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Forest soil CO_2 fluxes as a function of understory removal and N-fixing species addition

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Abstract

We report on the effects of forest management practices of understory removal and N-fixing species (*Cassia alata*) addition on soil CO_2 fluxes in an *Eucalyptus urophylla* plantation (EUp), *Acacia crassicarpa* plantation (ACp), 10-species-mixed plantation (Tp), and 30-species-mixed plantation (THp) using the static chamber method in southern China. Four forest management treatments, including (1) understory removal (UR); (2) *C. alata* addition (CA); (3) understory removal and replacement with *C. alata* (UR+CA); and (4) control without any disturbances (CK), were applied in the above four forest plantations with three replications for each treatment. The results showed that soil CO_2 fluxes rates remained at a high level during the rainy season (from April to September), followed by a rapid decrease after October reaching a minimum in February. Soil CO_2 fluxes were significantly higher ($P < 0.01$) in EUp (132.6 mg/(m^2·hr)) and ACp (139.8 mg/(m^2·hr)) than in Tp (94.0 mg/(m^2·hr)) and THp (102.9 mg/(m^2·hr)). Soil CO_2 fluxes in UR and CA were significantly higher ($P < 0.01$) among the four treatments, with values of 105.7, 120.4, 133.6 and 112.2 mg/(m^2·hr) for UR+CA, UR, CA and CK, respectively. Soil CO_2 fluxes were positively correlated with soil temperature ($P < 0.01$), soil moisture ($P < 0.01$), NO_3^--N ($P < 0.05$), and litterfall ($P < 0.01$), indicating that all these factors might be important controlling variables for soil CO_2 fluxes. This study sheds some light on our understanding of soil CO_2 flux dynamics in forest plantations under various management practices.

Key words: soil CO_2 fluxes; forest management practices; understory removal; N-fixing species addition; forest plantation

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Introduction

Global warming and global climate change have become significant terms during the past decade (Cox et al., 2000; Giardina and Ryan, 2000; Luo et al., 2001; Tang et al., 2003). Greenhouse gases (GHG) such as CO_2, N_2O and CH_4 are continuing to increase at an unprecedented rate in the atmosphere (Mosier et al., 1998; Baggs and Blum, 2004). According to the Intergovernmental Panel on Climate Change (IPCC, 2001), the globally averaged atmospheric concentration of CO_2 has been increasing at a rate of 0.5% per year during the past decades. A considerable amount of atmospheric GHG are produced and consumed through soil processes, and annual soil CO_2 fluxes have the potential to influence the global climate (Schlesinger, 1997; Exnerová and Cienciala, 2009). Therefore, it is important to understand the factors that may dramatically alter soil CO_2 fluxes rates and influence global carbon cycling (Andrews et al., 2000). Previous studies have shown that soil CO_2 fluxes can be affected by factors, such as substrate quality (Kravchenko et al., 2002; Baggs and Blum, 2004; Bowden et al., 2004; Maljanen et al., 2006), soil temperature (Song et al., 2006), soil moisture (Subke et al., 2003; Arnold et al., 2005; Wang et al., 2005), root biomass (Hanson et al., 2000; George et al., 2003), N availability (Prasolova et al., 2000), microbial biomass (Fisk and Fahey, 2001), and litterfall (Yan et al., 2006).

According to the China State Forestry Bureau (2005), the total area of forest plantations in China is about 53.6 million ha, accounting for approximately 30% of total forest area in China. In southern China, plantations mostly consist of *Eucalyptus* spp., *Acacia* spp. and some native species (Xue et al., 2005). Therefore, forest plantations play an important role in carbon cycling in southern China and it is important to evaluate the forest soil carbon balance as well as forest soil CO_2 fluxes.

Previous studies have also shown that forest management practices can significantly influence soil GHG

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fluxes by altering environmental variables (Houghton and Hacker, 1999; Yashiro et al., 2008). However, the effects of management practices on soil CO_2 fluxes in forest plantations have not been thoroughly investigated and remain largely unknown. In southern China, the removal of understory vegetation and the addition of N-fixing species, especially legume species, are two common practical afforestation techniques used to improve tree growth rate and wood quality (Hu et al., 2007). It is assumed that both understory removal and N-fixing species addition would have significant effects on soil CO_2 fluxes in different plantations. As part of our systematic field study on forest soil GHG fluxes as a function of forest management practices, the results on forest soil N_2O fluxes were already reported elsewhere by Li et al. (2010). Therefore, the specific objective of this follow-up research is to examine the effects of understory removal and N-fixing species addition on soil CO_2 fluxes. We aimed to investigate the seasonal variations of CO_2 fluxes under the treatments of understory removal and N-fixing species addition, the effects of these forest management practices on physical, chemical, and biological soil characteristics, as well as the main factors controlling variations in soil CO_2 emission rates.

1 Materials and methods

1.1 Site description

This study was carried out in the Heshan Hilly Land Interdisciplinary Experimental Station (22°41′N and 112°54′E), Chinese Academy of Sciences in Guangdong Province, China. The area has a subtropical monsoon climate with a mean annual precipitation of 1700 mm, falling mainly (ca. 80%) in the hot and rainy season from April to September. The October to March period is cool and dry. The mean annual temperature is 21.7°C with the maximum 29.2°C falling in July and the minimum 12.6°C in January. The soil type is classified as Humic Acrisol (FAO, 2006).

