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

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[1] The responses of soil methane (CH_4) net fluxes to nitrogen (N) addition in a N-fixing tree species (*Acacia auriculiformis* (*AA*)) and a non-N-fixing tree species (*Eucalyptus citriodora* (*EU*)) plantation were studied in southern China. Treatments were conducted at each plantation with three N levels (0, 50, and 100 kg N ha^{-1} yr^{-1} for control, medium-N, and high-N treatment, respectively, abbreviated as C, MN, and HN). From August 2010 to July 2011, CH_4 flux was measured biweekly using a static chamber and gas chromatography technique. The soils of both sites acted as sink of atmospheric CH_4. The CH_4 uptake rate in control of the *AA* site (36.3 ± 3.2 μg CH_4-C m^{-2} h^{-1}) was greater than that of the *EU* plantation (29.9 ± 0.9 μg CH_4-C m^{-2} h^{-1}). In the *AA* plantation, the averaged rates of CH_4 uptake for the MN (28.6 ± 2.3 μg CH_4-C m^{-2} h^{-1}) and HN treatment (23.8 ± 2.8 μg CH_4-C m^{-2} h^{-1}) were decreased by 21% and 35%, respectively, compared to the control. However, there was no change of soil CH_4 uptake between N-treated plots and the controls in the *EU* site. Our results indicated that there might be large difference of inhibitive effect of N deposition on soil CH_4 oxidation between the *AA* and *EU* plantations. The projected increase of N deposition would weaken the capability of N-fixing tree species plantations for atmospheric CH_4 sink in tropical and subtropical regions.

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1. Introduction

[2] Humans have altered regional and global cycles of N more than any other element [*Vitousek et al.*, 1997]. Atmospheric N deposition rates have increased dramatically during recent decades because of intensive agricultural and industrial activities [*Gruber and Galloway*, 2008]. Globally, the quantity of N deposition increased from 41 Tg N yr^{-1} in 1950 to 103 Tg N yr^{-1} in 2000 [*Galloway et al.*, 2008]. Worldwide N deposition was projected to increase by 50%–100% by 2030 relative to 2000, with the greatest absolute increases occurring over East and South Asia [*Reay et al.*, 2008]. As a developing country, China has a dramatic increase in atmospheric N deposition since 1980s [*Liu et al.*, 2011]. N deposition via precipitation in southern China has been reported to range from 30 to 73 kg N ha^{-1} yr^{-1} [*Xu et al.*, 2001; *Zhou and Yan*, 2001; *Huang et al.*, 2010], and was projected to increase in the coming decades [*Galloway et al.*, 2004; *Liu et al.*, 2011]. Excess N deposition has aroused concerns about its negative impacts on ecosystem health and services [*Galloway et al.*, 2008], such as loss of biodiversity [*Sala et al.*, 2000; *Lu et al.*, 2010], N saturation and soil acidification [*Aber et al.*, 1998; *Vogt et al.*, 2006], and inhibition of the capability of CH_4 oxidization in forest soils [*Steudler et al.*, 1989; *Aronson and Helliker*, 2010].

[3] Methane is an important greenhouse gas (GHG) with a global warming potential of 25 times more than carbon dioxide (CO_2) over a 100 year period, contributing about 17% to climate warming [*Intergovernmental Panel on Climate Change*, 2007]. The global atmospheric concentration of CH_4 has increased from a preindustrial value of about 0.715 ppm to 1.803 ppm in 2009 [*World Meteorological Organization*, 2010]. After a short-term period of stabilization during 1990–2006, the atmospheric CH_4 levels are increasing again since 2007 [*Bloom et al.*, 2010], leading to intensified research efforts regarding variability in sources and sinks of atmospheric CH_4 [*Bodelier*, 2011]. Forest soils are an important CH_4 sink or source through the activity of methanotrophic and methanogenes bacteria [*Castro et al.*,

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Table 1. Indices of the Tree Structure in *AA* and *EU* Plantations[a]

	AA Plantation			*EU* Plantation		
	Acacia auriculiformis	Other Plants	Total	*Eucalyptus citriodora*	Other Plants	Total
Stem density (tree ha^{-2})	357	1719	2076	1186	776	1961
Mean height (m)	12.2	5.6		11.5	4	
Diameter at breast height (cm)	15	4.8		11.1	3.9	
Tree age (yr)	27			27		
Basal area (m^2 ha^{-2})	7.3	5.2	12.5	14.7	2	16.7
Percentage of basal area (%)	59	41	100	88	12	100

[a]The survey was conducted in July 2010 (27 yr after tree planting) before the first N application.

1995; *Le Mer and Roger*, 2001]. The diffusivity of CH_4 through the soil profile is the primary limiting factor upon CH_4 oxidation, which is influenced by soil moisture and bulk density [*Teh et al.*, 2005; *Kolb*, 2009]. Furthermore, soil available N contents (NH_4^+ and NO_3^-) can limit CH_4 oxidation directly by competing with the monooxygenase enzyme of methanotrophs [*Hanson and Hanson*, 1996; *Nyerges and Stein*, 2009].

[4] Increased N availability due to N deposition may inhibit the oxidation capacity of forest soils for atmospheric CH_4 [*Aronson and Helliker*, 2010]. Laboratory studies indicated that oxidation of CH_4 by a variety of methanotrophs was inhibited competitively by N input [*Ferenci et al.*, 1975]. It has generally been accepted that the consumption of CH_4 in forest soil is inhibited by N addition [*Steudler et al.*, 1989; *Castro et al.*, 1994; *Mochizuki et al.*, 2012]. However, not all studies support the general conclusion. *Bradford et al.* [2001a] found that N deposition had no significant effect on soil CH_4 oxidation in a temperate deciduous woodland in southwest England. Positive effects of N addition on soil CH_4 uptake rates were observed in severely N-limited forests [*Börjesson and Nohrstedt*, 2000; *Steinkamp et al.*, 2001]. Further studies should be undertaken to better understand the mechanisms responsible for N deposition-induced suppression of CH_4 uptake in forest soils.

[5] According to *Food and Agriculture Organization of the United Nations* (*FAOUN*) [2010], forest plantations occupy about 264 million ha worldwide. The total area of plantations in China is 53.6 million ha, accounting for approximately 30% of the total forest area (available from the seventh national forest resources inventory of China [in Chinese], http://www.forestry.gov.cn/portal/main/s/65/content-326341.html). The percentage of forest land cover in the Pearl River Delta, Guangdong Province, increased from 26% in 1970 to 49.5% in 2010 [*Peng et al.*, 2009; *Zhang et al.*, 2012], most of which are *Eucalyptus* spp., *Acacia* spp., and some native species [*Chen et al.*, 2011]. Afforestation may affect CH_4 fluxes by altering some key physical and chemical properties in soils, and soil microbial activity as well [*Merino et al.*, 2004]. Most studies focused on the effect of plantation on mitigation of GHGs and C sequestration [*Liu and Greaver*, 2009; *Peichl et al.*, 2010]. Few efforts have been made to investigate the effect of tree species on the fluxes of soil CH_4 uptake [*H. Wang et al.*, 2010; *Christiansen and Gundersen*, 2011].

[6] In this study, we investigated the effect of N addition on soil CH_4 fluxes in an *Acacia auriculiformis* (*AA*) (N-fixing tree species) and a *Eucalyptus citriodora* (*EU*) (non-N-fixing tree species) plantation in southern China, where atmospheric N deposition has elevated dramatically in recent years [*Fang et al.*, 2011]. The main objective was to determine the differential effect of N addition on soil CH_4 uptake in the two plantations. We hypothesized that (1) the rate of soil CH_4 uptake in the *EU* plantation would be higher than that of the *AA* site, due to higher soil available N contents in the later; (2) N addition would significantly inhibit soil CH_4 uptake in both plantations because of elevated soil N availability; and (3) the inhibitive effect of N addition on soil CH_4 oxidation would be higher in the *AA* stand because of additional N input into the soil via biological N fixation for the *AA* plantation.

