Subtropical plantations are large carbon sinks: Evidence from two monoculture plantations in South China

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ABSTRACT

Quantifying the net carbon (C) storage of forest plantations is required to assess their potential to offset fossil fuel emissions. In this study, a biometric approach was used to estimate net ecosystem productivity (NEP) for two monoculture plantations in South China: Acacia cissocarpa and Eucalyptus urophylla. This approach was based on stand-level net primary productivity (NPP, based on direct biometric inventory) and heterotrophic respiration (Rh). In comparisons of Rh determination based on trenching vs. tree girdling, both trenching and tree girdling changed soil temperature and soil moisture relative to undisturbed control plots, and we assess the effects of corrections for disturbances of soil moisture and soil moisture on the estimation of soil CO₂ efflux partitioning. Soil microbial biomass and dissolved organic carbon were significantly lower in trenched plots than in tree girdled plots for both plantations. Annual soil CO₂ flux in trenched plots (Rh,t) was significantly lower than in tree-girdled plots (Rh,g) in both plantations. The estimates of Rh,g and Rh,t, expressed as a percentage of total soil respiration, were 58 ± 4% and 74 ± 6%, respectively, for A. cissocarpa, and 64 ± 3% and 78 ± 5%, respectively, for E. urophylla. By the end of the experiment, the difference in soil CO₂ efflux between the trenched plots and tree-girdled plots had become small for both plantations. Annual Rh (mean of the annual Rh,g and Rh,t) and net primary production (NPP) were 470 ± 25 and 800 ± 118 g C m⁻² yr⁻¹, respectively, for A. cissocarpa, and 420 ± 35 and 2380 ± 187 g C m⁻² yr⁻², respectively, for E. urophylla. The two plantations in the developmental stage were large carbon sinks: NEP was 330 ± 76 g C m⁻² yr⁻¹ for A. cissocarpa and 1960 ± 178 g C m⁻² yr⁻¹ for E. urophylla.

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1. Introduction

Forest plantations occupy approximately 200 million ha worldwide and support the increasing local and global demands for wood (FAO, 2007). These forest plantations have also been considered as potential fast-response carbon sinks that may mitigate the rise of atmospheric CO₂ concentrations (Hoen and Solberg, 1994; Sands et al., 1999; Hunter, 2001; Kurz et al., 2009). Since the 1980s, large-scale reforestation and afforestation programs have greatly increased the plantation area in China to about 62 million ha. This represents about one-third of the global plantation area and is the greatest plantation area for any country (Piao et al., 2009). These plantations resulted in an increase of forest biomass carbon stocks (Fang et al., 2001). Quantifying the carbon balance of these plantations is necessary not only to assess the magnitude of the Northern Hemisphere and global carbon sinks, but also to define new objectives for the management of terrestrial ecosystems in order to slow the rate of increase in atmospheric CO₂. However, the carbon balance of plantations in China has seldom been studied (Piao et al., 2009).

Although the eddy covariance net ecosystem exchange (NEE) is a useful method for measuring CO₂ flux in forest ecosystems, NEE may underestimate respiration at night in calm winds, and methods for removing this bias remain controversial (Balchocchi, 2008). In addition, biometric sites that are part of a network of national or regional forest inventories (Gillis et al., 2005) are more abundant than covariance sites. Forest C fluxes can be inferred from the difference between biometric measurements of forest C stocks at two points in time with a long interval (Clark et al., 2001). Biometric measurements can provide estimates of the component-level changes driving stand-level fluxes. An advantage of this biometric method of determining C fluxes is that information about the individual ecological elements contributing to fluxes is available because measurements are made of individual components at the plot scale.

The potential for forest plantations to serve as large C sinks can be evaluated by net ecosystem productivity (NEP), which can be simply estimated by the difference between net primary
productivity (NEP) and heterotrophic respiration \( R_h \) (Odum, 1969; Gower et al., 2001; Chapin et al., 2002). The correct estimation of NEP requires the accurate determination of \( R_h \) vs. \( R_b \). The partitioning of \( R_b \) is an important issue in forest ecosystem ecology, plant physiology, soil science, and global climate change modelling (Bond-Lamberty et al., 2004b; Kuzyakov, 2006). For example, \( R_b \) and \( R_h \) may respond differently to environmental variables and microbial community composition (Boone et al., 1999; Lavigne et al., 2003; Li et al., 2006; Schindlbacher et al., 2008), suggesting that sources of CO\(_2\) efflux from soil differ depending on time scale and plant species (Bond-Lamberty et al., 2004b; Kuzyakov, 2006). Thus, the contribution of each \( R_b \) component must be known to understand the effects of global change on net exchange of CO\(_2\) between terrestrial ecosystems and the atmosphere (Bond-Lamberty et al., 2004b; Chen et al., 2009). Yet one of the challenges involved in accurate assessment of NEP is the separation of soil CO\(_2\) flux \( (R_b) \) into a heterotrophic component \( (R_h) \), respiration of microorganisms decomposing litter and soil organic C and an autotrophic component \( (R_a) \) respiration \( \) of roots and associated rhizosphere microorganisms (Epron et al., 2001; Bond-Lamberty et al., 2004b; Scott-Denton et al., 2006).

Developing a method for accurately determining \( R_b \) and \( R_h \) has been the objective of a number of studies. A variety of techniques for the estimation of \( R_b \) have been described but each has drawbacks and underlying assumptions (Hanson et al., 2000; Baggs, 2006; Kuzyakov, 2006; Fu et al., 2008; Chen et al., 2009, 2010a,b). Techniques for estimating \( R_b \), \( R_h \), and \( R_a \) include component integration, root exclusion, isotope tracing, and girding (Edwards and Harris, 1977; Jensen, 1993; Högb erg et al., 2001; Lee et al., 2003). The mean contribution of \( R_b \) to \( R_h \) was estimated to be 40–50% by Hanson et al. (2000). This contribution is subject to large spatial variabilities among ecosystems (Subke et al., 2006) and significant seasonal variability (Epron et al., 2001; Lavigne et al., 2003; Lee et al., 2003). The estimates of these contributions will also be affected by the perturbations inherent to the partitioning methodology (Bond-Lamberty et al., 2004b; Kuzyakov, 2006).

Plot trenching is commonly used to estimate \( R_b \) and \( R_a \) because of its simplicity and low cost (Hanson et al., 2000; Bond-Lamberty et al., 2004a). In this approach, respiration is measured in plots with roots (in which respiration will reflect both \( R_b \) and \( R_a \)) and in plots without roots (in which respiration will reflect only \( R_b \)). However, plot trenching damages roots and fungal hyphae (Bhupinderpal-Singh et al., 2003), modifies biophysical conditions and substrate supply for microbial respiration (Lee et al., 2003), and may change the soil microbial population or composition (Högb erg and Högb erg, 2002). Tree girdling is another approach that has recently been used to measure soil respiration. Tree girdling causes little initial disturbance to the root–soil system and can be used on a large scale. Girdling removes the bark and phloem around the youngest xylem so that the flow of carbohydrates from canopy to roots is terminated (Högb erg et al., 2001; Scott-Denton et al., 2006; Chen et al., 2010a).

