Annals of Forest Science (2018) 75: 40
https://doi.org/10.1007/s13595-018-0717-7

ORIGINAL PAPER

The dynamics of carbon accumulation in *Eucalyptus* and *Acacia* plantations in the Pearl River delta region

Hui Zhang[1] · **HuaBo Duan**[1] · **MingWei Song**[2] · **DongSheng Guan**[3,4]

Received: 6 August 2017 / Accepted: 22 February 2018 / Published online: 16 March 2018

Abstract

• ***Key message*** **Plantation type and age strongly influence the quantity of carbon stored in forest ecosystems. The marked increase in total ecosystem carbon stock achieved over time by the *Eucalyptus* and *Acacia* plantations has confirmed that the afforestation of degraded soils can contribute positively to carbon sequestration.**

• ***Context*** Reforestation has been widely conducted to restore and protect the eroded red soil in south China in recent decades. The question as to whether the content of soil organic carbon (SOC) can be boosted by establishing plantations of fast-growing tree species remains unresolved.

• ***Aims*** We addressed whether the afforestation of degraded soils can contribute positively to carbon sequestration, and whether the accumulation of SOC is more effective under a nitrogen fixing species such as *Acacia* than under *Eucalyptus*.

• ***Methods*** Here, a study was undertaken to measure the quantity of total ecosystem carbon (TEC) accumulated by plantations of both *Eucalyptus* and *Acacia* spp. in the Pearl River Delta region of southern China.

• ***Results*** The quantity of TEC increased significantly with stand age in both plantation types ($P < 0.05$). The largest single component of TEC was SOC, with stand age having a considerable effect on both SOC and overall biomass. The accumulation of SOC in the top 100 cm of the soil profile was higher under *Acacia* than under *Eucalyptus* ($P < 0.05$).

• ***Conclusion*** In terms of carbon sequestration, the afforestation of *Eucalyptus* and *Acacia* represent an effective forest management practice. The accumulation of SOC is more effective under *Acacia* than under *Eucalyptus.*

Keywords Total ecosystem carbon · Forest type · Stand age · Biomass · Soil organic carbon

---

Contribution of the co-authors
Hui Zhang: data collection, analyzed the data, and writing the manuscript.
HuaBo Duan: analyze the experimental data and revise the manuscript.
MingWei Song: designed experiment program (including all experimental data), further help the first author with the laboratory experiment, and co-wrote the manuscript.
DongSheng Guan: experimental design, coordinating the research project, and supervised the field measurement.

Handling Editor: Barry Alan Gardiner

✉ MingWei Song
songmw@mail.hzau.edu.cn

✉ DongSheng Guan
eesgds@mail.sysu.edu.cn

[1] College of Civil Engineering, Shenzhen university, Shenzhen 518060, China

[2] College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China

[3] Department of Environmental Science, School of Environmental Science and Engineering, Sun Yat-sen University, Guangzhou 510275, China

[4] Guangdong Provincial Key Laboratory of Environmental Pollution Control and Remediation Technology, Sun Yat-sen University, Guangzhou 510275, China

1 Introduction

Forest ecosystems store globally about 80% of the above-ground carbon and over 50% of soil organic carbon (SOC) (Batjes 1996), and so make an important contribution to the regulation of the global carbon balance and to the mitigation of climate change. Although there is a continuing decline in the area of natural forest, afforestation/reforestation is on the increase, thereby promoting carbon sequestration and restoring the quality of degraded land (Kelty 2006; Wei, Li et al. 2013; Xie, Guo et al. 2013). Both plantation species composition and stand age are major determinants of the carbon budget (Chen, Zhang et al. 2011; Tang and Li 2013; Wei, Li et al. 2013; Xie, Guo et al. 2013). Rapidly growing plantation species fix considerable quantities of carbon over the short term (Laclau 2003; Peichl and Arain 2006; Chen, Zhang et al. 2011; Xie, Guo et al. 2013): *Eucalyptus* and *Acacia* plantations have been estimated to accumulate around 2 kg m^{-2} SOC over a 17-year period, while over a 29-year growing period, Norway spruce (*Picea abies*) and oak (*Quercus* sp.) managed only 0.9 and 0.2 kg m^{-2}, respectively (Bhattacharya, Kim et al. 2016). Tree species native to the subtropics are typically rather intolerant of degraded soil, so species belonging to the genera *Eucalyptus* and *Acacia*, which are both tolerant and fast growing, are favored for reforestation (Yang, Liu et al. 2009; Chen, Zhang et al. 2011).

A rational assessment of the size of the carbon pool in a plantation requires the whole ecosystem to be considered. It has been suggested that most of the carbon accumulated in forest ecosystems is due to their high accumulation of biomass (Dou, Deng et al. 2013; Cheng, Lee et al. 2015), and that SOC should increase naturally with stand age following the reforestation of degraded soil (Xie et al., 2013). The dependency of SOC on plantation age is not universally acknowledged, since there are examples in which it has been shown to decrease somewhat during the establishment phase, before gradually increasing with stand age (Kasel, Singh et al. 2011; Assefa, Rewald et al. 2017). Since *Acacia* spp., unlike *Eucalyptus* spp., are able to fix atmospheric nitrogen, their growth results in an improvement to soil fertility; as a result, the accumulation of SOC under *Acacia* dominated plantations has been found to be generally superior to that achievable under *Eucalyptus* (Kasel, Singh et al. 2011). Some authors have argued that the high productivity of *Eucalyptus* and *Acacia* plantations results in a substantial export of nutrients in forest products such as nitrogen and phosphorus, and thus a slight decrease or no change in SOC was observed over time (Santana, Knicker et al. 2015; Cook, Binkley et al. 2016). *Eucalyptus* and *Acacia* plantations used for wood production are typically maintained for less than 10 years (Attiwill 1994; Inagaki, Kamo et al. 2010), so there is little evidence regarding the extent of their longer term capacity to store carbon. Furthermore, little attention has been given to the amount of

Table 1 A summary description of the study *Eucalyptus* and *Acacia* plantations

Type	Period	DBH (cm)	Height (cm)	Stand density (n/hm^{-2})	Aspect	Gradient	Total nitrogen (mg kg^{-1})	pH value	Bulk density (g cm^{-3})
Eucalyptus	Young	7.13 ± 1.35Aa	8.55 ± 3.06 Aa	2761 ± 102Aa	SW	25–60°	329.48 ± 180.50Aa	4.57 ± 0.29A	1.53 ± 0.09a
	Middle-aged	12.38 ± 0.94Bb	14.65 ± 0.31 Bb	1719 ± 122Bb	SW	22–52°	408.90 ± 206.86Aa	4.24 ± 0.16Ba	1.52 ± 0.16a
	Mature	15.07 ± 2.80Bb	18.58 ± 4.74Bc	1367 ± 445Bb	SW	18–65°	693.82 ± 325.50B	4.08 ± 0.16Bb	1.45 ± 0.15a
Acacia	Young	8.70 ± 0.53Aa	7.07 ± 0.06Aa	1541 ± 17A	SW	23–51°	497.94 ± 257.27Aa	4.19 ± 0.19A	1.58 ± 0.17Aa
	Middle-aged	12.43 ± 1.84Ab	9.83 ± 1.54 Ab	1244 ± 142B	SW	27–48°	636.48 ± 350.84Aa	4.39 ± 0.09B	1.60 ± 0.10Aa
	Mature	18.73 ± 1.70B	14.90 ± 1.25Bc	830 ± 12C	SW	20–63°	949.16 ± 587.95Bb	4.05 ± 0.11C	1.38 ± 0.19B
Forest type		ns	ns	**	–	–	*	*	ns

Values shown as mean ± standard deviation; different lowercase ($P < 0.05$) and uppercase ($P < 0.01$) letters within a column indicate a significant difference between the various ages of a given forest type

DBH diameter at breast height (1.3 m), *ns* not significant

*Significant difference ($P < 0.05$); **significant difference ($P < 0.01$) between the *Eucalyptus* and *Acacia* plantations

SOC stored deeper in the soil profile in these two plantation types (Kasel, Singh et al. 2011; Souza-Alonso, Guisande-Collazo et al. 2015; Cook, Binkley et al. 2016), even though it has been claimed that, globally, the proportion of soil carbon present in the top 30 cm of the soils accounts for only around 30% or so of the carbon present in the top 100 cm (Batjes 2014).

