⁻¹ upon a control (N-free addition with an ambient N deposition rate of 30 kg N ha⁻¹ year⁻¹) in Moso bamboo forests composed of 1- and 3-year-old bamboo cohorts since January 2013.

RESULTS

Net ecosystem productivity and drivers

Under the N-free treatment, the mean woody biomass increment is 7.28 ± 0.46 t C ha⁻¹ year⁻¹, but there was a net loss of soil organic carbon (SOC) of -0.51 ± 0.32 t C ha⁻¹ year⁻¹, so that net ecosystem productivity (NEP) is 6.77 ± 0.36 t C ha⁻¹ year⁻¹ (Table 1). In response to N addition, woody biomass increment increased by 33.1, 36.8, and 23.9%, respectively (Fig. 1), with significantly increased density and diameter at breast height (DBH) of resprouting bamboos (fig. S1). SOC further decreased annually compared to the control SOC loss, mainly at depths of 0 to 20 cm and 20 to 40 cm (Fig. 2). The sum of positive biomass increment and SOC losses contributes to a NEP sink increase of 24.5, 29.9, and 18.3%, respectively (Table 1). N addition treatments significantly increased soil available P (AP) concentration in growth season, although this enhancement weakened with time (fig. S2A).

The response rates of woody biomass increment, SOC change, and NEP to a unit N deposition varied with N addition rate (Table 2). Change in the N response efficiency (Δ NEP; the difference in response rate per unit N addition between different N levels) of both biomass increment and NEP became negative when N addition exceeded 60 kg N ha⁻¹ year⁻¹, that is, a nonlinear saturating response (Fig. 3) (10).

N₂O and CH₄ fluxes and drivers

Mean annual soil N₂O emission was 4.8 kg N₂O-N ha⁻¹ under the N-free treatment, which is equivalent to CO₂eq emissions of 2.2 t CO₂eq ha⁻¹ year⁻¹ (Table 1). The average N₂O emissions increased by 23.8, 12.8, and 4.8 kg CO₂eq ha⁻¹ year⁻¹ per 1 kg N ha⁻¹ year⁻¹

input as a response to N additions of 30, 60, and 90 kg N ha⁻¹ year⁻¹, respectively (Table 2 and figs. S3 and S4A). We performed random forest analysis (30) to identify the main predictors of N₂O fluxes among biotic and abiotic factors and applied structural equation modeling (SEM) (31) to identify direct and indirect relationships between N₂O emissions and environmental factors. The SEM (fig. S5) explained 60.4% of the variation in N₂O emissions through positive relationships with NO₃⁻, microbial biomass carbon, pH, and total P.

The average annual soil CH₄ sink rate was 8.0 kg CH₄ ha⁻¹ under the N-free treatment, a CO₂eq uptake of 0.2 t CO₂eq ha⁻¹ year⁻¹ (Table 1). Nitrogen addition significantly reduced the CH₄ consumption by soil methanotrophy by 10.3 to 29.7%, and this inhibition was enhanced with increasing N addition rate (Table 1 and figs. S4B and S6). The mean soil CH₄ uptake rate decreased by 0.1, 0.3, and 0.1 kg CO₂eq ha⁻¹ year⁻¹ per 1 kg N ha⁻¹ year⁻¹ input in response to N additions of 30, 60, and 90 kg N ha⁻¹ year⁻¹, respectively (Table 2). The SEM (fig. S7) explained 63.3% of the variation in CH₄ consumption through positive relationships with total potassium (K) and AP content, as well as pH value, but negative effects of NH₄⁺, total N, and NO₃⁻ content.

Net ecosystem C uptake and offset by N₂O and CH₄

Combining N₂O emission and CH₄ uptake, assuming global warming potential (GWP) at 100-year time horizon gives a net source of 0.56 t Ceq ha⁻¹ under the N-free treatment (Table 1) and of 0.70 to 0.79 t Ceq ha⁻¹ under the three N addition treatments, an increase of 23.5 to 39.9% compared to the control experiment. The average net sources of these two GHGs increased by 6.7, 3.8, and 1.4 kg Ceq ha⁻¹ year⁻¹ per 1 kg N ha⁻¹ year⁻¹ input in response to N additions of 30, 60, and 90 kg N ha⁻¹ year⁻¹, respectively (Table 2). At the ecosystem scale, NEP increased by 1.24 to 2.03 t C ha⁻¹ year⁻¹, while GHG emissions increased by 0.14 to 0.23 t Ceq ha⁻¹ year⁻¹ under N additions. That is, the ecosystem remained a net GHG sink, but 10.7 to 12.1% of the increase in C sequestration (NEP) was offset by a higher net GHG source caused by N₂O emissions and CH₄ sinks (Table 1). After accounting for altered non-CO₂ emissions from added N, the net ecosystem C uptake was 6.2 t Ceq ha⁻¹ year⁻¹ under the N-free treatment and 7.3 to 8.0 t Ceq ha⁻¹ year⁻¹ under N addition treatments, an increase of 17.8 to 29.0% compared with the N-free treatment (Table 1). The average net ecosystem Ceq sink increased by 48.7, 30.0, and 12.2 kg C ha⁻¹ year⁻¹ per 1 kg N ha⁻¹ year⁻¹ input in response to N addition treatments of 30, 60, and

Table 1. Annual change in biomass carbon and soil carbon, global warming potential (GWP) of annual soil N₂O and CH₄ emission, and annual net change in ecosystem carbon (Δ , megagrams of Ceq hectare⁻¹year⁻¹) (means \pm SD; $n = 3$). Different lowercase letters indicate significant differences among N addition rates for the same variable ($P < 0.05$).

Treatment	Δ Woody biomass C			Δ Soil C	NEP C	GWP			Δ Ecosystem C	Offset rate (%)
	Aboveground	Belowground	Subtotal			N ₂ O	CH ₄	Subtotal		
Control	4.17 \pm 0.18c	3.11 \pm 0.29c	7.28 \pm 0.46c	-0.51 \pm 0.32b	6.77 \pm 0.36c	0.61 \pm 0.10b	-0.050 \pm 0.007a	0.56 \pm 0.09b	6.20 \pm 0.28c	8.32 \pm 0.99
N30	5.46 \pm 0.15ab	4.34 \pm 0.28ab	9.80 \pm 0.43ab	-1.37 \pm 0.12a	8.43 \pm 0.54ab	0.81 \pm 0.10a	-0.045 \pm 0.006ab	0.77 \pm 0.10a	7.66 \pm 0.64ab	9.17 \pm 1.78
N60	5.76 \pm 0.05a	4.33 \pm 0.15a	10.09 \pm 0.18a	-1.29 \pm 0.08a	8.80 \pm 0.21a	0.83 \pm 0.10a	-0.035 \pm 0.006b	0.79 \pm 0.10a	8.01 \pm 0.11a	8.97 \pm 0.91
N90	5.08 \pm 0.13b	4.02 \pm 0.22b	9.10 \pm 0.35b	-1.09 \pm 0.19a	8.01 \pm 0.28b	0.73 \pm 0.09ab	-0.035 \pm 0.006b	0.70 \pm 0.08ab	7.31 \pm 0.35b	8.74 \pm 1.29