Unfortunately, root trenching and tree girdling change environmental conditions, and in particular may increase soil moisture (Ross et al., 2001; Staples et al., 2001) and may decrease extractable C and microbial C and N (Ross et al., 2001). However, the girdled plots and girdled plots have not been directly compared for their effects on soil moisture and soil temperature. Changes in soil moisture induced by trenching and tree girdling have been inadequately considered in most previous studies, despite the possible consequenc es on microbial biomass (Epron et al., 1999; Ngo et al., 2007).

The current study concerns estimation of \( R_b \) and NEP in monoculture plantations in China. In China, the dominant plants of monoculture plantations include Acacia, Eucalyptus, Pinus, and Populus. Fast-growing species such as Acacia crassicarpa and Eucalyptus urophylla have been extensively planted and managed for pulpwood production in many tropical and subtropical regions because of their high productivity with short rotations (Attwill, 1994). Our knowledge is limited, however, about the C storage of these plantations (Piao et al., 2009). The objectives of this study were: (1) to compare the changes in soil microbial C, soil temperature, and soil moisture caused by girdling and trenching; (2) to assess the effects of corrections for disturbances of soil moisture and soil moisture on the estimation of soil CO\(_2\) efflux partitioning; (3) to determine \( R_b \) in two plantations (A. crassicarpa and E. urophylla) by tree girdling and trenching approaches; and (4) to use ecological inventory methods to estimate the components of NEP for the two dominant subtropical plantations in South China.

2. Methods

2.1. Site description

The study was conducted in plantations that contained monocultures of A. crassicarpa and E. urophylla at the Heshan Hilly Land Interdisciplinary Experimental Station (112°50′E, 22°34′N), Chinese Academy of Sciences (CAS). The field station is located in Heshan County, Guangdong Province, which is a subtropical hilly land region of South China. The plantations, each of which occupies 50 ha, were established in 2005, when A. crassicarpa and E. urophylla saplings were planted with a spacing of 3 m × 2 m. The site is characterized by a typical southern climate of subtropical monsoon and laterite soil. In this region, there is a distinct wet season and dry season. The wet season starts in March and ends in September, and the dry season starts in October and ends in February. The mean annual precipitation was 1295 mm between 1984 and 2006, and 80% of the precipitation occurred during the wet season. Annual precipitation in 2007 was 1180 mm, which was lower than the mean annual precipitation for the previous 22 years. The precipitation in 2007 was mainly distributed from April to September, and was highest in August and lowest in November. The mean annual temperature is 21.7 °C. In 2007, the mean soil temperature at 5 cm soil depth was higher in the A. crassicarpa plantation (22.9 ± 1.3 °C) than in the E. urophylla plantation (21.2 ± 1.3 °C), and the highest soil temperature was in July and lowest in January or February. Understory vegetation was dominated by Dicranopteris dichotoma (Thunb.) Bernh, but was mowed monthly throughout the experiment in all plots.

2.2. General approach of biometric approach

NEP reflects many vegetative processes, soil processes, and feedback associated with C metabolism, including photosynthesis and respiration, and responses of ecosystems to climate variation and other perturbations. Forest NEP over a given period of time is determined as the balance between NPP of vegetation and \( R_h \) of soil. As presented in previous research (Gower et al., 2001; Ehman et al., 2002; Luyssaert et al., 2007):

\[
\text{NEP} = \text{NPP} - R_h
\]

where NPP is the net primary production and \( R_h \) is the heterotrophic respiration (primarily from soil microorganisms and soil fauna). \( R_h \) is the difference between total soil CO\(_2\) emission and the CO\(_2\) released by autotrophic roots and associated rhizosphere organisms \( (R_a) \) (Edwards and Harris, 1977):

\[
R_h = R_b - R_a
\]

We use Wiant’s (1967) definition of root respiration \( (R_b) \): all respiration derived from organic compounds originating in plants including the respiration of living root tissue, the respiration of symbiotic mycorrhizal fungi and associated microorganisms, and
the respiration of organisms that decompose root exudates and recently dead root tissues in the rhizosphere. The following relation (Landsberg and Gower, 1997; Gower et al., 2001) can be used to estimate NPP:

\[ NPP = \Delta B_s + \Delta B_t + \Delta B_r + L - H \]  

(3)

where \( \Delta B_s \) is the increment of living biomass aboveground (including leaf, stem, bark, and branch tissue), which is usually determined based on allometric relationships between tree biomass and easily measured parameters such as tree height and the diameter at breast height (DBH) (see Section 2.4). \( L \) is the annual litter production (Clark et al., 2001), which includes coarse and fine litter that falls to the soil surface (see Section 2.3) and root turnover in soil; in the current study, fine root turnover rate was 1.45 per year for A. crassicarpa and 0.91 for E. urophylla (Zhang et al., unpublished data). \( \Delta B_t \) is the fine root production increment, which is measured in the current study by the sequential coring method (see Section 2.5). \( \Delta B_r \) is the coarse root annual production, which was allometrically estimated (see Section 2.4). \( H \) is herbivory consumption but it is often ignored because it is assumed to be a relatively minor factor (Landsberg and Gower, 1997; Gower et al., 2001).

2.3. Annual litter production

In total, 15 litter traps (1 m x 1 m) made of nylon mesh (1-mm mesh size) were installed at each plantation. The litter fall traps were raised 100 cm above the ground, and the litter fall was collected monthly from May 2007 to May 2008. The litter was categorized into leaves, twigs, and seeds, and was oven-dried at 65 °C to constant weight. Because of the rapid decomposition of leaf material in traps under subtropical weather conditions, we corrected leaf mass by assuming that the leaves had been shed 0.5 months earlier and had a decay rate of \( k = 0.02 \) month\(^{-1} \), as suggested by O’Connell (1987).