1.2 Experimental design

The plantations, previously a barren land occupying a total area of 50 ha, were established in the spring of 2005, with tree saplings planted at 3 m × 2 m spacing (Li et al., 2010). In the mixed plantations, native species were interplanted in the barren land in 2005. Four typical plantation types were selected for this study, specifically a *E. urophylla* plantation (EUp), *A. crassicarpa* plantation (ACp), 10-species-mixed plantation (Tp), and 30-species-mixed plantation (THp) (Fig. 1, Table 1). Three replicates were studied in each plantation, totaling twelve stands (Fig. 1). The study period was from June 2007 to May 2008.

The fast growing and N-fixing *Cassia alata* was applied to study the effects of N-fixing species addition (Khanna, 1997). Four horizontally neighboring plots (10 m × 10 m; 1 m spacing) were established in each plantation in March 2007 and four treatments including understory removal (UR), *C. alata* addition (CA), understory removal and replacement with *C. alata* (UR+CA), and the control, i.e., without any operations (CK), were randomly applied to the four plots (Fig. 1). Understory was removed close to the ground with a sharp spade so as not to disturb the original

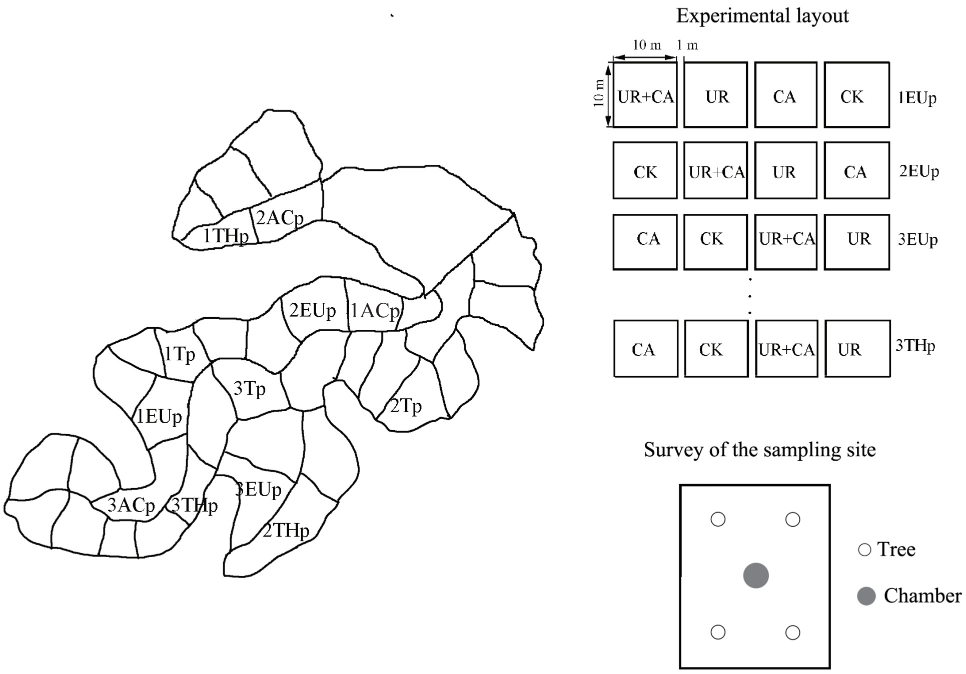

Fig. 1 Schematic experimental layout. Four plantation types, three replications and a total of 12 stands were used. In each stand, there were four horizontally neighboring plots (10 m × 10 m; 1 m spacing). The plantation types were *E. urophylla* plantation (EUp), *A. crassicarpa* plantation (ACp), 10-species mixed plantation (Tp), and 30-species mixed plantation (THp). Treatments were (1) understory removal (UR); (2) *C. alata* addition (CA); (3) understory removal and replacement with *C. alata* (UR+CA); and (4) control without any disturbances (CK).

Table 1 Vegetation and soil characteristics of four plantations in 2007 (Li et al., 2010)

Plantation type	EUp	ACp	Tp	THp
Plantation characteristics				
Age (yr)	2	2	2	2
Tree density (trees/ha)	1734	1734	1734	1734
Average tree height (m)	8.9	4.2	1.4	1.4
Mean Diameter Breast Height (cm)	7.4	4.8	2.0	1.8
Canopy coverage (%)	75	70	25	30
Dominant species	I	II	III	III and IV
Soil characteristics				
Soil pH	4.35	4.39	4.26	4.46
Soil organic carbon (g/kg)	18.17	22.12	23.13	17.68
Total N (g/kg)	0.79	0.75	1.22	0.88
Exchangeable K (mg/kg)	16.03	17.53	24.14	19.52
Exchangeable Na (mg/kg)	7.09	6.56	10.27	7.29

EUp: *E. urophylla* plantation; ACp: *A. crassicarpa* plantation; Tp: 10-species mixed plantation; THp: 30-species mixed plantation.

