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Effects of prescribed burning on carbon accumulation in two paired vegetation sites in subtropical China

Yuanqi Chen[1,2,3], Jianbo Cao[2,4], Lixia Zhou[2], Feng Li[2,4] and Shenglei Fu[5*]

Abstract

Background: Prescribed burning is a common practice of site preparation before afforestation in subtropical forests. However, the effects of prescribed burning on carbon (C) dynamics of an ecosystem are poorly understood. Therefore, a *Eucalyptus urophylla* plantation (EU) and a naturally recovered shrubland (NS), each treated with prescribed burning and no burning were examined in subtropical China.

Methods: Biomass of trees and shrubs in the 1st, 3nd, 4th, and 6th year after treatments were estimated by quadrat survey and allometric equations. Biomass of herbs and forest floors were estimated by harvest method. Plant biomass C storage was calculated by plant biomass multiplying by its C concentration. Soil organic C (SOC) storage in the 6th year after treatments was estimated by SOC concentration multiplying by soil bulk density and soil volumes.

Results: Tree biomass C storage was significantly higher in the burned EU (BEU) than in the unburned EU (UEU) in the 1st year after treatments, yet the difference decreased over time. Conversely, tree biomass C storage was lower in the burned NS (BNS) than in the unburned NS (UNS), although the difference was not significant. However, in the 6th year after treatments, the total plant biomass C storage was 14.56% higher in the BEU than that in the UEU, and 59.93% higher in the BNS than that in the UNS, respectively, although the significant difference was only found between UNS and BNS. In addition, neither SOC storage at 0–20 cm nor ecosystem C storage in either the EU or NS was significantly affected by prescribed burning.

Conclusions: Prescribed burning has little impact on overall C storage of forest ecosystems, we consider that prescribed burning may be an option for forest site preparation regarding plant biomass C accumulation.

Keywords: Prescribed fire, Reforestation, Plant biomass carbon, Soil organic carbon, Forest management

Background

Prescribed burning is used widely as a forest management technique to prepare sites for seeding or planting, reduce fuel loads and control plant disease (Muqaddas et al. 2016). Meanwhile, prescribed burning in forest management can reduce resource competition between target trees and shrubs, improve above and below-ground ecosystem structures and functions, and help maintain the biodiversity and ecological balance of forest ecosystems (Glitzenstein et al. 2012). In addition, prescribed burning influences soil physical, chemical and biological properties (Certini 2005; Alcañiz et al. 2018), such as soil structure, soil texture, soil organic matter content and soil microbial activity (Granged et al. 2011; Williams et al. 2012; Hu et al. 2016). Thus, prescribed burning could affect carbon (C) accumulation in forest ecosystem. However, the effect of prescribed burning on C dynamics was inconsistent. For instance, surface fires significantly reduced C sequestration by forests in a short term study, especially causing forest floor C and nitrogen (N) losses (North and Hurteau 2011). Meanwhile, surface soil C and N were decreased in burned plots (Alcañiz et al. 2016; Pellegrini et al. 2018).

* Correspondence: fsl@henu.edu.cn
[5]Key laboratory of Geospatial Technology for the Middle & Lower Yellow River Regions, Ministry of Education, College of Environment and Planning, Henan University, Kaifeng 475004, China
Full list of author information is available at the end of the article

Conversely, Rau et al. (2009) found that prescribed burning caused only immediate increases in surface soil C and N concentration, but over longer periods of time no statistically detectable change occurred. Furthermore, prescribed burning could affect plant biomass C accumulation through altering soil nutrient availability (Scharenbroch et al. 2012). Therefore, understanding the role of prescribed burning in forest C dynamics is very important for C cycling (Fahey et al. 2010; Landry et al. 2015). Previous studies have compared plant biomass, SOC concentration and pyrogenic C concentration pre- and post-fire (Pellegrini et al. 2015; Fultz et al. 2016; Krishnaraj et al. 2016), but total C storage in the forest ecosystem has been less considered. In addition, the effects of prescribed burning on forest C stocks in different vegetation types remain unclear.

