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ORIGINAL ARTICLE

Does tree species composition affect soil CO_2 emission and soil organic carbon storage in plantations?

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Abstract

Key message **Mixed tree plantations are potential silvicultural systems to increase soil carbon storage through altering litter and root inputs and soil physiochemical properties.**

Abstract Afforestation and reforestation are major strategies for global climate change mitigation. Different tree species composition can induce diverse changes in soil CO_2 emission and soil carbon sequestration in tree plantation. This study employed three plantations of monoculture and mixed *Pinus yunnanensis* and *Eucalyptus globulus* to estimate the effect of tree species composition on soil CO_2 emission and soil organic carbon storage in subtropical China. We found that tree species composition had a significant effect on the soil CO_2 emission and soil organic carbon storage. Soil CO_2 emission was lower in the mixed plantation than in the *P. yunnanensis* plantation, whereas it was higher than in the *E. globulus* plantation. Differences in soil CO_2 emission among the three plantations were determined by leaf litterfall mass, fine root biomass, soil available nitrogen, pH, soil bulk density, and soil C:N ratio. Soil organic carbon storage was 34.5 and 23.2 % higher in the mixed plantation than in the *P. yunnanensis* and *E. globulus* plantations, respectively. Higher soil organic carbon stock in the mixed plantation was attributed to lower C/N ratio of leaf litter and soil, greater fine root biomass and soil organic carbon content, and lower soil CO_2 emission. We conclude that mixed tree plantation can enhance soil carbon sequestration, but can decrease or increase soil CO_2 emission through altering litter and root inputs and soil physiochemical properties.

Keywords Tree species · Soil organic carbon storage · Soil CO_2 emission · Mixed tree plantation

Introduction

Afforestation and reforestation are regarded as major strategies for mitigating global climate change, and forest plantations are being established at an increasing rate throughout much of the world (FAO 2001, 2005, 2010). The plantation area in China ranked the first in the world, accounting for 31.8 % of the total forest areas (Department of Forest Resources Management SFA 2010). Most plantations planted with single tree species (e.g., Pinus, Cunninghamia, and Eucalyptus) (SFA 2007; Peng et al. 2008). Mixed stands have the potential to increase production, diversity, and carbon and nutrient storage (Moghaddam 2014). In recent decades, mixed plantations have been developed as a prospective silvicultural management approach for substituting single plantations in China as well as in other countries (Borken and Beese 2006; Vesterdal et al. 2008). A shift in forest cover changes the balance between sink and source for carbon, which can modify the dynamics of soil organic carbon (SOC) and CO_2 emissions (Vitale et al. 2012; Houghton 2013). Therefore, assessing the different properties in SOC stock and soil CO_2 emissions among the pure and mixed

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plantations can improve our understanding of how changes in vegetation cover alter the SOC storage and CO_2 emissions.

SOC is one option for atmospheric CO_2 mitigation (IPCC 2000; Duarte et al. 2013). A small change in SOC storage can induce a large alteration in the atmospheric CO_2 levels at the regional scale (Barger et al. 2011). Therefore, there is increasing interest in quantifying the SOC contribution to CO_2 mitigation (Wani et al. 2014). Changes of soil SOC stock in forest depend on the complex interactions between climate, soil, management, and vegetation cover (Lal 2005; Wagai et al. 2008; Schmidt et al. 2011). Vegetation composition can modify the balance between inputs and outputs of soil CO_2, which determines soil carbon sequestration processes (Jobbagy and Jackson 2000; Jandl et al. 2007). Therefore, there remain too many uncertainties about the effects of tree species composition on SOC storage and soil CO_2 emissions (Johnston et al. 2004; Kelliher et al. 2006; Wang et al. 2013).

Forest tree species composition influences SOC storage by the altering microclimates nearby the forest floor, physiochemical properties in litter, distribution of the root systems and root exudates in soil profile, distribution of carbon within the soil matrix, microbial community structure, and biomass (Jandl et al. 2007; Lucas-Borja et al. 2012). Several studies have shown that mixed forests can increase soil carbon concentrations and SOC stocks (Kaye et al. 2000; Forrester et al. 2006, 2013; Epron et al. 2013). However, little is understood about the mechanism controlling the differences in amount and fractions distribution of SOC between monoculture and mixed forests.

