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Biomass accumulation and carbon sequestration in an age-sequence of *Zanthoxylum bungeanum* plantations under the Grain for Green Program in karst regions, Guizhou province

Jianzhong Cheng[a,*], Xinqing Lee[a,*], Benny K.G. Theng[b], Like Zhang[a,c], Bin Fang[a,c], Fushan Li[a,c]

[a] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China
[b] Landcare Research, Private Bag 11052, Palmerston North 4442, New Zealand
[c] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Ensuring ecological security in the environmental degradation has always been a top priority in China. Under the Grain for Green Program (GGP), millions of hectares of farmland in the karst region of Guizhou province have been converted into *Zanthoxylum bungeanum* plantations in order to arrest and reverse "rocky desertification". The aim of this study was to estimate biomass increment and carbon accumulation in four different aged (1-, 4-, 7- and 10-year-old) Z. *bungeanum* stands, as well as the distribution of carbon stock among the various biomass components and soil depths. The total plant biomass measured for the four stands of different ages was 0.05, 6.76, 12.22, and 16.71 Mg ha^{-1}, respectively. Compared with other plant species in the region, *Z. bungeanum* plantations has a larger capacity for accumulating biomass. The C content in components of *Z. bungeanum* tree ranged from 40.47% to 48.64% with the mean value of 44.67%. The use of the standard coefficient (50%) in converting biomass into C storage results in 10% overestimation. Soil organic carbon (SOC) storage at the top soil (0–30 cm) increased from 75.22 Mg C ha^{-1} in 1-year-old stand to 80.06 Mg C ha^{-1} in 10-year-old stand, and decreased with increasing soil depth for each stand age. Total ecosystem C storage increased with plantation age, averaging 75.24, 79.79, 84.43, and 87.62 Mg C ha^{-1}, respectively, of which more than 90% was stored in the soil. Our study suggests that the protection of SOC in surface soils during plantation management practices plays a crucial role in improving the C sequestration. Data of plantation area and annual biomass C accumulation rate (under the GGP in Guizhou province) indicate a net C sink of 6.35 × 10^{6} Mg in 2010, corresponding to a 4.92% compensation of C emission from energy consumption in that year. Besides increasing C storage over time, the large-scale planting of *Z. bungeanum* has the potential of restoring severely degraded soils in the karst region of SW China.

1. Introduction

Global climate change and variability resulting from a great increase in the amount of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases (GHGs) in the atmosphere is currently one of the most serious environmental problems to humankind. Forest is a critical component of terrestrial ecosystems, playing a significant role in regulating the global carbon balance, offsetting the increasing CO_2 concentration, and mitigating global climate change. In recent years, as the area of natural forest decreases continuously, afforestation/reforestation through converting various non-forest lands into forest lands is on the increase and undoubtedly an important dimension of carbon storages (Xu et al., 2007). Therefore, sequestering carbon to planted forests represents one of the important clean development mechanisms (CDM). In 1999, the Chinese government initiated a nationwide Grain for Green Program (GGP) also known as the Sloping Land Conversion Program (SLCP), and later named the Conversion of Cropland to Forest and Grassland Program (CCFGP) (Ostwald et al., 2007), which is intended to prevent further soil erosion, control desertification and improve land quality. In practice, the GGP helped to restore the ecological balance in mountainous areas by returning steep cultivated lands to forests and pastures.

* Corresponding authors. Tel.: +86 851 84391908.
E-mail addresses: chengjianzhong@vip.gyig.ac.cn (J. Cheng), xinqinglee@hotmail.com (X. Lee).

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Indeed, the replacement of annual crops by perennial plants, over the past decade or so, has led to a marked improvement of the natural environment. According to the annual reports on the Development of Chinese Forestry, 233,344 (1000 ha) of lands, including 8,268 (1000 ha) of croplands and 15,076 (1000 ha) of barren lands, had been planted under the GGP during the period of 1999–2010. The largest converted area, recorded in 2003, comprised 6,196 (1000 ha) of 3,086 (1000 ha) croplands and 3,110 (1000 ha) barren lands (State Forestry Administration, 1999–2011).

Under the ordinance of GGP, lands of severe rocky desertification should be given priority to return to forests. Located in the central of karst regions of southwest China, Guizhou province has the most extensive area of steep, degraded barren land and cropland. A large proportion (81%) of the cultivated land is on a slope of ≥6°, while about 20% of the total cultivated land area is on slopes of over 25° (Xu et al., 2011). As such, Guizhou is high on the list of provinces for implementation of the GGP. By the end of 2011, 1,199 (1000 ha) of lands, including 439 (1000 ha) of steep croplands and 760 (1000 ha) of barren lands, have been planted in Guizhou province under the GGP, accounting for 4.97% of the national GGP-lands (including 5.31% of steep croplands and 4.80% of barren lands, respectively) (State Forestry Administration, 1999–2011). It is expected that 703 (1000 ha) of steep croplands (>25°) will be converted to forests over the period from 2014 to 2020 (Guizhou Provincial Forestry Department, 2014). Therefore, the large-scale implementation of the GGP in the karst region will lead to an extensive new forests and ultimately contribute to regional carbon cycle and reduction of atmospheric CO_2 in the long run (Persson et al., 2013; Xu et al., 2007). In using forestation as a strategy to sequester carbon, the program also conforms to the "Kyoto Protocol" (Huang et al., 2007).