Plantation forest plays a crucial role in alleviating CO_2-concentration increases (Marín-Spiotta and Sharma 2013). China has plantations of approximately 69 million hectares, which is approximately one third of the world's plantation area (State Forestry Bureau 2014). Furthermore, more than 60% of the plantation area in China is distributed in the subtropics (Wang et al. 2010). *Eucalyptus*, a fast-growing species, is widely planted in southern China and many other countries throughout the world because of its wide adaptability, high productivity, and rapid economic returns (Fischer et al. 2017). *Eucalyptus* plantations cover 4.50 million hectares in China and represent approximately 34% of the total plantation area in southern China (China Forestry Database n.d.; China Science Daily 2015). The rotation period of *Eucalyptus* plantations is approximately 4 to 8 years (Quality and Technology Supervision of Hainan Province, China 2004). Prescribed burning regularly occurs in site preparation for plantation forests or during rotation in subtropical China. Therefore, evaluating the effects of prescribed burning on the C dynamics of plantation ecosystems is urgently necessary to understand how C cycling responds to it. Additionally, the vegetation types or restoration treatments could cause different responses to prescribed burning (Shorohova et al. 2008; Wang et al. 2013), so a *Eucalyptus* plantation and a naturally recovered shrubland with no planted tree were tested in the present study.

We addressed the following two questions: (1) How does prescribed burning affect plant biomass C storage and SOC storage? (2) Do the vegetation types cause the different responses of C accumulation to prescribed burning? Inventory data from the Heshan National Field Research Station of Forest Ecosystem was used to estimate plant biomass C storage and SOC storage on a *Eucalyptus* plantation and a naturally recovered shrubland with burning and no burning treatments at the early developmental stages of vegetation.

Methods

Site description

The experiment was conducted at the Gonghe Experimental Site, Heshan National Hilly Land Interdisciplinary Experimental Station (112°50′ E, 22°34′ N), Chinese Academy of Sciences (CAS). This site is located in Heshan City, Guangdong Province, China. The Gonghe Experimental Site was established in 2005 on hilly land with similar site characteristics, which included 14 forest types (e.g., monoculture, mixed, exotic, or native plantations) or management techniques (burning or clear-cutting) (Chen et al. 2015). This region belongs to typical subtropical monsoon climate. The mean annual temperature was 21.7 °C and the precipitation was around 1700 $mm{\cdot}yr.^{-1}$. The average elevation is 10–80 m, and the soil is an acid Acrisol with a pH of approximately 4.0.

Prescribed burning was carried out to prepare sites for planting seedlings in March 2005 (Sun et al. 2011, dry weight of the aboveground biomass was less than 15.0 $Mg{\cdot}ha^{-1}$). The daily air temperature was approximately 16.5 °C, and the precipitation was 109.6 mm in March 2005. The previous vegetation type was shrubland, and after logging all trees (*Pinus elliotti*), all vegetation in the experimental site was slashed. Logging residues were left in the unburned plots, but were burned in the burned plots. *E. urophylla* seedlings were planted at a spacing of 2 m × 3 m in the plots of *Eucalyptus* plantations in May 2005. In the plots of naturally recovered shrubland, no seedlings were planted, where the plant communities were recovered naturally after treatments. Two paired vegetation sites (a naturally recovered shrubland vs. a *E. urophylla* plantation) were selected for this study. Thus, this study included the following four treatments: burned and unburned naturally recovered shrubland (BNS, UNS), and burned and unburned *E. urophylla* plantation (BEU, UEU). Each treatment plot has three replicates, each with an area of 1 ha. Additionally, all plots were arranged in a completely randomized design. The burned plots are more than 100 m away from the unburned plots. Understory vegetation in this studied site was highly dominated by the *Dicranopteris dichotoma* (Sun et al. 2011). The SOC concentration was 9.45 ± 0.21 $mg{\cdot}g^{-1}$, the soil nitrogen concentration was 0.67 ± 0.02 $mg{\cdot}g^{-1}$, and the soil pH was 4.05 ± 0.02 at 0–20 cm soil layer before burning treatment in all plots. The soil bulk density at the top 0–10 cm soil layer was not affected by prescribed burning in these studied plots (Wang et al. 2013).