I: *Eucalyptus urophylla*; II: *Acacia crassicarpa*; III: *Liquidambar formosana*; *Magnolia glauca*; *Tsoongiodendron odorum*; *Castanopsis hystrix*; *Michelia macclurei*; *M. Maudiae*; *Jacaranda acutifolia*; *Sterculia lanceolata*; *Dillenia indica*; *Elaeocarpus apiculatus*; IV: *C. fissa*; *M. chapensis*; *Elaeocarpus japonicus*; *Ormosia pinnata*; *Delonix regia*; *Hedysarum fruticosum*; *Pterocarpus santalinus*; *Dracontomelon duperreranum*; *Cinnamomum parthenoxylon*; *Radermachera sinica*; *Dolichandrone caudafelina*; *Garcinia oblongifolia*; *G. subelliptica*; *Maesa perlaria*; *Loropetalum chinensis*; *Syzygium jambos*; *Bischofia javanica*; *Burmann cinnamon*; *Machilus chinensis*; *Quercus dentate*.

soil in November, 2006. The *C. alata* were planted (0.5 m × 0.5 m) at the same time and all grew well during the study period.

1.3 Measurements of soil CO_2 fluxes

Soil CO_2 fluxes were collected and measured once or twice a month using the static chamber method. The detailed procedures of gas sampling were described by Li et al. (2010). The samples were transferred to the laboratory and immediately analyzed using gas chromatography (HP 5890 Series, GC System, Hewlett Packard, USA). Specifically, CO_2 was separated using a 2 m stainless steel column (Porapak Q; Hewlett Packard, USA) with an inner diameter of 2 mm, 60/80 mesh, oven temperature of 55°C, with pure N_2 as a carrier gas at a flow rate of 30 mL/min. The gas concentrations were plotted as a function of time. Because gas concentrations in the closed chamber increased linearly with time (Song et al., 2006; Yashiro et al., 2008), the outliers from the dataset that did not fit the linear change in gas concentrations (R^2 < 0.7) were excluded. The percentage of outliers was 4.5% for CO_2.

1.4 Measurements of environmental variables

Along with gas sample collection, relevant physical and chemical soil properties such as soil temperature, soil moisture, pH, soil organic carbon (SOC), content of soil NO_3^--N and NH_4^+-N, fine root biomass (0–2 mm diameter), and microbial biomass carbon (MBC) were measured as per Li et al. (2010). Three 1 m^2 litter traps were placed in each plantation randomly at 0.5 m above the ground surface (Hergoualc'h et al., 2008). The trap was made of a plastic net that allowed water to percolate easily but retained litter.

1.5 Statistical analysis

Statistical analysis was performed using SPSS 13.0. The normality of variables was checked using K-S Test, SPSS. Two-way ANOVA (using type of plantation and treatment as the main factors) was used to compare the difference of CO_2 fluxes among the four plantations, and to assess the significance of the impacts of UR, CA and their interactions on CO_2 fluxes. Log transformation was carried out when necessary. The correlations between soil CO_2 fluxes and the environmental parameters were also analyzed. Differences among treatments and vegetation types were compared using Tukey's HSD test. All comparison and correlation tests were conducted at the 0.05 level.

2 Results

2.1 Seasonality of soil CO_2 fluxes, soil temperature, and moisture under CK

Figure 2a indicates that soil CO_2 fluxes varied widely under CK in the four plantations throughout the experimental period. Soil CO_2 flux rates exhibited a similar variation trend, in which CO_2 fluxes stayed at a high level during the rainy season (from April to September) when soil temperature and soil moisture were relatively high, followed by a rapid decrease after October and minimum in February when both soil temperature and soil moisture were low (Fig. 2b, c). Soil CO_2 fluxes ranged from 42.0–184.7, 37.8–225.0, 47.8–167.7 and 33.4–172.2 mg/(m^2·hr) for EUp, ACp, Tp and THp, respectively, showing a shift in CO_2 fluxes rates in the transition from the fast-growing plantation to the slow-growing stand. The values of soil CO_2 fluxes under CK were significantly higher (P < 0.05) in EUp and ACp than in Tp and THp, with mean values of 125.7, 127.6, 115.2 and 118.7 mg/(m^2·hr) for EUp, ACp, Tp and THp, respectively. The results also showed that soil temperature was significantly lower (P < 0.01) in EUp and ACp than in Tp and THp, while soil moisture was significantly higher (P < 0.01). The mean values of soil temperature were 22.7, 23.3, 24.1 and 23.8°C, and soil moisture 17.4%, 16.7%, 12.0% and 11.9% soil for EUp, ACp, Tp and THp, respectively.