2.4. Estimates of aboveground living biomass and coarse root biomass based on allometric relationships

Aboveground living biomass \( (B_s) \) and coarse root biomass \( (B_r) \) were estimated using allometric relationships. In November 2006, height \( (H) \) and diameter at breast height \( (\text{DBH}) \) were determined for seven typical trees in each plantation using a measuring pole for \( H \) and a measuring tape for \( \text{DBH} \). These trees were then cut down at the base, and the fresh stems, branches, and foliage were weighed. The coarse roots (diameter >5 mm) were excavated manually and weighed. All samples were then oven-dried (65 °C) to constant weight. Values for \( \text{DBH}^2 H \) and \( B_{ab} \) and \( B_c \) were natural log-transformed before the relationship between \( \text{DBH}^2 H \) and \( B_{ab} \) or between \( \text{DBH}^2 H \) and \( B_c \) was examined by linear regression with the standard form of a linear model:

\[ \ln(B_i) = a + b \ln(\text{DBH}^2 H) \]  

(4)

where \( B_i \) = biomass of \( B_{ab} \) or \( B_c \), and \( a \) and \( b \) are statistical parameters. Each equation was then back-transformed to the power model in the form:

\[ B_i = \exp(a) \times (\text{DBH}^2 H)^b \times CF \]  

(5)

where \( CF \) is a correction factor computed as:

\[ CF = \exp \left( \frac{\text{RSE}_2}{2} \right) \]  

(6)

where RSE is the residual standard error of the regression obtained from the model regression procedure (Sprugel, 1983; Chave et al., 2005). Most studies have ignored this correction factor and therefore tend to underestimate individual biomass (Schnitzer et al., 2006).

The DBH and \( H \) of about 60 trees in each plantation were measured seven times in 2007 (7 February, 5 May, 5 June, 4 July, 3 August, 21 September, and 28 November), which were in the days when soil CO\(_2\) flux was determined (see Section 2.7). Allometric relationships were then used to estimate \( B_{ab} \) and \( B_c \) on these dates.

Biomass data of \( B_{ab} \) and \( B_c \) were converted into C mass, using the following equivalences: 1 kg dry matter \( = 0.468 \) kg C for A. crassicarpa and 0.457 kg C for E. urophylla based on our own measurements.

2.5. Measuring fine root biomass

The change in fine root biomass \( (\Delta B_i) \) was determined in randomly selected areas of each plantation February 2007 and February 2008 using a sequential soil coring method. Briefly, 17 soil cores (8 cm diameter, 40 cm depth) were taken randomly in each plantation using a steel corer. Each soil core was divided into four sections (0–10, 10–20, 20–30, and 30–40 cm depth). Each soil section was soaked and carefully passed through a 0.5-mm mesh sieve to separate roots, which were sorted by size (<5 mm or >5 mm diameter) and vitality (live or dead, assessed visually based on color, elasticity, and resilience). The weights of root samples were recorded after the roots were oven-dried at 65 °C to a constant mass. The difference in \( B_i \) values (2008–2007) was used as the fine root biomass increment \( (\Delta B_i) \).

Soil coring was also used to quantify root biomass in girdled plots on 7 February 2007 (before girdling) and 7 August 2007 (6 months later). The procedure was the same as described in the previous paragraph but only four soil cores were randomly selected for each plot to avoid excessive soil disturbance. Biomass data of \( B_i \) were converted into C mass, using the following equivalents: 1 kg dry matter \( = 0.522 \) kg C for A. crassicarpa and 0.480 kg C for E. urophylla based on our own measurements.

2.6. Girdling and trenching treatments

The tree-girdling treatment was described in detail by Chen et al. (2010a). Briefly, six plots \((10 \text{ m} \times 10 \text{ m}) \) were designated in each plantation, and the understory vegetation was mowed in each plot in January 2007. In order to exclude the disturbances from the roots outside the plots, the plot perimeters were trenched to a depth of 40 cm. Trees in three randomly selected plots in each plantation were girdled on 11 February 2007, and those in the other plots were not girdled. Plots without girdled trees are referred to as control plots. Each plot contained about 20 trees. In the girdling treatment, the bark and cambium of all trees were removed in a 10-cm band around the circumference of the trunk about 1 m above the ground. The leaves of A. crassicarpa started to fall 3 months after girdling, and no leaves remained on the trees 5 months after girdling. Leaf litter was removed periodically so that it did not accumulate on the soil surface in girdled plots. The leaves of E. urophylla did not fall until 7 months after girdling, and 70% of the trees were still alive 1 year after girdling.

Twelve trench plots \((1 \text{ m} \times 1 \text{ m}) \) each) were established in each plantation in October of 2006. To ensure that trench plots contained as small a quantity of roots as possible, all the trench plots were located in the center of a 3 m \( \times \) 2 m area occupied by four saplings. Each trench plot was prepared by making vertical cuts in the soil along the boundaries to 100 cm depth with a steel hoe such that all roots crossing the boundaries of the trench plots were severed but not removed. Pieces of 0.5-cm thick polyethylene board were then inserted into the vertical cuts to prevent roots from growing into the plots. Roots in the trench plots were killed by cutting all the aboveground parts of all plants in the plots at the litter surface. We did not remove the residual roots in the trenched plot
to avoid disturbing the soil. Moreover, we found that, after trenching, soil CO2 flux decreased and eventually reached an asymptote after 5 months (Yi et al., 2007), indicating that the residual root decomposition in the trench plots was rapid due to the humid and high temperature in subtropical China.

2.7. Measurements of soil CO2 flux

Soil CO2 flux was measured as described by Chen et al. (2010a). Briefly, soil CO2 flux was measured monthly from March of 2007 to March of 2008 in each plot (10 m × 10 m or 1 m × 1 m) using static chambers and a gas chromatograph (Wang and Wang, 2003). Each static chamber consisted of two parts: a steel collar (20 cm diameter and 5 cm height) attached to a circular sink (18 cm of inner diameter and 22 cm of outer diameter), and a removable top PVC chamber (20 cm diameter and 20 cm height). Five steel collars were randomly located in each 10 m × 10 m plot, and one was located in each 1 m × 1 m plot, and they were anchored firmly in the soil (5 cm deep) for the duration of the study. During each sampling, the removable chamber was placed on top of the sink collar and sealed with water. We did not install a fan inside the chamber because a fan could alter the concentration gradient of CO2 efflux and cause a bias in measurement (Davidson et al., 2002). The soil CO2 efflux was sampled from 09:00 to 10:00 because previous studies in the area suggested that Rs rates during this time interval were close to daily means (Tang et al., 2006). The efflux measurement lasted for 30 min on each sampling. Before removing a gas sample from the chamber with a syringe, we filled and emptied the syringe five times to mix the air inside the chamber. Gas samples (60 ml) were then collected every 10 min (after 0, 10, 20, and 30 min) from each 6280-ml chamber using a 100-ml plastic syringe. CO2 concentration in the syringe was analyzed in the laboratory within 24 h (a preliminary test showed that the CO2 concentration in the syringe did not change within 36 h) with a gas chromatograph (HP 6890, Agilent Technologies, Palo Alto, CA, USA). The gas chromatograph configurations for CO2 analysis and the methods for CO2 efflux calculation followed those described by Wang and Wang (2003). The CO2 efflux was calculated based on the rate of change in CO2 concentration within the chamber, which was estimated as the slope of linear regression between concentration and time. All the coefficients of determination (r2) of the linear regression were greater than 0.95. Soil temperature and soil moisture were measured (March to September of 2007) with DS1923-F5 Hygrochron temperature/relative humidity loggers (Dallas Semiconductor, United States) at 5-cm depth in two plots of each plot type in each plantation. Data were acquired every 10 s, 30-min averages were stored, and daily averages were calculated.