Forest tree species composition affects soil CO_2 emissions through changing soil physical and chemical properties that influence the activities of microbe and fine root (Kelliher et al. 2006; Kumar et al. 2014). Tree species composition alters soil chemical, physical, and biological processes through their root system, canopy structure, leaf structure, and litter quality (Borken and Beese 2006; Jonard et al. 2007; Ullah et al. 2008). Soil CO_2 emissions were widely reported to be a significant different in the pure and mixed stands (Borken and Beese 2005; Berger et al. 2010; Wang et al. 2013; Gahagan et al. 2015). Therefore, it is important to explore the dynamics of soil CO_2 release in the conversion processes of monoculture forests to mixed forests.

In this study, we aimed to examine the characteristics and the influencing factors of soil CO_2 emissions and SOC storage in the monoculture and mixed plantations of *Pinus yunnanensis* and *Eucalyptus globulus* widely distributed in subtropical China, Yunnan. The chief queries of the study were as follows: (1) What are the effects of tree species composition on soil CO_2 emissions and SOC storage? and (2) How can the changes of soil properties under the conversion of monoculture forests to mixed forests affect soil CO_2 emissions and SOC storage in these plantations?

Materials and methods

Site description

This study was conducted in the northeastern Yunnan Province (25°03′25″N, 102°46′15″E), with subtropical plateau monsoon climate. Annual mean temperature and rainfall are about 15 °C and 979 mm, respectively. Precipitation fluctuates with a strong seasonal pattern. The rainy season (about 85 % rainfall of annual precipitation) is from May to October and a dry season (only about 15 % rainfall of all year) from November to April of next year. The study site was on a 2–4 % sloping terrain and an elevation of 1995–2100 m. The soil derived from purple shale materials was well drained and stone-free, with low organic matter content and compact texture.

Experimental design and measurements of soil CO_2 emission and soil temperature

Three plantations of monoculture and mixed *P. yunnanensis* and *E. globulus* (Table 1) were sampled and replicated in triplicate (30 m × 15 m) with spatial interspersion (at least 500 m apart for the each plantation). These plantations were adjacently established in 1980 after a clear-cut on a bushwood and had similar topography, soil texture, stand age, and management history. Within each replicated plot of three plantations, three 3 m × 3 m subplots were randomly set up to measure soil CO_2 emission over the experimental days. Soil CO_2 emission measurements were conducted three times every month in the beginning, middle, and end of each month from March 2012 to February 2013. We measured CO_2 emission between 10:00 and 16:00 h in a small polyvinyl chloride (PVC) collar (10 cm in diameter and 5 cm in height) installed 2–3 cm into the soil 3 days in advance. We removed all ground vegetation in the collars 3 days in advance by clipping to avoid interference of respiration from above plants. Soil CO_2 emission was measured using the Li 6400-09 soil respiration chamber (Li Inc, Lincoln, NE, USA) connected to a portable infrared gas analyzer (Li Inc). The instrument belonged to the platform of sharing the large instruments and equipment in Southwest Forestry University. Soil temperature (ST) was monitored simultaneously using a copper/constantan thermocouple penetration probe (Li6400-09 TC, Li Inc) inserted in the soil to a depth of 5 cm in the vicinity of the soil respiration chamber.

Table 1 Site conditions at the *P. yunnanensis*, *E. globulus,* and mixed plantations in the Kunming city of Yunnan Province

Site	Stem density (trees ha^{-1})	Soil types	Litter layer thickness (cm)	Average DBH (cm)	Average height (m)	Canopy coverage (%)
Pinus yunnanensis	1420	Red soil	4–5	23	19	65
Eucalyptus globulus	1480	Red soil	1–2	26	21	68
Mixed plantation	1470	Red soil	3–4	28	25	74

Mixed plantation was in a 1:2 mixture of *P. yunnanensis* and *E. globulus*

Sampling and analysis of soil, litterfall, and fine root

On each measurement day, soil cores (6 cm diameter) in each subplot were sampled in the location of PVC collar where the soil respiration chamber was placed after soil CO_2 emission measurements. Soil samples from soil cores were then collected to analyze soil properties (e.g., soil water, pH, bulk density, soil organic matter, total soil nitrogen, and soil available nitrogen in 0–5 cm soil layer). Soil samples were sieved to remove all visible plant material and air-dried for measurements of soil properties. Soil water (SW) at depths of 0–5 cm was determined gravimetrically after drying approximately 20 g of fresh soil at 105 °C for 48 h. pH was measured by direct potentiometry. Soil organic carbon (SOC) and total carbon in leaf litter were determined by the dichromate oxidation with external heating procedure, total nitrogen (TN) in soil and leaf litter by the Kjeldahl digestion method, and soil available nitrogen (AN) by alkaline hydrolysis diffusion method (Lu 2004).