2. Materials and Methods

2.1. Site Description

[7] This study is conducted at the Heshan National Field Research Station of Forest Ecosystems (112°50′E, 22°34′N), which is located in the middle of Guangdong Province, Southern China. The region has a tropical monsoon climate with a distinct wet and dry season. The mean annual temperature and precipitation are 22.5°C and 1534 mm from 2004 to 2009 [*Wu et al.*, 2011]. Atmospheric N deposition in precipitation is about 43.1 ± 3.9 kg N ha^{-1} yr^{-1}, with 1:1 ratio for NH_4^+ to NO_3^- (unpublished data, measured from July 2010 to June 2012). We selected two plantations, one with a N-fixing and one with a non-N-fixing tree species, for experimental sites. The two sites were located 500 m apart. The survey conducted in July 2010 (before the start of N addition) showed that the main species in the canopy layer of the *AA* plantation was *Acacia auriculiformis*, and the *EU* plantation was *Eucalyptus citriodora.* Indices of the tree structure of both plantations are given in Table 1. The soils in both sites are classified as Acrisol [*FAOUN*, 2006]. Soil bulk density (SBD) is 1.3 and 1.2 g cm^{-3} for *AA* and *EU* site, respectively. A pretreatment survey of the general soil properties showed no differences among the treated plots in each plantation before N treatment (data not shown).

2.2. Experimental Treatment

[8] Two N treatments and a reference control were established within each plantation in July 2010: control (C, without N addition), medium-N (MN, 50 kg N ha^{-1} yr^{-1}) and high-N (HN, 100 kg N ha^{-1} yr^{-1}). The experiment was a randomized complete block design: each of the two N treatments and a control were randomly located in three blocks per plantation type, with a total of 9 plots (10 × 10 m). Each plot was surrounded by a 10 m wide buffer strip. Ammonium nitrate (NH_4NO_3) solutions were sprayed monthly to the

floor with a backpack sprayer starting from August 2010 to July 2011. NH_4NO_3 was weighed and dissolved in 10 L water for each plot. Each control plot received 10 L water simultaneously.

2.3. Field Sampling and Measurements

[9] Soil CH_4 fluxes (summation the rate of CH_4 production and consummation) were measured biweekly from August 2010 to July 2011 using a static chamber method, and thus represent the balance between CH_4 production and consummation. Two static chambers were installed in each plot in June 2010, two months before the first gas sampling campaign. The chambers were made of polyvinylchloride (PVC) pipe with an internal diameter of 25 cm and included two parts: (1) permanent collar and (2) chamber. The collars were permanently installed in the field to a depth of 5 cm. The headspace height of the chamber was 30 cm and hence the headspace volume was 14,719 mL. During gas collecting, the chamber was fitted tightly to the collar with a rubber band. Gas samples were collected from each chamber from 09:00 to 10:00 A.M. (local time). Diurnal studies in tropical forests of southern China showed that soil CH_4 flux measured during the midmorning (09:00–10:00 LT) was close to the daily mean [*Tang et al.*, 2006]. Gas samples were collected with 60 mL plastic syringes (Double-Dove group CO., LTD, Shanghai, China) at 0, 15 and 30 min intervals after the chamber closure. Before each sampling, syringe was flushed 2 or 3 times with chamber gas to mix the headspace. CH_4 concentrations were analyzed within 24 h using a gas chromatograph (Agilent 5890 D, USA) equipped with a flame ionization detector (FID). Calibration gas (CH_4 at 3.52 ppm) was obtained from the Institute of Atmospheric Physics, Chinese Academy of Sciences (Beijing, China). The calculation of CH_4 flux followed that described by *Zhang et al.* [2008], by a linear regression of chamber gas concentration versus the incubation time [*International Atomic Energy Agency*, 1992; *Holland et al.*, 1999].

[10] Atmospheric pressure was measured at sampling site using an air pressure gauge (Model THOMMEN 2000, Switzerland). Air temperature (inside chamber), soil temperature (5 cm depth) and moisture (0–10 cm depth) were measured simultaneously in each gas sampling. Temperature was measured using a digital thermometer (TES-1310, Ltd., China). Soil moisture content (0–10 cm depth) was detected using an ADR probe (Amplitude Domain Reflectometry, Model Top TZS-I, China), and converted to water-filled pore space (WFPS) as the following formula:

$$WFPS = Vol/(1 - SBD/2.65) \quad (1)$$

where *WFPS* is water-filled pore space (%), *Vol* is volumetric water content (%), *SBD* is soil bulk density (g cm^{-3}), and 2.65 is the density of quartz (g cm^{-3}).

[11] Soil samples were collected in July 2011 (after 1 yr of N application) for analyzing chemical properties. Five soil cores (3.5 cm diameter) were collected randomly from each plot at 0–10 cm depth and combined to one composite sample, resulting in three samples for each treatment per plantation type. After removing stones and coarse roots, the samples were passed through a 2 mm mesh and divided into two parts. One part of fresh soil was used for the analysis of NH_4^+-N, NO_3^--N, microbial biomass C (MBC), and microbial biomass N (MBN) concentrations. The other part was air-dried at room temperature (25°C) for the estimation of other chemical parameters. Soil moisture contents and pH values (1:2.5 soil/water suspension) were determined immediately after sieving. Gravimetric water content was determined through oven drying at 105°C for 48 h. Soil pH value was measured using a pH meter (HM-30 G, TOA Corp., Japan). Soil NH_4^+ and NO_3^- contents were analyzed colorimetrically after being extracted using 2 M KCl. Soil organic carbon (SOC) was determined by wet digestion with a mixture of potassium dichromate and concentrated sulphuric acid [*Liu et al.*, 1996]. Total N concentration was determined by the micro-Kjeldahl digestion [*Bremner and Mulvaney*, 1982], followed by detection of ammonium with a UV-8000 Spectrophotometer (Metash Instruments Corp., Shanghai, China). Soil MBC was estimated by chloroform fumigation-extraction [*Vance et al.*, 1987], and MBN by applying the procedure of *Brookes et al.* [1985]. Available P was extracted with 0.03 M ammonium fluoride and 0.025 M hydrochloric acid and analyzed colorimetrically [*Anderson and Ingram*, 1989].

[12] Two litterfall traps (1.0 × 1.0 m with a mesh size of 1 mm) were established in each plot. Litterfall was collected monthly and sorted into categories of leaf, seed, branch and miscellaneous material. The samples were oven-dried at 65°C for 48 h and weighed to determine biomass. Soil coring method was used to investigate fine root (≤2 mm) biomass [*Vogt and Persson*, 1991]. A total of three soil cores (0–20 cm depth) were collected using an 8.7 cm diameter stainless steel core from each plot. Fine root samples were oven-dried at 65°C for 48 h and weighed.

2.4. Statistical Analysis

[13] Two-way Repeated Measures Analysis of Variance was used to examine the effect of N treatments on soil CH_4 fluxes from August 2010 to July 2011. One-way ANOVA was used to examine the difference in soil pH, NH_4^+, NO_3^-, and available P among treatments, as well as the difference in CH_4 uptake rate between sites. Linear regression analysis was performed to quantify the relationship between CH_4 fluxes and soil temperature or WFPS. Repeated measures ANOVA analysis was performed using the MIXED procedure; ANOVA and linear regression were performed using the GLM procedure in SAS (SAS Institute Inc., Cary NC, USA). Graphic illustrations were generated using Origin 8.0 software (Origin Lab Corporation, Northampton, MA, USA). Statistically significant difference was set at $p = 0.05$ level unless otherwise stated. Mean values ±1 standard error are reported in the text.