2.8. Calibration of soil CO2 flux in girdled and trench plots

To assess the effects of corrections for disturbances such as soil temperature and soil moisture on the estimation of soil CO2 efflux models, partitioning, relationships between soil CO2 flux with soil temperature and soil moisture (W) were examined using regression models. First, we determined the relationship of soil CO2 flux with soil moisture and soil temperature using a linear model (Eq. (7)) and an exponential model (Eq. (8)) (Boone et al., 1998; Burton et al., 2004; Chen et al., 2009). The form of linear model was:

\[ R = a + b \times W \]  \quad (7)

where \( R \) is soil moisture (\%) at 10 cm depth, and \( a \) and \( b \) are constants fitted with the least-squares technique. The form of exponential model was:

\[ R = a \times \exp(bT) \] \quad (8)

where \( T \) is soil temperature (°C) at 10 cm depth, and \( a \) and \( b \) are constants fitted with the least-squares technique. Finally, we fit a model that considered both soil temperature and soil moisture. This model, which is referred to as the T/W model (Xu and Qi, 2001; Burton et al., 2004), was:

\[ R = a \times \exp(bT) \times (W)^c \] \quad (9)

where \( T \) is soil temperature (°C) at 10 cm depth; \( W \) is soil moisture (\%) at 10 cm depth; and \( a, b, \) and \( c \) are constants fitted with the least-squares technique. We reconstructed the soil CO2 flux for girdled and trench plots using the T/W model and with soil temperature and soil moisture from control plots as independent variables.

2.9. Measurements of soil chemical characteristics

Composite soil samples were collected in each plot (five for 10 m × 10 m plot and one for 1 m × 1 m plot) four times (in March, July, November of 2007 and March of 2008), with each composite sample being a mix of four randomly selected soil cores. Soil microbial biomass (\( C_{mic} \)) determined using the chloroform fumigation–extraction method (Vance et al., 1987). Briefly, two 20-g subsamples of field-moist soil were used in fumigated or not fumigated (control) treatments. Soluble organic carbon in the filtered K2SO4 extracts of both fumigated and non-fumigated samples was determined using a total organic carbon analyzer (Shimadzu TOC-VCPH). \( C_{mic} \) was calculated as 2.22 × \( E_C \) (Wu et al., 1990), where \( E_C \) is carbon extracted from fumigated soil minus carbon extracted from nonfumigated soil. The non-fumigated C content is referred to hereafter as \( K_2SO_4 \)-extractable carbon, which is a proxy for dissolved organic carbon (DOC) in the soil (Scott-Denton et al., 2006). A subsample of 20 g soil was oven-dried at 105 °C for 24 h to determine soil moisture. All results are expressed on an oven-dry soil basis.

2.10. Statistical analysis

We compared the data from the trench, girdled, and control plots to evaluate the treatment effects. Mean values of the variables (\( C_{mic} \) and DOC) for trenching, girdling, and control treatments in each sample event were subjected to one-way ANOVA. One way repeated-measures ANOVA (RM ANOVA) was used to determine differences between the treatment variables continuously monitored (soil temperature, soil moisture, and soil CO2 efflux) and between the two plantations through the experimental period. If a significant test statistic was obtained (\( P \leq 0.05 \)) using one-way ANOVA or one-way RM ANOVA, Bonferroni t-test multiple comparison procedures were used to identify significant differences among the treatments. Significance was determined at \( P \leq 0.05 \), and all statistical analyses were performed using SigmaPlot 11.0 (SPSS, Inc., Chicago, IL).

3. Results

3.1. Changes in soil environment caused by tree girdling and trenching

The soil temperature and soil moisture data differed in the trench, girdled and control plots in both plantation types using one way RM-ANOVA analysis (Fig. 1). During the “wetter season” (March–May), the “wet season” (June–August), and the “dry season” (September–February), Bonferroni t-test multiple comparison procedures showed that soil temperature was higher in girdled plots than in control plots (\( P < 0.05 \)) for both plantations (Fig. 2A and B). Compared to control plots, soil temperature in trench plots was increased (\( P < 0.05, n = 92 \)) during the dry season for both
plants, but soil temperature did not differ among these plots ($P < 0.05$, $n = 182$) during the wetter season (Fig. 2A and B). During the wetter season, soil moisture was highest in trench plots ($P < 0.001$, $n = 92$) and lowest in girdled plots ($P < 0.001$, $n = 92$) for both plantations (Fig. 2C and D). During the wet season, soil moisture was highest in girdled plots ($P < 0.001$, $n = 92$) and lowest in trench plots ($P < 0.001$, $n = 92$) for A. crassicarpa; for E. urophylla, soil moisture was lower in girdled plots ($P < 0.001$, $n = 92$) than in trench and control plots (Fig. 2C and D). During the dry season, soil moisture was highest in the girdled plots ($P < 0.001$, $n = 182$) and lowest in the control plots ($P < 0.001$, $n = 182$) for both plantations (Fig. 2C and D).

The $C_{mic}$ and DOC data significantly differed among treatment plots for both plantations based on one-way ANOVA. In both plantations, Bonferroni $t$-test multiple comparison procedure showed that $C_{mic}$ was significantly lower in trench plots than in girdled plots ($P < 0.001$ for A. crassicarpa and $P = 0.016$ for E. urophylla, $n = 4$) and control plots ($P < 0.001$ for A. crassicarpa and $P = 0.011$ for E. urophylla, $n = 4$) (Fig. 2A and B). $C_{mic}$ was significantly lower in girdled plots than in control plots for A. crassicarpa ($P = 0.009$, $n = 4$) but not for E. urophylla ($P = 0.944$, $n = 4$). Trends for DOC were similar to those for $C_{mic}$, i.e., DOC was significantly lower in trench plots than in girdled plots ($P = 0.004$, $n = 4$) and control plots ($P < 0.001$, $n = 4$) for A. crassicarpa. For E. urophylla, DOC was significantly lower in trench plots than in control plots ($P = 0.024$, $n = 4$) but did not differ between girdled plots and trench ($P = 0.239$, $n = 4$) or control ($P = 0.230$, $n = 4$) plots (Fig. 2C and D).