The working hypotheses of the present research were threefold: (a) SOC can be boosted significantly as a result of afforestation, and especially, the accumulation of SOC is more effective under a nitrogen fixing species such as *Acacia* than under *Eucalyptus*; (b) a significant proportion of the SOC is held at depth in the soil profile; and (c) the two tree species are both effective in sequestering carbon. To test these hypotheses, the objectives of the study were to characterize the accumulation and allocation of total ecosystem carbon (TEC) in a sample of *Eucalyptus* (*E. urophylla*) and *Acacia* (*A. mangium*) plantations located in the Pearl River Delta (PRD) region of southern China, and establish the effect of species, stand age, and biomass on the SOC level in the top 100 cm of the soil. The wider purpose of the research was to provide a baseline for forest management, in particular with a view to enhancing the carbon sequestration capacity of forest ecosystems and identifying the species best suited for afforestation in the PRD.

2 Materials and methods

2.1 Local climate and soils

The PRD lies in the Chinese province of Guangdong (21° 31′–23° 10′ N, 112° 45′–113° 50′ E). Its climate is subtropical and monsoonal, characterized by hot, humid summers and mild winters. The region has a mean annual rainfall of 1600 mm, with the main rainy season occurring during July and August. The mean annual temperature is approximately 21 °C, while the daytime temperature exceeds 30 °C on around 120 days per year. The chosen sites, at which 10 were planted exclusively with Acacia and 11 exclusively with *Eucalyptus*, with both tree species adjacent to each other, lie in hilly land in the neighborhood of the cities Guangzhou, Zhuhai, and Heshan. The *Eucalyptus* plantations were measured in the period November–December 2010 and the *Acacia* ones between December 2010 and January 2011. The local red soils were, prior to the establishment of the plantations, covered with a combination of small shrubs and grass. A full description of the soils' physicochemical characteristics are given in Table 1. The plantations fell into three age groups: young (less than 6 years), middle-aged (6–15 years), and mature (over 16 years). Further descriptive details of the sites are given by Zhang et al. (2012) and are reproduced in Table 1.

2.2 Biomass and soil sampling

At each site, the canopy biomass captured within a 30 m × 30 m quadrat was measured. The understorey biomass (shrubs, ferns and grasses) was estimated from a destructive harvest of the central 1 m^2 of each of five 2 m × 2 m quadrats. The contribution of the litter layer was obtained from a set of five 1 m × 1 m quadrats arranged along the diagonal of the main 30 m × 30 m quadrat. Felled dead wood and standing dead trees of trunk diameter > 2.5 cm and height > 1 m were included within the coarse woody debris (CWD) fraction. The Zhang et al. (2012) estimate of the relative contribution to the

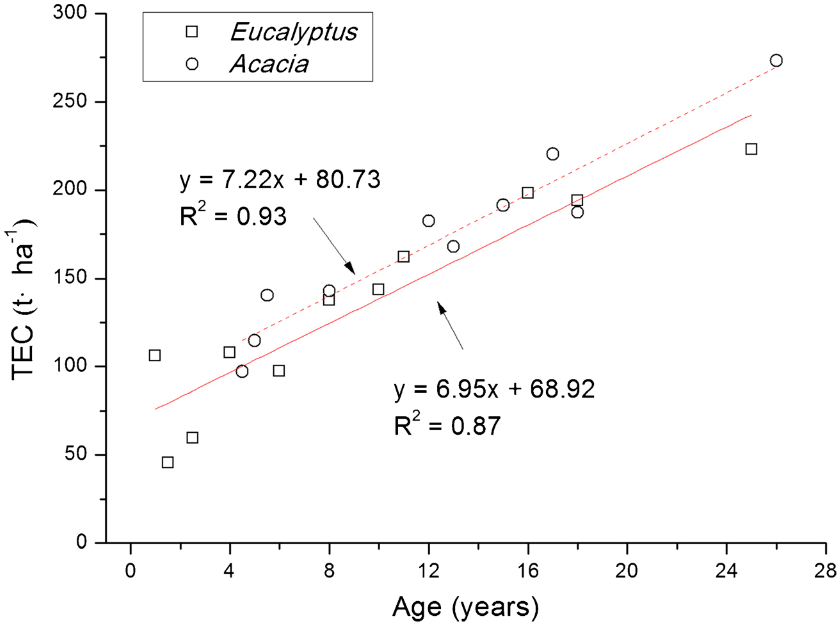


Fig. 1 The relationship between total ecosystem carbon and stand age in both a *Eucalyptus* and an *Acacia* plantation

Table 2 Variation in the size of the TEC stock and its components in the plantations (Mg ha^{-1})

Type	Period	Canopy tree layer biomass carbon	Secondary biomass carbon	Total biomass carbon	SOC	TEC
Eucalyptus	Young	27.31 ± 16.46Aa	2.14 ± 0.85A	29.45 ± 17.28 Aa	50.31 ± 32.10a	79.76 ± 31.93Aa
	Middle-aged	68.47 ± 11.81Bb	6.35 ± 1.00B	74.82 ± 12.54 Bb	60.31 ± 15.84a	135.13 ± 27.33Ab
	Mature	93.21 ± 3.15Bc	9.03 ± 0.89C	102.24 ± 3.59 Bc	102.66 ± 13.90b	204.90 ± 15.70Bc
Acacia	Young	38.72 ± 2.95 Aa	4.53 ± 0.36Aa	43.24 ± 2.79Aa	74.13 ± 20.63a	117.38 ± 21.70Aa
	Middle-aged	56.46 ± 11.68 a	13.55 ± 2.42Bb	70.01 ± 12.93b	101.07 ± 13.73a	171.08 ± 21.20b
	Mature	76.83 ± 11.69Bb	17.31 ± 1.07Bc	94.14 ± 12.05Bc	132.70 ± 34.94b	226.84 ± 43.38Bc
Forest type		ns	**	ns	*	ns

Total biomass carbon included canopy tree layer biomass carbon and the secondary biomass and its various components (shrubs, herbaceous species, litter layer and CWD). Values are means ± standard deviation. Different lowercase and uppercase letters in the same column indicate significant differences among different ages for same forests type according to LSD (least significant difference) test at $P < 0.05$ and $P < 0.01$ level, respectively

ns not significant

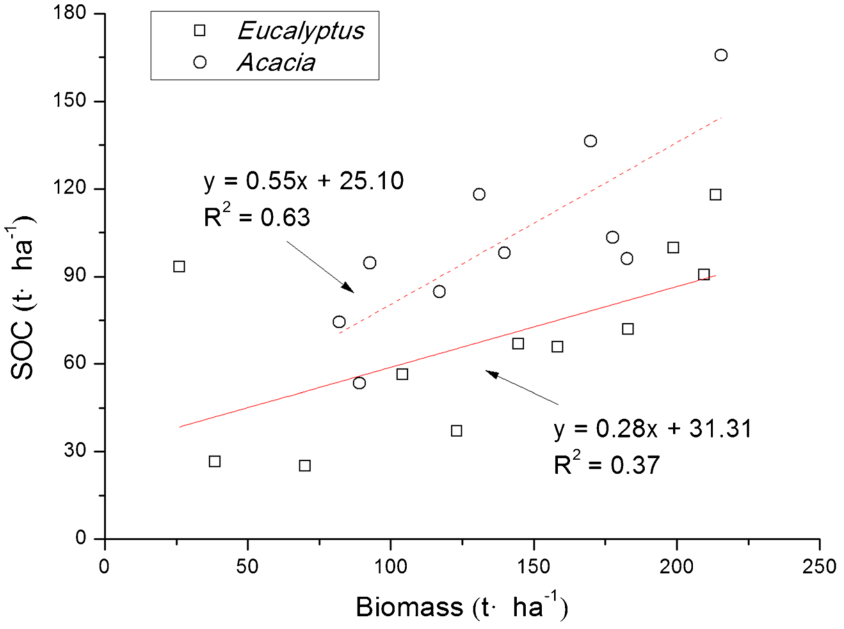
*Significant difference ($P < 0.05$); **significant difference ($P < 0.01$) between the *Eucalyptus* and *Acacia* plantations

overall biomass of the various fractions (trees, shrubs, herbaceous species, litter, and CWD) was adopted. Estimates of the SOC, total nitrogen content (TN), and hydrolyzable nitrogen (HN) in the top 100 cm of the soil profile were obtained from samples taken from each of an upper, mid, and lower slope location: an equal number of 500 g soil aliquots was taken from the top 10 cm of the profile, from the next 10 cm (10–20 cm), from 20–30, 30–40, 40–50, 50–75, and 75–100 cm, producing a total of 231 soil samples (11 sites × three locations × seven soil depths) from the *Eucalyptus* plantations and 210 (10 × 3 × 7) from the *Acacia* plantations. Samples of undisturbed soil from each of the various layers were also collected using a soil sample ring kit (100 cm^3), and the cutting ring method was used to measure soil bulk density (Lu 1999).