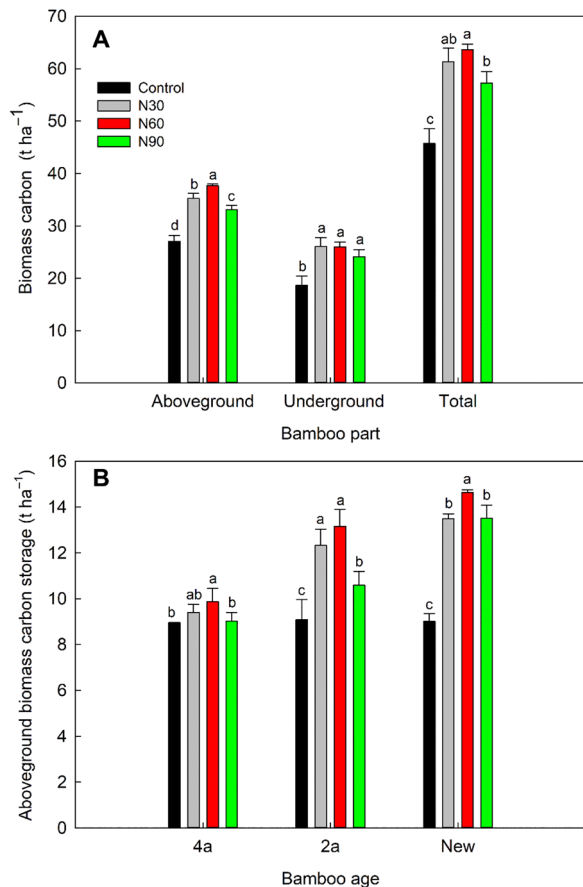


Fig. 1. Moso bamboo forest biomass carbon. The aboveground and belowground biomass carbon (A) and carbon storage of 0-, 2-, and 4-year-old Moso bamboos (B) in uneven aged Moso bamboo forests under N addition treatment.

90 kg N ha⁻¹ year⁻¹, respectively (Fig. 4 and Table 2). As for NEP responses to N addition, the responses of the net GHG balance of the ecosystem were found to saturate when N addition rate exceeded 60 kg N ha⁻¹ year⁻¹ (Fig. 3).

DISCUSSION

The NEP of Moso bamboo forest under the N-free treatment of 6.77 ± 0.36 t C ha⁻¹ year⁻¹ (Table 1) is close to NEP of 6.03 ± 0.6 t C ha⁻¹ year⁻¹ obtained from eddy covariance data (17). Biomass increment response to N addition (increasing 23.9 to 36.8%) (Fig. 1) was far higher than previously measured effects of added N to the growth of temperate forest (<20%) (6, 7), which likely reflects the always-young structure of the bamboo plantation with very high trees growth rate causing a high N demand. Soil P availability could limit biomass increment in humid tropical forests and Moso bamboo forests (24) and was generally expected to decline with declining pH (fig. S2B). In this study, soil AP significantly increased with N addition rates (fig. S2A). The AP were most likely derived from applied fertilizer (N, 15%; P₂O₅, 6%; K₂O, 20%), larger litterfall and P return (32), and faster decomposition of leaf litter (26) and fine roots (27) induced by N addition, which may swamp the effect of declining pH. The increase in soil AP and N addition could sustain enhanced P uptake by plants (24), as well as higher carboxylation ef-

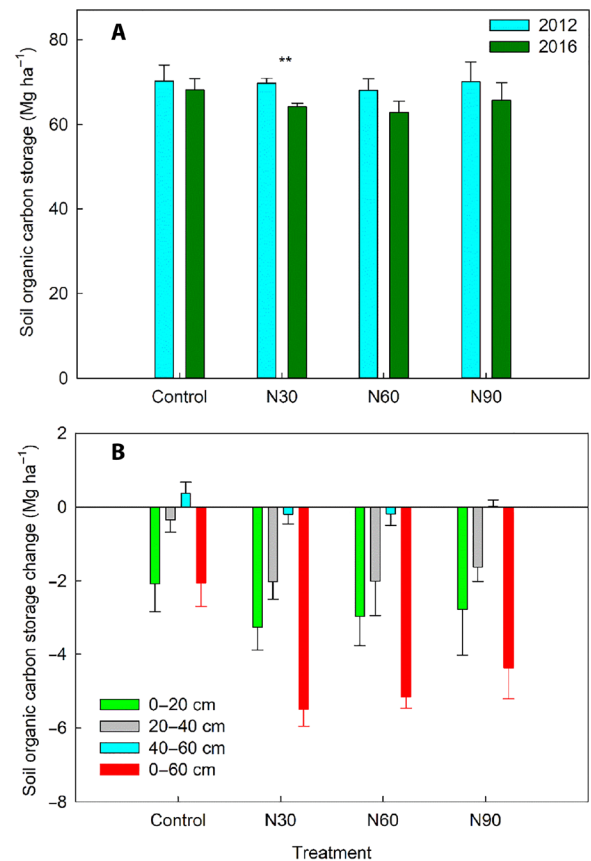


Fig. 2. Soil carbon storage and change at different soil depths under N addition treatment in Moso bamboo forests.

iciency and photosynthetic rates (especially the youngest plants) (25), and a higher density and DBH of resprouting new bamboos cohorts (fig. S1), which, together, contributed to the increases in woody biomass increment and NEP.

Our results showed that the ratio of carbon sequestration per unit N incorporated in the aboveground woody biomass was 27:1 to 43:1 (Table 2) for N addition rates below the saturation threshold. This ratio is slightly higher than in European forests (20:1 to 40:1) (4) or (21:1 to 26:1) (33) and in a global meta-analysis (20:1 to 30:1) (34), but only half of the ratios reported for northeastern and north-central United States (51:1 to 82:1) (3). The ratios of woody biomass carbon increment per unit N were 84:1 and 47:1 under N addition treatments of 30 and 60 kg N ha⁻¹ year⁻¹, respectively (Table 2), which is close to the reported ratio for tree carbon (73:1) across the northeastern and north-central United States (3). The response rates of NEP sink to per unit N were 55:1 and 34:1 under N addition treatments of 30 and 60 kg N ha⁻¹ year⁻¹, respectively (Table 2), which is close to the values for European forests (35:1 to 47:1) (35) and higher than a mean value for global forests (25:1) (14).