3.2. Soil CO$_2$ efflux as affected by trenching and tree girdling

According to one-way RM-ANOVA, soil CO$_2$ efflux over the whole year significantly differed among treatment plots for both plantations ($F_{(2,44)} = 28.573$, $P < 0.001$ for A. crassicarpa and $F_{(2,44)} = 21.788$, $P < 0.001$ for E. urophylla). The multiple comparison procedures showed that soil CO$_2$ efflux was significantly lower in trench plots ($R_{ht}$) than in girdled plots ($R_{hg}$) for A. crassicarpa ($P = 0.024$, $n = 15$) and E. urophylla ($P = 0.012$, $n = 15$) (Fig. 3). Both $R_{ht}$ and $R_{hg}$ were significantly lower than soil CO$_2$ efflux in control plots ($R_c$) for A. crassicarpa ($P < 0.001$ and $P = 0.004$, $n = 15$) and for E. urophylla ($P < 0.001$ and $P < 0.015$, $n = 15$). For A. crassicarpa, the mean values of $R_{ht}$, $R_{hg}$, and $R_c$ were 1166 ± 165, 1444 ± 247, and 1904 ± 229 nmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively (Fig. 3A). For E. urophylla, the mean values of $R_{ht}$, $R_{hg}$, and $R_c$ were 1059 ± 99, 1250 ± 128, and 1607 ± 153 nmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively (Fig. 3B).

For A. crassicarpa, the ratio of $R_{ht}$ to $R_c$ ranged from 29 to 93% with a mean of 58 ± 4%, and the ratio of $R_{hg}$ to $R_c$ ranged from 39 to 134%, with a mean of 74 ± 6% (Fig. 3A). For E. urophylla, the ratio of $R_{ht}$ to $R_c$ ranged from 39 to 93%, with a mean of 64 ± 3%, and the ratio of $R_{hg}$ to $R_c$ ranged from 53 to 127%, with a mean of 78 ± 5% (Fig. 3B).

The ratio of $R_{ht}$ to $R_{hg}$ ranged from 0.57 to 1.20 (with a mean of 0.86 ± 0.10) for A. crassicarpa, and ranged from 0.58 to 1.20 (with a mean of 0.87 ± 0.09) for E. urophylla (Fig. 4). For both plantations, the ratios of $R_{ht}$ to $R_{hg}$ were mostly less than 1.0 for
most of the experiments but approached 1.0 at the end of the experiment.

Simple exponential and linear models showed that soil temperature ($T$) and soil moisture ($W$) were positively related with soil CO$_2$ fluxes in the trenched plots ($R_{\text{trench}}$), girdled plots ($R_{\text{girdled}}$), and control plots ($R_{\text{control}}$) for both plantations (Tables 1 and 2). The fitted $T/W$ model, which included both $T$ and $W$, explained 69–92% and 47–65% of the variance in soil CO$_2$ flux for A. crassicarpa and E. urophylla plantations, respectively (Tables 1 and 2).

To assess the effects of corrections for such disturbances of soil moisture and soil moisture on the estimation of soil CO$_2$ efflux, soil CO$_2$ fluxes in trenched plots ($R_{\text{trench}}$) and girdled plots ($R_{\text{girdled}}$) for both plantations were reconstructed by applying the fitted $T/W$ model with $T$ and $W$ data from the control plots (Fig. 5). One-way

Fig. 2. Soil microbial biomass (mg C kg$^{-1}$ dry soil) and dissolved organic carbon (mg C kg$^{-1}$ dry soil) in trenched plots, girdled plots, and control plots in A. crassicarpa (A and C) and E. urophylla (B and D) plantations. Values are means ± standard error (n = 3). Within each panel, values with different letters are significantly different (P < 0.05) based on a one-way ANOVA.

Fig. 3. Soil CO$_2$ efflux (nmol CO$_2$ m$^{-2}$ s$^{-1}$) measured in trenched plots, girdled plots, and control plots in A. crassicarpa (A) and E. urophylla (B) plantations. Values are means ± standard error (n = 3).
Fig. 4. The ratio of soil CO₂ efflux in trenched plots (Rₜ) to soil CO₂ efflux in girdled plots (Rₐ) in A. crassicarpa and E. urophylla plantations.

Table 1
Results of regression analysis for the relationship between soil CO₂ flux and soil temperature (T) and soil moisture (W) in trenched, girdled, and control plots in the A. crassicarpa plantation.

<table>
<thead>
<tr>
<th></th>
<th>R = a + b(W)</th>
<th>a</th>
<th>b</th>
<th>r²</th>
<th>F₁,49</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rₜ</td>
<td>-2982.217</td>
<td>53.971</td>
<td>0.422</td>
<td>0.366</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rₐ</td>
<td>-4084.584</td>
<td>72.028</td>
<td>0.450</td>
<td>0.381</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rₛ</td>
<td>-4521.070</td>
<td>84.508</td>
<td>0.568</td>
<td>0.594</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>R = a × exp(b × T)</th>
<th>a</th>
<th>b</th>
<th>r²</th>
<th>F₁,49</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rₜ</td>
<td>560.694</td>
<td>0.071</td>
<td>0.340</td>
<td>0.228</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rₐ</td>
<td>83.878</td>
<td>0.091</td>
<td>0.399</td>
<td>0.382</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rₛ</td>
<td>190.587</td>
<td>0.106</td>
<td>0.372</td>
<td>0.503</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

Rₜ, Rₛ, and Rₐ are soil CO₂ flux (nmol CO₂ m⁻² s⁻¹) in trenched, girdled, and control plots, respectively; T and W are soil temperature and soil moisture at 10-cm depth, respectively; a, b, and c are equation coefficients for Eqs. (7)-(9); RMSE is root mean squared error.

RM-ANOVA showed that the reconstructed values for Rₘ were significantly lower than the fitted Rₘ for the three seasons for both plantations (P < 0.05) (Fig. 5). During wetter season, there was no difference between the reconstructed Rₘ and fitted Rₘ for both plantations (P = 0.091 for A. crassicarpa and P = 0.112 for E. urophylla, n = 92). During the wet season, the reconstructed Rₘ was significantly higher than the fitted Rₘ, for A. crassicarpa (P < 0.001, n = 92) but was lower than the fitted Rₘ for E. urophylla (P < 0.001, n = 92). During the dry season, the reconstructed Rₘ was significantly lower than the measured Rₘ for both plantations (P < 0.001, n = 182).

Over the whole year, the reconstructed Rₘ was significantly lower than the fitted Rₘ for both plantations (F₁,729 = 193.883, P < 0.001 for A. crassicarpa and F₁,729 = 165.136, P < 0.001 for E. urophylla) (Fig. 5). The reconstructed Rₘ was significantly lower than the fitted Rₘ for E. urophylla (F₁,729 = 129.565, P < 0.001) but not for A. crassicarpa (F₁,729 = 3.606, P = 0.097).