3. Results

3.1. Soil Temperature and Water-Filled Pore Space

[14] Soil temperature at 5 cm depth and WFPS (0–10 cm) exhibited clear seasonal patterns in the controls of both plantations, and followed the seasonal patterns of air temperature and rainfall, respectively, at Heshan Station (Figure 1). The soils were warmer and wetter from April to September (growing season), and became cooler and dryer from November to March of next year (dormant season). The annual mean soil temperatures (5 cm depth) were 20.3 ±

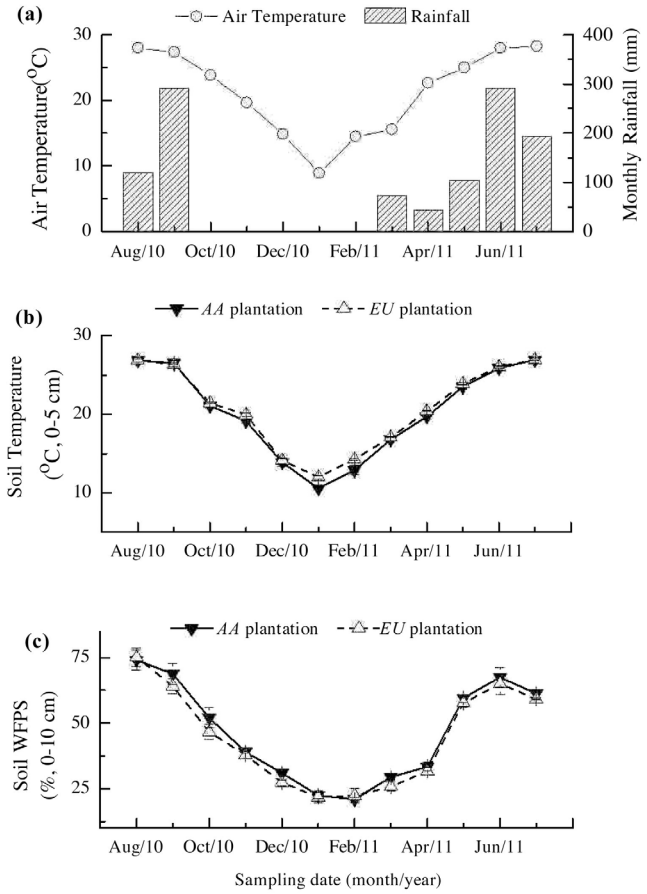

Figure 1. Weather and microclimate conditions at the experiment site. (a) Monthly rainfall and air temperature from August 2010 to July 2011, (b) seasonal patterns of soil temperature at 5 cm depth, and (c) soil water-filled pore space at 0–10 cm depth. Error bars represent standard error of means (n = 3).

0.7°C and 20.7 ± 0.9°C for the controls of *AA* and *EU* plantations, respectively. The average of WFPS (0–10 cm) were 46.6% and 44.9% for the controls in the *AA* and *EU* sites, respectively. Monthly means of WFPS and temperature were similar between *AA* and *EU* plantations (One-way ANOVA test, $p > 0.05$). There was no difference between the N-treated plots and controls at each plantation in terms of soil temperature ($p = 0.57$ and 0.61 for *AA* and *EU*, respectively) and WFPS ($p = 0.63$ and 0.70 for *AA* and *EU*, respectively).

3.2. Soil CH_4 Fluxes

[15] The soils of both *AA* and *EU* plantations were net sink of atmospheric CH_4 during the study period (Figures 2a and 2b). The averaged soil CH_4 uptake rate in controls of *AA* (36.3 ± 3.2 μg CH_4-C m^{-2} h^{-1}) was greater than that of *EU* plantation (29.9 ± 0.9 μg CH_4-C m^{-2} h^{-1}; $p = 0.046$). In *AA* plantation, the annual mean rates of CH_4 uptake were significantly decreased by 21%, and 35% in MN (28.6 ± 2.3 μg CH_4-C m^{-2} h^{-1}), and HN treatments (23.8 ± 2.8 μg CH_4-C m^{-2} h^{-1}), respectively, relative to the controls (Figure 2a; $p = 0.011$). However, no significant difference was found among the treatments of the *EU* site (Figure 2b).

[16] The rates of CH_4 uptake and soil WFPS were positively correlated in the controls of both plantations ($p < 0.01$, $R^2 = 0.23$ and 0.19 for the *AA* and *EU* site, respectively) (Figure 3). Under similar soil WFPS condition, CH_4 uptake rate was generally greater in *AA* than in *EU* site when WFPS < 70%. Soil CH_4 uptake rates were not correlated to soil temperatures (5 cm depth) in both plantations during the study period ($p > 0.05$).

3.3. Seasonal Patterns of CH_4 Uptake

[17] Soil CH_4 uptake rates in the N-treated plots showed a similar seasonal pattern to the controls of each plantation (Figures 4a and 4b). The rates of CH_4 uptake of both plantation types were greater in fall and lower in spring (Figures 4a and 4b). Two-way repeated measures ANOVA test showed that CH_4 uptake rates in N-treated plots of the *AA* plantation significantly decreased ($p = 0.034$) following N inputs compared with the controls (Figure 4a).

3.4. Other Soil Properties

[18] The soils showed pronounced variations with N treatment levels (Table 2). HN treatments increased contents of soil NH_4^+ and NO_3^- in *AA* plantation, while only increased NO_3^- contents in the *EU* site (Table 2). Soil CH_4 uptake negatively related to soil NO_3^- or NH_4^+ contents in the *AA* plantation (Figures 5a and 5b), while only negatively related to NO_3^- contents ($p < 0.01$, $R^2 = 0.28$) in the *EU* plantation (Figures 5c). After one year of N inputs, there were no changes of SOC and soil available P among plots in each plantation ($p > 0.05$, Table 2). In *AA* plantation, soil total N (TN) concentrations increased following N addition, and the difference between the controls and the HN plots was significant (Table 2). Accordingly, N addition significantly decreased C/N ratio in *AA* plantation (Table 2). For the *EU* plantation, soil TN concentrations and C/N ratio had no change following N addition (Table 2; $p > 0.05$). Soil MBC decreased in the same way in MN- and HN-treated plots of *AA* plantation, compared to their controls (Table 2). There was no response of soil MBN to N addition at both plantations (Table 2). Soil pH value decreased significantly only in the HN-treated plots of *AA* plantation (Table 2). Fine root biomass (to a depth of 20 cm, diameter ≤2 mm) was significantly decreased by N addition at the *AA* plantation (Table 2). The annual total litterfall mass of the controls at the *AA* site was greater than that at the *EU* plantation ($p = 0.02$, Table 2). There was no N treatment effect on litterfall mass at each plantation (Table 2).

4. Discussion

4.1. Effect of Soil Temperature and Water-Filled Pore Space

[19] Soil CH_4 uptake was correlated negatively with WFPS in our study, which was consistent with previous studies [*Castro et al.*, 1995; *Kiese et al.*, 2003; *Davidson and Nepstad*, 2004; *Christiansen and Gundersen*, 2011]. We found that CH_4 uptake in the two plantation soils was increased mainly in fall of 2010, which coincided with lower soil water content. Methanotrophs use CH_4 as the only C and energy source and oxygen availability is the main factor limiting their activity [*Le Mer and Roger*, 2001]. Lower WFPS might lead to greater soil aeration, which favors

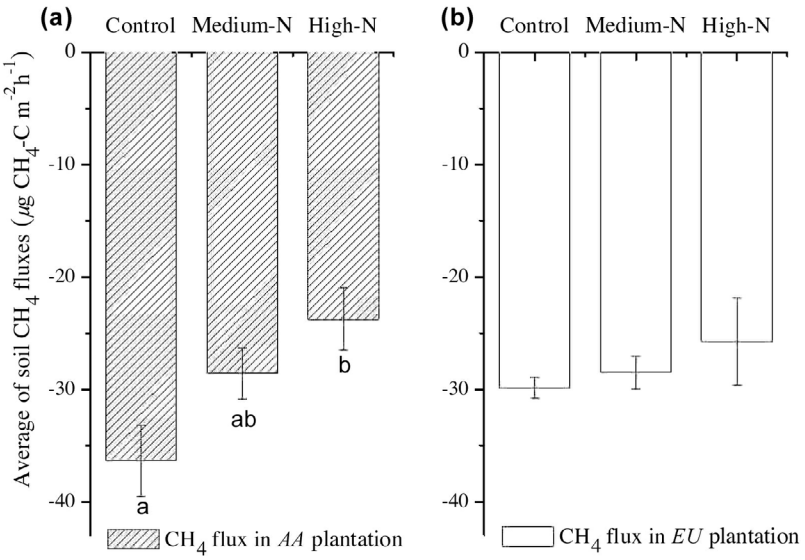

Figure 2. Comparisons of mean soil CH_4 fluxes between N treatment plots and the controls at (a) *AA* and (b) *EU* plantations. Error bars indicate ±1 SE (n = 3). Different letters "a, b" denote significant difference ($p \leq 0.05$) between treatments.

diffusion of atmospheric CH_4 and O_2 into soil profile for methanotrophs bacteria [*Ball et al.*, 1997; *Kolb*, 2009].