2.3 Laboratory analyses

SOC contents were obtained from air-dried (at room temperature) soil samples after the removal of surface organic matter and fine roots. Samples from each layer within a site were mixed in equal proportion and passed through a 0.149-mm sieve. The carbon content of the soil and biomass components was determined using a wet oxidation method (Forestry Standards of the People's Republic of China method LY/T1237-1999). Soil pH was measured using a Toledo Five Easy pH meter (Mettler, Giessen, Germany). Three replicates of the surface soil (0–10 cm) were assessed for their TN content using a Foss 2300 Kjeltec Analyzer Unit (Foss Analytical AB, Höganäs, Sweden). A 0.0050–1.0000 g sample of either soil or

Fig. 2 The relationship between soil organic carbon and total biomass in both a *Eucalyptus* and an *Acacia* plantation



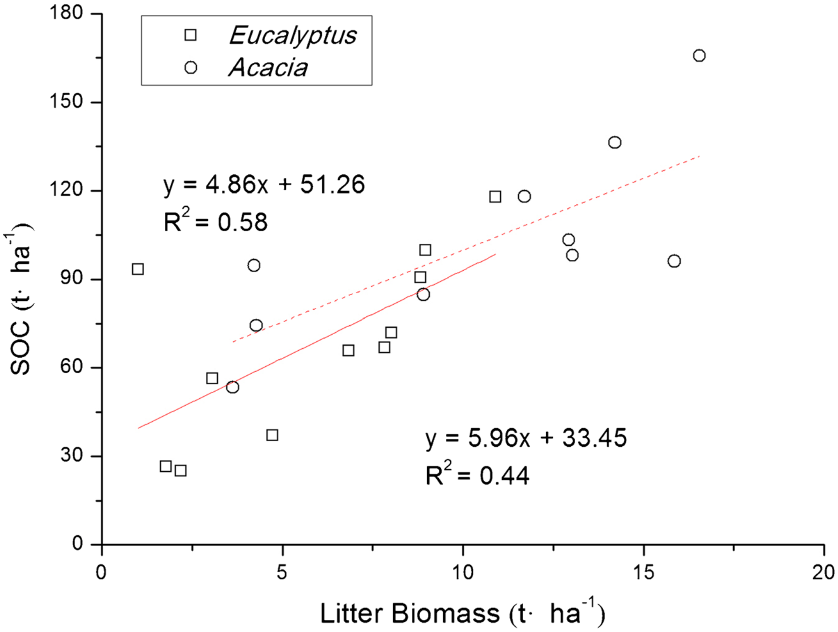


Fig. 3 The relationship between soil organic carbon and the biomass stored in the litter in both a *Eucalyptus* and an *Acacia* plantation

biomass was digested in 5 mL 0.8 M $K_2Cr_2O_7$ and 5 mL 18 M H_2SO_4, held at 170–180 °C for 5 min, and titrated with 0.2 M $FeSO_4 \cdot 7H_2O$. An estimate for the quantity of biomass carbon was obtained by multiplying the weighed biomass by its derived proportion of carbon. The quantity of carbon present in the canopy was estimated by assuming that 50% of the biomass was carbon (Lieth and Whittaker 1975; Razakamanarivo, Grinand et al. 2011), while the quantity stored in the various soil layers was calculated by multiplying soil bulk density by both the depth of the layer and the concentration of carbon present. The TEC was obtained by summing the quantities of carbon stored in the biomass and in the soil.

2.4 Statistical analysis

The means and associated standard deviations of the proportion of carbon and quantity of carbon stored in the biomass and soil, as well as the TN contents were calculated. A two-way analysis of variance was used to test for the effect of tree type and stand age on the proportion or the quantity of carbon stored in the biomass and in the soil, as well as the distribution of SOC and TN content within the top 100 cm of the soil. Regression analyses were performed between TEC content and stand age, SOC content, and the amount of biomass represented in the CWD and litter layer. All calculations and

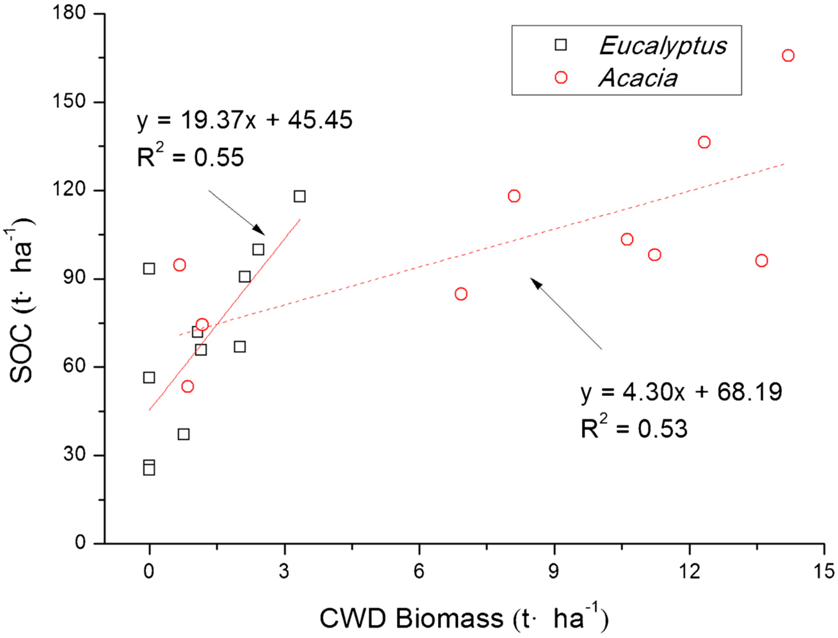


Fig. 4 The relationship between soil organic carbon and the biomass stored in the coarse woody debris in both a *Eucalyptus* and an *Acacia* plantation

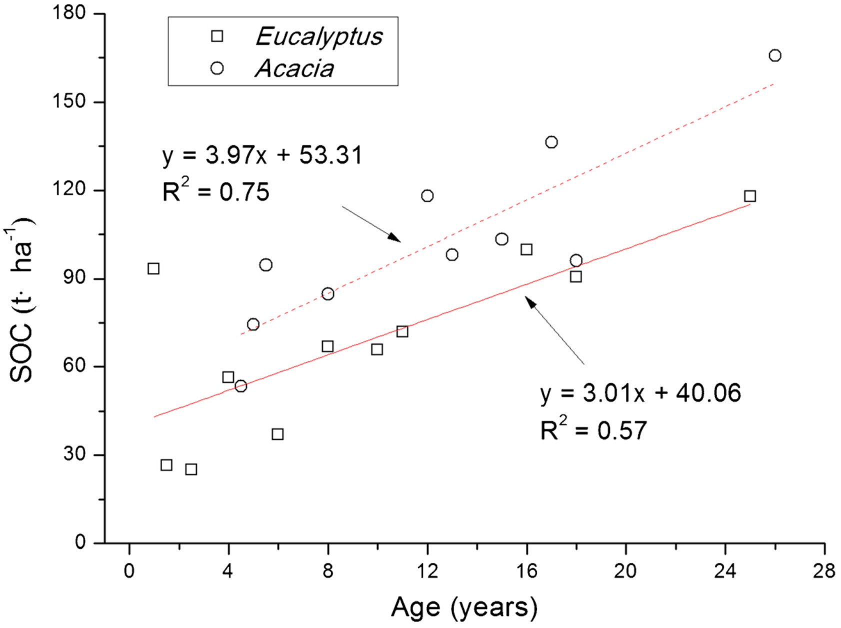


Fig. 5 The relationship between soil organic carbon and stand age in both a *Eucalyptus* and an *Acacia* plantation

analyses were carried out using the software package SPSS v17.0 (SPSS Inc., Chicago, IL, USA).