Our previous studies at this site indicated that N deposition increased soil available N (NO₃⁻-N and NH₄⁺-N) (28) and that N released from the larger litterfall and N return (32) and faster decomposition of leaf litter and fine roots (26, 27) produced more reaction substrates for nitrification and denitrification and thus increase N₂O emissions. In the present study, N addition treatments significantly decreased the diversity of ammonia oxidizing archaea and denitrobacteria (norB)

Downloaded from https://www.science.org on October 09, 2023

Table 2. The response rate (kilograms of Ceq hectare⁻¹ year⁻¹ per 1 kg N ha⁻¹ year⁻¹) of woody biomass carbon, soil carbon, and GWP of soil N₂O and CH₄ emission to nitrogen addition from 2013 to 2016 (means ± SD; n = 3). ΔBC, woody biomass increment including above- and underground biomass. Different lowercase letters indicate significant differences among N addition rates for the same variable (P < 0.05).

	Aboveground biomass C	ΔBC C	SOC	NEP C	GWP			Ecosystem C
					N ₂ O	CH ₄	Subtotal	
N30	43.1 ± 7.6a	84.1 ± 14.0a	-28.7 ± 9.6a	55.4 ± 12.5a	6.5 ± 0.3a	-0.17 ± 0.03b	6.7 ± 0.3a	48.7 ± 12.6a
N60	26.5 ± 3.5b	46.8 ± 7.4b	-13.0 ± 6.2b	33.8 ± 2.6b	3.5 ± 0.5b	-0.25 ± 0.03a	3.8 ± 0.6b	30.0 ± 2.9b
N90	10.1 ± 2.4c	19.1 ± 5.9c	-5.5 ± 1.7b	13.6 ± 4.9c	1.2 ± 0.4c	-0.18 ± 0.02b	1.4 ± 0.4c	12.2 ± 5.0c

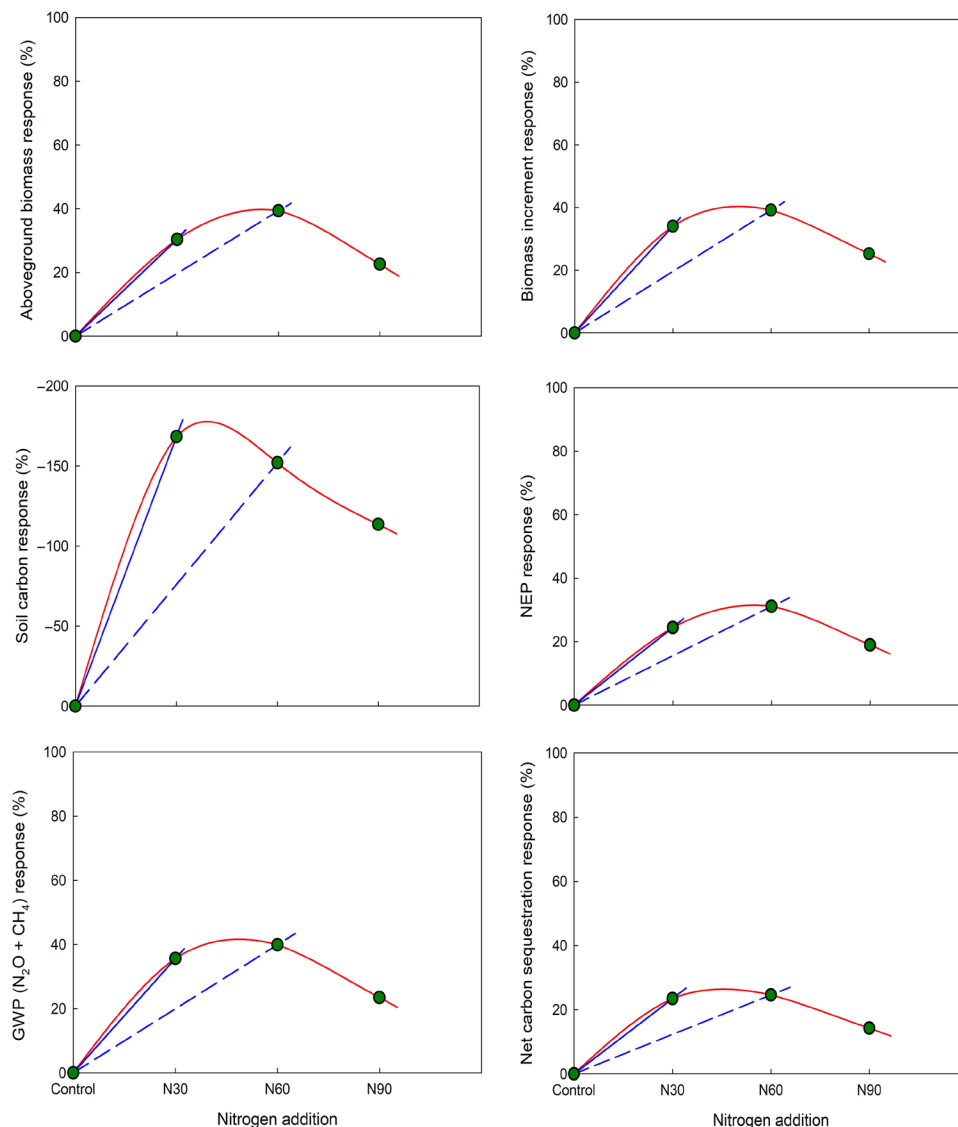


Fig. 3. Responses of Moso bamboo forest to N addition gradient. NRE, the response per unit N addition, is indicated by the slopes in the straight lines. ΔNRE is the difference in NRE between different N levels, indicating the difference between the slopes. Under N limited conditions, the indices increase linearly with excess N; thus, NRE is highest and constant with changing N input, while ΔNRE equals 0. Under high N enrichment, the indices show a slower than linear response; thus, NRE decreases with N, while ΔNRE is smaller than 0. The dash lines indicate the N saturation threshold for these indices nonlinearity.

(fig. S8, A and B), but the N30 treatment significantly increased the amount of norB ($P < 0.05$) (fig. S9B), indicating that the N₂O emission may be mainly driven by denitrification process in the Moso bamboo forest.