Plant biomass survey

In July 2005, a permanent quadrat plot of 900 m^2 (30 m × 30 m) was established in each of three replicates for the *E. urophylla* plantation (EU) and the naturally recovered shrubland (NS). Vegetation inventories were carried out in the 1st, 3rd, 4th and 6th year, respectively. The height (H) and diameter (D) at breast height for trees, and H and basal diameter for shrubs (D) were measured for each inventory. Allometric eqs. ($Y = a \times (D^2 \times H)^b$, where a and b are statistic parameters; H and D are the height and diameter at breast height for trees, and height and basal diameter for shrubs) based on the H and D were applied to calculate biomass of trees and shrubs in each treatment (Chen et al. 2015).

Biomass of herbs and forest floor mass (dead plant materials on soil surface) were estimated by harvest method only in the 6th year for multiple reasons. To avoid destroying the permanent quadrat plots, three 1 m × 1 m subplots around only the quadrat were selected randomly and all above- and below-ground biomass of herbs, and forest floors in the subplots were harvested as separate samples. All samples were taken back to the laboratory and then were dried in an air-oven at 65 °C to obtain constant weights for the estimation of biomass. C concentrations of herb and forest floor samples were analyzed by the traditional potassium dichromate oxidation method (Lu 1999).

Tree and shrub biomass C storage per unit area were calculated as follows: tree/shrub biomass per unit area × 0.5 (assuming a constant C concentration of 50%). Herb biomass C storage and forest floor mass C storage per unit area were calculated as following: herb biomass/forest floor mass per unit area × measured C concentration.

Soil sample collection and analysis

Surface soil samples were collected in the 6th year after treatments. The soils were sampled with a corer (3.0 cm in diameter) at 0–10 cm and at 10–20 cm depths from nine randomly selected microsites in each quadrat. Three cores at the same depth from the same slope positions were combined to yield one pooled sample, and three pooled samples were collected for each quadrat plot. Visible plant residues and roots were removed by hand. Then, the soil samples were sieved by a 2-mm mesh screen for soil physicochemical property analysis. SOC concentration was determined by the traditional potassium dichromate oxidation method (Lu 1999). SOC storage at a specific depth in a given area was calculated as

$$\mathrm{SOCS} = \mathrm{SOC} \times \mathrm{TH} \times \mathrm{BD} \times (1 - \mathrm{PF})/10$$

where SOCS is soil organic C storage (Mg·ha^{-1}); SOC is the soil organic C concentration (g·kg^{-1}); TH is the thickness of the soil horizon (cm); BD is the bulk density (g·cm^{-3}); and PF is the mass percentage of fragments, sand and stone (> 2 mm). Soil bulk density for soil samples from both the 0–10 and 10–20 cm layers was determined using a steel ring sampler of 100 cm^3 volume (5 cm diameter). Soil bulk density was calculated by dividing the weight of the dried soil by the volume of the soil (Guo et al. 2016).

Data analysis

Tree and shrub biomass C storage were analyzed by repeated-measures ANOVA, with burning as the between-subject factor and stand age as the within-subject factor. One-way ANOVA was employed to test the effects of burning on biomass C storage of tree and shrub at the same stand age, herb biomass C storage, forest floor C storage and SOC storage in the *E. urophylla* plantation and the naturally recovered shrubland. Two-way ANOVA was performed to reveal the effects of burning and vegetation types on plant biomass C storage, SOC storage, ecosystem C storage, and soil bulk density. Pearson correlation analyses were conducted in order to determine the relationship between plant biomass C storage and SOC storage. When required to meet the assumptions of normality and homogeneity of variance, data were reciprocally or square-root transformed. Statistical significance was determined at $P < 0.05$. All these analyses were performed using SPSS software (IBM, Chicago, USA).