We followed the measurement method designed by Fang et al. (2007) to measure the leaf litterfall mass once every month in the three plantations. The soil coring method was used to investigate fine root (diameter <2 mm) biomass in each subplot when measuring soil CO_2 emission. Soil cores from the soil surface down to 5 cm were collected in the location of PVC collar where the soil respiration chamber was placed, using a 6-cm diameter stainless steel core. Litterfall and fine root samples were oven dried at 65 °C and weighed.

Calculation and data analysis

SOC stock (kg C m^{-2}) at 0–5 cm was calculated by: SOC stock $= C \times D \times E \times (1 - G) \div 100$, where C, D, E, and G are soil organic carbon concentration (g kg^{-1}), bulk density (g cm^{-3}), soil depth (cm), and pebbles volume percentage (%, diameter >2 mm), respectively (Wu et al. 2003).

We used analysis of variance (ANOVA) to test the effects of tree species composition, sampling month and their interaction on the SOC stock and soil CO_2 emission. Multiple comparisons of means among plantations were performed using Duncan test. Relationships between soil CO_2 emission, soil temperature and soil water content were examined using regression modeling techniques. All statistical nonlinear regression and significant difference analyses were performed using SPSS 22.0 (SPSS for windows, Chicago, IL). All the data normality and equal variance were tested. Pearson's correlation coefficients were used to express the relationships of SOC stock and soil CO_2 emission to soil properties.

Result

Soil CO_2 emission

Soil CO_2 emission was affected by tree species composition ($P < 0.01$), while it was also significantly influenced by the sampling month and the interaction of tree species composition and sampling month ($P < 0.05$, Table 2). The soil CO_2 emission was ranked in the order of *P. yunnanensis* plantation > mixed plantation > *E. globulus* plantation (Fig. 1a). Mean soil CO_2 emission was 32 and 21 % higher in the *P. yunnanensis* plantation than in the mixed and *E. globulus* plantations, respectively. Soil CO_2 emission in the mixed plantation displayed a seasonal trend with the highest value in July, in consistent with the maximum of ST (Fig. 1a, b). Soil CO_2 emission in the *P. yunnanensis* and *E. globulus* plantations was characterized by having the highest values in June, which followed the maximum of SW (Fig. 1a, c). The lowest value of soil CO_2 emission in the three plantations was in the cool–dry January.

Temporal variations of soil CO_2 emission in the three plantations were positively related to the dynamics of soil temperature and soil water (Fig. 2). ST explained 83.7 % of the seasonal dynamics of soil CO_2 emission. In contrast, SW can explain above 87.2 % of soil CO_2 emission variations. Soil CO_2 emission in wet seasons (May–October)

Table 2 The effects (F statistics) of tree species composition and sampling month on soil CO_2 emission and SOC stock

Source	*df*	Soil CO_2 emission (mg CO_2–C m^{-2} h^{-1})	SOC stock (g C m^{-2})
Tree species composition	2	10.86**	9.47**
Sampling month	11	7.53*	4.65
tree species composition × sampling time	22	6.29*	3.44