The reconstructed Rₜ and Rₐ were 1171.1 ± 120.8 and 1436.1 ± 210.9 nmol CO₂ m⁻² s⁻¹, respectively, for A. crassicarpa (Fig. 5A), and 1003.2 ± 133.8 and 1272.0 ± 127.5 nmol CO₂ m⁻² s⁻¹, respectively, for E. urophylla (Fig. 5B). The fitted Rₜ and Rₐ were 1173.4 ± 124.4 and 1573.4 ± 156.6 nmol CO₂ m⁻² s⁻¹, respectively, for A. crassicarpa (Fig. 5A), and 1048.6 ± 86.9

Fig. 5. Fitted soil CO₂ efflux (Fit-Rₜ, Fit-Rₐ, Fit-Rₘ) by the T/W model with T and W data in trenched, girdled, and control plots, and reconstructed soil CO₂ efflux (Re-Rₜ, Re-Rₐ, Re-Rₘ) by the T/W model with T and W data in control plots in A. crassicarpa (A) and E. urophylla (B) plantations. T and W are soil temperature and soil moisture at 10-cm depth, respectively. The inset plots show mean annual values of Fit-Rₜ and Re-Rₜ in trenched and girdled plots in the wetter season, the wet season, and the dry season. Values are means ± standard error (n = 3). Within each season, bars with different letters are significantly different (P < 0.05) as determined by a one-way RM ANOVA.
Table 3
Results of regression analysis for aboveground living biomass ($B_{a}$) (including foliage, branch, and bole biomass) and coarse root biomass ($B_{r}$) based on height ($H$) and diameter at breast height (DBH) for A. crassica and E. urophylla plantations using a linear model (Eq. (4)).

<table>
<thead>
<tr>
<th>Plantation</th>
<th>Allometric relationship including CF</th>
<th>$a$</th>
<th>$b$</th>
<th>$r^2$</th>
<th>RSE</th>
<th>CF</th>
<th>$F_{1,15}$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. crassica</td>
<td>$B_{a} = 126.27(DBH^{2}H)^{0.44}$</td>
<td>0.439</td>
<td>4.830</td>
<td>0.586</td>
<td>0.128</td>
<td>1.008</td>
<td>7.964</td>
<td>0.037</td>
</tr>
<tr>
<td>E. urophylla</td>
<td>$B_{a} = 21.64(DH)^{0.50}$</td>
<td>0.504</td>
<td>3.064</td>
<td>0.609</td>
<td>0.142</td>
<td>1.010</td>
<td>8.207</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Data for the linear model were determined in December of 2006; $a$ and $b$ are equation coefficients; RSE is the residual standard error of each linear model; CF is the correction factor for the back transformation of the regression error.

Table 4
Measurements and estimates of tree components and NPP in A. crassica and E. urophylla plantations.

<table>
<thead>
<tr>
<th>Component of NPP</th>
<th>A. crassica</th>
<th>E. urophylla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>3.60 (0.08)</td>
<td>6.21 (0.24)</td>
</tr>
<tr>
<td>DBH (cm)</td>
<td>2.59 (0.13)</td>
<td>6.03 (0.31)</td>
</tr>
<tr>
<td>Foliage (g DW m$^{-2}$)</td>
<td>198.73 (12.17)</td>
<td>–</td>
</tr>
<tr>
<td>Branch (g DW m$^{-2}$)</td>
<td>135.87 (18.97)</td>
<td>–</td>
</tr>
<tr>
<td>Bole (g DW m$^{-2}$)</td>
<td>175.43 (17.64)</td>
<td>–</td>
</tr>
<tr>
<td>Aboveground living biomass (g DW m$^{-2}$)</td>
<td>510.02 (33.45)</td>
<td>1366.08 (141.73)</td>
</tr>
<tr>
<td>Coarse root (g DW m$^{-2}$)</td>
<td>106.51 (15.01)</td>
<td>332.39 (59.86)</td>
</tr>
<tr>
<td>Fine root (g DW m$^{-2}$)</td>
<td>41.36 (3.74)</td>
<td>107.36 (25.36)</td>
</tr>
<tr>
<td>Litter (g C m$^{-2}$ yr$^{-1}$)</td>
<td>–</td>
<td>252.14 (19.40)</td>
</tr>
<tr>
<td>$\Delta$Aboveground living biomass (g C m$^{-2}$ yr$^{-1}$)</td>
<td>–</td>
<td>400.64 (42.80)</td>
</tr>
<tr>
<td>$\Delta$Coarse root (g C m$^{-2}$ yr$^{-1}$)</td>
<td>–</td>
<td>105.71 (22.13)</td>
</tr>
<tr>
<td>$\Delta$Fine root (g C m$^{-2}$ yr$^{-1}$)</td>
<td>–</td>
<td>40.81 (4.93)</td>
</tr>
<tr>
<td>NPP (g C m$^{-2}$ yr$^{-1}$)</td>
<td>–</td>
<td>800.30 (118.01)</td>
</tr>
</tbody>
</table>

$\Delta$ represents the annual increment of tree components. Coarse root and living biomass in December of 2007 were estimated using allometric relationships based on height and DBH determined in December of 2006. Except for fine root and litter values, values are means (standard errors) of 7 replicate trees in December of 2006 and of 3 replicate plots in December of 2007. Fine root mass was measured in December of 2006 and 2007 using a soil core method in 3 replicate plots.

3.3. Estimation of NPP and its components

On 10 December 2006, the allometric relationships between height and DBH and $B_{a}$ (including foliage, branch, and bole biomass) and $B_{r}$ were estimated with a power model for A. crassica ($B_{a} = 126.27(DBH^{2}H)^{0.44}$, $B_{r} = 21.64(DBH^{2})^{0.50}$) and for E. urophylla ($B_{a} = 41.15(DBH^{2})^{0.68}$, $B_{r} = 45.28(DBH^{2})^{0.48}$) (Table 3). These allometric relationships explained 39–72% of the variance of $B_{a}$ or $B_{r}$. The fine root biomass ($B_{r}$) on 10 December 2006, as determined by soil coring, was 41.36 $\pm$ 3.47 g m$^{-2}$ for A. crassica and 43.04 $\pm$ 5.57 g m$^{-2}$ for E. urophylla (Table 4). For A. crassica, the contributions to total biomass were 30% for foliage, 21% for branches, 27% for the bole, 16% for coarse roots, and 6% for fine roots (Table 4). For E. urophylla, the bole, coarse roots, and fine roots represented 39, 32, and 3% of total biomass (Table 4).