Results

Tree biomass C storage

Repeated-measures ANOVA indicated that prescribed burning did not show any significant effect on tree biomass C storage in the EU and NS (Fig. 1a and b). While, tree biomass C storage in the BEU was 83.63%, 7.10%, 20.99% and 20.63% higher than in the UEU at 1, 3, 4 and 6 years of age, respectively, and the difference was significant at 1 year of age and not at 3, 4 and 6 years of age. At 1 year of age, tree biomass C storage in the BEU (7.18 Mg C·ha^{-1}) was higher than in the UEU (3.91 Mg C·ha^{-1}) ($F = 26.87$, $P = 0.007$; Fig. 1a). By contrast, tree biomass C storage in the BNS was 12.07%, 74.67%, 60.92% and 99.21% lower than in the UNS at 1, 3, 4, and 6 years of age, although the differences were not significant (all $P > 0.178$; Fig. 1b). In addition, two-way ANOVA showed that vegetation types significantly affected tree biomass C storage at 6 years of age (Table 1), and tree biomass C storage was significantly higher in the EU than that in the NS. But the burning did not significantly affect tree biomass C storage. Meanwhile, the interaction effect of vegetation types and burning was not significant (Table 1).

Shrub biomass C storage

Shrub biomass C storage was 0.16 to 0.92 and 0.29 to 0.91 Mg C·ha^{-1} from 1 to 6 years of age for the EU and NS, respectively. Repeated-measures ANOVA showed that the effect of burning on shrub biomass C storage was not significant in the EU (Fig. 1c) or in the NS (Fig. 1d). Interestingly, shrub biomass C storage was slightly higher both in the BEU than in the UEU and in the BNS than in the UNS at 1, 3, 4, and 6 years of age, although the differences were not significant (all $P > 0.211$). Two-way ANOVA indicated that neither vegetation

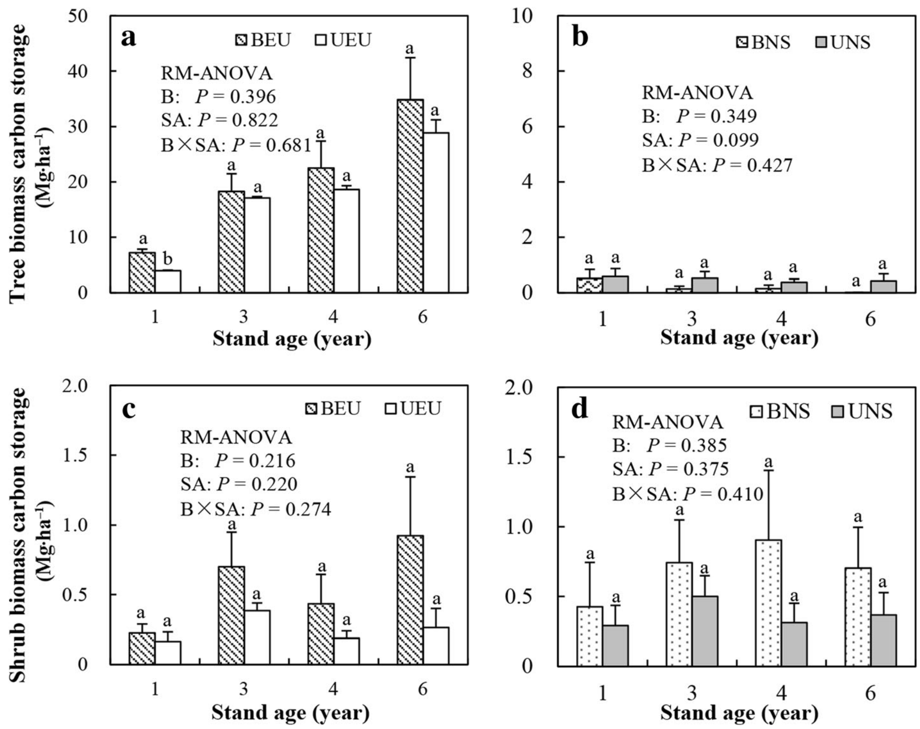

Fig. 1 Tree biomass carbon storage (**a, b**) and shrub biomass carbon storage (**c, d**) in the 1st year to 6th year after treatments, respectively, corresponding to 2006 to 2011. BEU, UEU, BNS and UNS refers to the burned *Eucalyptus* plantation, unburned *Eucalyptus* plantation, burned naturally recovered shrubland and unburned naturally recovered shrubland, respectively. Values are means + SE, $n = 3$. Lowercase letters indicate significant differences in tree/ shrub biomass carbon storage between burned and unburned treatments in the *Eucalyptus* plantation or naturally recovered shrubland at the same stand age at the $P = 0.05$ level. B: burning; SA: stand age. The inserted P-values were from repeated measures ANOVA

types nor burning significantly affected shrub biomass C storage at 6 years of age, and the interaction effect of vegetation types and burning was not significant (Table 1).