Z. bungeanum is a suitable species for plantation/afforestation in the karst region under the GGP to restore the rocky desertification, due to its adaptability to drought tolerance, calcareous soil, poor habitat, and fast growth. Further, the fruit of *Z. bungeanum* tree can be sold to supplement the income of farmers in poor karst areas of Guizhou. Because of their economic and ecological functions, in terms of fruit/wood production and erosion control, plantations of *Z. bungeanum* have been the subject of many investigations (Lu et al., 2012; Moberg and Persson, 2011). The chemical and biological characteristics of this plant species have also been studied (Lan et al., 2014; Xia et al., 2011). However, there is little information on the rate at which *Z. bungeanum* plantations can accumulate biomass and increase C storage, particularly in the karst region of SW China. In view of the large area of actual and potential planting of *Z. bungeanum* under the GGP in Guizhou and other parts of China, an improved understanding of C sequestration in *Z. bungeanum* plantations at a regional and national scale is required on the part of scientific researchers, forest managers, and policy makers.

In this paper, we examined the changes of plant biomass C and soil C storages in four different aged *Z. bungeanum* plantations under the GGP in the Hua Jiang Karst Canyon of Guizhou province. The focus of this study was to: (1) examine the above- and below-ground biomass across an age-sequence of four *Z. bungeanum* plantation stands (1-, 4-, 7-, and 10-years old); (2) estimate C pools in plant biomass and soil of four different aged *Z. bungeanum* plantations; and (3) implicate the C storages by restoring the degraded karst regions under the GGP in Guizhou province.

2. Materials and methods

2.1. Site description

The study site is situated on the Hua Jiang Karst Canyon (HJKC) of Guizhou province, southwest China, located at a latitude of 25°39.2′–41′N and a longitude of 105°36.5′–46.5′E. The total area of this study region is 51.62 km^2, of which 87.92% is karst. The undulating land at an elevation of 500–1,200 m is degraded as a result of human activity and climatic change. The terrain is broken, the vegetation is sparse, the soil is eroded, water runs off, and some bed rock is exposed. The area has a typical subtropical monsoon climate, with most of the mean annual precipitation of 1,100 mm occurring during the period from April to October. The average annual number of sunshine hours is 2,500 h and that of frost-free days is 225 d, while the active accumulated temperature (≥10 °C) is 6,542 °C. The mean annual air temperature is 18.4 °C, the highest temperature being 32.4 °C, and the lowest 6.6 °C. The barren land (25°39.6′N, 105°40.3′E) in the HJKC is a typical alkaline and calcareous soil with an organic carbon content of 1.22%, a total nitrogen content of 0.23%, and a bulk density of soil (0–30 cm) of 1.03 g cm^{-3}.

Ecological restoration under the GGP has increased vegetation coverage in the HJKC from 21.4% in 2001 to 53.2% in 2005 (Chen et al., 2007). Indeed, the HJKC with its extensive cover of Z. *bungeanum* has become a demonstrable example of how rocky desertification may be arrested under the GGP in Guizhou province and all over China. Admittedly, there are no shrubs and herbs in the understory of Z. *bungeanum* plantations, because both are regularly removed by local farmers. Our study design consists of a chronosequence of *Z. bungeanum* stands with an age of 1, 4, 7, and 10 years.

2.2. Biomass estimation

According to on-site inspection, three standard sampling plots (20 m × 20 m) were established in each forest stand, and the height (H) and circumference at the base of the stem (CBS) of every tree were measured in the sampling plots (Table. 1). Three standard trees were chosen and logged from standard sampling plots for biomass determination, using the segmenting method. Standard trees were divided into seven components: stem, branch, foliage, bark, thorn, fruit, and root. Root samples were obtained by total excavation of the standard trees, extending radially out from the trunk and downwards to bed rock until no more roots were visible. In the case of mature trees, however, some of the roots were so firmly attached to the bedrock as to make them inextractable. The fresh weights of all components were measured in-situ, and samples (500–1,000 g) of every component in each standard tree were collected for moisture content and C concentration analysis.

Table 1
Stand characteristics of the 1-, 4-, 7-, and 10-year-old *Z. bungeanum* plantations under the GGP (mean ± SD).

Stand age (years)	CBS (cm)	H (m)	CD (m)	Density (plants ha^{-1})
1	2.77 ± 0.46^{d}	0.67 ± 0.08^{b}	0.42 ± 0.10^{c}	1665
4	17.53 ± 3.16^{b}	2.95 ± 0.22^{a}	3.58 ± 0.43^{b}	1250
7	24.73 ± 0.87^{a}	3.12 ± 0.47^{a}	4.68 ± 0.50^{ab}	950
10	26.58 ± 3.76^{a}	3.29 ± 0.15^{a}	4.81 ± 1.05^{a}	850

Note: CBS: circumference at the base of the stem; H: tree height; CD: crown diameter. Means in a column followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test).

Table 2
Biomass production in different components of the 1-, 4-, 7-, and 10-year-old *Z. bungeanum* plantations ($\times 10^{-1}$ Mg ha^{-1}, mean ± SD).