Data availability Data presented are available at https://doi.org/10.6084/m9.figshare.5853420.v3 (Song et al. 2018)."

3 Results

3.1 TEC stock

The stock of TEC increased with stand age in both plantation types (Fig. 1): the associated coefficients of determination (R^2) were 0.87 for the *Eucalyptus* and 0.93 for the *Acacia* plantations. The quantity of TEC was significantly greater in the mature than in the middle-aged or the young plantations, ranging from 79.8 to 204.9 t ha^{-1} under *Eucalyptus* and from 117.4 to 226.8 t ha^{-1} under *Acacia*.

3.2 Biomass carbon stock

Both stand age and plantation type had a major impact on the accumulation of carbon and on its distribution between the various components (Table 2). The middle-aged and mature plantations both produced significantly more total biomass carbon than the young ones ($P < 0.01$). The contribution of the understorey layer, litter layer, and CWD were all nonnegligible. This was especially the case for the *Acacia* stands, in which the proportion was 8% in both the middle-aged and mature plantations, compared to, respectively, 5 and 4% for the *Eucalyptus* stands.

Table 3 The effect of stand age and tree species on the accumulation of SOC (g kg^{-1})

Type	Period	0~10 cm	10~20 cm	20~30 cm	30~40 cm	40~50 cm	50~75 cm	75~100 cm
Eucalyptus	Young	8.21 ± 3.42Aa	4.51 ± 2.91Aa	3.10 ± 2.14a	2.88 ± 2.00a	2.89 ± 1.91a	2.37 ± 1.87a	2.25 ± 1.82a
	Middle-aged	11.65 ± 1.66Aa	5.73 ± 1.91Aa	4.62 ± 1.66ab	3.31 ± 1.12a	2.83 ± 1.20a	2.67 ± 1.18a	2.19 ± 0.71a
	Mature	18.95 ± 2.56Bb	11.59 ± 1.38Bb	7.76 ± 1.83b	6.46 ± 0.69b	5.66 ± 0.82b	4.73 ± 0.65a	4.16 ± 0.90a
Acacia	Young	9.91 ± 1.50A	7.84 ± 2.79a	6.04 ± 2.33a	5.39 ± 1.83a	4.15 ± 1.80a	2.81 ± 1.06a	3.07 ± 1.62a
	Middle-aged	17.43 ± 2.51B	10.98 ± 3.67a	7.39 ± 0.78a	5.42 ± 1.45a	4.56 ± 1.24a	3.93 ± 0.91a	3.68 ± 0.59a
	Mature	25.73 ± 2.36C	15.93 ± 5.82b	11.69 ± 4.37b	9.22 ± 4.02a	8.12 ± 3.21a	6.07 ± 1.99b	5.33 ± 1.81a
Forest type		*	*	*	*	ns	ns	ns

Values shown as mean ± standard deviation. Different lowercase ($P < 0.05$) and uppercase ($P < 0.01$) letters within a line indicate a significant difference between the various ages of a given forest type. ns: not significant, *: significant difference ($P < 0.05$) between the *Eucalyptus* and *Acacia* plantations

ns not significant

*Significant difference ($P < 0.05$) between the *Eucalyptus* and *Acacia* plantations

3.3 Correlations between biomass and SOC

In this study, significant positive correlations were established between SOC storage and total biomass (Fig. 2), between SOC storage and litter biomass (Fig. 3), and between SOC storage and the CWD biomass (Fig. 4); the relationships were particularly strong for the *Acacia*-based plantations. The accumulation of litter and CWD biomass was more effective in the *Acacia* plantations (respectively, 4.0–15.5 and 0.9–13.4 t ha^{-1}) than in the *Eucalyptus* ones (respectively, 2.0–9.6 and 0–2.6 t ha^{-1}), which implies that the volume of raw material contributing to SOC is greater in the former plantation type.

3.4 SOC stock

SOC stock increased with stand age (Fig. 5), with associated R^2 values of 0.57 for the *Eucalyptus* stands and 0.75 for the *Acacia* stands. A significant positive correlation existed between the SOC storage in the top 100 cm of the soil and both stand age and forest type ($P < 0.05$, Table 2). The *Acacia* trees were more effective accumulators of SOC than the *Eucalyptus* ones*:* SOC storage under the former ranged from 74.1 to 132.7 t ha^{-1}, while under the latter, the range was only 50.3–102.7 t ha^{-1}. The overall contribution of SOC to TEC was highly significant: 60% in the case of *Acacia* and 53% in the case of *Eucalyptus*.

3.5 The soils' organic carbon and nitrogen content, carbon/nitrogen ratio, and bulk density

The variation in SOC content between the various soil layers in the two plantation types is summarized in Table 3. The SOC content in the top 100 cm of the soil increased markedly with stand age, ranging from 3.7 to 8.5 g kg^{-1} under *Eucalyptus*, and from 5.6 to 11.7 g kg^{-1} under Acacia. SOC content decreased gradually with increasing soil depth. At all of the sites, significantly ($P < 0.01$) more SOC was concentrated in the upper 20 cm of the soil than was found deeper in the profile. The SOC content of the top 10 cm was 3.6–5.3 (*Eucalyptus*) and 3.2–4.8 (*Acacia*) times higher than that present in the lowest 25 cm (75–100 cm), while the respective increases in the 10–20 cm layer were in the range 2.0–2.8 and 2.6–3.0. The TN content and carbon/nitrogen ratio both rose gradually with stand age, ranging from, respectively, 329.5–693.8 t kg^{-1} and from 10.4–11.7 (*Eucalyptus*), and from 497.9–949.2 t kg^{-1} and 11.2–12.4 (*Acacia*). In both plantation types, the TN content and the carbon/nitrogen ratio decreased gradually with soil depth, independently of stand age: both variables were at their highest in the surface soil layer, ranging from 1346.2–211.4 t kg^{-1} and from 14.1–8.9 (*Eucalyptus*) and from 1857.2–259.4 t kg^{-1} and 15.1–9.7 (*Acacia*) (Table 4, Fig. 6). The soils' bulk density changed in the opposite sense with

Table 4 Variation in TN across the top 100 cm of the plantation soils (mg kg^{-1})

Soil depth (cm)	*Eucalyptus*			*Acacia*		
	Young	Middle-aged	Mature	Young	Middle-aged	Mature
0~10	581.99 ± 152.58Aa	829.53 ± 137.88A	1346.19 ± 135.02A	894.80 ± 66.23Aa	1300.16 ± 327.84A	1857.18 ± 696.77Aa
10~20	446.77 ± 190.27ABab	489.97 ± 85.11Ba	902.27 ± 110.79B	738.49 ± 258.03Aa	760.72 ± 255.60Ba	1256.52 ± 559.87Aab
20~30	309.36 ± 171.31Bb	423.46 ± 33.54Bab	669.38 ± 85.60Ca	499.50 ± 132.93Bb	680.34 ± 102.97Bab	1051.64 ± 475.61ABb
30~40	249.94 ± 103.67Bbd	315.74 ± 25.77Cb	601.75 ± 46.59CDa	494.46 ± 81.42Bab	504.71 ± 115.16Bbc	844.95 ± 396.08ABbd
40~50	262.51 ± 123.78Bbd	315.90 ± 62.02Cb	502.31 ± 37.36Dab	354.24 ± 115.34Bbd	487.84 ± 71.80 Bbc	671.62 ± 237.44Bbd
50~75	244.38 ± 125.62Bbd	263.78 ± 87.04Cbd	469.77 ± 65.86DEab	244.73 ± 99.47Bcd	386.73 ± 145.84Cd	485.84 ± 136.63ABd
75~100	211.43 ± 126.42 Bd	223.94 ± 62.54Cbd	365.08 ± 64.57DEb	259.36 ± 88.34Bcd	334.86 ± 131.05Cd	476.35 ± 128.41ABd

Values shown as mean ± standard deviation. Different lowercase ($P < 0.05$) and uppercase ($P < 0.01$) letters within a line indicate a significant difference between the various soil type of a given forest type and forest age both stand age and soil depth. Independently of stand age, the bulk density of the upper (0–20 cm) layer was significantly lower than that of the lower (50–100 cm) layer: the range was 1.2–1.6 g cm^{-3} under *Eucalyptus*, and 1.2–1.8 g cm^{-3} under *Acacia* (Fig. 7).