Herb biomass C storage

Two-way ANOVA showed that both the prescribed burning and vegetation types significantly affected herb biomass C storage (Table 1). Vegetation types caused a different response of herb biomass C storage to prescribed burning. In the EU, prescribed burning did not significantly affect herb biomass C storage ($F = 1.04$, $P = 0.365$), which was 12.92% lower in the BEU (7.50 Mg C·ha^{-1}) than in the UEU (8.62 Mg C·ha^{-1}) (Fig. 2). Whereas herb biomass C storage was 67.19% higher in the BNS (12.77

Table 1 Effects of burning (B), vegetation types (VT) and their interaction effects on C storage in tree biomass, shrub biomass, herb biomass, total plant biomass (the sum of tree, shrub and herb biomasses), forest floors, and soil organic C (SOC) storage at 0–20 cm depth, ecosystem C storage (the sum of tree biomass C, shrub biomass C, herb biomass C, forest floors C and SOC), and soil bulk density in the 6th year after treatments

Factors	B		VT		B × VT	
	F	*P*	*F*	*P*	*F*	*P*
Tree biomass C	0.48	0.508	**62.60**	**0.000**	0.64	0.449
Shrub biomass C	3.19	0.112	0.05	0.826	0.35	0.573
Herb biomass C	**8.50**	**0.019**	**9.69**	**0.014**	**20.51**	**0.002**
Total plant biomass C	1.48	0.259	**46.24**	**< 0.001**	< 0.01	0.961
Forest floors C	2.80	0.133	**6.38**	**0.035**	0.34	0.574
SOC storage	0.00	0.968	0.07	0.799	1.14	0.316
Ecosystem C	0.23	0.642	**12.08**	**0.008**	0.28	0.608
Soil bulk density (0–10 cm)	1.88	0.208	0.04	0.842	0.47	0.512
Soil bulk density (10–20 cm)	0.37	0.560	1.24	0.298	1.73	0.224

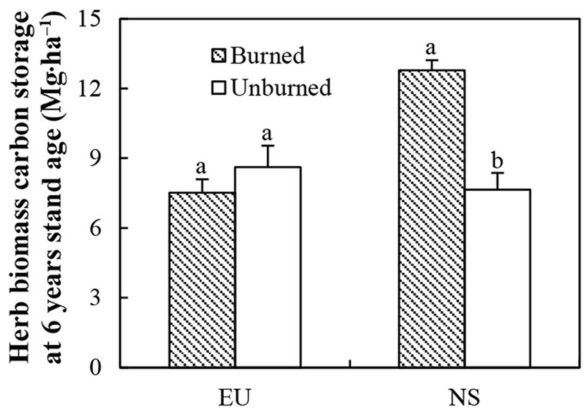

Fig. 2 Herb biomass carbon storage in the 6th year (2011) after treatments. EU and NS refers to the *Eucalyptus* plantation, and naturally recovered shrubland, respectively. Values are means + SE, $n = 3$. Lowercase letters indicate significant differences in herb biomass carbon storage between burned and unburned treatment in the same vegetation type at the $P = 0.05$ level

Mg C·ha^{-1}) than in the UNS (7.64 Mg C·ha^{-1}), and the difference was significant ($F = 37.08$, $P = 0.004$; Fig. 2). The interaction effect of vegetation types and burning on herb biomass C storage was significant (Table 1).

Forest floor C storage

Two-way ANOVA suggested that vegetation types significantly affected forest floor C storage (Table 1). Forest floor C storage was significantly higher in the EU than in the NS (Table 2). However, burning did not significantly affect forest floor C storage. And the interaction effect of vegetation types and burning on forest floor C storage was not significant (Table 1). One-way ANOVA showed that forest floor C storage in the BEU was lower 16.16% than in the UEU, although the difference was not significant (Table 2). In the NS, burning significantly affected forest floor C storage, which was 77.10% lower in the BNS than in the UNS (Table 2).