[20] Soil temperature variation had no effect on soil CH_4 uptake in the present study, which was consistent with previous results from tropical forests in southern China [*Tang et al.*, 2006; *H. Wang et al.*, 2010; *Zhang et al.*, 2011]. In contrast, soil CH_4 oxidation in temperate or boreal regions was generally positively correlated with soil temperature [*Maljanen et al.*, 2006]. In our study, almost all of soil temperatures were between 15 and 30°C, within the optimum temperature (22 to 38°C) for CH_4 oxidation [*de Visscher et al.*, 2007]. Therefore, we concluded that soil temperature might not be a primary factor controlling CH_4 oxidization in tropical plantations of Southern China.

4.2. Methane Uptake

[21] The CH_4 uptake rates observed in the present study are similar to those found in some other tropical forests within the Pearl River Delta region (2.5 to 4.3 kg CH_4-C ha^{-1} yr^{-1}) [*Tang et al.*, 2006; *Zhang et al.*, 2008; *Zhang et al.*, 2011], or other tropical plantations in southern China (2.3 to 3.4 kg CH_4-C ha^{-1} yr^{-1}) [*Werner et al.*, 2006; *Yan et al.*, 2008; *H. Wang et al.*, 2010]. The CH_4 uptake rates in the present study were also within the range (0.8 to

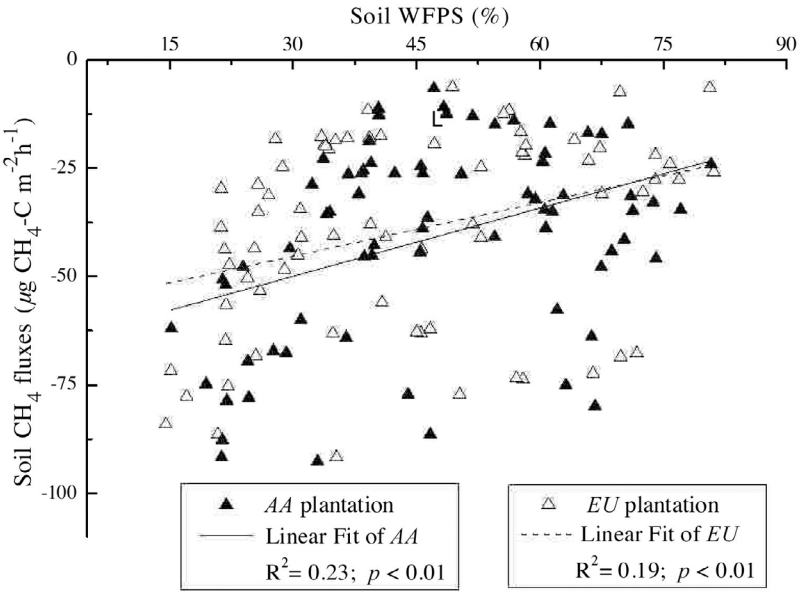

Figure 3. Correlations between CH_4 flux and soil water-filled pore space (WFPS) for the controls in both stands.

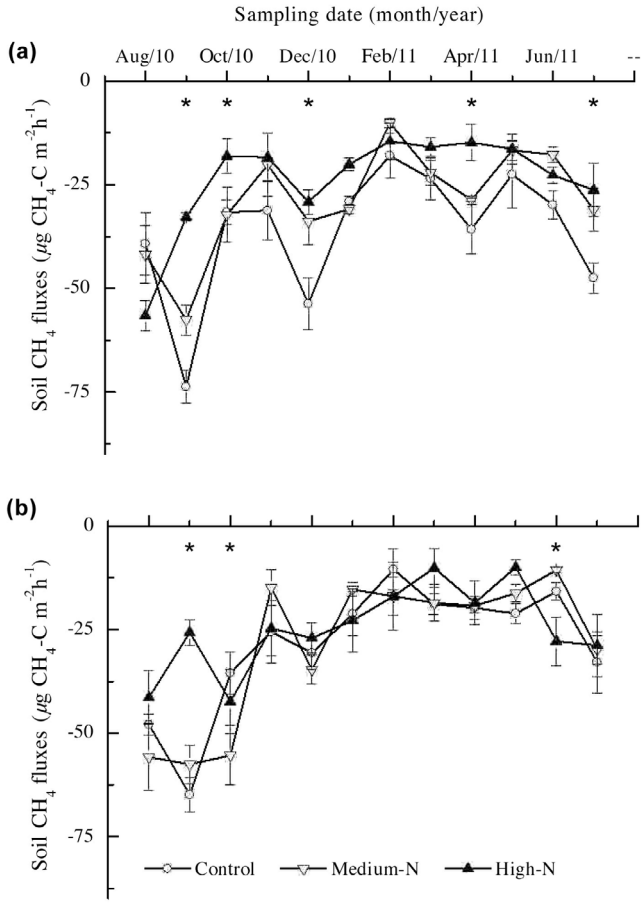

Figure 4. Seasonal pattern of soil CH_4 uptake in (a) *AA* and (b) *EU* plantation. Asterisk (*) indicates significant differences between control and at least one of N addition treatments at $p = 0.05$ level. Error bars indicate ± 1 SE (n = 3).

4.7 kg CH_4-C ha^{-1} yr^{-1}) reported for tropical forests in other regions [*Steudler et al.*, 1991; *Kiese et al.*, 2003; *Davidson and Nepstad*, 2004; *Werner et al.*, 2007; *Davidson et al.*, 2008].

[22] Contrary to our expectation, the *AA* plantation had higher CH_4 uptake rate than the *EU* site, although soil NH_4^+ and NO_3^- concentrations in the *AA* were approximately 20% and 31% higher, respectively. This seems in contrast with the fact that higher soil NH_4^+ or NO_3^- level could inhibit the activity of methanotroph bacteria. Owing to their ability to fix atmospheric N_2 through microbial symbiosis, *Acacia* spp. can improve plant growth and thereby increase soil C and N cycling and stocks in soils [*Macedo et al.*, 2008; *Voigtlaender et al.*, 2012]. In terms of the present study, the litterfall input, fine root biomass and SOC content were higher in the *AA* than the *EU* site (Table 2). As a consequence, the structural stability and macropores, all of which favor the diffusiveness of CH_4 and O_2 into the soil profile [*Merino et al.*, 2004], are greater in the *AA* site. Therefore CH_4 oxidation in the *AA* site was higher than the *EU* site.

[23] Contrary to the present study, some previous studies did not find a positive influence of *Acacia* spp. [*Fest et al.*, 2009] or *Acacia mangium* [*Konda et al.*, 2010] on the magnitude of CH_4 uptake. This might be due to the young growing stage of the plantations studied. For example, *Konda et al.* [2008] made the measurements at the plantation of 7 yr old. In our study, the improved SOC and soil fertility of the *AA* compared to that of the *EU* plantation might be a result of 27 yr restoration [*F. Wang et al.*, 2010]. If these plantations result in higher CH_4 uptake as observed in our study, there would be a greater potential of atmospheric CH_4 sink, since globally there are 8.3 million hectares of *Acacia* spp. plantation, with 96% in Asia [*FAOUN*, 2010].