Significant levels: ** $P < 0.01$, * $P < 0.05$

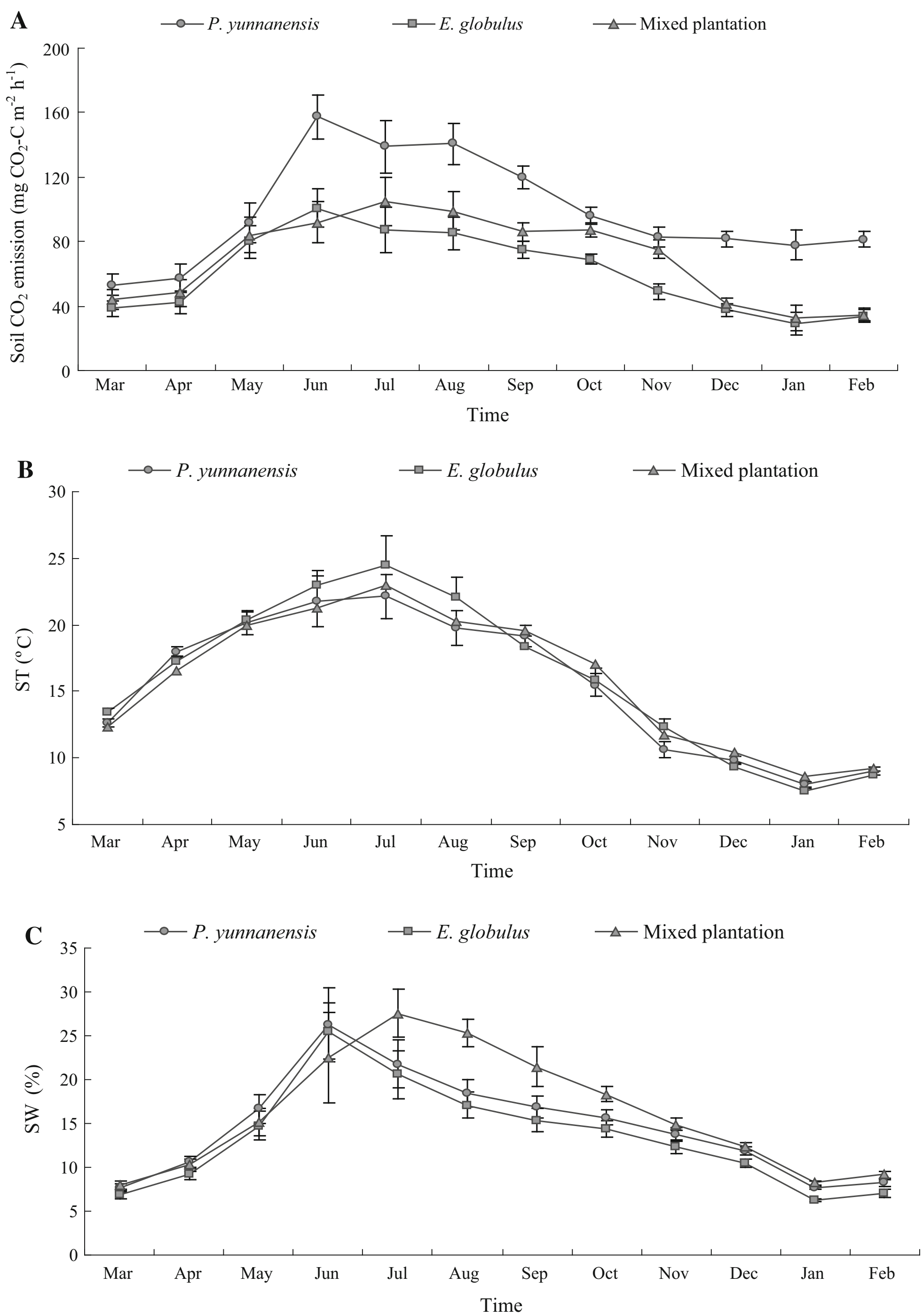

Fig. 1 Temporal variations of soil CO_2 emission (**a**), soil temperature (ST) (**b**), and soil water content (SW) (**c**) in the *P. yunnanensis*, *E. globulus,* and mixed plantations