4 Discussion

4.1 The effect of tree species and stand age on stored SOC

The soil's carbon pool reflects a balance between its loss through decomposition and its gain through the decomposition of leaf litter and CWD (Dou, Deng et al. 2013; Chen, Yu et al. 2017), the growth of the understory and root expansion (Cheng, Lee et al. 2015). There are two considerations which could explain the positive effect of stand age on SOC storage: the first relates to the increasing size of the carbon input from the understory layer, the litter, and the CWD as the plantation ages (Zhang, Guan et al. 2012; Zhao, Kang et al. 2014); the second is a consequence of the very low level of SOC (25 t ha^{-1}) present in the upper 30 cm of the soil prior to afforestation, giving the opportunity for a large increase as the trees aged (Chen, Yu et al. 2017). The ability of *Acacia* plants to biologically fix nitrogen through their symbiosis with *Rhizobium* spp. should favor SOC accumulation (Yang, Liu et al. 2009). A correlation of determination > 0.8 obtained between carbon and nitrogen storage in both plantation types (Fig. 8), and the fact that the level of nitrogen was higher under *Acacia* than under *Eucalyptus* (Table 1) supports the notion that increasing the nitrogen status of the soil enhances the storage of SOC. The outcome validates the superiority, in terms of SOC accumulation, of nitrogen fixing over nonfixing tree species (hypothesis a), and is consistent with related studies comparing the effect on SOC of nitrogen fixing trees and nonfixing ones (Resh, Binkley et al. 2002). Overall, assuming a similar land use history and a similar climate, the

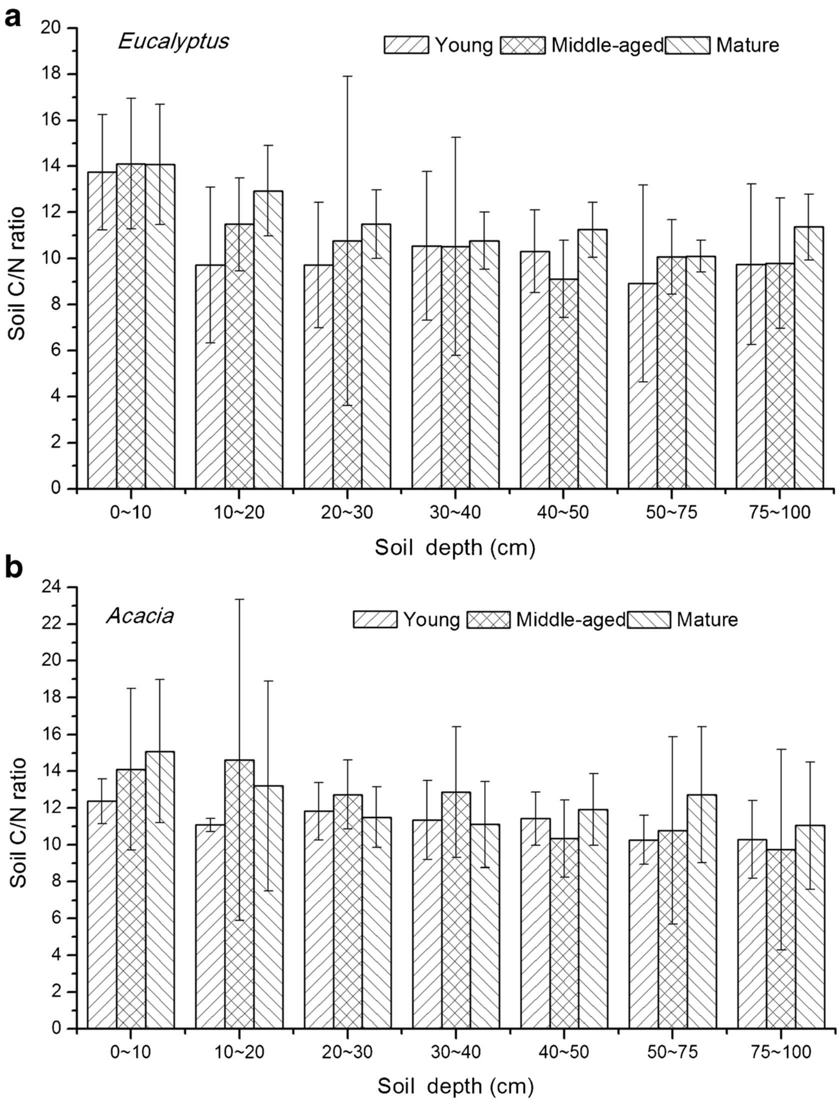


Fig. 6 The carbon/nitrogen ratio of soil of different depths for different aged *Eucalyptus* (**a**) and *Acacia* (**b**) stands

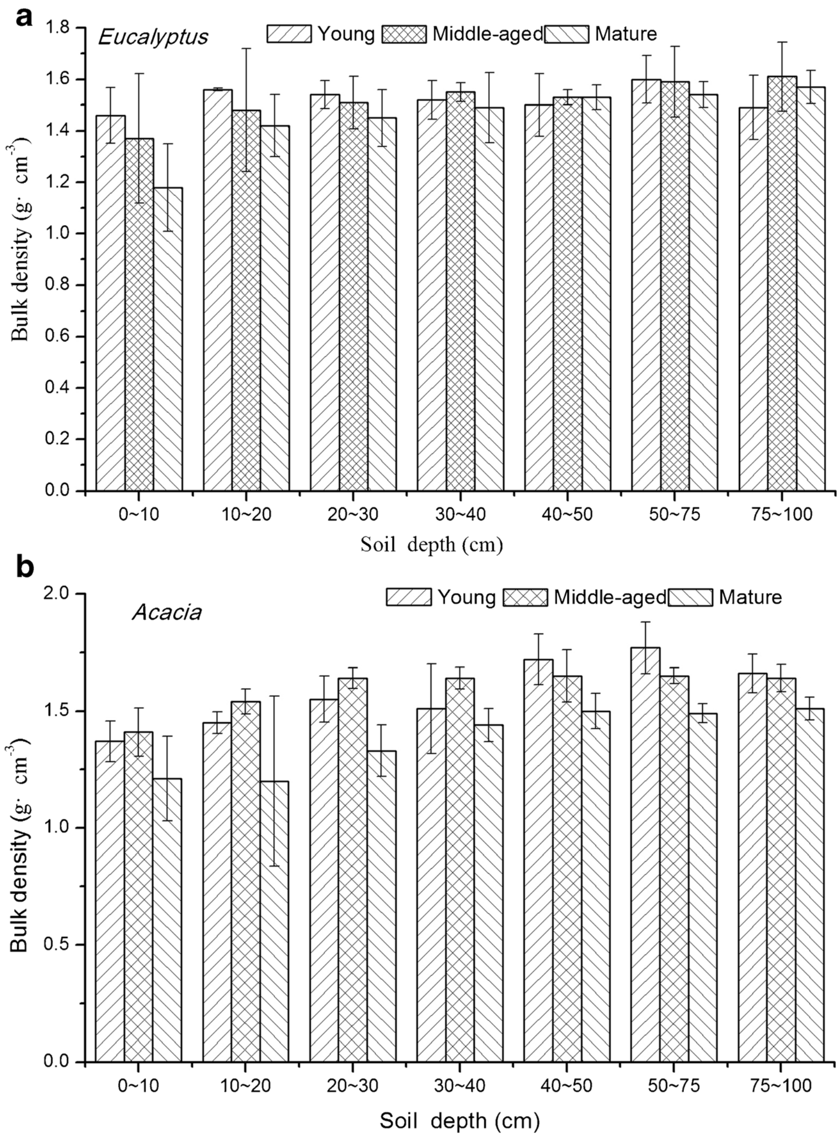


Fig. 7 The bulk density of soil at different soil depths under *Eucalyptus* (**a**) and *Acacia* (**b**) plantations

accumulation of SOC in a given soil type is mainly dependent on the nature of the long-term vegetation present (Yang and Wang 2005; Xian, Zhang et al. 2009): thus, tree species and tree age, both individually and in combination, are strong determinants of the size of the SOC stock.