On 7 December 2007, the aboveground and coarse root biomass, as estimated by the allometric relationships, were 1366.08 $\pm$ 141.73 and 332.39 $\pm$ 59.86 g DW m$^{-2}$, respectively, for A. crassica, and 4740.26 $\pm$ 289.36 and 1289.11 $\pm$ 109.84 g DW m$^{-2}$, respectively, for E. urophylla (Table 4). The fine root biomass, as determined by soil coring, was 107.36 $\pm$ 25.36 for A. crassica and 163.36 $\pm$ 41.89 g DW m$^{-2}$ for E. urophylla (Table 4). After the biomass data of the annual increments of litter, fine root, coarse root, aboveground were converted into C mass (Table 4), the net primary production (NPP) was estimated with 800.30 $\pm$ 118.01 g C m$^{-2}$ yr$^{-1}$ for A. crassica and 2379.34 $\pm$ 186.93 g C m$^{-2}$ yr$^{-1}$ for E. urophylla (Table 4). For A. crassica, heterotrophic respiration ($R_{h}$) was 469.92 $\pm$ 25.43 g C m$^{-2}$ yr$^{-1}$ for trench and girdled plots, which was the mean of the annual $R_{h}(444.49 \pm 47.3 g C m^{-2} yr^{-1})$.
4. Discussion

4.1. Changes in soil microbial carbon, dissolved organic carbon, soil temperature, and soil moisture

Soil temperature and soil moisture are among the most important factors controlling the decomposition of soil organic matter (SOM) (Raich and Potter, 1995; Buchmann, 2000). In the present study, soil moisture and soil temperature were changed by trenching and tree girdling, and the effects differed among seasons and plantations. In the A. crassicarpa plantation, soil temperature was highest in girdled plots while in the E. urophylla, soil temperature was similar in trenched and girdled plots, and was higher in the latter two plots than in control plots. The different effects of the treatments (trenching, girdling, and control) and plantation types on soil temperature in our experiment may be explained by differences in light interception. The A. crassicarpa leaves started to fall 3 months after girdling, and no leaves remained on the plants 5 months after girdling, while the E. urophylla leaves did not fall until 7 months after girdling, and 70% of the trees were still alive 1 year after girdling (Chen et al., 2010a). This difference in leaf retention could have resulted from more light penetrating to the soil in girdled plots with A. crassicarpa than with E. urophylla. Our results on the effect of girdling on soil temperature differ from the results of previous reports in other forest ecosystems, which indicated that soil temperature was not changed by tree girdling (Högberg et al., 2001; Ekberg et al., 2007; Li et al., 2009).

For both plantations, soil moisture was highest in the trenched plots during the wetter season but lowest in the trenched plots during the wetter season. This difference might be explained by the small size and lack of roots in the trenched plots, which could have reduced their ability to reduce soil water when water was more abundant and to retain soil water when water was less abundant. The effect of girdling also differed among seasons. In the wetter season, girdling decreased soil moisture relative to the control in both plantations. This might be explained by an initial increase in water uptake by roots in response to the girdling wound (Chapin and Slack, 1979).

Soil temperature and soil moisture are two of the most important biophysical factors controlling variations in soil CO2 efflux (Davidson et al., 1998; Joffre et al., 2003; Reichstein et al., 2003). The changes in soil moisture and soil temperature induced by trenching and girdling would be expected to change soil CO2 flux in the trenched and girdled plots (Ngao et al., 2007). In the present research, Rs-w was significantly altered by the changes in the two soil biophysical factors induced by girdling, while Rs-w was not altered by the changes in these factors induced by trenching. These results confirmed our hypotheses that trenching and girdling induced changes in soil biophysical factors (soil temperature and soil moisture) that altered soil CO2 flux. It follows that disturbances of soil biophysical factors should be accounted for when researchers estimate soil CO2 efflux after trenching and girdling.

In both plantations, Cmic and DOC tended to be highest in the control plots, intermediate in the girdled plots, and lowest in the trenched plots. This is consistent with previous reports that trenching and girdling decrease Cmic and DOC (Ross et al., 2001; Staples et al., 2001; Högberg and Högberg, 2002; Scott-Denton et al., 2006; Ngao et al., 2007; Weintraub et al., 2007; Chen et al., 2010a). The decrease in Cmic and DOC caused by trenching and girdling might be explained by the absence of living plant roots and a subsequent reduction in root exudates, which are a major source of labile carbon inputs to soil (Kuzyakov et al., 2000; Bertin et al., 2003). Why Cmic and DOC were greater in the girdled plots than in the trenched plots is unclear, but perhaps girdling generated a greater pulsed input of dead roots, and this pulse functioned as a primer for the decomposition of soil organic carbon.

In summary, the effects of trenching and tree girdling on soil moisture, soil temperature, Cmic, and DOC were season- and plantation-dependent. This means that, in the calculation of how soil CO2 efflux is partitioned between autotrophic and heterotrophic respiration, correcting for the environmental disturbances caused by trenching and girdling is necessary and warrants.

4.2. Estimates of soil CO2 efflux

Although our estimates of the contribution of Rs to Rso (58–78%) were in the range (10–50%) reported in the literature (Hanson et al., 2000; Subke et al., 2006), our estimates were higher than the mean of 54% reported for forest soil and higher than those in a beech forest (40%) (Epron et al., 1999) and a Eucalyptus stand (41%) (Epron et al., 2006). We considered that the discrepancies in the proportion of Rs to Rso might vary not only with plant species but also with the method used for partitioning soil respiration. In the current study, Rso-w was significantly lower than Rs-w in both plantations for most of the experimental period, perhaps because some roots in girdled plots remained alive and continued to release CO2 and there was greater decomposition of dead roots in girdled plots than in trenched plots (Binkley et al., 2006; Chen et al., 2010a). At the end of the experiment, values for Rs, Rs-w, and Rs-g were similar in both plantations, presumably because those roots that remained alive after girdling had finally died. The results suggest that girdling and trenching will provide similar estimates of soil CO2 flux if sufficient time passes after plots are established. This is consistent with the view that root exclusion via trenching and girdling has value for estimating the SOM-derived and root-derived CO2 if the rhizosphere priming effect is assumed to be small (Kuzyakov, 2006).

4.3. Estimation of NEP and NPP components by the biometric approach

According to the biometric approach and the data collected in this study, young sub tropical plantations of A. crassicarpa and E. urophylla are large carbon sinks. The NEP, however, was substantially lower for the A. crassicarpa plantation (330.38±75.8 g C m−2 yr−1) than for the E. urophylla plantation (1958.63±177.75 g C m−2 yr−1). Because Rs was similar for the two plantations in the current study (469.92±25.43 g C m−2 yr−1 for A. crassicarpa and 420.71±34.78 g C m−2 yr−1 for E. urophylla), the differences in NEP estimates resulted from differences in NPP estimates. The NPP estimation for the E. urophylla plantation (2379.34±186.93 g C m−2 yr−1) was three times for A. crassicarpa (800.30±118.01 g C m−2 yr−1).