4.3. Effect of N Addition

[24] The inhibitive effect of N addition on CH_4 uptake in the *AA* was greater than that of *EU* plantation. The observations may be due to differences in soil N saturation thresholds between the two sites. There was no impact of adding N in the *EU* plantation probably because there was less N to begin with. Symbiotic N fixers (*Azotobacteria*) are abundant in the *AA* plantation (but not in the *EU* stand), which act to incorporate large amounts of new N into soil because of legumes plants fixing more atmospheric N_2 [*Hedin et al.*, 2009]. Therefore, the *AA* plantation presents an initial N-rich soil, and the *EU* plantation dominated by a fast-growing tree species (*Eucalyptus* spp., non-N-fixing tree species) did not. The threshold for N addition to decrease consumption needed less additional N in *AA* than

Table 2. Soil Properties (0–10 cm Depth), Fine Root and Litter Mass at the Two Plantations[a]

	AA Plantation				*EU* Plantation			
	Control	Medium N	High N	*P* Values	Control	Medium N	High N	*P* Values
SOC (g kg^{-1})	22.1 (2.3)	19.0 (1.6)	21.4 (0.2)	$p > 0.05$	15.5 (0.9)	15.6 (2.1)	16.1 (0.8)	$p > 0.05$
NH_4^+ (mg kg^{-1})	16.0 (1.0) b	19.5 (1.4) b	23.5 (1.2) a	***p = 0.04***	13.4 (2.0)	13.9 (2.7)	14.3 (2.9)	$p > 0.05$
NO_3^- (mg kg^{-1})	17.8 (1.4) b	27.3 (3.5) ab	33.1 (2.0) a	***p = 0.01***	13.6 (2.6) b	21.1 (2.3) a	23.6 (2.3) a	***p = 0.03***
Total N (g kg^{-1})	1.6 (0.1) b	1.8 (0.3) ab	2.2 (0.10) a	***p = 0.04***	1.5 (0.1)	1.5 (0.29)	1.8 (0.19)	$p > 0.05$
C/N ratio	13.8 (1.7) a	11.4 (1.7) ab	9.6 (0.24) b	***p = 0.02***	10.3 (0.8)	10.5 (1.0)	9.0 (0.8)	$p > 0.05$
Available P (mg kg^{-1})	1.8 (0.2)	1.9 (0.2)	1.9 (0.6)	$p > 0.05$	1.6 (0.3)	1.1 (0.3)	2.0 (0.3)	$p > 0.05$
MBC (mg kg^{-1})	254 (13.7) a	215 (9.7) b	204 (14.6) b	***p = 0.03***	288 (21.3) a	279 (24.4) a	206 (22.7) b	***p = 0.04***
MBN (mg kg^{-1})	41.4 (3.6)	51.5 (5.7)	46.1 (6.5)	$p > 0.05$	43.9 (5.6)	31.1 (0.4)	38.9 (6.7)	$p > 0.05$
pH	3.83(0.03) a	3.80 (0.04) a	3.73 (0.03) b	***p = 0.03***	3.91 (0.05)	3.90 (0.04)	3.81 (0.02)	$p > 0.05$
Fine root (g m^{-2})	92.9 (13.6) a	62.8 (6.4) b	63.2 (6.3) b	***p = 0.03***	74.4 (3.2)	87.0 (7.2)	85.8 (6.4)	$p > 0.05$
Litter mass (g m^{-2} yr^{-1})	694.1 (25)	668.5 (56)	745.0 (24)	$p > 0.05$	590.2 (14)	477.4 (14)	483.9 (44)	$p > 0.05$

[a]Soil samples were collected in July 2011 after 1 yr of N additions. Values are presented as means with SE in parentheses (n = 3). Different letters between treatments denote significant difference (Tukey's HSD test, $p \leq 0.05$). Fine root (<2 mm) was sampled to a depth of 0–20 cm. The *p* values are given in boldface when $p = 0.05$. *AA*, *Acacia auriculiformis*; *EU*, *Eucalyptus citriodora*; SOC, soil organic carbon; C/N ratio, SOC/total N ratio; MBN, microbial biomass N.

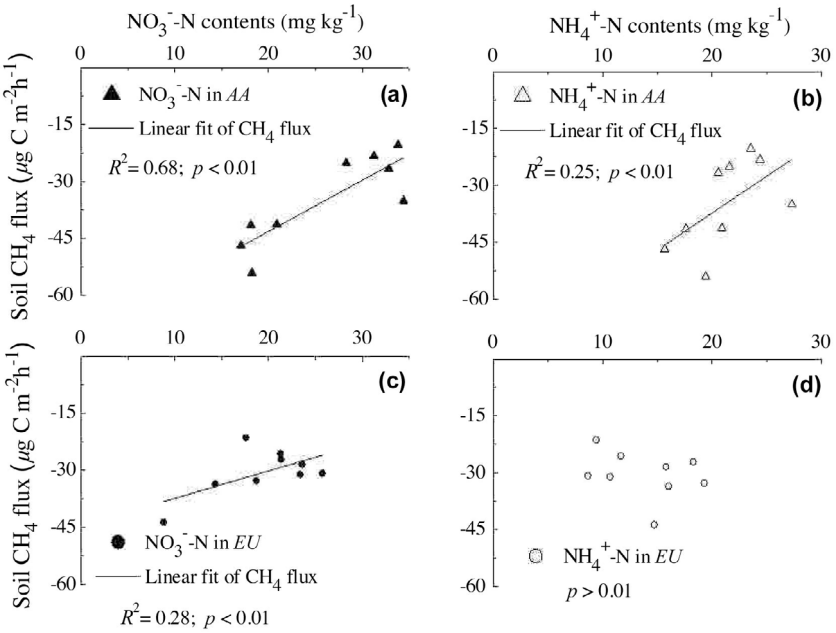

Figure 5. Relationships between CH_4 fluxes and soil NH_4^+ and NO_3^- contents in the (a, b) *AA* and (c, d) *EU* plantation. CH_4 fluxes were measured in field at the same day of soil sampling (17 July 2011).

EU, because of initial higher soil N content of *AA* plantation. Several factors, which caused the large difference of inhibitive effect of N addition on soil CH_4 oxidation between the two plantation types, are described below.

[25] First, high soil inorganic N concentrations in N treatments may lower the rates of CH_4 oxidation. Exceptionally high soil NH_4^+ and NO_3^- contents significantly suppressed CH_4 oxidation at *AA* plantation, as was originally hypothesized. The results were consistent with the previous findings [*Steudler et al.*, 1989; *King and Schnell*, 1994; *Castro et al.*, 1995; *Kim et al.*, 2012]. Methanotrophic bacteria have the ability to oxidize NH_4^+ in favorable conditions [*Hanson and Hanson*, 1996]. The existence of high NH_4^+ contents could act as competitive substrates for CH_4 oxidation organisms [*Bédard and Knowles*, 1989], or enzymatic activity of CH_4 monooxygenase [*Ferenci et al.*, 1975]. Furthermore, NO_3^- and/or NO_2^- produced from the NO_3^- reduction were perhaps toxic to CH_4-oxidizing microbes [*Dunfield et al.*, 1995; *Reay and Nedwell*, 2004]. We did not observe any change of soil NH_4^+ concentration in the *EU* plantation after N treatments. This was probably due to the tight nutrient cycling in the *EU* site, whereby N inputs were rapidly immobilized [*Attiwill et al.*, 1996].

[26] Second, the suppressive effect of N on the activation of CH_4 oxidation bacteria is another potential mechanism [*Castro et al.*, 1994]. A significant decrease of MBC following N input was an indirect evidence for the lower CH_4 oxidation in HN plots at the *AA* plantation, since the decrease of MBC may incur corresponding shrinkage of the organism pool responsible for CH_4 oxidation. In contrast, MBN was not changed in HN plots of *AA* plantation relative to the control. The potential reason might be abundance N absorbed by other preferable N microbes, which were easier subject to environmental factor changes (such as pH, nutrient availability, etc.) than methanotrophic bacteria [*Hanson and Hanson*, 1996]. Therefore, N addition might stimulate population growth of the other microbes in soil of *AA* plantation, which could result in outcompeting methanotrophic bacteria for N, O_2 and/or other nutrient.