4.2 Effect of biomass on SOC storage

Early stand development in a poor soil requires as rapid as possible a buildup of SOC in order for the plants to thrive. One aim of reforestation is to generate a large volume of biomass over a long period, in order to boost SOC in the PRD (Xie, Guo et al. 2013). Our study has confirmed that SOC content is positively correlated with biomass, which agrees with related studies based on the performance of other plantation tree species used for reforestation purposes in southern China (Zhang 2009; Dou, Deng et al. 2013; Wang, Guan et al. 2014). For example, Dou et al. (2013) found that reforetation of *P. massoniana* under eroded red soil after 18–30 years significantly increased soil C levels; the C accumulation following the reforestation appeared to be due to a combination of large biomass input and low C decomposition (Dou, Deng et al. 2013). Wang et al. (2014) have shown that SOC in the top 100 cm of a variety of mangrove forest soils varied from 184 to 279 t ha^{-1}, in line with the biomass of the canopy layer (60–385 t ha^{-1}). Similarly, Zhang (2009) have demonstrated that the SOC content of the uppermost 100 cm of the soil profile under a stand of evergreen broad-leaved trees ranged from about 85 t ha^{-1} in a young forest to 151 t ha^{-1} in a mature one, again reflecting increases in the biomass represented in the litter and CWD.

4.3 The vertical distribution of SOC

The SOC content of the surface layer in the present mature plantations was comparable to that measured in 7-year-old

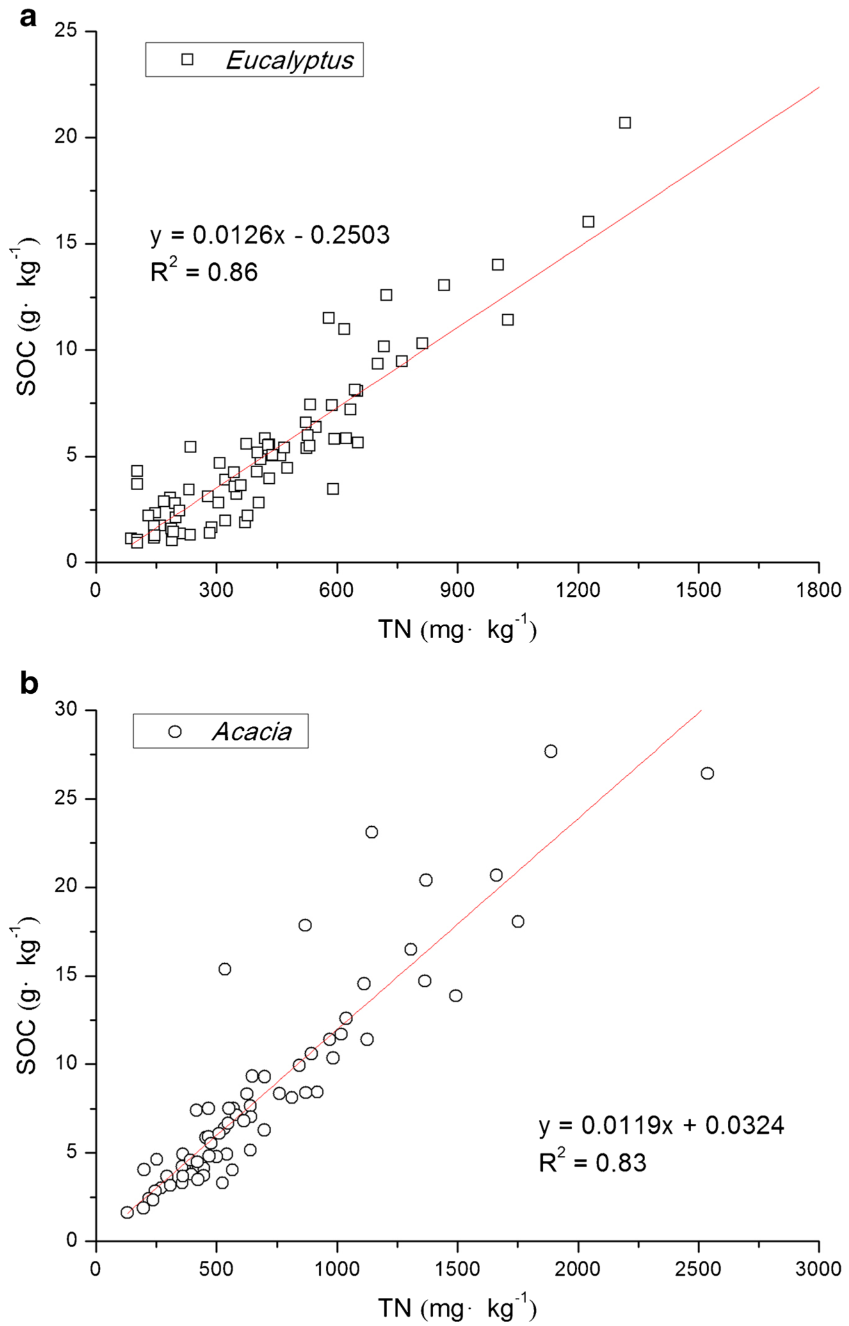


Fig. 8 The relationship between soil organic carbon and total nitrogen content in both a *Eucalyptus* (a) and an *Acacia* (b) plantation

plantations of either subtropical *Eucalyptus* (~ 20 g kg^{-1}) or *Acacia* (~ 25 g kg^{-1}) provided with a dressing of phosphate fertilizer before planting (Santana, Knicker et al. 2015). The vertical distribution of SOC in the soil is in line with that observed in similar studies based on either tropical or subtropical *Eucalyptus* (Mishra, Sharma et al. 2003; Cao, Fu et al. 2010) or *Acacia* (Lemma, Kleja et al. 2006; Laik, Kumar et al. 2009) plantations, as well as in other plantation types monitored in southern China (Dou, Deng et al. 2013). Other factors affecting SOC were the soil's TN content, bulk density, and carbon to nitrogen ratio (Table 5); their vertical distribution also determined the significantly high SOC present in surface soil layer ($P < 0.01$). It is therefore clearly important to maintain the SOC at and immediately below the soil surface.