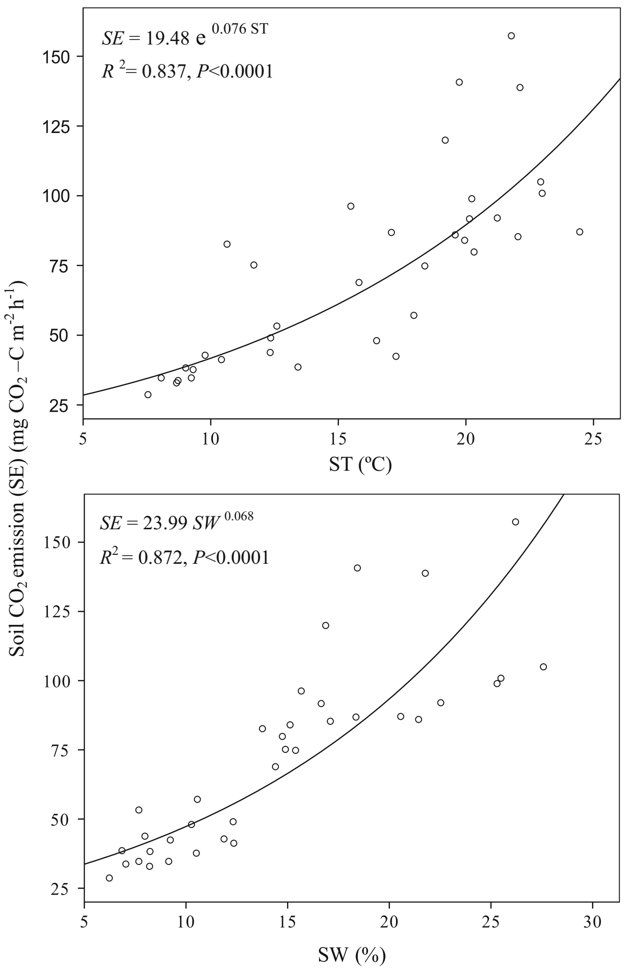

Fig. 2 Relationships between soil CO_2 emission (SE), soil temperatures (ST), and soil water content (SW) in the *P. yunnanensis, E. globulus,* and mixed plantations

was 1.38–1.48 times as big as that in dry seasons (November–April of next year).

SOC stock

SOC stock was impacted by tree species composition, while it was not affected by sampling month (Table 2). SOC stock in the mixed plantation was 34.5 % higher than that in the *P. yunnanensis*, and 23.2 % higher than that in the *E. globulus* plantation (Fig. 3). ST and SW showed no significant differences among *E. globulus*, *P. yunnanensis*, and mixed plantations. They may not be the factors controlling the differences in SOC stock across the three plantations (Fig. 3). The differences in C/N ratio of leaf litterfall, fine root biomass, soil CO_2 emission, and SOC content had a significant effect on SOC stock. Higher SOC stock in the mixed plantation was related closely to lower soil CO_2 emission and C/N ratio in the leaf litterfall, and greater fine root biomass and SOC content (Fig. 4a–c; $p < 0.05$).

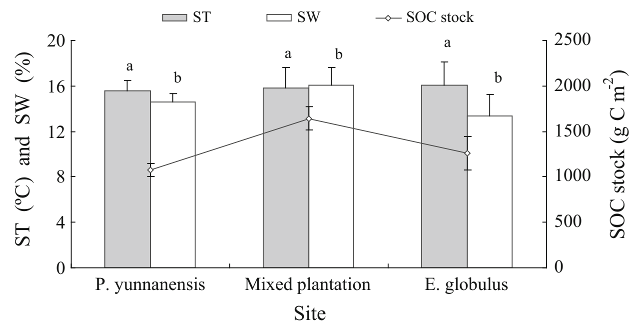

Fig. 3 SOC stock and its relationships to soil temperatures (ST) and soil water content (SW) in the *P. yunnanensis*, *E. globulus,* and mixed plantations (*bars* indicate SE; $n = 12$). Treatments with the *same letter* were not significantly different (ANOVA with Tukey-HSD, $P < 0.05$)

Influencing factors of soil CO_2 emission and SOC stock

In this study, in addition to ST and SW, the leaf litterfall mass, fine root biomass, pH, and AN were also positively correlated with soil CO_2 emission, whereas soil bulk density, SOC, and C/N ratio showed a negative relationship with soil CO_2 emission (Table 3). SOC stock was significantly related to fine root biomass, SOC, TN, and soil bulk density. In contrast, negative correlation was detected between C/N ratio in litter and in soil, and SOC stock (Table 3; Fig. 4a). No significant correlations can be found between soil CO_2 emission and TN, and also between SOC stock, and leaf litterfall mass, pH, and AN (Table 3).