SOC storage

Prescribed burning did not significantly affect SOC storage in the EU or in the NS either at the 0–10 cm or at the 10–20 cm soil layers (Table 2). In the 0–20 cm soil layer, SOC storages were 30.48, 35.80, 34.66 and 28.91 Mg C·ha^{-1} for the BEU, UEU, BNS and UNS, respectively (Table 2). In addition, two-way ANOVA showed that neither vegetation types nor prescribed burning significantly affected SOC storage, and the interaction effect of vegetation types and burning on SOC storage was not significant at the 0–20 cm soil layer (Table 1).

Ecosystem C storage in the 6th year

In this study, total plant biomass C storage was the sum of tree, shrub, and herb biomass C storage. Ecosystem C storage was the sum of total plant biomass C, forest floor C, and SOC storage at the 0–20 cm layer. The total plant biomass C storage were 43.21, 37.72, 13.48 and 8.43 Mg C·ha^{-1} for the BEU, UEU, BNS and UNS, respectively (Table 2). Two-way ANOVA showed that burning did not significant affect total plant biomass C storage, yet vegetation types did significantly affect total plant biomass C storage. There was a significantly higher total plant biomass C storage in the EU than in the NS. In addition, total plant biomass C storage was 14.56% and 59.93% higher when burning was present in the EU and NS, respectively, while the significant difference was observed only in the NS (Table 2).

Two-way ANOVA indicated that prescribed burning did not significantly affect ecosystem C storage, yet the vegetation types did (Table 1). Ecosystem C storage was higher in the EU than in the NS (Table 2). One-way ANOVA suggested that there was no significant difference in ecosystem C storage both between in the BEU (77.02 Mg C·ha^{-1}) and UEU (77.49 Mg C·ha^{-1}), and between in the BNS (49.62 Mg C·ha^{-1}) and UNS (40.16 Mg C·ha^{-1}), although it was 23.56% higher in the BNS than in the UNS (Table 2).

Table 2 Total plant biomass C storage (the sum of tree, shrub and herbs biomass C storage), forest floors C storage, and soil organic C (SOC) storage at the different depths as well as ecosystem C storage (the sum of total plant biomass C, forest floors C, and SOC storage) in the 6th year after treatments. *P* and *F* values were from the results of one-way ANOVA. EU, NS, UB, B stand for *Eucalyptus* plantation, naturally recovered shrubland, and the treatments of unburning and burning, respectively

C storage (Mg C·ha^{-1})	EU			NS		
	UB	B	*P* (*F*)	UB	B	*P* (*F*)
Total plant biomass	37.72 ± 2.81	43.21 ± 8.11	0.557 (0.41)	8.43 ± 1.04	13.48 ± 0.73	**0.017 (15.74)**
Forest floor	3.98 ± 0.54	3.33 ± 0.95	0.585 (0.35)	2.82 ± 0.30	1.48 ± 0.36	**0.046 (8.11)**
SOC (0–10 cm)	23.32 ± 2.52	20.13 ± 5.89	0.676 (0.20)	19.49 ± 4.73	22.50 ± 2.08	0.369 (1.02)
SOC (10–20 cm)	12.48 ± 0.60	10.05 ± 3.06	0.479 (0.61)	9.42 ± 1.96	12.15 ± 0.23	0.239 (1.91)
SOC (0–20 cm)	35.80 ± 2.96	30.48 ± 8.90	0.601 (0.32)	28.91 ± 4.11	34.65 ± 1.44	0.258 (1.74)
Ecosystem	77.49 ± 4.23	77.02 ± 17.56	0.980 (0.00)	40.16 ± 4.26	49.62 ± 1.54	0.105 (4.36)

Soil bulk density

Two-way ANOVA indicated that neither prescribed burning nor vegetation types affected soil bulk density at the 0–10 and 10–20 cm soil layers. Meanwhile, the interaction effects of prescribed burning and vegetation types on soil bulk density were not significant (Table 1).