Components	Stand age (years)				Mean value
	1	4	7	10	
Stem	0.10 ± 0.08^{c}	13.90 ± 8.40^{bc}	29.60 ± 12.60^{ab}	46.70 ± 18.60^{a}	22.60 ± 20.80
Branch	0.05 ± 0.04^{b}	19.10 ± 5.60^{ab}	31.20 ± 15.00^{a}	42.10 ± 24.50^{a}	23.10 ± 20.50
Bark	0.04 ± 0.03^{c}	3.10 ± 0.60^{bc}	7.00 ± 2.10^{ab}	10.80 ± 4.10^{a}	5.23 ± 4.66
Thorn	0.01 ± 0.00	0.78 ± 0.60	1.11 ± 0.52	1.34 ± 1.34	0.81 ± 0.85
Foliage	0.20 ± 0.10^{b}	16.90 ± 7.70^{a}	19.20 ± 13.10^{a}	16.50 ± 3.60^{a}	13.20 ± 10.40
Fruit	none	4.70 ± 0.70^{b}	17.70 ± 6.90^{a}	24.60 ± 9.70^{a}	11.76 ± 11.49
AGB	0.40 ± 0.30^{c}	58.60 ± 19.00^{bc}	105.80 ± 47.40^{ab}	141.90 ± 53.80^{a}	76.70 ± 63.80
Root (BGB)	0.09 ± 0.03^{c}	8.97 ± 3.38^{bc}	16.35 ± 4.04^{ab}	25.14 ± 11.74^{a}	12.64 ± 11.10
BGB/AGB	0.23	0.15	0.15	0.18	0.16
TPB	0.50 ± 0.30^{c}	67.60 ± 2.24^{bc}	122.20 ± 46.3^{ab}	167.10 ± 65.50^{a}	89.32 ± 74.06

Means in a row followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test); AGB: above-ground biomass; BGB: below-ground biomass; TPB: total plant biomass.

2.3. Soil sampling

Soil samples were taken from the top 30 cm of the profile with three replicates for each age stand. At each sampling point, soil samples were collected from three depths (0–10, 10–20, 20–30 cm) using a soil corer. Bulk density was determined by weighing the whole sample and drying subsamples in an oven at 105 °C to a constant weight (the cylinder method). The content of soil organic carbon was measured using air-dried subsamples.

2.4. Carbon fraction analysis and carbon storage calculation

Each subsample of the different tree components in each chronosequence was taken to the laboratory and oven-dried at 60 °C to a constant weight. Dry weights of every component were determined and mechanically ground into pass through a 0.5 mm mesh screen. In addition, air-dried soil samples were treated with 10% hydrochloric acid for 12 h to remove carbonates, dried at 70 °C for 48 h, milled, and passed through a 0.25 mm mesh screen. The powder samples of tree components and mineral soils were analyzed for the C concentrations using a vario macro elemental analyzer (Elementar Analysensysteme GmbH, Germany). The carbon storage in the tree components and soil depths is estimated as follows:

Carbon storage (CS) in each stand (Mg ha^{-1}) = $\sum$ (carbon content in different components (Mg Mg^{-1}) × biomass in different components (Mg ha^{-1}))

CS in 30 cm soil depths (Mg ha^{-1}) = $\sum$ (organic C content in different depths (kg Mg^{-1}) × soil bulk density in different depths (Mg m^{-3}) × 0.10(m) × 10,000(m^{2} ha^{-1})/1,000)

2.5. Statistical analysis

The differences in biomass, carbon content, and carbon storage among different stand ages were compared using a one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test. The relationship between biomass, carbon storage in biomass and base of the stem was obtained using the power function fitting, and R^2 of the model parameters were used to determine goodness of fit. All statistical analyses, based on a significant level of $p < 0.05$, were conducted using SPSS 13.0 software package (SPSS Inc. Chicago, USA).

3. Results

3.1. Biomass and its distribution in different components of Z. bungeanum plantations

In plantation of *Z. bungeanum*, tree density decreased with the steady increases of crown diameter (CD) and height (H) (Table 1). Above-ground biomass (AGB), below-ground biomass (BGB), and total plant biomass (TPB) of the *Z. bungeanum* plantations increased markedly with stand age (Table 2). The AGB increased from 0.04 Mg ha^{-1} in the 1-year-old stand to 14.19 Mg ha^{-1} in the 10-year-old stand. Similarly, the BGB increased from 9.00 kg ha^{-1} in the 1-year-old stand to 2.51 Mg ha^{-1} in the 10-year-old stand. Statistical analysis indicated a significant difference in TPB between 10-, 7-year-old stands and 1-year-old stand ($p < 0.05$), and between 10-year-old stand and 4-year-old stand ($p < 0.05$), but the values measured for the other stand ages were not significantly different (Table 2).

Except for that of the foliage, the biomass of all tree components increased with stand age (Table 2). For the 1-year-old stand, biomass decreased in the order: foliage > stem > root > branch > bark > thorn. For the 10-year-old, however, the decline in biomass production was in the order: stem > branch > root > fruit > foliage > bark > thorn. The contribution of foliage biomass to TPB in 1-year-old stand was higher than that in the other stands (4-, 7-, and 10-year- old) (Fig. 1). The ratio of foliage biomass to TPB decreased with the increasing stand age. Conversely, the contributions of fruit biomass to TPB increased