Discussion

Effects of tree species composition on soil CO_2 emission

In this study, tree species composition had a significant effect on soil CO_2 emission across the sampling month. Soil CO_2 emission was lower in the mixed plantation than in the *P. yunnanensis* plantation, and was higher than in the *E. globulus* plantation. Generally, the change of broad leaved forest to mixed forest can increase soil CO_2 emission, as the proportion of coniferous trees increased (Borken and Beese 2005; Tang et al. 2006; Wang et al. 2013; Augusto et al. 2015). Therefore, soil CO_2 emission in mixed forest was higher in comparison with the *E. globulus* forest as coniferous tree species were imported in mixed forest. On the other hand, increased broad leaved trees in the mixed forest versus in coniferous forest, however, reduced the rate of soil CO_2 emission. The discrepancy between the effects of import coniferous and broadleaved

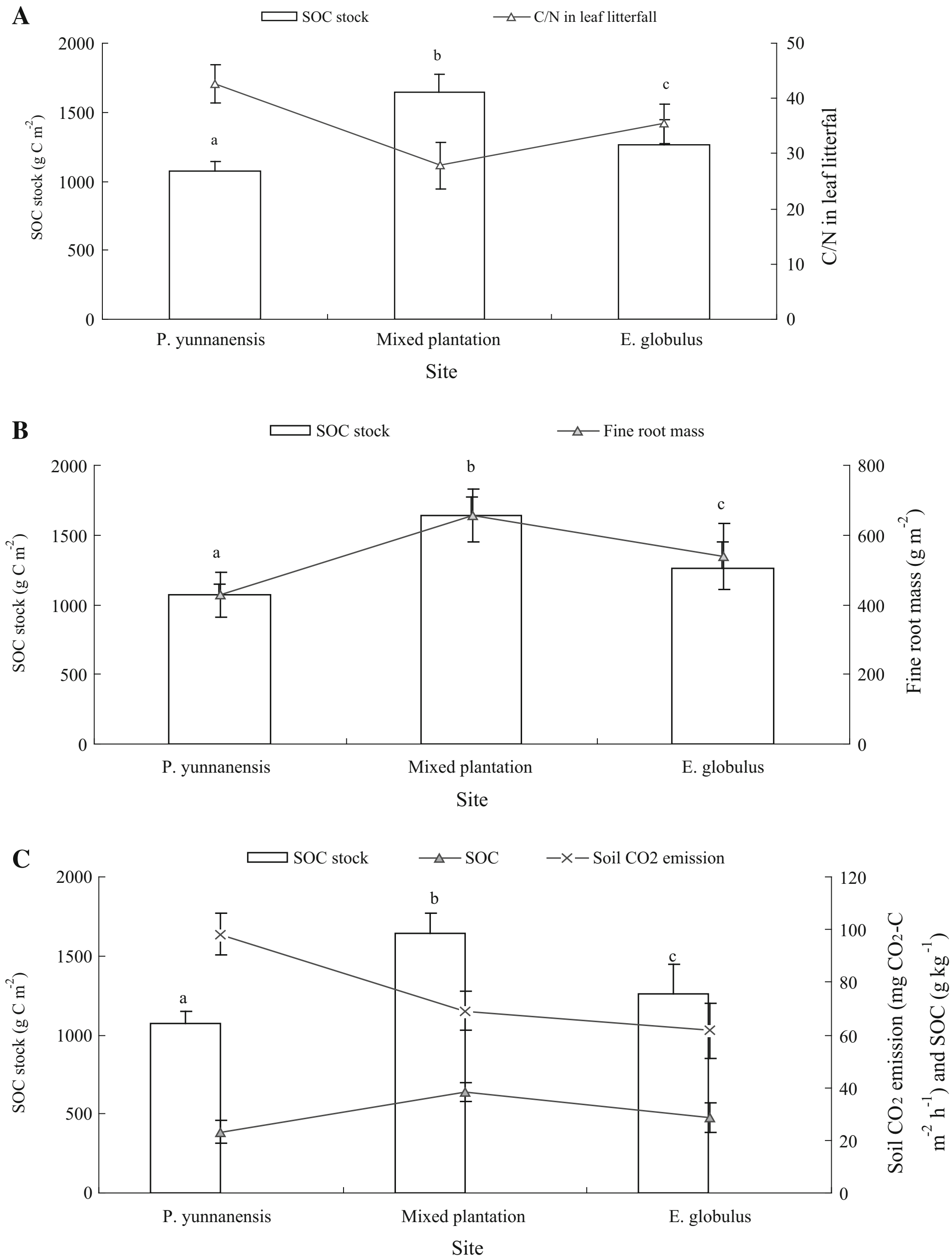

Fig. 4 Correlation of SOC stock to C/N in leaf litterfall mass (**a**), fine root biomass (**b**), and soil CO_2 emission and SOC (**c**) in the *P. yunnanensis, E. globulus,* and mixed plantations (*bars* indicate SE; $n = 12$). Treatments with the *different letters* were significantly different (ANOVA with Tukey-HSD, $P < 0.05$)

Table 3 Relationships between soil properties, soil CO_2 emission, and SOC stock in the *P. yunnanensis*, *E. globulus,* and mixed plantations

Parameter	Leaf litterfall mass ($g\ m^{-2}\ year^{-1}$)	Fine root mass ($g\ m^{-2}$)	pH	Bulk density ($g\ cm^{-3}$)	SOC ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	AN ($mg\ kg^{-1}$)	C/N in soil
Soil CO_2 emission ($mg\ CO_2$–$C\ m^{-2}\ h^{-1}$)	0.810**	0.722*	0.757*	−0.656*	−0.763*	0.503	0.760*	−0.656*
SOC stock ($g\ C\ m^{-2}$)	0.526	0.825**	0.430	0.861**	0.926**	0.758*	0.523	−0.752*

Values are Pearson's correlation coefficients; * $P < 0.05$, ** $P < 0.01$

trees on soil CO_2 emission may be due to the diversity interactions of tree species and soil ecological processes in the plantation (Raich and Tufekciogul 2000). Tree species cover can exert a diverse effect on the soil CO_2 emission through the modification effects of site microclimate, quantity and quality of aboveground and underground detritus, and soil characters (Borken and Beese 2005; Hojjati and Lamersdorf 2010; Wang et al. 2013).