The correlations of vegetation C storage and SOC storage

Pearson correlation analyses showed that the tree biomass C storage was significantly and positively correlated to the forest floor C storage, total plant biomass C storage, and ecosystem C storage ($P = 0.020$, < 0.001 and < 0.001, respectively; Table 3), yet the herb biomass C storage was negatively correlated to forest floor C storage ($P = 0.039$). The significantly positive correlations between forest floor C storage and total plant biomass C storage was also be found ($P = 0.035$). Meanwhile, there were significantly positive correlations between forest floor C storage, total plant biomass C storage, SOC storage and ecosystem C storage ($P = 0.025$, < 0.001 and 0.019, respectively; Table 3).

Discussion

Effects of prescribed burning on plant biomass C storage

Plant biomass C storage was influenced by prescribed burning. In the naturally recovered shrubland, the effect could be ascribed to the difference in herb biomass C storage in that the plant communities were dominated by herbs. In the *Eucalyptus* plantation, tree biomass C storage contributed a large proportion of plant biomass C storage.

Prescribed burning significantly increased tree biomass C storage in the 1st year in the *Eucalyptus* plantation; however, the effect was gradually weakened with increasing stand age. We speculated that prescribed burning accelerated nutrient return from residues (e.g., logging plant residues) on the soil surface shortly after burning, which promoted plant growth. Butler et al. (2017) found that prescribed burning increased the availability of soil phosphorus. Hence, prescribed burning enhanced tree and shrub biomass C storage. However, after a period of time, the nutrients derived from the decomposition of residues and litter in unburned plots with abundant logging residues could become richer than those in burned plots. As a result, the effect of prescribed burning on tree biomass in the *Eucalyptus* plantation was gradually weakened. In addition, the decreased soil N and soil available P in the burned *Eucalyptus* plantation after 3 years of treatments could be responsible for that (Sun et al. 2011). Furthermore, it could be ascribed to the physiological trait of *Eucalyptus*. The biomass of fast-growing *Eucalyptus* increased fast as the nutrients were relatively abundant at the early stage. That prescribed burning increased tree biomass C storage to some extent in *Eucalyptus* plantations in the present study was consistent with that observed in Chinese fir plantations by Zhou et al. (2016).

Table 3 The Pearson correlations (*r*) between biomass C storage of tree, shrub, herb, forest floor, total plant and soil organic C storage.

	Tree	Shrub	Herb	Forest floor	Plant	SOC	EC
Tree	–	0.215	−0.493	0.657*	0.99**	0.291	0.906**
Shrub	–	–	0.029	−0.267	0.262	0.186	0.254
Herb	–	–	–	−0.600*	−0.374	0.140	−0.269
Forest floor	–	–	–	–	0.610*	0.302	0.639*
Plant	–	–	–	–	–	0.356	0.935**
SOC	–	–	–	–	–	–	0.662*

Note: Tree, shrub, herb, forest floor, plant, SOC, and EC stand for the C storage of tree biomass, shrub biomass, herb biomass, forest floor, and total plant biomass; soil organic carbon storage, and ecosystem carbon storage; respectively. *indicates $P < 0.05$, **indicates $P < 0.01$

The herbs in the studied vegetation types were dominated by *D. dichotoma*. *D. dichotoma* is a light-demanding heliophyte and has a high light compensation point (Chen et al. 2016; Zhu et al. 2016) that is intensively controlled by canopy cover. In the *Eucalyptus* plantation, less biomass of *D. dichotoma* was found for the greater tree biomass. This result was supported by the results of Bataineh et al. (2006). Nevertheless, in the naturally recovered shrubland, plants were dominated by herbs such as *D. dichotoma*. Meanwhile, prescribed burning has been shown to accelerate nutrient return from residues on the soil surface, which promoted plant growth (Carter and Foster 2004; Close et al. 2011; Gautam and Mandal 2016). Furthermore, the litter of *D. dichotoma* decomposed slowly (Ma et al. 2009), and nutrient return from the litter of *D. dichotoma* was also slow. In addition, prescribed burning did not affect the germination of *D. dichotoma*. As a result, the herb biomass C storage in the BNS was higher than that in the UNS.