Most studies that estimated the SOC level focused on the organic layer and surface horizons in the upper 30 cm of the soil. However, the roots of plant and thus input of organic matter extend to deep subsoil horizons, and soil carbon level would be greatly underestimated if one does not include the amounts stored in subsoil (Rumpel and Kögel-Knabner 2011; Wiesmeier, Prietzel et al. 2013; Zhang, Wang et al. 2015). For instance, Zhang et al. (2015) claimed that the proportion of SOC in a cropping soil 30–200-cm depth can reach more than 70% of total SOC (Zhang, Wang et al. 2015). In this study, we

Table 5 Correlations between SOC content and soil properties in *Eucalyptus* and *Acacia* plantations of different stand age

Forest type	Bulk density	pH value	TN	C/N
Acacia	− 0.745**	−0.482**	0.912**	0.374**
Eucalyptus	− 0.582**	−0.631**	0.971**	0.680**

*Correlation is significant at the 0.05 level (two-tailed); **correlation is significant at the 0.01 level (two-tailed)

found that the content of SOC at deeper horizons (30–100 cm) is still high, especially for mature forests (> 4 g kg^{-1}). Subsoil SOC showed significant correlation with stand age and forest type ($P < 0.05$) (Table 3). Hypothesis (b) was confirmed: a substantial presence of SOC was detected up to 50 cm below the soil surface in the *Eucalyptus* plantations ($P < 0.05$), and the SOC content of mature plantation was significant higher than that of the middle-aged and young ones ($P < 0.05$), showing that carbon is able to accumulate at a deeper level than can readily be explained by the presence of a greater root biomass (Bauhus, Khanna et al. 2000). Meanwhile, under *Acacia*, the upper 75 cm of the soil profile also showed a significant SOC accumulation with stand age ($P < 0.05$), perhaps reflecting the activity of nitrogen fixing bacteria (Inagaki, Kamo et al. 2011), as is shown in Table 4. However, because in this study the soils were not sampled below a depth of 100 cm, it is not possible to conclude definitively that carbon sequestration was limited to the top 100 cm of the soil profile. Thus, future attempts to document soil carbon under tree plantations will need to monitor the status of the soil at depths below 100 cm.

4.4 Implications for carbon sequestration achieved by fast-growing plantation trees

Sequestering carbon in the soil, ultimately in the form of stable humus, may well prove to be a more productive method for mitigating the negative effects of climate warming than its more temporary storage in the form of biomass (Thuille and Schulze 2006; Farley 2007). The measured SOC content within the top 100 cm of soil under mature *Eucalyptus* (102.66 t ha^{-1}) and *Acacia* (132.70 t ha^{-1}) trees was rather lower than the estimated means derived from both national (193.6 t ha^{-1}) (Zhou, Yu et al. 2000) and global (189.0 t ha^{-1}) data (Dixon, Solomon et al. 1994). Even within the red soils typical of subtropical climates, the present estimates are considerably lower than what was derived from an analysis of a 20-year-old *Mytilaria laosensis* plantation (174.8 t ha^{-1}) (Liu and Liu 2012). However, they are substantially higher than the reported levels in both a 24-year-old *Pinus massoniana* plantation (38.2 t ha^{-1}) and a secondary forest (68.5 t ha^{-1}) (Xie, Guo et al. 2013). The TEC contents of both the mature *Eucalyptus* (204.9 t ha^{-1}) and *Acacia* (226.8 t ha^{-1}) plantations were also below that of both

Table 6 Implications for carbon sequestration by *Eucalyptus* and *Acacia* plantations in Guangdong Province

Energy consumption (Carbon emissions)				*Eucalyptus*						*Acacia*						Total TEC
				Young		Middle-aged		Mature		Young		Middle-aged		Mature		
2000 (Mt C)	2001 (Mt C)	2002 (Mt C)	2003 (Mt C)	Area (× 10^4 ha)	TEC (Mt C)	Area (× 10^4 ha)	TEC (Mt C)	Area (×10^4 ha)	TEC (Mt C)	Area (×10^4 ha)	TEC (Mt C)	Area (×10^4 ha)	TEC (Mt C)	Area (×10^4 ha)	TEC (Mt C)	(Mt C)
63.30	68.20	76.08	87.76	3.987	3.180	4.059	5.485	2.866	5.872	1.569	1.842	2.523	4.316	0.917	2.080	22.776

Data on energy consumption is from China Statistics Press China Energy Statistical Yearbook 2004. (3/2005); unit is Mt (10^6 t) standard coal; according to the NDRC (National Development and Reform Commission), 1 Mt standard coal is equal to 0.67 Mt. C; resource: forest area during various periods is acquired by China Forestry Statistical Yearbook nationally based (258.8 t ha^{-1}) (Zhou, Yu et al. 2000) and globally based (275.0 t ha^{-1}) means (Dixon, Solomon et al. 1994). Comparisons with other plantation types in the PRD suggest that, on the basis of TEC, both *Eucalyptus* and *Acacia* are less effective accumulators of carbon than certain native evergreen broad-leaved species (Sun and Guan 2014), but are more effective than *Pinus massoniana* (Zhang, Xu et al. 2011). Overall, *Eucalyptus* and *Acacia* are both able to sequester carbon with a satisfactory level of efficiency and so are well suited for afforestation purposes in the PRD. Given that stand age had a marked effect on TEC stock in both plantation types (Table 1; Fig. 1), the conclusion is that the use of a rapidly growing tree species for the afforestation of a poor soil should represent an effective forest management practice where the aim is to sequester carbon as fast as possible (hypothesis c).

The consideration of succession is important when estimating the size of a plantation's carbon pool. As is shown in Table 6, the quantity of carbon accumulated in over the period 2000–2003 in PRD was 22.8 Mt., which corresponded to 26%–36% of the total carbon (1.29×10^8 t) emitted as a result of the burning of fossil fuels in Guangdong Province over the period 2000–2003 (China Statistics Press 2005; SFA 2005). Stands of mature *Eucalyptus* and *Acacia* account for just 24% of the total plantation area in the PRD: whereas they have accumulated some 8.0 Mt carbon, maintaining them for some additional years should further increase their contribution to carbon sequestration.

5 Conclusions

The marked increase in TEC stock achieved over time by the *Eucalyptus* and *Acacia* plantations has confirmed that the afforestation of degraded soils can contribute positively to carbon sequestration. The largest single component of TEC was SOC. The major factors determining SOC accumulation in the top 100 cm of the soil profile were the species of tree, the stand age, and the biomass input. The accumulation of SOC under *Acacia* was more effective than under *Eucalyptus*. Protection of the SOC present in the surface layer of the soil is very important in the context of carbon sequestration, especially for *Acacia* plantations. The deeper soil layers (below 50 cm for *Eucalyptus*, and below 75 cm for *Acacia*) also represent a substantial carbon sink. The indications are that the afforestation of poor soils using rapid growing tree species should be an effective management practice for improving carbon budgets and compensating for the carbon emitted as a result of the burning of fossil fuel.

Acknowledgements This research was supported by the National Natural Science Foundation of China (Grant numbers 51039007, 41101494, and 40971054). Experimental facilities were provided by Guangdong Provincial Key Laboratory of Environmental Pollution Control and Remediation Technology, the School of Environmental Science and Engineering, Sun Yat-sen University.

Compliance with ethical standards

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

References

Assefa D, Rewald B, Sanden H, Rosinger C, Abiyu A, Yitaferu B, Godbold DL (2017) Deforestation and land use strongly effect soil organic carbon and nitrogen stock in Northwest Ethiopia. Catena 153:89–99

Attiwill PM (1994) Ecological disturbance and the conservative management of eucalypt forests in Australia. For Ecol Manag 63:301–346

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 47:151–163

Batjes NH (2014) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 65:10–21

Bauhus J, Khanna P, Menden N (2000) Aboveground and belowground interactions in mixed plantations of Eucalyptus globulus and Acacia mearnsii. Can J For Res 30:1886–1894

Bhattacharya SS, Kim K-H, Das S, Uchimiya M, Jeon BH, Kwon E, Szulejko JE (2016) A review on the role of organic inputs in maintaining the soil carbon pool of the terrestrial ecosystem. J Environ Manag 167:214–227

Cao Y, Fu S, Zou X, Cao H, Shao Y, Zhou L (2010) Soil microbial community composition under Eucalyptus plantations of different age in subtropical China. Eur J Soil Biol 46:128–135. https://doi.org/10.1016/j.ejsobi.2009.12.006

Chen D, C Zhang JW, Zhou L, Y Lin SF (2011) Subtropical plantations are large carbon sinks: evidence from two monoculture plantations in South China. Agric For Meteorol 151:1214–1225

Chen Y, Yu S, Liu S, Wang X, Zhang Y, Liu T, Zhou L, W Zhang SF (2017) Reforestation makes a minor contribution to soil carbon accumulation in the short term: evidence from four subtropical plantations. For Ecol Manag 384:400–405