2.2 Comparison of soil CO_2 fluxes among plantations and treatments

The two-way ANOVA showed significant differences in soil CO_2 fluxes rates among the four plantations (P < 0.01) (Fig. 3A) and the four treatments (P < 0.01) (Fig. 3B). As shown in Fig. 3A, soil CO_2 fluxes in EUp and ACp were significantly higher than in Tp and THp, and regardless of treatments, the mean values were 132.6, 139.8, 94.0 and 102.9 mg/(m^2·hr) for EUp, ACp, Tp and THp, respectively. Compared to CK, soil CO_2 fluxes in UR and CA were significantly higher (P < 0.01) among the four treatments, with the mean values of 105.7, 120.4, 133.6, and 112.2 mg/(m^2·hr) for UR+CA, UR, CA, and CK, respectively (Fig. 3B). The ANOVA results showed that the interactions between plantation and treatment were significant (P < 0.01) (Table 2), suggesting that the effect of treatments on

Table 2 Effects of plantations and treatments on the soil properties

Soil property	Plantation				
	EUp	ACp	Tp	THp	
Soil CO_2 fluxes (mg/(°C))	132.6 ± 3.8 A	139.8 ± 3.8 A	94.0 ± 3.8 B	102.9 ± 3.7 B	
Soil temperature (°C)	23.0 ± 0.3 b	23.3 ± 0.3 b	24.1 ± 0.3 a	24.1 ± 0.3 a	
Soil moisture (%, *V/V*)	16.3 ± 0.5 A	16.6 ± 0.5 A	13.0 ± 0.5 B	13.0 ± 0.5 B	
SOC (g/kg)	18.2 ± 1.0	19.4 ± 1.3	16.4 ± 0.95	17.9 ± 1.2	
NO_3^--N (mg/kg)	5.8 ± 0.6 b	8.7 ± 0.6 a	8.0 ± 0.6 a	8.0 ± 0.6 a	
NH_4^+-N (mg/kg)	5.8 ± 0.3	6.1 ± 0.3	5.4 ± 0.3	5.7 ± 0.3	
Fine root biomass (g/m^2)	142.8 ± 22.3	107.8 ± 18.3	143.9 ± 18.8	175.1 ± 23.3	
MBC (mg/kg)	214.0 ± 40.7	209.4 ± 38.3	142.5 ± 38.3	165.5 ± 40.7	
Litterfall (g/(m^2·hr))	652.3 ± 34.4 A	703.8 ± 53.5 A	94.1 ± 16.4 B	104.0 ± 17.3 B	
Soil property	Treatment				Plantation × Treatment
	UR+CA	UR	CA	CK	
Soil CO_2 fluxes (mg/(m^2·hr))	105.7 ± 3.7 B	120.4 ± 3.7 A	133.6 ± 3.8 A	112.2 ± 3.9 B	$P < 0.01$
Soil temperature (°C)	23.8 ± 0.3 ab	24.1 ± 0.3 a	23.3 ± 0.3 ab	23.2 ± 0.3 b	ns
Soil moisture (%, *V/V*)	15.1 ± 0.5 a	13.3 ± 0.5 b	15.7 ± 0.5 a	15.4 ± 0.5 a	ns
SOC (g/kg)	18.7 ± 1.0 ab	15.7 ± 1.0 b	20.0 ± 1.3 a	18.1 ± 1.1 ab	ns
NO_3^--N (mg/kg)	7.2 ± 0.6 B	7.3 ± 0.6 B	9.5 ± 0.6 A	6.3 ± 0.6 B	$P < 0.05$
NH_4^+-N (mg/kg)	5.4 ± 0.3	6.1 ± 0.3	5.7 ± 0.3	5.7 ± 0.3	ns
Fine root biomass (g/m^2)	85.5 ± 19.3 B	100.1 ± 16.5 B	211.4 ± 25.5 A	215.6 ± 20.8 A	ns
MBC (mg/kg)	243.8 ± 38.3	196.4 ± 42.9	230.1 ± 38.3	205.4 ± 38.3	ns
Litterfall (g/(m^2·hr))	–	–	–	–	–

Different letters indicate significant differences within plantations or treatments.
ns: no significant impact; MBC: microbial biomass carbon; –: default values.

CO_2 fluxes was different in the four plantations.

2.3 Soil physical and chemical characteristics

Among the four plantations, there were significant differences in soil temperature ($P < 0.05$), soil moisture ($P < 0.01$), NO_3^--N ($P < 0.05$) and litterfall ($P < 0.01$) (Table 2), suggesting that plantation type had significant effects on these environmental soil properties. Soil temperature was significantly lower, while soil moisture was significantly higher in EUp (23.0°C and 16.3%) and ACp (23.3°C and 16.6% than in Tp (24.1°C and 13.0% and THp (24.1°C and 13.0% (Table 2). The NO_3^--N was significantly higher in ACp (8.7 mg/kg) among the four plantations, but not significant with regard to SOC, NH_4^+-N, fine root biomass and MBC. As for litter fall, values in EUp (652.3 g/(m^2·yr)) and ACp (703.8 g/(m^2·yr)) were significantly higher than in Tp (94.1 g/(m^2·yr)) and THp (104.0 g/(m^2·yr)) (Table 2).

The soil temperature in the UR stands differed remarkably from the control, showing a significant ($P < 0.05$) increase in soil temperature during both the rainy and dry seasons (Table 2). At the same time, as compared to CK, soil moisture under UR treatment decreased significantly ($P < 0.05$), i.e., 13.3%. In contrast, CA treatment did not show any significant effects on either soil temperature or moisture. Conversely, however, UR treatment (15.7 g/kg) resulted in a significant reduction ($P < 0.05$) in SOC values, specifically, 18.7, 20.0 and 18.1 g/kg in UR+CA, CA and CK, respectively. In addition, NO_3^--N content of the stands treated by CA (9.5 mg/kg) were significantly higher ($P < 0.01$) than UR+CA (7.2 mg/kg), UR (7.3 mg/kg), and CK (6.3 mg/kg). Fine root biomass in stands under UR+CA (85.5 g/m^2) and UR (100.1 g/m^2) were significantly lower ($P < 0.01$) than in CA (211.4 g/m^2) and CK (215.6 g/m^2), presumably due to the death of fine roots after understory harvesting. Neither plantation type nor treatment exerted a significant influence on NH_4^+ -N and MBC in the top 10 cm layer (Table 2).