[27] Third, the lower pH after N addition might contribute to the decrease in CH_4 uptake rate [*Hütsch*, 1998]. Most of the soils which pose substantial CH_4 oxidation capacity have pH values within the range of 3 $\sim$ 7.5 [*Born et al.*, 1990], with the optimal values of 5.0 $\sim$ 6.5 [*Le Mer and Roger*, 2001; *Kolb*, 2009]. Soil pH values of the two plantations were below 4 (Table 2). A significant decrease of pH value was associated with an increase of N treatment level in the *AA* plantation, and thus might lead to decreased CH_4 oxidation rate. Similarly, *Bradford et al.* [2001b] reported that the decrease of pH in a beech forest in Southwest England contributed to a decrease in soil CH_4 uptake. In addition, aluminum (Al^{3+}) release from exchangeable cations exchange in soils might increase as pH values decrease [*Bradford et al.*, 2001b]. Al^{3+} toxicity after N input might also inhibit soil CH_4 uptake in HN treatments of the *AA* plantation. Furthermore, work would be needed to establish whether such a link exists.

5. Conclusions

[28] In the present study, soil CH_4 fluxes following N addition were measured in two plantations either with N-fixing tree species (*AA* plantation) or non-N-fixing tree species (*EU* plantation) in the tropical region. Soils of the two plantations were all net sink of atmospheric CH_4. There were differential effects of N addition on soil CH_4 uptake in the two plantations. Nitrogen addition significantly lowered soil CH_4 uptake in the *AA* plantation, however, there was no effect of N addition in the *EU* site. Alterations in CH_4 uptake might be resulted from N addition-induced changes in soil available N contents (NH_4^+, NO_3^-) and pH value, which affected the activities of bacteria responsible for CH_4 oxidation. As far as we known, our study is among the first to

investigate the effect of N deposition on soil CH_4 fluxes between reforestation with N-fixing species and non-N-fixing species. Our results implied that the projected increase of N deposition would potentially decrease the capacity of *AA* plantation as a sink of atmospheric CH_4 considering the large area of *AA* plantation in tropical/subtropical regions.

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References

Aber, J., M. McDowell, K. Nadelhoffer, A. Magill, G. Berntson, M. Kamakea, S. McNulty, W. Currie, L. Rustad, and I. Fernandez (1998), Nitrogen saturation in temperate forest ecosystems: Hypotheses revisited, *BioScience*, *48*(11), 921–934, doi:10.2307/1313296.

Anderson, J. M., and J. S. I. Ingram (1989), *Tropical Soil Biology and Fertility: A Handbook of Methods*, CAB Int., Wallingford, U. K.

Aronson, E. L., and B. R. Helliker (2010), Methane flux in non-wetland soils in response to nitrogen addition: A meta-analysis, *Ecology*, *91*(11), 3242–3251, doi:10.1890/09-2185.1.

Attiwill, P. M., P. J. Polglase, C. J. Weston, and M. A. Adams (1996), Productivity and nutrient cycling in forests of south-eastern Australia, in *Nutrition of Eucalypts*, edited by P. M. Attiwill and M. A. Adams, pp. 191–227, CSIRO, Melbourne, Australia.

Ball, B. C., K. A. Smith, L. Klemedtsson, R. Brumme, B. K. Sitaula, S. Hansen, A. Prieme, J. MacDonald, and G. W. Horgan (1997), The influence of soil gas transport properties on methane oxidation in a selection of northern European soils, *J. Geophys. Res.*, *102*(D19), 23,309–23,317, doi:10.1029/97JD01663.

Bédard, C., and R. Knowles (1989), Physiology, biochemistry, and specific inhibitors of CH_4, NH_4^+, and CO oxidation by methanotrophs and nitrifiers, *Microbiol. Rev.*, *53*(1), 68–84.

Bloom, A. A., P. I. Palmer, A. Fraser, D. S. Reay, and C. Frankenberg (2010), Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data, *Science*, *327*, 322–325, doi:10.1126/science.1175176.

Bodelier, P. L. E. (2011), Interactions between nitrogenous fertilizers and methane cycling in wetland and upland soils, *Curr. Opin. Environ. Sustainability*, *3*, 379–388, doi:10.1016/j.cosust.2011.06.002.

Börjesson, G., and H. Nohrstedt (2000), Fast recovery of atmospheric methane consumption in a Swedish forest soil after single-shot N-fertilization, *For. Ecol. Manage.*, *134*, 83–88, doi:10.1016/S0378-1127(99)00249-2.

Born, M., H. Dorr, and J. Levin (1990), Methane consumption in aerated soils of the temperate zone, *Tellus, Ser. B*, *42*, 2–8, doi:10.1034/j.1600-0889.1990.00002.x.

Bradford, M. A., P. A. Wookey, P. Ineson, and H. M. Lappin-Scott (2001a), Controlling factors and effects of chronic nitrogen and sulphur deposition on methane oxidation in a temperate forest soil, *Soil Biol. Biochem.*, *33*, 93–102, doi:10.1016/S0038-0717(00)00118-8.

Bradford, M. A., P. Ineson, P. A. Wookey, and H. M. Lappin-Scott (2001b), The effects of acid nitrogen and acid sulphur deposition on CH_4 oxidation in a forest soil: A laboratory study, *Soil Biol. Biochem.*, *33*, 1695–1702, doi:10.1016/S0038-0717(01)00091-8.

Bremner, J. M., and C. S. Mulvaney (1982), Nitrogen total, in *Methods of Soil Analysis, Agronomy, Chemical and Microbiological Properties. Part 2*, vol. 9, 2nd ed., edited by A. L. Page, pp. 595–624, Am. Soc. of Agron., Madison, Wisc.

Brookes, P. C., A. Landman, G. Pruden, and D. S. Jenkinson (1985), Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil, *Soil Biol. Biochem.*, *17*, 837–842, doi:10.1016/0038-0717(85)90144-0.

Castro, M. S., W. T. Peterjohn, J. M. Melillo, P. A. Steudler, H. L. Gholz, and D. Lewis (1994), Effects of nitrogen fertilization on the fluxes of N_2O, CH_4, and CO_2 from soils in a Florida slash pine plantation, *Can. J. For. Res.*, *24*, 9–13, doi:10.1139/x94-002.

Castro, M. S., P. A. Steudler, J. M. Melillo, J. D. Aber, and R. D. Bowden (1995), Factors controlling atmospheric methane consumption by temperate forest soils, *Global Biogeochem. Cycles*, *9*(1), 1–10, doi:10.1029/94GB02651.

Chen, D. M., C. L. Zhang, J. P. Wu, L. X. Zhou, Y. B. Lin, and S. L. Fu (2011), Subtropical plantations are large carbon sinks: Evidence from two monoculture plantations in South China, *Agric. For. Meteorol.*, *151*, 1214–1225, doi:10.1016/j.agrformet.2011.04.011.

Christiansen, J. R., and P. Gundersen (2011), Stand age and tree species affect N_2O and CH_4 exchange from afforested soils, *Biogeosciences*, *8*, 2535–2546, doi:10.5194/bg-8-2535-2011.

Davidson, E. A., and D. C. Nepstad (2004), Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest, *Global Change Biol.*, *10*, 718–730, doi:10.1111/j.1365-2486.2004.00762.x.

Davidson, E. A., D. C. Nepstad, F. Y. Ishida, and P. M. Brando (2008), Effects of an experimental drought and recovery on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest, *Global Change Biol.*, *14*, 2582–2590.

de Visscher, A., P. Boeckx, and O. van Cleemput (2007), Artificial methane sinks, in *Greenhouse Gas Sinks*, edited by D. Reay et al., pp. 184–200, CABI, New York, doi:10.1079/9781845931896.0184.