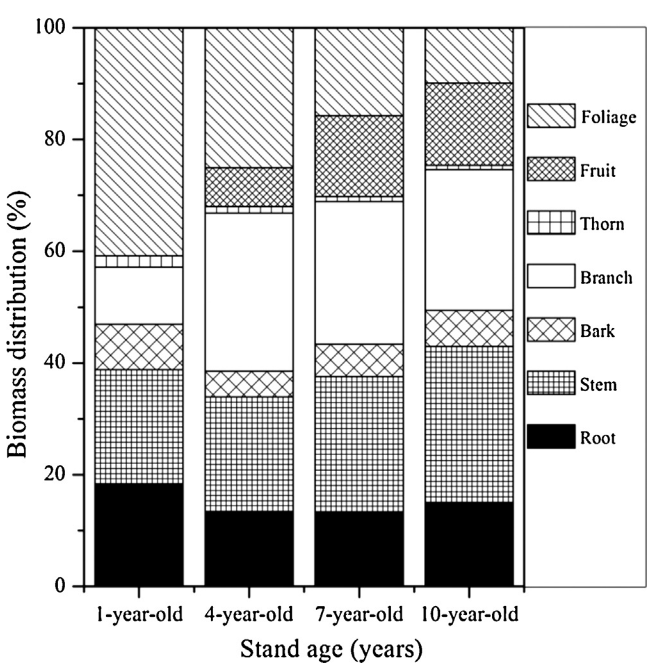

Fig. 1. Percentage distribution of biomass in various components of *Z. bungeanum* trees as a function of stand age.

Table 3
Carbon concentration (%) in the biomass of four different age classes of *Z. bungeanum* plantations (mean ± SD).

Stand age (years)	Root	Stem	Branch	Thorn	Bark	Foliage	Fruit
1	44.85 ± 0.45[b]	44.59 ± 0.29	41.31 ± 0.17[c]	46.10 ± 0.77[b]	40.47 ± 0.49	42.97 ± 0.95	none
4	45.25 ± 1.86[b]	44.85 ± 0.22	43.07 ± 0.23[ab]	48.64 ± 1.75[a]	42.02 ± 0.59	43.76 ± 0.29	47.48 ± 0.54
7	47.84 ± 1.72[a]	45.11 ± 0.26	42.16 ± 1.48[bc]	46.43 ± 0.74[b]	41.09 ± 2.26	43.24 ± 0.82	46.26 ± 0.92
10	47.18 ± 1.15[ab]	45.25 ± 0.79	43.92 ± 0.32[a]	47.02 ± 0.27[ab]	41.92 ± 1.24	43.53 ± 0.57	47.45 ± 0.35
Mean value	46.28 ± 1.78	44.95 ± 0.47	42.61 ± 1.21	47.05 ± 1.35	41.37 ± 1.32	43.38 ± 0.68	47.06 ± 0.83

Note: Means in a column followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test).

with stand age (Fig. 1). In addition, The BGB/AGB ratio was 0.23, 0.15, 0.15, and 0.18 in the 1-, 4-, 7-, and 10- year- old plantations, respectively.

3.2. Carbon fraction in the biomass components and soil layers

The carbon fraction in the more lignified biomass components (fruits, thorns, roots, stems) for the 1-, 4-, 7-, and 10- year-old plantations, ranged from 44.59% (±0.29) to 48.64% (±1.75) (Table 3). The corresponding vale for the less lignified components (foliage, barks, and branches) varied between 40.47% (±0.49) and 43.92% (±0.32). For any given component, the carbon content in the 4-, 7- and 10- year-old stands were generally greater than that in the 1-year-old stand (Table 3). For different biomass components, LSD results indicated a significant difference ($p < 0.05$) in C concentration was observed among thorns, foliage and barks, but not so among fruits, thorns, and roots. Across all stand age groups, thorns had the highest C concentration with mean value of 47.05%, and barks had the lowest with a mean of 41.37%. The average C concentration decreased in the order: fruit > root > stem > foliage > branch > bark (Table 3). As already remarked on, there were significant differences in C concentrations between more lignified components (fruits, thorns, roots) and less lignified components (foliage, branches, and barks) ($p < 0.05$), but not between roots and stems.

In the top 30 cm of soil, the concentration of soil organic carbon (SOC) increased with plantation age, from 2.39% for the 1-year-old stand to 2.49% for the 10-year-old stand (Table 4). Irrespective of stand age, the average SOC concentrations decreased with increasing soil depth, ranging from 2.82% at 0–10 cm depth to 2.14% at 20–30 cm depth. Average total N (TN) in the soil (0–30 cm) ranged from 0.27% to 0.30%, with the highest TN being measured for the 4-year-old plantation and the lowest for the 7-year-old plantation. Like SOC, TN tended to decline with increasing soil depth (Table 4). The C/N ratio of the 0–10 cm mineral soils ranged from 8.17 to 9.51, and also decreased with depth. However, there were no significant differences in the C/N ratio between the 10–20 cm and 20–30 cm soil layers for the same stand age.

3.3. Carbon accumulation in biomass and soil

The total carbon pool in a given component of Z. *bungeanum* may be derived from the biomass production and C concentration of the component (Table 5). Biomass C storage refers to C stored in both AGB and BGB (root), although most of this carbon was found in the AGB. The average amount of C stored in the AGB was 17.00 kg C ha^{-1} for the 1-year-old plantation, and 2.58, 4.65, and 6.37 Mg C ha^{-1} for the 4-, 7- and 10-year-old plantations, respectively (Table 5). Root biomass C storage steadily increased from 4.00 kg C ha^{-1} in the 1-year-old plot to 0.41, 0.78, and 1.19 Mg C ha^{-1} in the 4-, 7-, and 10-year-old plots, representing 19.6%, 13.7%, 14.3%, and 15.7% of the total biomass C storage (TBCS) in the four age classes (Table 5).