Previous studies in temperate woodlands found that N addition decreased soil CH₄ consumption by 14 to 51% (36, 37), consistent with our results. The oxidation of both CH₄ and ammonium (NH₄⁺) relies on the same methane monooxygenase enzyme (MMO), and

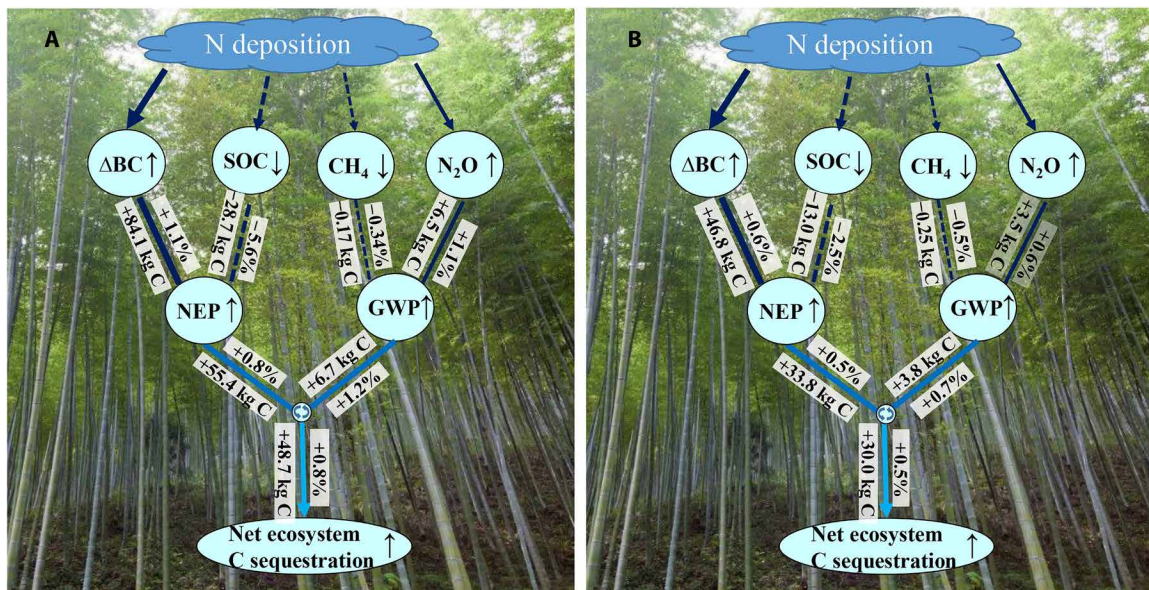


Fig. 4. The carbon benefits of per unit N addition in Moso bamboo forest ecosystem. The responses of the ecosystem carbon process to per unit nitrogen addition when nitrogen addition was not more than (A) 30 kg N ha⁻¹ year⁻¹ and (B) 60 kg N ha⁻¹ year⁻¹. Solid lines indicate positive responses, and dashed lines indicate negative responses. ΔBC, woody biomass carbon increment. (Photo credit: Quan Li, Zhejiang A&F University).

thus, more NH₄⁺ likely suppressed CH₄ consumption through competition for MMO (38). Furthermore, NO₂⁻ resulting from NH₄⁺ oxidation and NO₃⁻ can poison methanotrophic bacteria (39), increased soil available NO₃⁻ induced by N deposition in this study site (28), and thus also inhibit CH₄ oxidation. The optimum pH range for most methanotrophic bacteria is from 4 to 7.5. The significantly lower pH value induced by N input in the current study site (fig. S2B) could inhibit the activity of methanotrophic bacteria, thus suppress CH₄ consumption (40), and contributed to cumulative effect of years of N addition on steadily declining CH₄ uptake rates (fig. S4B). These effects contributed to the significantly negative correlation between soil CH₄ uptake and soil NH₄⁺ and total N content, as well as the significantly positive correlation between CH₄ uptake and pH (fig. S7). Moreover, our results show that N deposition significantly decreased the diversity of methanotrophs (fig. S8D) but significantly increased the amount of methanogen (fig. S9C), indicating that N deposition decreased CH₄ uptake, likely through two paths: a large decrease in CH₄ oxidation and slight increase in CH₄ emission. The mechanism by which total K and AP positively affect CH₄ uptake remains unclear and needs further study.

The contribution of current atmospheric N deposition input (30 kg N ha⁻¹ year⁻¹) (20) across southern China to the C uptake of the Moso bamboo forest ecosystem (biomass and soil) was estimated at 1.66 Mg C ha⁻¹ year⁻¹, accounting for 19.3 ± 5.4% of the total C sequestration (Table 1). Note that terrestrial plants may emit CH₄ under aerobic conditions when soils are saturated. To date, it is still unclear whether Moso bamboo can emit CH₄ and how N deposition may influence plant CH₄ emissions, which contributes to uncertainty of our results. Our previous study in the same site also found that N deposition significantly increased the loss of soil DOC and dissolved organic nitrogen (28) and soil respiration rate (41), which might contribute to soil C variation and N₂O emission. In addition, continued N fertilization and atmospheric N deposition can result in continuous declines in soil pH, which likely induce

aluminum toxicity or other problems, and eventually maybe suppress plant growth and C uptake capacity.

A meta-analysis across terrestrial ecosystems suggested that 53 to 76% of the increased CO₂ sequestration induced by N deposition may be offset by N-induced stimulation of N₂O and CH₄ emissions from multiple ecosystems at a global scale (14). In the present study, the proportion of CO₂ uptake offset by N₂O and CH₄ emissions was only 10.7 to 12.1%, indicating a lower effect than the global analysis (14). The present study reports the net N₂O and CH₄ fluxes changes induced by N deposition coincident with CO₂ fluxes in the same forest. Previous meta-analysis lacked collocated data for the three GHGs from the same ecosystem (14) and thus might overestimate the offset effect of N₂O and CH₄ fluxes.

The global forest C sequestration benefits induced by N deposition were estimated as 0.24 to 2.0 Pg C year⁻¹ using stoichiometric scaling approaches that multiply a C/N response by an estimate of the N deposition rate, assuming that the patterns of N assimilation in wood and soil in temperate forests are representative and the tree and soil C/N ratios are constant along N deposition gradients (3, 6). Using this simple approach, we estimated that N deposition could account for a 11.18 Tg C year⁻¹ sink in Moso bamboo forest biomass and a soil C loss of 3.81 Tg C year⁻¹, thus a net combined of 7.37 Tg C year⁻¹ sink (both trees and soil) in China over 4.43 million ha of plantations. These estimates were calculated by multiplying the C/N response measured in this study (84.1:1 for biomass and 55.4:1 for ecosystem) by an average regional N deposition rate of 30 kg N ha⁻¹ year⁻¹ (20). This estimation assumed that all Moso bamboo forests assimilated deposited N with the similar way in which the present Moso bamboo forest did (42), although the proportion of overall N allocation fraction between bamboo tissues and soil layers remains unknown, which will contribute to the uncertainty of our estimation to some extent.