2.4 Relationships between soil CO_2 fluxes and soil properties

Soil CO_2 fluxes were statistically correlated with soil temperature ($P < 0.01$), soil moisture ($P < 0.01$), NO_3^--N ($P < 0.05$) and litterfall ($P < 0.01$) (Table 3). The daily

Table 3 Correlation of CO_2 fluxes rate with soil properties in each plot

	CO_2 fluxes	Soil temperature	Soil moisture	SOC	NO_3^--N	NH_4^+-N	Fine root biomass	MBC	Litterfall
CO_2 fluxes	1.000								
Soil temperature	0.930**	1.000							
Soil moisture	0.940**	–0.998**	1.000						
SOC	0.598	-0.675*	0.694*	1.000					
NO_3^--N	0.655*	0.485	–0.536	–0.600	1.000				
NH_4^+-N	0.477	–0.396	0.359	0.525	0.353	1.000			
Fine root biomass	–0.438	–0.606	–0.558	–0.189	–0.400	–0.376	1.000		
MBC	0.591	–0.679*	0.720*	0.544	–0.331	0.306	0.163	1.000	
Litterfall	0.897**	–0.841**	0.846**	0.883**	–0.548	0.524	–0.501	0.648*	1.000

* Correlation significant at 0.05 level; ** correlation significant at 0.01 level.

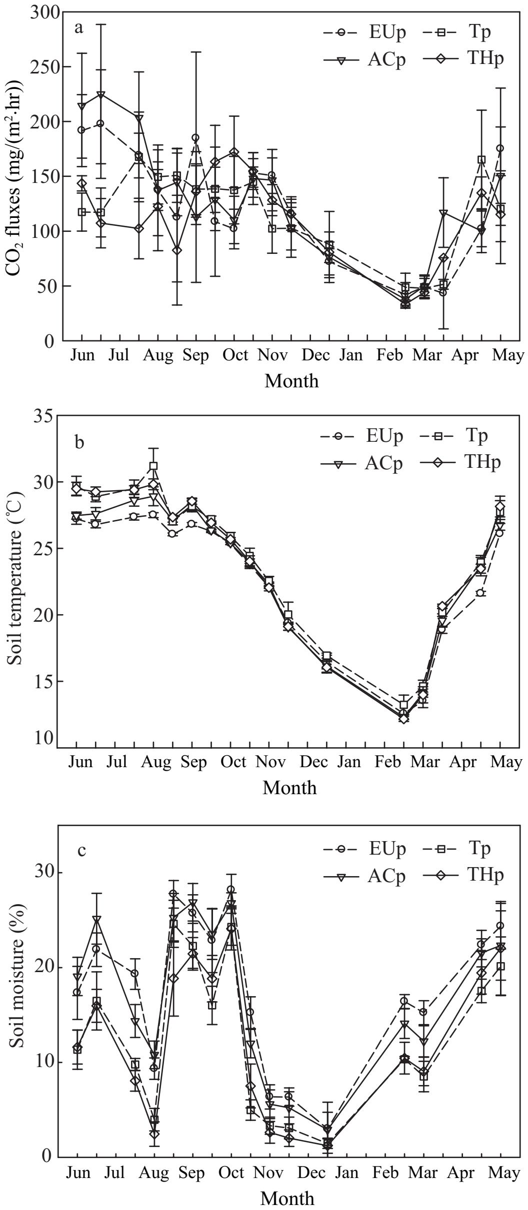

Fig. 2 Monthly variation of soil CO_2 fluxes (a), soil temperature (b), and soil moisture (c) in CK for *E. urophylla* plantation (EUp), *A. crassicarpa* plantation (ACp), 10-species mixed plantation (Tp) and 30-species mixed plantation (THp) from June 2007 to May 2008. Dots represent the means of all chambers at every sampling time and error bars represent standard errors (n = 6).

soil CO_2 flux rates (F_{CO_2}, mg/(m^2·hr)) and daily soil temperature and moisture over the measurement period were plotted and fitted using the regression equations (Table 4). The corresponding values of regression parameters as well as the coefficient of determination R^2 are summarized in