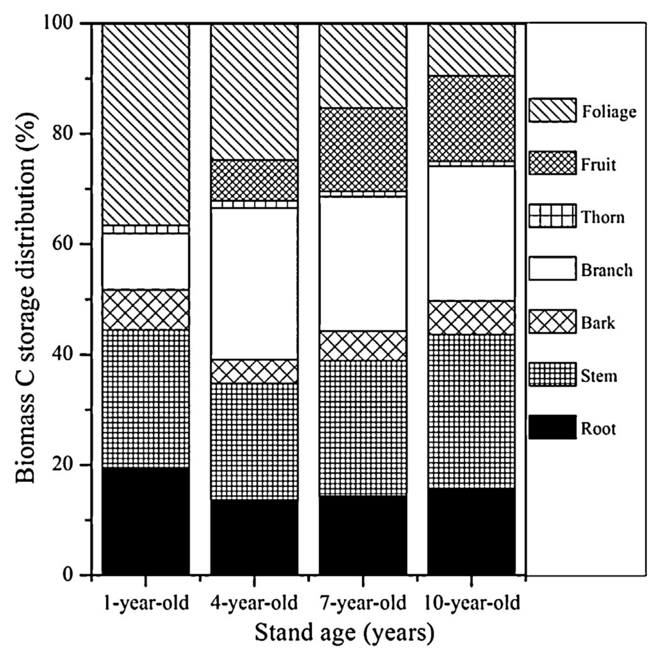

Fig. 2. Percentage distribution of biomass C storage in various components of *Z. bungeanum* trees as a function of stand age.

Table 4
Soil organic carbon (SOC) and total nitrogen (TN) concentrations in four different age classes of *Z. bungeanum* plantations (mean ± SD).

Variables	Soil depth	Stand age (years)			
		1	4	7	10
SOC (%)	0–10 cm	2.76 ± 0.35	2.80 ± 0.39	2.89 ± 0.02	2.83 ± 0.04
	10–20 cm	2.27 ± 0.28	2.30 ± 0.08	2.36 ± 0.07	2.45 ± 0.26
	20–30 cm	2.13 ± 0.28	2.12 ± 0.14	2.12 ± 0.13	2.20 ± 0.03
Mean value		2.39	2.41	2.46	2.49
TN (%)	0–10 cm	0.32 ± 0.01	0.34 ± 0.03	0.30 ± 0.00	0.33 ± 0.01
	10–20 cm	0.29 ± 0.02	0.29 ± 0.01	0.27 ± 0.02	0.30 ± 0.01
	20–30 cm	0.27 ± 0.02	0.28 ± 0.02	0.25 ± 0.01	0.26 ± 0.01
Mean value		0.29	0.30	0.27	0.30
C/N ratio	0–10 cm	8.53 ± 0.80	8.17 ± 0.46	9.51 ± 0.08	8.69 ± 0.46
	10–20 cm	7.70 ± 0.54	8.09 ± 0.09	8.75 ± 0.89	8.29 ± 0.50
	20–30 cm	7.86 ± 0.59	7.68 ± 0.65	8.60 ± 1.01	8.54 ± 0.55
Mean value		8.03	7.98	8.96	8.51

Table 5
Carbon pools in biomass, soil and total ecosystem in the 1-, 4-, 7-, and 10-year-old *Z. bungeanum* plantations ($\times 10^{-1}$ Mg C ha^{-1}, mean ± SD).

Components	Stand age (years)			
	1	4	7	10
Stem	0.05 ± 0.04^{c}	6.25 ± 3.78^{bc}	13.35 ± 5.68^{ab}	21.10 ± 8.40^{a}
Branch	0.02 ± 0.02^{b}	8.24 ± 2.36^{ab}	13.18 ± 6.30^{a}	18.50 ± 10.88^{a}
Bark	0.02 ± 0.01^{c}	1.31 ± 0.25^{bc}	2.87 ± 0.88^{ab}	4.55 ± 1.85^{a}
Thorn	0.00 ± 0.00	0.39 ± 0.31	0.52 ± 0.24	0.63 ± 0.64
Foliage	0.08 ± 0.05^{b}	7.40 ± 3.29^{a}	8.35 ± 5.79^{a}	7.20 ± 1.61^{a}
Fruit	none	2.22 ± 0.32^{b}	8.25 ± 3.37^{ab}	11.67 ± 4.61^{a}
AGB	0.17 ± 0.12^{c}	25.81 ± 8.25^{bc}	46.51 ± 20.86^{ab}	63.68 ± 24.08^{a}
Root (BGB)	0.04 ± 0.01^{c}	4.08 ± 1.62^{bc}	7.78 ± 1.62^{ab}	11.88 ± 5.65^{a}
TPB	0.20 ± 0.13^{c}	29.89 ± 9.87^{bc}	54.29 ± 20.39^{ab}	75.56 ± 29.66^{a}
SOC (0–30 cm)	752.22 ± 27.22	768.01 ± 18.06	790.01 ± 38.75	800.60 ± 34.86
Total ecosystem	752.42	797.90	844.30	876.16

Note: Means in a row followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test).

Most of the carbon in the AGB was stored in the stems and branches, while only a small amount was associated with thorns and barks (Fig. 2). There was also a marked increase in fruit biomass C with stand age. The contribution of fruit C storage to TBCS was from zero for the 1-year-old stand to 15.4% for the 10-year-old stand (Fig. 2). The TBCS was 0.02, 2.99, 5.43, 7.56 Mg C ha^{-1} for the 1-, 4-, 7- and 10-year-old stands, respectively, corresponding to an annual rate of biomass C accumulation of 0.02, 0.99, 0.81, and 0.71 Mg C ha^{-1} year^{-1}.