Nitrogen deposition of 30 kg N ha⁻¹ year⁻¹ was scaled up to increase N₂O emission by 0.86 Tg Ceq year⁻¹ and decrease CH₄

uptake by $0.02 \text{ Tg Ceq year}^{-1}$ in the region considered, leaving a net GHG sink of 6.49 Tg Ceq every year. Considering a scenario where N deposition increase by 50 to 100% in 2030 relative to 2000 (23), it can be inferred that the bamboo forests remain net GHG sinks but weakening over time due to the saturating C uptake enhancement (Fig. 3 and Table 2). Our results provide new evidence of the effects of N deposition on net ecosystem C uptake of Moso bamboo forests and also new data to test the accuracy of terrestrial ecosystem models for quantifying the effects of N deposition on net ecosystem C uptake of tropical forests in China.

METHODS

Study site

The study site was located at Qingshan Town, Lin'an City ($30^{\circ}14'N$ and $119^{\circ}42'E$), Zhejiang Province, China. The area has a monsoonal subtropical climate with four distinct seasons. The mean annual precipitation is 1420 mm, and the mean annual temperature is $15.6^{\circ}C$, which ranges from $24^{\circ}C$ in July to $3^{\circ}C$ in January. The area receives an average of approximately 1847 hours of sunshine per year and sees an average of 230 frost-free days per year. The monthly air temperature and rainfall for the observation period (2013–2016) are shown in fig. S10.

The Moso bamboo forest was originally established in the late 1970s from native evergreen broadleaf forests in sites of similar topography (southwest slopes of approximately 6°) and soil type (Ferrisols derived from granite). The bamboo forest was managed with annual fertilization (N, 15%; P_2O_5 , 6%; K_2O , 20%; 450 kg ha^{-1}), ploughing, weeding with herbicide (26), digging bamboo shoots, and biennial mature bamboo thinning. There were several understory species with a forest floor coverage of 5% and a total herbal biomass of 14.6 kg ha^{-1} . The initial stand and soil characteristics can be found in (41).

Moso bamboo exhibits a different growth pattern than arborous species. Shoots usually begin to emerge from the ground at the end of March and complete their height and diameter growth within the following 2 months. Afterward, the diameter, height, and volume of the young bamboos remain unchanged, owing to scarce secondary cambium, and the bamboos begin to accumulate biomass (17). Moso bamboo forests are characterized by alternating high and low recruitment years, as a result of long-term management activities. The recruitment of Moso bamboo shoots at the study site happened only during even-numbered years (e.g., 2012, 2014, and 2016) (17). Furthermore, since the biomass accumulating capacity of Moso bamboo tends to decrease rapidly 4 years after shoot emergence (17), Moso bamboos more than 4 years old are usually harvested in November during even-numbered years to maximize the economic benefits. Thus, the Moso bamboo forests are uneven aged forests with a 2-year interval (24). The fast growth pattern, biennial new bamboo recruitment and mature bamboo thinning, and long durable time of bamboo products make Moso bamboo forest to always keep a high and continuous productivity and C sequestration capacity.

Experimental design and measurement

In November 2012, 12 experimental plots of 20 m by 20 m were established with a 20-m-wide buffer zone to avoid disturbing the nearby plots. Three N addition treatments (low N, medium N, and high N) and a control (N-free addition) with three replicate plots per treatment were established randomly in Moso bamboo forests. Nitrogen

deposition over most parts of southern China, the main distribution area of Moso bamboo forests, has reached $30 \text{ kg N ha}^{-1} \text{ year}^{-1}$ with an average NH_4^+/NO_3^- ratio of 1.28 (20, 27) and was predicted to reach $50 \text{ kg N ha}^{-1} \text{ year}^{-1}$ by 2050 (22). Referring to the similar methods simulating atmospheric N deposition across global forests (7, 9), NH_4NO_3 was used as N source and the N addition rate equaling, doubling, and tripling the local N deposition rate with a low N treatment of $30 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (N30), a medium N treatment of $60 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (N60), and a high N treatment of $90 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (N90) (26, 41). Beginning in January 2013, quantitative NH_4NO_3 was weighed, mixed with 10 liters of water, and sprayed evenly onto the forest floor of each plot using an electric sprayer at the beginning of every month for a total of 12 equal applications over the entire year throughout the experimental period. These water-based additions were equivalent to an increase of 0.3 mm of rainfall per year (26, 41). Each control treatment plot received 10 liters of N-free water to control for the effects of the added water.

Sample collection

In November 2016, the DBH and age of each Moso bamboo were recorded in each plot, which included three age stages (bamboo shoots emerging in 2012, 2014, and 2016). Nine bamboos (three at each age stage) that were close to the mean DBH were cut in each plot, and the leaf, branch, trunk, and underground trunk were collected, then oven-dried at $65^{\circ}C$ to a constant weight, and weighed to calculate the biomass proportion of the different organs. Three subplots of 1 m by 1 m were set up in each plot, and the rhizomes and roots at a depth of 0 to 60 cm were collected and mixed into a sample. The samples were cleaned, then oven-dried at $65^{\circ}C$ to a constant weight, and weighed. Oven-dried samples were ground with a grinder (DFT-50A, Wenling LINDA Machinery Co. Ltd., Wenling City, China) for C content analysis. Five soil cores at three depths of 0 to 20 cm, 20 to 40 cm, and 40 to 60 cm were randomly collected from each plot and mixed together, respectively. The cutting ring method was used to measure the bulk density of soil at the three depths. Soil samples were sieved through a 2-mm mesh to remove roots, plant residues, and stones for the analysis of C content. The total carbon value was determined using a Sumigraph NC-80 high-sensitivity CN analyzer (Shimadzu, Japan). The methods for analyzing soil physicochemical properties and microbe biomass were the same as those described by Li *et al.* (29). The soil samples at a depth of 0 to 20 cm were also collected from each plot in spring and summer every year to measure soil physicochemical properties and microbe biomass (29).

Fluxes in N_2O and CH_4 were measured using widely applicable static chamber and gas chromatography techniques (43). The static chambers were made of opaque polyvinyl chloride panels consisting of a square base box (0.4 m by 0.4 m by 0.1 m) with a U-shaped groove (50 mm wide and 50 mm deep) at the top of the edge to hold a removable top (0.4 m by 0.4 m by 0.4 m). In each plot, three boxes were inserted directly into the soil to a depth of 10 cm a month before the first sampling and remained fixed during the entire observation period. The chamber tops were placed onto the base boxes during gas sampling with the grooves being filled with water to act as an air seal. A small fan was installed inside at the top of each chamber to generate turbulence in the chamber during sampling. A 60-ml plastic syringe attached to a three-way stopcock was used to collect gas samples at 0, 10, 20, and 30 min following chamber closure. The gas samples were injected into vacuum bags made of inert aluminum-coated plastic (Desen Inc., Dalian, China), and the

concentrations of N₂O and CH₄ were analyzed within 2 days using gas chromatography (GC-2014, Shimadzu Corporation, Kyoto, Japan). The chamber tops were immediately removed after sampling. Gas samples were collected once in the middle of each month. Sampling time was between 9:00 and 10:00 a.m., as during this period, GHG fluxes have been demonstrated to be close to daily means (43). Soil temperature was monitored with button thermometers (iButton DS1923, Wdsen Electronic Technology Co. Ltd., China), which automatically recorded soil temperature at 1-hour intervals. A button thermometer was buried at 5-cm depth in the middle of each base box, and the recorded data were collected once every 6 months; the recorded temperature in the sampling time was used for further analysis. Soil volumetric water content at 5-cm depth was monitored in each chamber with TDR100 (Spectrum Technologies Inc., USA) immediately after the gas samples were collected.