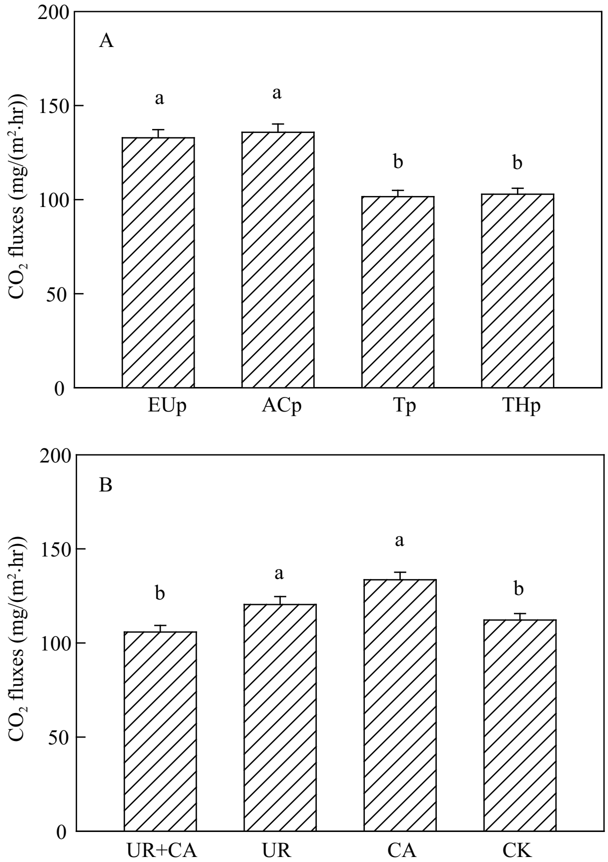

Fig. 3 Comparison of soil CO_2 fluxes among the four plantations (A) and the four treatments (B). Error bars represent standard errors (n = 384). Treatments superscripted with different letters are significantly different at the level of P = 0.01 by Tukey's HSD test.

Table 4. The CO_2 fluxes were strongly correlated to soil temperature and soil moisture when soil moisture was < 12% in all plantations (Table 4). Values of Q_{10} (= $e^{10\beta}$) were also expected when soil moisture was ⩾12%, ranging from 1.8 to 2.2. Statistical tests also showed that Q_{10} was significantly higher for EUp (2.2) and ACp (2.0), but significantly lower for Tp (1.8) and THp (1.8) (Table 4).

Figure 4 shows that soil CO_2 fluxes increased with an increase in litterfall for all four plantations. In addition, the CO_2 fluxes were significantly correlated with the content of soil NO_3^--N in ACp (R^2 = 0.792, P < 0.05) and under CA treatment (R^2 = 0.376, P < 0.05) as shown in Fig. 5, implying that soil NO_3^--N concentration might be an important explanatory variable controlling soil CO_2 flux dynamics. However, no significant correlation between CO_2 fluxes and soil SOC, NH_4^+-N, and fine root biomass was observed (Table 3).

Table 4 Models for the relationship between soil CO_2 fluxes (F_{CO_2}, mg/(m^2·hr)), soil temperature (T, °C) and soil moisture (M, %) in CK plots

Plantation	$F_{CO_2} = aT + bM + c$ (soil moisture <12%)						$F_{CO_2} = \alpha e^{\beta T}$ (soil moisture ⩾12%)					
	a	b	c	n	P-value	R^2	α	β	Q_{10}	n	P-value	R^2
EUp	9.2	1.8	37.0	25	< 0.05	0.467	19.2	0.08	2.2	77	< 0.05	0.309
ACp	7.7	1.3	40.5	27	< 0.05	0.516	27.8	0.07	2.0	75	< 0.01	0.371
Tp	5.4	3.3	13.7	72	< 0.01	0.557	50.6	0.06	1.8	30	< 0.05	0.332
THp	4.1	3.4	28.8	65	< 0.01	0.518	49.7	0.06	1.8	37	< 0.05	0.259

a, b, c, α and β are the coefficient. Q_{10} value is obtained from β ($Q_{10}e^{10\beta}$).

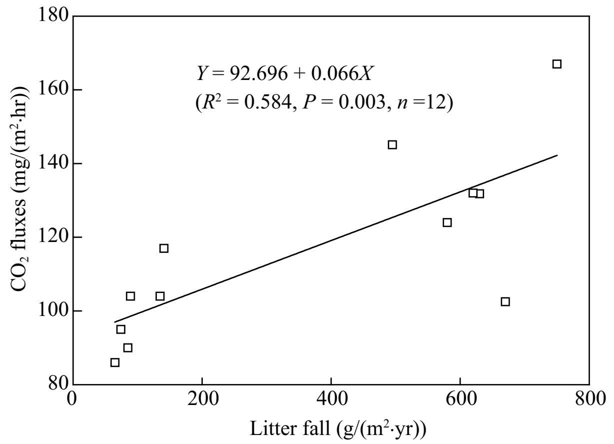

Fig. 4 Correlation between soil CO_2 fluxes and litter fall in the four plantations.

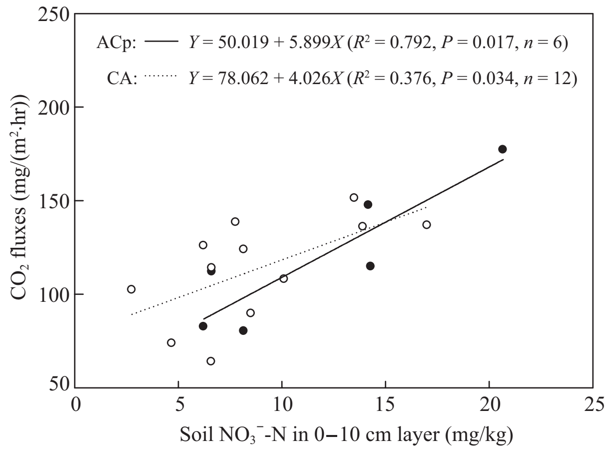

Fig. 5 Variation of soil CO_2 fluxes as a function of soil NO_3^--N concentration in ACp and under CA treatment.