Based on soil bulk density and organic carbon concentration, the SOC storage of *Z. bungeanum* plantations increased with stand age. The SOC storage of 0–30 cm soil layer increased from 75.22 Mg C ha^{-1} for the 1-year-old stand to 80.06 Mg C ha^{-1} for the 10-year-old stand (Table 5). Across all stand age groups, the SOC storage decreased rapidly with the increase of soil depth, being greater in the top layer (0–10 cm) than in deeper layers (10–20 and 20–30 cm). No significant differences in SOC storage, however, were observed among the three depth intervals (0–10, 10–20, and 20–30 cm) for any given age stand (Fig. 3).

The total C storage (biomass C plus SOC) amounted to 75.24, 79.79, 84.43, and 87.62 Mg C ha^{-1} for the 1-, 4-, 7- and 10-year-old plantations, respectively. Across all stand age groups, most of C accumulated in the SOC rather than the biomass (Table 5). Indeed, 99.97% of the total carbon in the 1-year-old plantation was stored in the soil.

This proportion decreased with stand age, and fell to 91.38% in the 10-year-old plantation (Table 5).

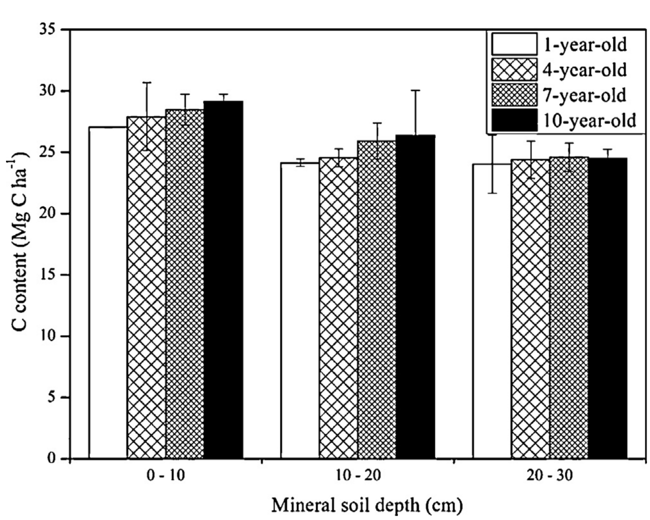

Fig. 3. Carbon storage at different depths of the soil profile for 1-, 4-, 7-, and 10-year-old *Z. bungeanum* stands (error bars indicate the standard deviation).

Table 6
Models selected for the estimation of AGB, BGB, TPB, and carbon accumulated in AGB, BGB, TPB in the four age classes of *Z. bungeanum* plantations.

Model	R^2 (%)	SEE	CF	N	MSR	SIG
AGB = 0.0023 × CBS$^{2.6582}$	98.60	0.33	1.06	12	0.11	0.01
BGB = 0.0007 × CBS$^{2.4538}$	99.00	0.25	1.03	12	0.06	0.00
TPB = 0.0030 × CBS$^{2.6206}$	98.80	0.29	1.04	12	0.09	0.00
ABCS = 0.0010 × CBS$^{2.6717}$	98.60	0.33	1.05	12	0.11	0.00
BBCS = 0.0003 × CBS$^{2.476}$	99.00	0.26	1.03	12	0.07	0.00
TBCS = 0.0013 × CBS$^{2.6343}$	98.90	0.29	1.04	12	0.08	0.00

Note: AGB = above-ground biomass (Mg ha^{-1}); BGB = below-ground biomass (Mg ha^{-1}); TPB = total plant biomass (Mg ha^{-1}); ABCS = above-ground biomass C storage (Mg ha^{-1}); BBCS = below-ground biomass C storage (Mg ha^{-1}); TBCS = total biomass C storage (Mg ha^{-1}); CBS = circumference at the base of the stem (cm); R^2 = coefficient of determination; SEE = model's standard error; CF (correction factor) = exp (SEE^2/2); MSR = mean square residuals; N = sample size.

3.4. Regression models for biomass and biomass C storage

Table 6 shows the allometric equations using power functions correlating biomass and C storage for the various components with the circumference at the base of the stem (CBS). Statistically, all the correlations are highly significant ($p < 0.01$). Among the tree components the correlation was highest ($p \le 0.001$) for the below-ground biomass (BGB) and below-ground biomass C storage (BBCS). For the other components, such as above-ground biomass (AGB), total plant biomass (TPB), above-ground biomass C storage (ABCS), and total biomass C storage (TBCS), the models can explain more than 98% of the variation. The models that used height (H), crown diameter (CD) and CBS^2 × H as predictive variables of biomass and C storage, failed to show a good fit (results not shown).