It is clear that species with a high photosynthetic nitrogen use efficiency (PNUE) and maximum net photosynthetic rate (Pmax) tend to have high growth rates or high productivity habitats (Aber and Federer, 1992; Hikosaka, 2004). In the same site that was used for the current experiment, we found that Pmax and PNUE were significantly higher for E. urophylla (25.0±3.2, 214.0±41 μmol m−2 s−1) than for A. crassicarpa (21.4±2.8, 77.4±11 μmol m−2 s−1) (Zhang et al., 2009). Hence, we inferred that the higher NPP of E. urophylla reflected its higher Pmax and PNUE. However, this high rate of productivity is often associated with high rates of nutrient and water use rarely lasts for long periods because of drought and nutrient limitations (Whitehead and Beadle, 2004).
Our estimation of NPP for the *A. crassicarpa* plantation in the current study was similar to the estimation by Qin et al. (2007), which was 841 g C m⁻² yr⁻¹ for another *A. crassicarpa* plantation. Compared to other plantations or forests in subtropical China, the NPP of the *A. crassicarpa* plantation was higher than those of *Cunningham- 
hamia lanceolata* plantations and Masson pine forests, but was lower than those of *Castanopsis kawakamii* plantations, *Casuarina equi- 
setifolia* plantations, evergreen coniferous forests, and evergreen 
wide-leafed forests (Table 5). Compared to other biomes, the NPP of the *A. crassicarpa* plantation was similar to that of temperate 
humid forests (738–783 C m⁻² yr⁻¹) and evergreen Mediterranean 
wide forests (801 C m⁻² yr⁻¹), marginally lower than that of ever-
green tropical humid forests (864 C m⁻² yr⁻¹), but higher than that of boreal forests (271–539 C m⁻² yr⁻¹) (Luysaert et al., 2007). Our estimation of NPP for *E. urophylla* was consistent with that of Stape et al. (2008), who reported an NPP range of 2054–3423 g C m⁻² yr⁻¹ for an *E. urophylla* plantation in Brazil, but was higher than that reported for other dominant plantations or forests in subtropical 
China. Our estimation of NPP for *E. urophylla* was remarkably higher 
than estimates for the dominant forest biomes; it was nearly 3× greater than that of evergreen tropical humid forests (Luysaert et al., 2007).

Our estimation of the NPP of the *A. crassicarpa* plantation was similar to those of *C. lanceolata* plantations and evergreen 
coniferous forests but was lower than those of *Pinus elliotti* plantations, *Castanopsis kawakamii* plantations, and evergreen 
wide-leafed forests in subtropical China (Table 5). Compared with other biomes worldwide, our estimation of NPP for *A. crassicarpa* plantation was higher than that of boreal forests (40–178 g C m⁻² yr⁻¹) and was lower than those of evergreen tem-
perate humid forests (398 g C m⁻² yr⁻¹), evergreen Mediterranean 
wide forests (380 g C m⁻² yr⁻¹), and evergreen tropical humid forests (403 g C m⁻² yr⁻¹) (Luysaert et al., 2007). Our estimation of NPP for *E. urophylla* was consistent with that of Stape et al. (2008), who reported an NPP ranging from 800 to 2700 g C m⁻² yr⁻¹ for an *E. urophylla* plantation in Brazil, but was higher than those for other 
dominant plantations or forests in subtropical China. Our estima-
tion of NPP for *E. urophylla* was remarkably higher than those for the 
dominant forest biomes worldwide; it was nearly 5× greater than that 
of evergreen tropical humid forests (Luysaert et al., 2007).

4.4. Uncertainties regarding the components of NPP

It is important to note that our estimation in NPP includes some uncertainties. First, we used a steel collar that was inserted 5 cm into soil to avoid leakage when measuring soil CO₂ flux. Such a deep collar would sever fine roots in humus soil layers and cause a greater decrease in soil CO₂ flux in control plots than girdling or trenching plots, because root density at 0–5 cm depth is greater in control plots than in the other two kinds of plots. This probably contributed to an overestimation of NEP and an underestimation of ratio of R₂₈ to R₅ or R₂₈ to R₅. Second, our techniques (trenching and girdling) for separat-
ing R₅ have inherent drawbacks in that the effects of residual 
roots are unknown but undoubtedly affect CO₂ efflux (Baggs, 2006; Kuzjakov, 2006; Ngo et al., 2007). The failure to account for these 
residual roots would result in the overestimation of R₂₈, and R₂₈. 
After 4 months, residual roots in trench plots were rare because 
of rapid decomposition resulting from high moisture and high tempera-
ture in subtropical China (Yi et al., 2007). Tree girdling reduced 
the biomass of living fine roots by 94% for *A. crassicarpa* and by only 
18% for *E. urophylla*, and the effect of tree girdling on soil CO₂ efflux 
depended on the tree species (Chen et al., 2010a). Moreover, we 
moved the understory vegetation monthly throughout the exper-
iment in all plots. Inevitably, this mowing would also enhance the 
decomposition of the residual roots early in the experiment. This 
again would lead to an overestimation of R₂₈ to and R₂₈ to R₅. It follows 
that, in the calculation of how soil CO₂ efflux is partitioned between 
R₅ and R₂₈, correcting for the residual roots caused by trenching and 
girdling is difficult and warrants further research.

Third, many studies have shown that when CO₂ efflux from soil is 
measured, higher values will be obtained if there is a small reduc-
tion in air pressure in the sampling chamber of few Pa (Xu et al., 
2006). In our measurement, the soil CO₂ efflux (R₂₈) values were 
overestimated because we removed 240 ml of air, which was about 
2.6% of the total chamber volume of 6.28 L. It follows that system-
atic error in measuring R₂₈ would have a greater effect on estimates 
of NPP in the *A. crassicarpa* plantation than in the *E. urophylla* 
plantation. For *E. urophylla*, R₂₈ was relatively small compared to NPP, 
and therefore the estimate of NPP in the *E. urophylla* plantation 
depended much more on the estimate of NPP than on the esti-
mate of R₂₈. This was not the case, however, for the *A. crassicarpa* 
plantation, in which R₂₈ was relatively large compared to NPP.

Fourth, the plantations in this study were at the developmental 
stage. Annual production was at its peak. One of the common 
patterns in these plantations is an increase in production early in 
development growth, followed by a peak near the time when 
maximum leaf area is achieved and the water resource becomes 
limiting (Ryan et al., 2004). After this peak in production and leaf 
area, the rate of increase in stand biomass declines by 20–80% over 
a period of years to centuries (Gower et al., 1996; Ryan et al., 1997). 
Moreover, this high NPP rarely lasts for several rotations because of 
limitations in water and nutrients (Whitehead and Beadle, 2004). 
Furthermore, the high NPP trade off against these life history 
strategies, such as higher nutrient/water requirements, that might 
constrain the usefulness of Eucalyptus as a carbon sink. We there-
fore suggest that, with respect to estimations of C sequestration and 
C cycling, the results of this study might be more meaningful 
for young plantations than old plantations.

The current study highlights that assessment of NPP estimates 
must include consideration of the methods used to obtain the 
estimates. Still, the results of the current paper indicate that *A. crus-
ricarpa* plantations and especially *E. urophylla* plantations in the 
developmental stage in South China are important C sinks.

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