3 Discussion

3.1 Seasonality of soil CO_2 fluxes under CK in four plantations

The annual mean soil CO_2 flux rates in the CK plots (Fig. 1) were lower than those observed in tropical forests of South America (187–421 mg CO_2/(m^2·hr)) (Davidson et al., 2004; Sotta et al., 2004; Tang et al., 2005), but were in the same range as found in temperate forests of the northern hemisphere ranging from 117 to 1100 mg CO_2/(m^2·hr) (Raich and Schlesinger, 1992).

Soil CO_2 fluxes in all plantations exhibited a similar seasonal pattern (Fig. 2). This is consistent with many results from tropical forests soils, which report that a decrease in soil CO_2 fluxes occurs during the dry season, likely caused by reduced rates of root respiration and/or soil microbial respiration (Verchot et al., 2000). In this study, soil CO_2 fluxes were accorded with the trend of soil temperature and soil moisture, suggesting the importance of both on soil CO_2 fluxes. As expected, soil CO_2 fluxes were strongly related to soil moisture and soil temperature, which is consistent with some previous studies (Janssens and Pilegaard, 2003; Song et al., 2006). This is probably due to the strong correlation between soil temperature and soil moisture ($P < 0.01$, $r = -0.998$) (Table 3).

The mean values of Q_{10} for soil CO_2 fluxes were 1.8–2.2 when soil moisture ⩾ 12% (Table 4), falling within the range observed in subtropical forests in China (1.75–2.55) (Huang et al., 1999). Presumably, microbial communities were better adapted to temperature change in EUp and ACp than in Tp and THp, thus maintaining their relatively high activity throughout the year. In relation to warm and moist forests, positive exponential relationships with soil temperatures have been found in tropical forests in the central Amazon (Sotta et al., 2004) and lowland tropical rainforests in southwest Costa Rica (Cleveland and Townsend, 2006). However, when soil moisture is sub-optimal or limiting, soil CO_2 fluxes may be less related to changes in other environmental variables, such as temperature (Kirschbaum, 2006). The effect of soil moisture on soil CO_2 fluxes were only observed during dry conditions < 12% (Mo et al., 2008). Below this threshold, our data indicated there was a positive relationship between soil moisture and CO_2 fluxes (Table 4). Effects of drought on soil CO_2 fluxes have been known to occur below a certain threshold (Inclan et al., 2007) and might be dependent upon soil texture (Dilustro et al., 2005).

3.2 Effects of plantation type on soil CO_2 fluxes

The higher soil CO_2 flux rates in EUp (132.6 mg/(m^2·hr)) and ACp (139.8 mg/(m^2·hr)) compared to Tp (94.0 mg/(m^2·hr)) and THp (102.9 mg/(m^2·hr)) suggested generally higher rates of net primary productivity (NPP) by the fast-growing species (Table 2). Strong relationships were found between NPP and soil CO_2 fluxes (Yan et al., 2006), suggesting that the greater rates of CO_2 release was caused by enhanced plant growth and photosynthetic production. Wang and Polglase (1995) also reported that soil respiration is proportional to NPP. Unfortunately, NPP was not detected in our study due to a number of practical difficulties, with litterfall was determined instead. It is likely that additional C from aboveground litterfall stimulated heterotrophic respiration, and thus enhanced soil CO_2 fluxes. It is well known that soil CO_2 fluxes results from decomposition of ground litter, soil organic matter and plant root respiration. Although the contribution of each component to total soil CO_2 fluxes could not be evaluated from the measurements made in this study, it could be assumed that increased soil CO_2 fluxes were related to increases in aboveground biomass and thus litterfall. Our results showed mean amount of litter fall during the study was 652.3, 703.8, 94.1 and 104.0 g/(m^2·yr) for EUp, ACp, Tp and THp, respectively, presumably due to the fast-growing species in EUp and ACp, and slow-growing species in Tp and THp. Total yearly soil CO_2 flux rates increased linearly with aboveground litter (Fig. 4), confirming that surface litter fall, and thus NPP, was one of the main drivers for soil CO_2 fluxes. However, further studies are needed to better understand the correlation between soil CO_2 fluxes and NPP.

3.3 Effects of CA on soil CO_2 fluxes

To date, only a few studies have been published on the effects of N-fixing species such as *C. alata* on soil

CO_2 fluxes. As clearly observed in CA treatment (Fig. 3 and Table 2), increased N inputs through N_2 fixation enhanced soil NO_3^--N levels and thereby accelerated C cycling and increased levels of soil CO_2 fluxes. N-fixing species can exhibit profound effects on soil properties through depositing high-nitrogen litter (Wedderburn and Carter, 1999). Compared to the CK stands (Table 2), there was a significant increase in the NO_3^--N concentration in CA, consistent with the variation of CO_2 fluxes in the same four treatments. The higher soil NO_3^--N concentration under CA treatment could be explained by increased N incorporation into the soil through litter-fall as well as enhanced root turnover in the system. N_2-fixing species can lead to a larger stimulation of growth and photosynthetic rates to elevated CO_2 than non-fixing species (Ainsworth and Rogers, 2007). Contrary to our studies, Verchot (2008) found that N-fixing trees did not appear to increase soil CO_2 emission in sandy Amazonian soils. Fest et al. (2009) reported that the presence of *Acacia dealbata* had no significant effects on soil CO_2 exchange or soil N status in *Eucalyptus delegatensis* forest.