Dunfield, P. F., E. Topp, C. Archambault, and R. Knowles (1995), Effect of nitrogen fertilizers and moisture content on CH_4 and N_2O fluxes in a humisol: Measurements in the field and intact soil cores, *Biogeochemistry*, *29*, 199–222, doi:10.1007/BF02186048.

Fang, Y. T., P. Gundersen, R. D. Vogt, K. Koba, F. S. Chen, X. Y. Chen, and M. Yoh (2011), Atmospheric deposition and leaching of nitrogen in Chinese forest ecosystems, *J. For. Res.*, *16*, 341–350, doi:10.1007/s10310-011-0267-4.

Food and Agriculture Organization of the United Nations (FAOUN) (2006), *World Reference Base for Soil Resources: a Framework for International Classification, Correlation and Communication, World Soil Resources Report*, vol. 103, Food and Agric. Org. of the U. N., Rome.

Food and Agriculture Organization of the United Nations (FAOUN) (2010). *Global Forest Resources Assessment 2010: Main Report, FAO Forestry Paper*, vol. 163, Food and Agric. Org. of the U. N., Rome.

Ferenci, T., T. Strom, and J. R. Quayle (1975), Oxidation of carbon monoxide and methane by pseudomonas methanica, *J. Gen. Microbiol.*, *91*, 79–91, doi:10.1099/00221287-91-1-79.

Fest, B. J., S. J. Livesley, M. Drösler, E. Gorsel, and S. K. Arndt (2009), Soil–atmosphere greenhouse gas exchange in a cool, temperate *Eucalyptus delegatensis* forest in south-eastern Australia, *Agric. For. Meteorol.*, *149*, 393–406, doi:10.1016/j.agrformet.2008.09.007.

Galloway, J. N., et al. (2004), Nitrogen cycles: Past, present, and future, *Biogeochemistry*, *70*(2), 153–226, doi:10.1007/s10533-004-0370-0.

Galloway, J. N., A. R. Townsend, J. W. Erisman, M. Bekunda, Z. C. Cai, J. R. Freney, L. A. Martinelli, S. P. Seitzinger, and M. A. Sutton (2008), Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions, *Science*, *320*, 889–892, doi:10.1126/science.1136674.

Gruber, N., and J. N. Galloway (2008), An Earth-system perspective of the global nitrogen cycle, *Nature*, *451*, 293–296, doi:10.1038/nature06592.

Hanson, R. S., and T. E. Hanson (1996), Methanotrophic bacteria, *Microbiol. Rev.*, *60*, 439–471.

Hedin, L. O., E. N. J. Brookshire, D. N. L. Menge, and A. Barron (2009), The nitrogen paradox in tropical forest ecosystems, *Annu. Rev. Ecol. Evol. Syst.*, *40*, 613–635, doi:10.1146/annurev.ecolsys.37.091305.110246.

Holland, E. A., G. P. Robertson, J. Greenberg, P. M. Groffman, R. D. Boone, and J. R. Gosz (1999), Soil CO_2, N_2O, and CH_4 exchange, in *Standard Soil Methods for Long-Term Ecological Research*, edited by G. P. Robertson, pp. 185–201, Oxford Univ. Press, New York.

Huang, D. Y., Y. G. Xu, B. Zhou, H. H. Zhang, and J. B. Lan (2010), Wet deposition of nitrogen and sulfur in Guangzhou, a subtropical area in South China, *Environ. Monit. Assess.*, *171*, 429–439, doi:10.1007/s10661-009-1289-7.

Hütsch, B. W. (1998), Methane oxidation in arable soil as inhibited by ammonium, nitrite, and organic manure with respect to soil pH, *Biol. Fertil. Soils*, *28*, 27–35, doi:10.1007/s003740050459.

International Atomic Energy Agency (1992), *Manual on Measurements of Methane and Nitrous Oxide Emission from Agriculture*, 91 pp., Int. At. Energy Agency, Vienna.

Intergovernmental Panel on Climate Change (2007), *Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry et al., Cambridge Univ. Press, Cambridge, U. K.

Kiese, R., B. Hewett, A. Graham, and K. Butterbach-Bahl (2003), Seasonal variability of N_2O emissions and CH_4 uptake by tropical rainforest soils of Queensland, Australia, *Global Biogeochem. Cycles*, *17*(2), 1043, doi:10.1029/2002GB002014.

Kim, Y. S., M. Imori, M. Watanabe, R. Hatano, M. J. Yi, and T. Koike (2012), Simulated nitrogen inputs influence methane and nitrous oxide fluxes from a young larch plantation in northern Japan, *Atmos. Environ.*, *46*, 36–44, doi:10.1016/j.atmosenv.2011.10.034.

King, G. M., and S. Schnell (1994), Effect of increasing atmospheric methane concentration on ammonium inhibition of soil methane consumption, *Nature*, *370*, 282–284, doi:10.1038/370282a0.

Kolb, S. (2009), The quest for atmospheric methane oxidizers in forest soils, *Environ. Microbiol. Rep.*, *1*(5), 336–346, doi:10.1111/j.1758-2229.2009.00047.x.

Konda, R., S. Ohta, S. Ishizuka, S. Arai, S. Ansori, N. Tanaka, and A. Hardjono (2008), Spatial structures of N_2O, CO_2, and CH_4 fluxes from *Acacia mangium* plantation soils during a relatively dry season in Indonesia, *Soil Biol. Biochem.*, *40*, 3021–3030, doi:10.1016/j.soilbio.2008.08.022.

Konda, R., S. Ohta, S. Ishizuka, J. Heriyanto, and A. Wicaksono (2010), Seasonal changes in the spatial structures of N_2O, CO_2, and CH_4 fluxes from *Acacia mangium* plantation soils in Indonesia, *Soil Biol. Biochem.*, *421*, 1512–1522, doi:10.1016/j.soilbio.2010.05.022.

Le Mer, J., and P. Roger (2001), Production, oxidation, emission and consumption of methane by soils: A review, *Eur. J. Soil Biol.*, *37*, 25–50, doi:10.1016/S1164-5563(01)01067-6.

Liu, G. S., N. H. Jiang, L. D. Zhang, Z. L. Liu (1996), *Soil Physical and Chemical Analysis and Description of Soil Profiles* (in Chinese), Stand. Press of China, Beijing.

Liu, L. L., and T. L. Greaver (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, doi:10.1111/j.1461-0248.2009.01351.x.

Liu, X. J., L. Duan, J. M. Mo, E. Z. Du, J. L. Shen, X. K. Lu, Y. Zhang, X. B. Zhou, C. E. He, and F. S. Zhang (2011), Nitrogen deposition and its ecological impact in China: An overview, *Environ. Pollut.*, *159*, 2251–2264, doi:10.1016/j.envpol.2010.08.002.

Lu, X. K., J. M. Mo, F. S. Gilliam, G. Y. Zhou, and Y. T. Fang (2010), Effects of experimental nitrogen additions on plant diversity in an old-growth tropical forest, *Global Change Biol.*, *16*, 2688–2700, doi:10.1111/j.1365-2486.2010.02174.x.

Macedo, M. O., A. S. Resende, and P. C. Garcia (2008), Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogenfixing trees, *For. Ecol. Manage.*, *255*, 1516–1524, doi:10.1016/j.foreco.2007.11.007.

Maljanen, M., H. Jokinen, A. Saari, R. Strömmer, and P. J. Martikainen (2006), Methane and nitrous oxide fluxes, and carbon dioxide production in soil of boreal forest fertilized with wood ash and nitrogen, *Soil Use Manage.*, *22*, 151–157, doi:10.1111/j.1475-2743.2006.00029.x.

Merino, A., P. Perez-Batallon, and F. Macias (2004), Responses of soil organic matter and greenhouse gas fluxes to soil management and land use changes in a humid temperate region of southern Europe, *Soil Biol. Biochem.*, *36*, 917–925, doi:10.1016/j.soilbio.2004.02.006.