Statistical analysis

The aboveground biomass of a Moso bamboo was calculated using a widely applied existing model, which was developed on the basis of biomass data from whole Moso bamboo in Zhejiang province with a correlation coefficient ($R^2 = 0.937$) and accuracy (96.43%) with 95% confidence intervals (44)

$$f(D, A) = 747.787D^{2.771} \left(\frac{0.1484A}{0.28 + A} \right)^{5.555} + 3.772 \quad (1)$$

where f is the aboveground biomass of a Moso bamboo including the leaf, branch, trunk, and underground trunk and D and A are the DBH (centimeters) and age of Moso bamboo, respectively.

The total aboveground biomass in each plot was the sum of the biomass of each bamboo (f). The total aboveground biomass carbon in each plot was the sum of the biomass carbon for each bamboo, which was calculated as the sum of the carbon from the different organs using carbon concentration multiplied by organ weight at each age stage. The annual aboveground biomass carbon increment was calculated as one-sixth of the current total biomass carbon due to biennial thinning of the Moso bamboo and the harvest of one-third of the biomass (i.e., 4-year-old bamboos) (45). Considering the leaf biomass contributing small fractions of 7.0 to 8.3% of total aboveground biomass increment and high decomposition rates of 0.34 to 0.47 year⁻¹ of leaf litter under the control and N addition treatments (26), leaf increment was excluded when calculating annual aboveground biomass carbon increment and subsequent net ecosystem carbon uptake.

The total belowground biomass carbon in each plot was calculated by extrapolating the biomass carbon of the rhizomes and roots via carbon concentration multiplied by the weight of the rhizomes or roots from three subplots. The ratio of belowground biomass to aboveground biomass was calculated, and this was then used to estimate the annual belowground biomass carbon increment according to the annual aboveground biomass carbon increment. The biomass carbon increment is the sum of the annual increments of the above- and belowground biomass carbon.

SOC storage was calculated using the following formula

$$\text{SOC} = \sum_i^n di \times bi \times 0.2 \quad (2)$$

where SOC is SOC storage at a depth of 0 to 60 cm, i is the soil layer (0 to 20 cm, 20 to 40 cm, and 40 to 60 cm), and di and bi are carbon concentration and bulk density at depth i , respectively.

NEP was calculated as the sum of annual woody biomass carbon increment and soil carbon increment. The soil N₂O and CH₄ fluxes were calculated using the following formula (41)

$$F = (dc/dt) \times (M/V_0) \times (273.15/T) \times (V/A) \quad (3)$$

where F (milligrams meter⁻² hour⁻¹) is the soil N₂O and CH₄ flux and positive and negative values that indicate emissions and uptake of N₂O and CH₄, respectively; dc/dt is the slope of the linear regression between the change in N₂O and CH₄ concentrations (dc) and change in time (dt) in the chamber; M and V_0 are the molar mass and molar volume of N₂O and CH₄ under standard conditions, respectively; T is the absolute air temperature during sampling; and V (cubic meters) and A (square meters) are the effective volume and bottom area of the chamber, respectively. The daily soil N₂O and CH₄ fluxes were accumulated to monthly and annual fluxes. The GWP was used to define the cumulative impacts of the emission of 1 g of CH₄ or N₂O on the planetary energy budget relative to 1 g of reference CO₂ gas over a period of 100 years. The GWP of fluxes of soil N₂O and CH₄ was calculated using the formula (15)

$$\text{GWP (t Ceq ha}^{-1}\text{)} = 25 \times F_{\text{CH}_4\text{-C}} \times 16/12 + 298 \times F_{\text{N}_2\text{O-N}} \times 44/28 \quad (4)$$

where $F_{\text{CH}_4\text{-C}}$ and $F_{\text{N}_2\text{O-N}}$ are annual fluxes of CH₄ and N₂O based on mass of C and N, respectively. Twenty five and 298 indicate the radiative forcing of CH₄ and N₂O, respectively, in terms of a CO₂eq unit at a 100-year time horizon. NRE, i.e., the response rate per unit N addition, was calculated using the formula (10)

$$\text{NRE} = 100\% \times (\text{Index}_{\text{treatments}} - \text{Index}_{\text{control}}) / \text{Index}_{\text{control}} / \text{N addition amount} \quad (5)$$

Index refers to aboveground biomass carbon, biomass carbon increment, soil carbon, NEP, GWP Ceq of CH₄ and N₂O fluxes, and net carbon sequestration of Moso bamboo forests. ΔNRE is the difference in NRE between different N levels, indicated by the difference between the slopes.

A classification random forest analysis was performed to identify the main predictors of N₂O and CH₄ fluxes among biotic and abiotic factors using the randomForest package (30) in R statistical software, version 3.0.2 (<http://cran.r-project.org/>). SEM (31) analysis was conducted to evaluate the direct and indirect relationships between N₂O and CH₄ fluxes and environmental factors using Amos 21.0 (IBM SPSS Amos, USA). Some goodness-of-fit indices, such as the χ^2 test, root mean square error of approximation and their P values, degrees of freedom, normed fit index, and comparative fit index, were used to identify the best-fit model. Our observation number of 72 is demonstrated to be acceptable.

Pearson's correlations between N₂O and CH₄ fluxes and soil physicochemical properties and microbe biomass were analyzed. One-way analysis of variance (ANOVA) and least significant difference tests were used to determine the statistical significance of the differences in biomass C, soil C, and N₂O and CH₄ fluxes among N addition treatments. All data were tested for homogeneity of variance and distribution normality before conducting the ANOVA. Data analyses were performed using SPSS 22.0 (SPSS Inc., Chicago, IL, USA) for Windows.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/12/eaaw5790/DC1>

Fig. S1. The stand characteristics of Moso bamboo forest.

Fig. S2. The soil properties of Moso bamboo forest.

Fig. S3. Monthly soil N₂O emission rate in Moso bamboo forest from 2013 to 2016.