Some previous studies determined the correlations between N fertilizer addition and soil CO_2 fluxes in forest systems. Montenegro and Abarca (2001) observed that N addition stimulated soil CO_2 fluxes rates in unshaded and shaded coffee plantations in Central Costa Rica. Cleveland and Townsend (2006) also found that soil CO_2 fluxes were significantly stimulated by two years of N addition in a tropical rain forest in Costa Rica. The increase in soil CO_2 fluxes was probably caused by increased microbial respiration following N addition (Montenegro and Abarca, 2001; Mutuo et al., 2005). In contrast, Mo et al. (2008) reported that N addition significantly reduced soil CO_2 fluxes and such results were also found in several temperate forests (Burton et al., 2004; Micks et al., 2004). However, the effect of legume species addition might be considered different from nitrogen fertilizer input. Therefore, a better understanding of the effect of N-fixing species on the CO_2 fluxes requires further research.

3.4 Effects of UR on soil CO_2 fluxes

In our study, the sum of soil CO_2 fluxes in all four plantations was enhanced significantly after UR treatment. The UR altered soil surface thermal properties (e.g., albedo) as well as energy and material balances (e.g., solar radiation and precipitation) near the ground, consequently inducing some changes in soil temperature and moisture on the soil surface (Zerva and Mencuccini, 2005), and thus increasing soil CO_2 flux rates. Some soil properties such as soil temperature and soil moisture, closely related to soil microorganisms and root activity, can strongly affect soil CO_2 flux rates by affecting the production and consumption of greenhouse gases (Smith et al., 1998). Ballard (2000) noticed that forest clear felling increased soil temperature, which led to increased biotic activity as well as CO_2 fluxes and decomposition rate. In this study, the SOCs at the UR stands were significantly lower than those in CK (Table 2), which was primarily attributed to the stimulated decomposition in the surface soil due to the increase in soil temperature caused by UR practice. Our results, as well as those reported in the literature, indicated that UR increased SOC decomposition and facilitated the production of CO_2 and decrease in SOC content. In addition, soil NO_3^--N and NH_4^+-N concentration increased slightly over time after UR operation throughout the entire experimental period. This increase in both NO_3^--N and NH_4^+-N after felling has also been reported (Vitousek and Matson, 1985; Wetson and Attiwill, 1996; Yashiro et al., 2008). Therefore, it was assumed that the release of NO_3^--N and NH_4^+-N was linked to the mineralization of organic matter as shown by CO_2-C production. This impact could be attributed to the disruption of soil structure, exposing the protected soil organic matter (Doran, 1982; Elliot, 1986) and better aeration after UR, resulting in increased organic matter decomposition.

3.5 Effects of UR+CA on soil CO_2 fluxes

As discussed above, UR and CA can enhance soil CO_2 fluxes by altering soil temperature, soil moisture and NO_3^--N content. Accordingly, CO_2 fluxes in the UR+CA treatment were expected to be higher than that in UR or CA treatment. As seen in Fig. 3, however, CO_2 fluxes under UR+CA treatment were lower than those under UR and CA treatments. This indicated that, although CA treatment might produce more nitrogen in the top soil, changed soil temperature and moisture by UR might mask the effect of nitrogen on CO_2 fluxes, thus counterbalancing the effect of CA on CO_2 fluxes. Table 2 shows that soil NO_3^--N concentration under UR+CA treatment was close to that under UR, suggesting an interaction between UR and CA treatments. Conversely, UR treatment may reduce the N-fixing function of *C. alata* by decreasing fine root biomass where N_2 fixation occurs by symbiotic bacteria associated with plant roots (Myrold et al., 1999). Table 2 shows that fine root biomass in UR+CA was significantly lower than that in CA. Therefore, it was assumed that the decrease in fine root biomass may contribute to the lowered CO_2 fluxes. Further studies are needed to better understand the interactions between UR+CA on soil CO_2 fluxes.

4 Conclusions

Based on the present study we concluded that: (1) all four plantations studied in southern China acted as sources of CO_2, with higher CO_2 fluxes during the rainy season and lower fluxes during the dry season; (2) plantation type may exert an important influence on soil CO_2 fluxes and soil CO_2 flux rates were significantly higher in EUp and ACp than in Tp and THp; (3) UR treatment increased soil CO_2 fluxes, presumably through a combined effect of soil temperature and moisture on SOC and soil microorganism activity, whereas CA treatment enhanced soil CO_2 flux rates due to the N-fixing function of *C. alata*; and (4) soil CO_2 flux rates were significantly related to various controlling factors such as soil temperature, soil moisture, NO_3^--N content, and litter-fall.

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