Tree species cover changes the input of quantity and quality of leaf litter and fine root biomass and, thus, influences soil CO_2 emission (Kaye et al. 2000; Forrester et al. 2006, 2013; Epron et al. 2013; Liu et al. 2014). In our study, leaf litterfall mass and fine root biomass had positive correlations with soil CO_2 emission. The leaf litterfall mass was the highest in the *P. yunnanensis* plantation among the three plantations, which coincided well with the greatest CO_2 emission. Litterfall is a key biological pathway for nutrient element transfer from vegetation to soils, acting as a main source of soil organic matter demanded by microbial respiration (Zhang et al. 2005; Luan et al. 2012). On the other hand, fine root biomass can change autotrophic respiration derived from roots, and thus affects soil CO_2 emission (Hertel et al. 2009). However, fine root biomass was highest in the mixed plantation (Forrester et al. 2013), not in the *P. yunnanensis* plantation where the soil CO_2 emission was biggest. Therefore, in comparison with fine root biomass, litter input can be most important factor driving the differences of soil CO_2 emission in the mixed and monoculture plantations in this study, as observed in some studies that compared different vegetation types (Sheng et al. 2010).

Forest tree species composition can impact soil CO_2 emission through the effect on soil physicochemical properties (Zhang et al. 2011; Liu et al. 2014). In this study, soil CO_2 emission was positively related to AN, while soil CO_2 emission was negatively related to C:N ratio. Soil available N concentration can increase soil microbial activity and root biomass (Zhang et al. 2005). Soil C:N ratio was an important factor reflecting soil nutrient availability (Ren et al. 2006). Furthermore, soil CO_2 emission was lower in the mixed plantation than in the *P. yunnanensis* plantation, which was associated with the higher C stock in the mixed plantation. Available data showed that the soil CO_2 emission negatively correlated with C stock (Hojjati 2008). Hence, the differences in soil CO_2 emission among the three plantations were significantly attributed to soil carbon and nitrogen status. We also found pH was positively correlated with soil CO_2 emission. Soil pH may have a positive influence on soil CO_2 emission because of the effect on microbial activity (Pandey et al. 2010). Soil bulk density was negatively correlated with soil CO_2 emission. Greater soil bulk density can contribute to lower oxygen availability in soils. This, in turn, constrains microbial activities, leading to the decrease in soil CO_2 emission (Chen et al. 2010).