Fig. S4. The global warming potential of non-CO₂ greenhouse gas.

Fig. S5. Direct and indirect effects of biotic and abiotic factors on N₂O emission.

Fig. S6. Soil CH₄ uptake rate between 2013 and 2016 in Moso bamboo forest.

Fig. S7. Direct and indirect effects of biotic and abiotic factors on CH₄ uptake.

Fig. S8. Soil microbe diversity in Moso bamboo forest.

Fig. S9. Soil microbe amount in Moso bamboo forest.

Fig. S10. The climate data for the study period.

REFERENCES AND NOTES

- Magnani, M., Mencuccini, M., Borghetti, P., Berbigier, F., Berninger, S., Delzon, A., Grelle, P., Hari, P., G. Jarvis, P., Kolari, A. S., Kowalski, H., Lankreijer, B. E., Law, A., Lindroth, D., Loustau, G., Manca, J. B., Moncrieff, M., Rayment, V., Tedeschi, R., Valentini, J., Grace, T. The human footprint in the carbon cycle of temperate and boreal forests. *Nature* **447**, 849–851 (2007).
- Saehle, P., Ciais, A., D. Friend, V., Prieur, Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions. *Nat. Geosci.* **4**, 601–605 (2011).
- R. Q. Thomas, C. D. Canham, K. C. Weathers, C. L. Goodale, Increased tree carbon storage in response to nitrogen deposition in the US. *Nat. Geosci.* **3**, 13–17 (2010).
- W. de Vries, S. Solberg, M. Dobbertin, H. Sterba, D. Laubhahn, G. J. Reinds, G.-J. Nabuurs, P. Gundersen, M. A. Sutton, Ecological implausible carbon response? *Nature* **451**, E1–E3 (2008).
- D. F. Cusack, W. L. Silver, M. S. Torn, W. H. McDowell, Effects of nitrogen additions on above- and belowground carbon dynamics in two tropical forests. *Biogeochemistry* **104**, 203–225 (2011).
- K. J. Nadelhoffer, B. A. Emmett, P. Gundersen, O. J. Kjønaas, C. J. Koopmans, P. Schleppei, A. Tietema, R. F. Wright, Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. *Nature* **398**, 145–148 (1999).
- A. H. Magill, J. D. Aber, W. S. Currie, K. J. Nadelhoffer, M. E. Martin, W. H. McDowell, J. M. Melillo, P. Steudler, Ecosystem response to 15 years of chronic nitrogen additions at the Harvard Forest LTER, Massachusetts, USA. *For. Ecol. Manag.* **196**, 7–28 (2004).
- R. A. Harrington, J. H. Fownes, P. M. Vitousek, Production and resource use efficiencies in N- and P-limited tropical forests: A comparison of responses to long-term fertilization. *Ecosystems* **4**, 646–657 (2001).
- S. D. Frey, S. Ollinger, K. Nadelhoffer, R. Bowden, E. Brzostek, A. Burton, B. A. Caldwell, S. Crow, C. L. Goodale, A. S. Grandy, A. Finzi, M. G. Kramer, K. Lajtha, J. LeMoine, M. Martin, W. H. McDowell, R. Minocha, J. J. Sadowsky, P. H. Templer, K. Wickings, Chronic nitrogen additions suppress decomposition and sequester soil carbon in temperate forests. *Biogeochemistry* **121**, 305–316 (2014).
- D. Tian, H. Wang, J. Sun, S. Niu, Global evidence on nitrogen saturation of terrestrial ecosystem net primary productivity. *Environ. Res. Lett.* **11**, 024012 (2016).
- D. A. Wardle, L. R. Walker, R. D. Bardgett, Ecosystem properties and forest decline in contrasting long-term chronosequences. *Science* **305**, 509–513 (2004).
- S. J. Hall, P. A. Matson, Nitrogen oxide emissions after nitrogen additions in tropical forests. *Nature* **400**, 152–155 (1999).
- J. A. Rosentreter, D. T. Maher, D. V. Erler, R. H. Murray, B. D. Eyre, Methane emissions partially offset “blue carbon” burial in mangroves. *Sci. Adv.* **4**, eaao4985 (2018).
- L. Liu, T. L. Greaver, A review of nitrogen enrichment effects on three biogenic GHGs: The CO₂ sink may be largely offset by stimulated N₂O and CH₄ emission. *Ecol. Lett.* **12**, 1103–1117 (2009).
- H. Tian, G. Cheng, C. Lu, X. Xu, D. J. Hayes, W. Ren, S. Pan, D. N. Huntzinger, S. C. Wofsy, North American terrestrial CO₂ uptake largely offset by CH₄ and N₂O emissions: Toward a full accounting of the greenhouse gas budget. *Clim. Change* **129**, 413–426 (2015).
- X. Ni, P. M. Groffman, Declines in methane uptake in forest soils. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 8587–8590 (2018).
- X. Song, X. Chen, G. Zhou, H. Jiang, C. Peng, Observed high and persistent carbon uptake by Moso bamboo forests and its response to environmental drivers. *Agric. For. Meteorol.* **247**, 467–475 (2017).
- L. Gu, Y. Zhou, T. Mei, G. Zhou, L. Xu, Carbon footprint analysis of bamboo scrimber flooring—Implications for carbon sequestration of bamboo forests and its products. *Forests* **10**, 51 (2019).
- P. van der Lugt, J. G. Vogtlander, “The environmental impact of industrial bamboo products—life-cycle assessment and carbon sequestration” (Technical Report No. 35, International Network for Bamboo and Rattan Organisation, 2016).
- Y. Jia, G. Yu, N. He, X. Zhan, H. Fang, W. Sheng, Y. Zuo, D. Zhang, Q. Wang, Spatial and decadal variations in inorganic nitrogen wet deposition in China induced by human activity. *Sci. Rep.* **4**, 3763 (2015).
- E. A. Holland, B. H. Braswell, J. Sulzman, J. F. Lamarque, Nitrogen deposition into the United States and Western Europe: Synthesis of observations and models. *Ecol. Appl.* **15**, 38–57 (2005).
- J. N. Galloway, F. J. Dentener, D. G. Capone, E. W. Boyer, R. W. Howarth, S. P. Seitzinger, G. P. Asner, C. C. Cleveland, P. A. Green, E. A. Holland, D. M. Karl, A. F. Michaels, J. H. Porter, A. R. Townsend, C. J. Vöosmarty, Nitrogen cycles: Past, present, and future. *Biogeochemistry* **70**, 153–226 (2004).
- D. S. Reay, F. Dentener, P. Smith, J. Grace, R. A. Feely, Global nitrogen deposition and carbon sinks. *Nat. Geosci.* **1**, 430–437 (2008).
- X. Song, H. Gu, M. Wang, G. Zhou, Q. Li, Management practices regulate the response of Moso bamboo foliar stoichiometry to nitrogen deposition. *Sci. Rep.* **6**, 24107 (2016).
- R. Zhang, J. Wu, Q. Li, H. Hänninen, C. Peng, H. Yao, X. Song, Y. Ying, Nitrogen deposition enhances photosynthesis in Moso bamboo but increases susceptibility to other stress factors. *Front. Plant Sci.* **8**, 1975 (2017).
- X. Song, G. Zhou, H. Gu, L. Qi, Management practices amplify the effects of N deposition on leaf litter decomposition of the Moso bamboo forest. *Plant and Soil* **395**, 391–400 (2015).
- X. Song, Q. Li, H. Gu, Effect of nitrogen deposition and management practices on fine root decomposition in Moso bamboo plantations. *Plant and Soil* **410**, 207–215 (2017).
- Z. Lei, H. Sun, Q. Li, J. Zhang, X. Song, Effects of nitrogen deposition on soil dissolved organic carbon and nitrogen in Moso bamboo plantations strongly depend on management practices. *Forests* **8**, 452 (2017).
- Q. Li, X. Song, H. Gu, F. Gao, Nitrogen deposition and management practices increase soil microbial biomass carbon but decrease diversity in Moso bamboo plantations. *Sci. Rep.* **6**, 28235 (2016).
- A. Liaw, M. Wiener, Classification and regression by randomForest. *R News* **2-3**, 18–22 (2002).
- J. B. Grace, *Structural Equation Modeling and Natural Systems* (Cambridge Univ. Press, 2006).
- J. Zhang, J. Lv, Q. Li, Y. Ying, C. Peng, X. Song, Effects of nitrogen deposition and management practices on leaf litterfall and N and P return in a Moso bamboo forest. *Biogeochemistry* **134**, 115–124 (2017).
- D. Laubhann, H. Sterba, G. J. Reinds, W. de Vries, The impact of atmospheric deposition and climate on forest growth in European monitoring plots: An individual tree growth model. *For. Ecol. Manag.* **258**, 1751–1761 (2009).
- K. Fleischer, K. T. Rebel, M. K. van der Molen, J. W. Erisman, M. J. Wassen, E. E. Vanloon, L. Montagnani, C. M. Gough, M. Herbst, I. A. Janssens, D. Gianelle, A. J. Dolman, The contribution of nitrogen deposition to the photosynthetic capacity of forests. *Global Biogeochem. Cycles* **27**, 187–199 (2013).
- K. Butterbach-Bahl, E. Nemitz, S. Zaehle, *The European Nitrogen Assessment: Nitrogen as a Threat to the European Greenhouse Balance*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven, B. Grizzetti, Eds. (Cambridge Univ. Press, 2011).
- P. A. Steudler, R. D. Bowden, J. M. Melillo, J. D. Aber, Influence of nitrogen fertilization on methane uptake in temperate forest soils. *Nature* **341**, 314–316 (1989).
- B. K. Sitaula, CH₄ uptake by temperate forest soil: Effect of N input and soil acidification. *Soil Biol. Biochem.* **27**, 871–880 (1995).
- P. L. E. Bodelier, H. J. Laanbroek, Nitrogen as a regulatory factor of methane oxidation in soils and sediments. *FEMS Microbiol. Ecol.* **47**, 265–277 (2004).
- G. M. King, S. Schnell, Ammonium and nitrite inhibition of methane oxidation by *Methylobacter albus* BG8 and *Methylosinus trichosporium* OB3b at low methane concentrations. *Appl. Environ. Microbiol.* **60**, 3508–3513 (1994).
- M. A. Bradford, P. A. Wookey, P. Ineson, H. M. Lappin-Scott, Controlling factors and effects of chronic nitrogen and sulphur deposition on methane oxidation in a temperate forest soil. *Soil Biol. Biochem.* **33**, 93–102 (2001).
- Q. Li, X. Song, S. X. Chang, C. Peng, W. Xiao, J. Zhang, W. Xiang, Y. Li, W. Wang, Nitrogen depositions increase soil respiration and decrease temperature sensitivity in a Moso bamboo forest. *Agric. For. Meteorol.* **268**, 48–54 (2019).
- W. de Vries, G. J. Reinds, P. Gundersen, H. Sterba, The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. *Glob. Chang. Biol.* **12**, 1151–1173 (2006).
- X. Tang, S. Liu, G. Zhou, D. Zhang, C. Zhou, Soil-atmospheric exchange of CO₂, CH₄, and N₂O in three subtropical forest ecosystems in southern China. *Glob. Chang. Biol.* **12**, 546–560 (2006).
- G. Zhou, E. Liu, Y. Shi, A. Liu, Y. Zhou, Accurate estimation for Moso bamboo (*Phyllostachys edulis*) biomass in Zhejiang province based on the lowest scale technique. *Sci. Sil. Sin.* **47**, 1–5 (2011).
- G. Zhou, P. Jiang, Density, storage and spatial distribution of carbon in *Phyllostachys pubescens* forest. *Sci. Sil. Sin.* **40**, 20–24 (2004).