Mochizuki, Y., K. Koba, and M. Yoh (2012), Strong inhibitory effect of nitrate on atmospheric methane oxidation in forest soils, *Soil Biol. Biochem.*, *50*, 164–166, doi:10.1016/j.soilbio.2012.03.013.

Nyerges, G., and L. Y. Stein (2009), Ammonia cometabolism and product inhibition vary considerably among species of methanotrophic bacteria, *FEMS Microbiol. Lett.*, *297*, 131–136, doi:10.1111/j.1574-6968.2009.01674.x.

Peichl, M., M. A. Arain, S. Ullah, and T. R. Moore (2010), Carbon dioxide, methane, and nitrous oxide exchanges in an age-sequence of temperate pine forests, *Global Change Biol.*, *16*, 2198–2212, doi:10.1111/j.1365-2486.2009.02066.x.

Peng, S. L., Y. P. Hou, and B. M. Chen (2009), Vegetation restoration and its effects on carbon balance in Guangdong Province, China, *Restor. Ecol.*, *17*(4), 487–494, doi:10.1111/j.1526-100X.2008.00399.x.

Reay, D. S., and D. B. Nedwell (2004), Methane oxidation in temperate soils: Effects of inorganic N, *Soil Biol. Biochem.*, *36*, 2059–2065, doi:10.1016/j.soilbio.2004.06.002.

Reay, D. S., F. Dentener, P. Smith, J. Grace, and R. A. Feely (2008), Global nitrogen deposition and carbon sinks, *Nat. Geosci.*, *1*(7), 430–437, doi:10.1038/ngeo230.

Sala, O. E., et al. (2000), Global biodiversity scenarios for the year 2100, *Science*, *287*, 1770–1774, doi:10.1126/science.287.5459.1770.

Steinkamp, R., K. Butterbach-Bahl, and H. Papen (2001), Methane oxidation by soils of an N limited and N fertilized spruce forest in the Black Forest, Germany, *Soil Biol. Biochem.*, *33*, 145–153, doi:10.1016/S0038-0717(00)00124-3.

Steudler, P. A., R. D. Bowden, J. M. Melillo, and J. D. Aber (1989), Influence of nitrogen fertilization on methane uptake in temperate forest soils, *Nature*, *341*, 314–316, doi:10.1038/341314a0.

Steudler, P. A., J. M. Melillo, R. D. Bowden, and M. S. Castro (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, doi:10.2307/2388252.

Tang, X. L., S. G. Liu, G. Y. Zhou, D. Q. Zhang, and C. Y. Zhou (2006), Soil-atmospheric exchange of CO_2, CH_4, and N_2O in three subtropical forest ecosystems in southern China, *Global Change Biol.*, *12*, 546–560, doi:10.1111/j.1365-2486.2006.01109.x.

Teh, Y. A., W. L. Silver, and M. E. Conrad (2005), Oxygen effects on methane production and oxidation in humid tropical forest soils, *Global Change Biol.*, *11*, 1283–1297, doi:10.1111/j.1365-2486.2005.00983.x.

Vance, E. D., P. C. Brookes, and D. S. Jenkinson (1987), An extraction method for measuring soil microbial biomass C, *Soil Biol. Biochem.*, *19*, 703–707, doi:10.1016/0038-0717(87)90052-6.

Vitousek, P. M., J. D. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and D. Tilman (1997), Human alteration of the global nitrogen cycle: Sources and consequences, *Ecol. Appl.*, *7*(3), 737–750, doi:10.2307/2269431.

Vogt, K. A., and H. Persson (1991), Measuring growth and development of roots, in *Techniques and Approaches in Forest Tree Ecophysiology*, edited by J. P. Lassoie and T. M. Hinckley, pp. 477–501, CRC Press, Boca Raton, Fla.

Vogt, R. D., H. M. Seip, T. Larssen, D. Zhao, R. Xiang, J. Xiao, J. Luo, and Y. Zhao (2006), Potential acidifying capacity of deposition experiences from regions with high NH_4^+ and dry deposition in China, *Sci. Total Environ.*, *367*, 394–404, doi:10.1016/j.scitotenv.2005.12.018.

Voigtlaender, M., J.-P. Laclau, J. L. de Moraes Gonçalves, M. de Cássia Piccolo, M. Z. Moreira, Y. Nouvellon, J. Ranger and J.-P. Bouillet (2012), Introducing *Acacia mangium* trees in *Eucalyptus grandis* plantations: Consequences for soil organic matter stocks and nitrogen mineralization, *Plant Soil*, *352*(1–2), 99–111, doi:10.1007/s11104-011-0982-9.

Wang, F. M., Z. A. Li, H. P. Xia, B. Zou, N. Y. Li, J. Liu, and W. X. Zhu (2010), Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China, *Soil Sci. Plant Nutr.*, *56*, 297–306, doi:10.1111/j.1747-0765.2010.00454.x.

Wang, H., S. R. Liu, J. M. Mo, and T. Zhang (2010), Soil-atmosphere exchange of greenhouse gases in subtropical plantations of indigenous tree species, *Plant Soil*, *335*, 213–227, doi:10.1007/s11104-010-0408-0.

Werner, C., X. H. Zheng, J. W. Tang, B. H. Xie, C. Y. Liu, R. Kiese, and K. Butterbach-Bahl (2006), N_2O, CH_4 and CO_2 emissions from seasonal tropical rainforests and a rubber plantation in Southwest China, *Plant Soil*, *289*, 335–353, doi:10.1007/s11104-006-9143-y.

Werner, C., R. Kiese, and K. Butterbach-Bahl (2007), Soil-atmosphere exchange of N_2O, CH_4, and CO_2 and controlling environmental factors for tropical rain forest sites in western Kenya, *J. Geophys. Res.*, *112*, D03308, doi:10.1029/2006JD007388.

World Meteorological Organization (2010), The state of greenhouse gases in the atmosphere based on global observations through 2009, *WMO Greenhouse Gas Bull.*, *6*, 1–4.

Wu, J. P., Z. F. Liu, X. L. Wang, Y. X. Sun, L. X. Zhou, Y. B. Lin, and S. L. Fu (2011), Effects of understory removal and tree girdling on soil microbial community composition and litter decomposition in two Eucalyptus plantations in South China, *Funct. Ecol.*, *25*, 921–931, doi:10.1111/j.1365-2435.2011.01845.x.

Xu, Y. G., G. Y. Zhou, T. S. Lou, Z. M. Wu, and Z. C. He (2001), Soil solution chemistry and element budget in the forest ecosystem in Guangzhou (in Chinese), *Acta Ecol. Sin.*, *21*, 1670–1681.

Yan, Y. P., et al. (2008), Fluxes of CH_4 and N_2O from soil under a tropical 20 seasonal rain forest in Xishuangbanna, Southwest China, *J. Environ. Sci.*, *20*, 207–215, doi:10.1016/S1001-0742(08)60033-9.

Zhang, H., D. S. Guan, and M. W. Song (2012), Biomass and carbon storage of *Eucalyptus* and *Acacia* plantations in the Pearl River Delta, South China, *For. Ecol. Manage.*, *277*, 90–97, doi:10.1016/j.foreco.2012.04.016.

Zhang, T., W. X. Zhu, J. M. Mo, L. Liu, and S. F. Dong (2011), Increased phosphorus availability mitigates the inhibition of nitrogen deposition on CH_4 uptake in an old-growth tropical forest, southern China, *Biogeosciences*, *8*, 2805–2813, doi:10.5194/bg-8-2805-2011.

Zhang, W., J. M. Mo, G. Y. Zhou, P. Gundersen, Y. T. Fang, X. K. Lu, T. Zhang, and S. F. Dong (2008), Methane uptake responses to nitrogen deposition in three tropical forests in southern China, *J. Geophys. Res.*, *113*, D11116, doi:10.1029/2007JD009195.

Zhou, G. Y., and J. H. Yan (2001), The influence of region atmospheric precipitation characteristics and its element inputs on the existence and development of Dinghushan forest ecosystems (in Chinese), *Acta Ecol. Sin.*, *21*, 2002–2012.