4. Discussion

4.1. Biomass accumulation

The total plant biomass (TPB) of 12.22 Mg ha^{-1} for the 7-year-old stand, and 16.71 Mg ha^{-1} for the 10-year-old stand of *Z. bungeanum* plantations (Table 2), was appreciably larger than that reported for other plant species. Working in the same karst region, Tian et al., 2011, for example, measured a TPB of 9.19 Mg ha^{-1} for a 7-year-old *Catalpa bungei* forest, and 5.86 Mg ha^{-1} for a *Dodonaea viscose* plantation. Similarly, the TPB for a 10-year-old mixed forest of *Betula luminifera* × *Populus euramevicana* was only 4.03 Mg ha^{-1}, and even less (1.12 Mg ha^{-1}) for a plantation of *Cupressus funebris* (Tian et al., 2011; Wang, 2011). For plantations of different species in non-karst regions with a comparable climate, Yin et al., 2010 reported a TPB of 1.70 Mg ha^{-1} for a 7-year old plantation of *Cinnamomum camphora*, and 0.68 Mg ha^{-1} for a mixed forest of *Michelia chapensis* × *Manglietia insignis*. These comparisons indicate that afforestation of the karst region with *Z. bungeanum* under the GGP, can lead to a rapid accumulation of biomass in both above- and below-ground parts. Thus, *Z. bungeanum* plantations can serve as an effective sink of atmospheric CO_2.

In addition, the distribution of biomass among the various components of *Z. bungeanum* trees was different from that of other tree species where stems generally made up the largest proportion of the biomass. In our study, however, stem biomass constituted only about a quarter of the total biomass in mature forests (7 and 10 years old) (Table 2; Fig. 1). The fruit biomass in 7- and 10-year-old stands of *Z. bungeanum* made up 14.5 and 14.8% of total biomass, respectively, as compared with 15.1% for a 7-year old citrus plantation (Wang et al., 2010), and 14.6–17.8% for a 8-year-old apple orchard (Wu et al., 2012). These observations indicate the important contribution of fruit to the biomass of fruit-bearing trees. Because of its large capacity for storing photosynthetic products, fruit is also the main object of planting trees, such as *Z. bungeanum*.

4.2. Biomass carbon

A factor of 50% is commonly used for converting dry biomass into carbon storage. (Malhi et al., 2004; Montagnini and Porras, 1998; Redondo-Brenes, 2007). In the present study, the C concentration for all components of *Z. bungeanum* ranged from 40.47% to 48.64% (Table 3). The mean value of 44.67% is lower than the average C concentration for *Masson pine* (57.72%) and Tea-oil *Camellia* (50.34%) (Zheng et al., 2008), but similar to that for *Acacia auriculiformis* (46.60%) and Mangrove (44.00%) (Lasco et al., 2000). The C concentrations of plantation forests are closely related to their chemical compositions, and vary with type of tree components (roots, stems, branches), type of wood (normal, tension or compression), geographical location, climate, and soil conditions (Pettersen, 1984; Romberger et al., 2004). All of these factors must be taken into account when evaluating C concentrations of trees under different climatic and edaphic conditions. The use of a conversion factor of 0.5, or a standard coefficient of 50%, is therefore an oversimplification, and would at least overestimate biomass C storage by 10%. In the present investigation, the mean value of 45% instead of measured C contents for all components seems more appropriate for calculating the C storage of *Z. bungeanum* plantations. However, the assumption that all components have a constant C fraction also does not provide the accurate calculation of C stock because of differences in the extent to which various components contribute to the total biomass. Therefore, should a fixed C content (such as 50% or mean value) instead of measured ones be used, or biomass amount be estimated individually, for all components, it would lead to large errors to the estimation of biomass C sequestration.

4.3. Soil organic carbon (SOC) storage

The mean SOC storage in the top 30 cm of the soil profile increased from 75.22 Mg C ha^{-1} for the 1-year-old stand to 80.06 Mg C ha^{-1} for the 10-year-old stand (Table 5). These values are much lower than the average SOC storage of 193.55 Mg C ha^{-1} for Chinese forest ecosystems (Zhou et al., 2000), but are higher than the 47.00 Mg C ha^{-1} measured for an *aspen-conifer* ecotone in montane forests (Dobarco and Van Miegroet, 2014). For soils under *Dodonaea viscose* and *Cupressus funebris* forests, Tian et al. (2011) measured a SOC storage of 50.52–126.84 Mg C ha^{-1} at a depth of 0–20 cm, which is consistent with our results.

Changes in SOC storage, following afforestation of former agricultural or abandoned lands, have been the subject of many investigations. Interestingly, the variation of SOC storage with plantation age does not show a consistent trend. Some studies indicated no significant increase in SOC stock with stand age (Farley et al., 2004; Peichl and Arain, 2006), while others found that SOC storage decreased in the early stage of forestation and then gradually increased with the stand age (Paul et al., 2002; Richter et al., 1999; Wang et al., 2013). Our results for a chronosequence of *Z. bungeanum* plantations indicate a positive and significant correlation ($p = 0.008$) between SOC storage and stand age (Table 5). This finding may be attributed, at least in part, to a large accumulation of soil organic matter (roots and litter) with plantation age (Gamboa et al., 2010; Turner et al., 2005; Zhao et al., 2014). Similar increases in soil C storage following afforestation have also been reported by Fonseca et al. (2011, 2012) and Zhao et al. (2014). These workers also found that the effect of stand age on SOC storage was closely related to the level of SOC content before afforestation. In the present investigation, the SOC storage in the barren (bare) land was 37.79 Mg C ha^{-1} (not shown in Table 5), while the value for the same land planted with *Z. bungeanum* (under the GGP) was 75–80 Mg C ha^{-1}. Therefore, soil with the low initial SOC content will easily increase carbon storage following reforestation (Guo and Gifford, 2002).