Acknowledgments

Funding: This study was sponsored by the National Natural Science Foundation of China (grant nos. 31470529 and 31270517) and the Natural Sciences and Engineering Research Council of Canada (NSERC) Discover Grant. **Author contributions:** X.S. and C.P. designed research. X.S. and Q.L. performed research, collected, and analyzed data. X.S., C.P., P.C., W. Xiang, W. Xiao, G.Z., and L.D. discussed and wrote the paper. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the corresponding author (X.S.).

Submitted 8 January 2019
Accepted 20 December 2019
Published 18 March 2020
10.1126/sciadv.aaw5790

Citation: X. Song, C. Peng, P. Ciais, Q. Li, W. Xiang, W. Xiao, G. Zhou, L. Deng, Nitrogen addition increased CO₂ uptake more than non-CO₂ greenhouse gases emissions in a Moso bamboo forest. *Sci. Adv.* **6**, eaaw5790 (2020).

Nitrogen addition increased CO₂ uptake more than non-CO₂ greenhouse gases emissions in a Moso bamboo forest

Xinzhang Song, Changhui Peng, Philippe Ciais, Quan Li, Wenhua Xiang, Wenfa Xiao, Guomo Zhou, and Lei Deng

Sci. Adv. **6** (12), eaaw5790. DOI: 10.1126/sciadv.aaw5790

View the article online

<https://www.science.org/doi/10.1126/sciadv.aaw5790>

Permissions

<https://www.science.org/help/reprints-and-permissions>

Use of this article is subject to the [Terms of service](#)

Science Advances (ISSN 2375-2548) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science Advances* is a registered trademark of AAAS.

Copyright © 2020 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).