Cheng J, Lee X, BK Theng LZ, Fang B, Li F (2015) Biomass accumulation and carbon sequestration in an age-sequence of Zanthoxylum bungeanum plantations under the Grain for Green Program in karst regions, Guizhou province. Agric For Meteorol 203:88–95

Press CS (2005) China energy statistical yearbook 2004. China Statistics Press. Access 3(/2005):2005

Cook RL, Binkley D, Stape JL (2016) Eucalyptus plantation effects on soil carbon after 20years and three rotations in Brazil. For Ecol Manag 359:92–98

Dixon RK, Solomon A, Brown S, Houghton R, Trexier M, Wisniewski J (1994) Carbon pools and flux of global forest ecosystems. Science 263:185–190

Dou X, Deng Q, Li M, Wang W, Zhang Q, Cheng X (2013) Reforestation of Pinus massoniana alters soil organic carbon and nitrogen dynamics in eroded soil in south China. Ecol Eng 52:154–160

Farley KA (2007) Grasslands to tree plantations: forest transition in the Andes of Ecuador. Ann Assoc Am Geogr 97:755–771

Inagaki M, Kamo K, Miyamoto K, Titin J, Jamalung L, Lapongan J, Miura S (2011) Nitrogen and phosphorus retranslocation and N:P ratios of litterfall in three tropical plantations: luxurious N and efficient P use by Acacia mangium. Plant & Soil 341:295–307

Inagaki M, Kamo K, Titin J, Jamalung L, Lapongan J, Miura S (2010) Nutrient dynamics through fine litterfall in three plantations in

Sabah, Malaysia, in relation to nutrient supply to surface soil. Nutr Cycl Agroecosys 88:381–395

Kasel S, Singh S, Sanders GJ, Bennett LT (2011) Species-specific effects of native trees on soil organic carbon in biodiverse plantings across north-central Victoria, Australia. Geoderma 161:95–106

Kelty MJ (2006) The role of species mixtures in plantation forestry. For Ecol Manag 233:195–204

Laclau P (2003) Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia. For Ecol Manag 180:317–333

Laik R, Kumar K, Das D, Chaturvedi O (2009) Labile soil organic matter pools in a calciorthent after 18 years of afforestation by different plantations. Appl Soil Ecol 42:71–78

Lemma B, Kleja DB, Nilsson I, Olsson M (2006) Soil carbon sequestration under different exotic tree species in the southwestern highlands of Ethiopia. Geoderma 136:886–898

Lieth H, Whittaker RH (1975) Primary productivity of the biosphere. Springer Verlag, New York

Liu E, Liu S (2012) The research of carbon storage and distribution feature of the Mytilaria laosensis plantation in south sub-tropical area. Acta Ecol Sin 32:5103–5109

Lu R (1999) Analytical methods of soil agricultural chemistry. Agriculture Science and Technology Press of China, Beijing, pp 15–20

Mishra A, Sharma S, Khan G (2003) Improvement in physical and chemical properties of sodic soil by 3, 6 and 9 years old plantation of *Eucalyptus tereticornis*. Biorejuvenation Sodic Soil For Ecol Manage 184:115–124

Peichl M, Arain MA (2006) Above-and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. Agric For Meteorol 140:51–63

Razakamanarivo RH, Grinand C, MA Razafindrakoto MB, Albrecht A (2011) Mapping organic carbon stocks in *Eucalyptus* plantations of the central highlands of Madagascar: a multiple regression approach. Geoderma 162:335–346

Resh SC, Binkley D, Parrotta JA (2002) Greater soil carbon sequestration under nitrogen-fixing trees compared with eucalyptus species. Ecosystems 5:217–231. https://doi.org/10.1007/s10021-001-0067-3

Rumpel C, Kögel-Knabner I (2011) Deep soil organic matter—a key but poorly understood component of terrestrial C cycle. Plant Soil 338: 143–158

Santana GS, Knicker H, González-Vila FJ, González-Pérez JA, Dick DP (2015) The impact of exotic forest plantations on the chemical composition of soil organic matter in Southern Brazil as assessed by Py–GC/MS and lipid extracts study. Geoderma Regional 4:11–19

SFA (2005) The sixth National Forest Resources Inventory (1999-2003). State Forestry Administration (SFA)

Song M, Duan H, Guan DS, Zhang H (2018) The dynamics of carbon accumulation in Eucalyptus and Acacia plantations in the Pearl River delta region. V3. FigShare [Dataset]. https://doi.org/10.6084/m9.figshare.5853420.v3

Souza-Alonso P, Guisande-Collazo A, González L (2015) Gradualism in Acacia dealbata Link invasion: impact on soil chemistry and microbial community over a chronological sequence. Soil Biol Biochem 80:315–323

Sun L, Guan D (2014) Carbon stock of the ecosystem of lower subtropical broadleaved evergreen forests of different ages in Pearl River Delta, China. J Trop For Sci:249–258

Tang G, Li K (2013) Tree species controls on soil carbon sequestration and carbon stability following 20years of afforestation in a valley-type savanna. For Ecol Manag 291:13–19

Thuille A, Schulze ED (2006) Carbon dynamics in successional and afforested spruce stands in Thuringia and the Alps. Glob Chang Biol 12:325–342

Wang G, Guan D, Zhang Q, MR Peart YC, Peng Y, Ling X (2014) Spatial patterns of biomass and soil attributes in an estuarine mangrove forest (Yingluo Bay, South China). Eur J Forest Res 133:993–1005. https://doi.org/10.1007/s10342-014-0817-3

Wei X, Li Q, Liu Y, Liu S, Guo X, Zhang L, Niu D, Zhang W (2013) Restoring ecosystem carbon sequestration through afforestation: a sub-tropic restoration case study. For Ecol Manag 300:60–67

Wiesmeier M, Prietzel J, Barthold F, Spörlein P, Geuß U, Hangen E, Reischl A, Schilling B, Lützow MV, Kögel-Knabner I (2013) Storage and drivers of organic carbon in forest soils of southeast Germany (Bavaria) – implications for carbon sequestration. For Ecol Manag 295:162–172

Xian J, Y Zhang TH, Wang K, Yang H (2009) Carbon stock and allocation of five restoration ecosystems in subalpine coniferous forest zone in Western Sichuan Province, Southwest China. Acta Ecol Sin 29:51–55

Xie J, Guo J, Yang Z, Huang Z, Chen G, Yang Y (2013) Rapid accumulation of carbon on severely eroded red soils through afforestation in subtropical China. For Ecol Manag 300:53–59

Yang J, Wang C (2005) Soil carbon storage and flux of temperate forest ecosystems in northeastern China. Acta Ecol Sin 25:2875–2882

Yang L, Liu N, Ren H, Wang J (2009) Facilitation by two exotic *Acacia*: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. For Ecol Manag 257:1786–1793

Zhang F, Wang X, Guo T, Zhang P, Wang J (2015) Soil organic and inorganic carbon in the loess profiles of Lanzhou area: implications of deep soils. Catena 126:68–74. https://doi.org/10.1016/j.catena.2014.10.031

Zhang H, Guan D, Song M (2012) Biomass and carbon storage of *Eucalyptus* and *Acacia* plantations in the Pearl River Delta, South China. For Ecol Manag 277:90–97

Zhang X, Xu Z, Zeng F, Hu X, Han Q (2011) Carbon density distribution and storage dynamics of forest ecosystem in Pearl River Delta of low subtropical China. China Environ Sci 31:69–77

Zhang XY (2009) Allocation characteristics of three chief forest biomass and carbon stock in Guangzhou. Ph.D. Thesis., Sun Yat Sen University,China

Zhao J, Kang F, L Wang XY, Zhao W, Song X, Zhang Y, Chen F, Sun Y, He T (2014) Patterns of biomass and carbon distribution across a chronosequence of Chinese pine (Pinus tabulaeformis) forests. PLoS One 9:e94966

Zhou Y, Yu Z, Zhao S (2000) Carbon storage and budget of major Chinese forest types. Chin J Plant Ecol 24:518–522