All these results reveal that there is no obvious and unidirectional trend of the SOC stocks after afforestation, or at least not one that can be easily discerned from our or other results. These inconsistent reports may be ascribed to a number of soil and environmental factors, such as climate, land use history, soil disturbance, soil properties, tree species, land cover, site management, and human activity. All these factors, individually or in combination, could determine or overshadow the effect of stand age on soil C accumulation (Peichl and Arain, 2006; Pregitzer and Euskirchen, 2004). Thus, site specific measurements following afforestation are needed to identify temporal changes in soil carbon stocks, while due care should be taken in extrapolating the results to different sites (Fonseca et al., 2012). For the chronosequence of karst soils under *Z. bungeanum* plantations, more than 90% of the carbon is stored in the top 30 cm of the soil profile. In other words, the topsoil in the karst region of SW China constitutes a major C pool in the overall ecosystem budget although it is vulnerable to natural erosion and human disturbance. Thus, good plantation management practices, as outlined in the GGP, need to be implemented to protect the soil and promote carbon sequestration (Zheng et al., 2008).

4.4. Implications for C sequestration by arresting rocky desertification

Rocky desertification, a process characterized by serious soil erosion and widespread bedrock exposure, is one of the most serious land degradation issues in karst areas, and hampers sustainable regional development (Xiong et al., 2009). Lying in the center of the karst region in southwest China, Guizhou province is subject to severe rocky desertification. In 2000, about 3.25×10^4 km^2 of the province had outcrops of carbonate rocks, making up 17.10% of its total land area (Jiang et al., 2014). In response to this environmental crisis, and in an attempt to improve living conditions in the karst area, the government has implemented the large-scale planting of *Z. bungeanum* under the Grain for Green Program (GGP). Admittedly, The GGP will not only improve the physical environment and arrest rocky desertification but also enhance ecosystem carbon sequestration.

Our investigation indicate that the biomass C storage (both above-ground and below-ground parts) in *Z. bungeanum* plantations can rapidly increase from 0.02 Mg ha^{-1} for the 1-year-old stand to 7.56 Mg ha^{-1} for the 10-year-old stand. A similar age-related increase in biomass C storage has also been observed by other workers (Kenzo et al., 2010; McMahon et al., 2010; Wang et al., 2013). The rate of biomass C accumulation was much greater in young plantations than in 10-year-old stands, peaking at

0.99 Mg C ha^{-1} $year^{-1}$ during the first 4 years of afforestation, in line with previous reports (McMahon et al., 2010; Wang et al., 2013). This finding is consistent with the rapid growth of *Z. bungeanum* trees in the early stages of planting, confirming that forestation with *Z. bungeanum* is conducive to C incorporation into tree biomass (Jandl et al., 2007).

By assuming that all plantation species in the karst region can be replaced by *Z. bungeanum* under the GGP, we can obtain a preliminary estimate of C sequestration as a result of reforestation in Guizhou under the GGP. In the past 10 years, about 1,180 (1000 ha) of cropped and barren land have been established in the province. The amount of sequestered carbon in 2010 was 6.35×10^6 Mg C, which corresponded to 4.92% of the total carbon (1.29×10^8 Mg C) emitted from energy consumption in that year (Geng et al., 2011). The above figures were obtained using the area of plantation per year for each stand from 1999 to 2010 in Guizhou under the GGP from the China Forestry Statistical Yearbook (State Forestry Administration, 1999–2011), and the biomass C accumulation rate for each stand of plantation over the same period (Table 5). Admittedly, our calculation only refers to changes in above- and below-ground biomass, and excludes any increases in carbon storage resulting from soil quality improvement under the GGP. Thus, if anything, the net amount of sequestered carbon would be underestimated.

Continuation of the GGP together with the maturation of *Z. bungeanum* trees over the next few years would lead to increased C sequestration in the medium term. In the long term, the large-scale conversion of farmland and abandoned land to *Z. bungeanum* plantations in the karst region will not only offset greenhouse gas emissions but also reverse rocky desertification, protect the fragile ecological environment, and increase farmer's incomes. There is a downside, however, to the large-scale cultivation of a single species, such as *Z. bungeanum*, in the form of a reduction in biodiversity, and an increase in vulnerability to diseases and pests. Although no significant outbreaks of diseases and insect pests have yet been observed, further studies on biomass accumulation and C sequestration in Z. *bungeanum* plantations should include potential ecological issues associated with monocultures in general (Wang et al., 2013).

5. Conclusions

In a chronosequence of Z. *bungeanum* plantations in the karst region of Guizhou province, China, the above-ground, below-ground and total plant biomass increased with stand age. The highest C concentration (48.67%) was observed in thorns, while the lowest (40.47%) was found in barks. The C concentrations for all tree components were markedly different but were generally lower than the values obtained using the standard coefficient (50%). This finding shows the importance of calculating different C fractions for each tree component, and that due care should be exercised when using a constant conversion factor to convert biomass to C storage. The amount of total ecosystem C stored in 1-, 4-, 7-, and 10-year-old stands of Z. *bungeanum* was 75.24, 79.79, 84.43, and 87.62 Mg C ha^{-1}, respectively, of which more than 90% was stored in the soil. Thus, minimizing soil disturbance at different levels of forest management activities has great potential to sequestrate more C. The results of this investigation indicate that expansion of Z. *bungeanum* plantations in the karst regions of China, under the Grain for Green Program, can improve the regional C budget and arrest rocky desertification. Nevertheless, long-term monitoring and further research are needed to assess the effects of large-scale forestation with *Z. bungeanum* on biomass production, carbon sequestration, and possible infestation by micro-organisms, diseases and insect pests.

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