Tree species cover can impact soil CO_2 emission through the effect on microclimate (e.g., soil temperature and soil water) within the forest ecosystem due to tree species shading and rainfall interception (Emmerich and Verdugo 2008; Liu et al. 2014). Soil CO_2 emission in the mixed forest was often higher than that in the monoculture forest for the favorite temperature and moisture (Tewary et al. 1982). In this study, there were not difference in soil temperature and soil water between mixed plantation, and two monoculture *E. globulus* and *P. yunnanensis* plantations, thought that the seasonal variation of soil CO_2 emission was significantly correlated with the dynamics of soil temperature and moisture. The microclimate effect extent of tree species cover on soil CO_2 emission varies with the type, size, and age of tree species (Liu et al. 2014). Therefore, the effect of soil temperature and soil water mediated by tree species cover cannot lead to the differences of soil CO_2 emission among the three plantations.

Effects of tree species composition on SOC storage

There are some disagreements about the effect of vegetation composition (e.g., coniferous, broadleaf, and mixed forests) on SOC stock. Some studies reported that SOC stock was generally higher in the broadleaf forest than in the coniferous forest (Niu et al. 2009; Wang et al. 2010; Augusto et al. 2015). Other results showed that SOC stock was relatively lower in the broadleaf forest than in the coniferous forest (Kasel and Bennett 2007; Schulp et al. 2008). There were no significant differences in SOC stock also reported in coniferous, broadleaf, and mixed forests (Wiesmeier et al. 2013). In this study, SOC stock was significantly higher in the mixed plantation than in the monoculture plantations. This indicates that mixed plantation has a positive effect on SOC storage compared with conifer and broadleaf plantations. Mixed plantation is recognized to have a larger potential to improve soil carbon sequestration compared with monoculture native conifer plantations (Kanowski and Catterall 2010; Gahagan et al. 2015). When conifers are imported in broadleaf stands, the amount and chemical nature of plant debris that enter the soil can change the SOC formation and accumulation (Berger et al. 2010). Furthermore, coniferous species litter decomposed faster in the mixed stand than in the monoculture stands, which can result in more carbon incorporation into the mineral soil in the mixed plantation (Wang et al. 2013). Our findings can provide support that mixed plantation can accumulate more SOC relative to monoculture coniferous and broadleaf plantations in the subtropical region.

Forest vegetation cover can increase SOC stock through several key factors, including the quantity of litterfall inputs and root turnover, litter quality, and soil chemistry (Jandl et al. 2007; Calder et al. 2011). In this study, SOC stock was positively related to fine root biomass, and negatively related to C/N ratio in litter. This indicated a higher quantity of SOC in the mixed plantations than in the coniferous and broadleaf plantations could be attributed to higher input of fine root biomass and higher quality of aboveground litter. This result was consistent with the finding from other studies where litter and fine root input drove SOC stock in forests (Russell et al. 2007). We also found that SOC stock was positively correlated with SOC and TN, and negatively correlated with soil C/N. High soil C and N concentrations stimulate tree growth, which, in turn, increases carbon inputs into soils through litterfall and rhizosphere deposition. This can promote SOC sequestration through decreasing decomposition rates of old litter and recalcitrant matter by suppression of soil microbes and by chemical stabilization (Jandl et al. 2007; Mo et al. 2008).

In this study, SOC stock had a negative relationship to soil CO_2 emission across the three plantations. Especially, SOC stock in the *P. yunnanensis* plantation was the lowest, whereas soil CO_2 emission was the highest. SOC storage was reported to have closely associated with soil CO_2 emission (Högberg and Read 2006; Hojjati and Lamersdorf 2010). SOC in conifer forests is more susceptible to losses through microbial respiration than that in broad-leaved and in mixed forests (Roman Dobarco 2014). This indicates that mixed forests have great potential in increase of SOC storage mainly through reducing soil CO_2 emission, especially in the transformation of coniferous plantation to mixed plantation.

Author contribution statement SW wrote the manuscript, and SW, HW and JL conducted the field work and soil analysis.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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