Forest floor C storage was significantly affected by prescribed burning in the naturally recovered shrubland. In the *Eucalyptus* plantation, forest floor C storage was also higher in unburned plots than in burned plots, yet not significantly. The observed forest floor C storage was not consistent with that reported by Kim et al. (2016). The following two possible reasons could be responsible for this difference. On the one hand, the pre-fire residues could be mixed on the forest floor and have a slow decomposition rate (Jiang et al. 2012). On the other hand, prescribed burning reduced the occurrence of diseased plants and insect pests (Houdeshell et al. 2011; Hall et al. 2016), so the litter production could be reduced. Although burning decreased the litter decomposition rate by shifting soil microbial communities (Sun et al. 2011; Holden et al. 2013), some of the soil microbial parameters changes (e.g., soil microbial biomass C, ß-glucosidase, and phosphatase activities) were ephemeral, and only some of these changes lasted for 3 years (Fontúrbel et al. 2016). The intensity of prescribed burning could be responsible for these changes. Espinosa et al. (2018) found that litter productivity showed no significant difference 1 year after low intensity prescribed burning. In addition, great total plant biomass could produce more forest litter, it was supported by the positive relations between forest floor biomass C and total plant biomass C storage in this study.

Effects of prescribed burning on SOC storage

Prescribed burning did not affect SOC storage in the 0–10 and 10–20 cm soil layers in both the *Eucalyptus* plantation and naturally recovered shrubland. The observed SOC storage was consistent with previous studies (Neill et al. 2007; Roaldson et al. 2014). However, Rau et al. (2009) found that burning increased C and N within the first 0–3 cm of soil, and this change was not statistically detectable when integrated into the 0–8 or 0–52 cm layers. In this study, the effect of prescribed burning on SOC was likely diluted in the 0–10 cm soil layer. Therefore, the soil thicknesses can have a dilution effect that is associated with the actual impacts of fire on soil properties (Armas-Herrera et al. 2016). Meanwhile, the season of prescribed burning could be responsible for this effect. Early season burns had less dramatic short-term effects on the soil abiotic conditions than late season burns (Hamman et al. 2008). In our study, the prescribed burning was conducted in March 2005. In addition, in this studied area, Sun et al. (2009) reported that SOC concentration in the 0–10 cm soil layer significantly decreased after 3 years of prescribed burning in *Eucalyptus* plantations, but we did not detect this effect after 6 years. This result suggested that the effect of prescribed burning on SOC could last for less than 6 years. Wang et al. (2016) found that prescribed burning changed the SOC release only in the 1st year. Additionally, the burning intensity drives the post-fire temporal pattern of SOC accumulation (Sawyer et al. 2018). Low- and moderate-intensity prescribed burning could have little effect on SOC storage on the long-term scale. Besides, the little effect of prescribed burning on SOC in the EU could be due to the nature of *Eucalyptus*, which is an exotic species with fast growth rate and could sequester more soil organic C as greater biomass C accumulation than native species. However, this was not supported by our previous result that the soil organic C accumulation was not significantly different between the plantations with fast-growing species (i.e. *E. urophyll*a, and *Acacia crassicarpa*) and plantations with slow-growing species (*Castanopsis hystrix*, and a mixture of 10 native tree species) at the early development stages (Chen et al. 2017).

Effects of prescribed burning and vegetation types on ecosystem C storage

The ecosystem C storage was not affected by prescribed burning in both the *Eucalyptus* plantation and naturally recovered shrubland. The observed ecosystem C storage was consistent with that reported by others (Scheller et al. 2011). Santos et al. (2003) found that the negative effects of burning on the C balance of the ecosystem were more or less neutralized after only 12 months. Meanwhile, the effects of burning on C in ecosystems depended on the intensity of prescribed burning (Keeley 2009). However, the vegetation types had a significant effect on ecosystem C storage as the difference in plant biomass C storage was mainly induced by plant traits (Chen et al. 2015). It was also supported by the significantly positive correlations between total plant biomass C storage and ecosystem C storage. The interaction effects of prescribed burning and vegetation types on herb biomass C storage were apparent. Different plant species, vegetation types, and forest types could lead to various responses to burning (Prévosto et al. 2011; Balch et al. 2015; Lutz et al. 2017; Pellegrini et al. 2018). Therefore, the vegetation types should be considered when assessing the effects of prescribed burning on ecosystem C dynamics.

There were several limitations in the present study. The SOC data were absent before the prescribed burning for the studied plots in spite of the similar site characteristics at the experimental sites, and the information on the SOC dynamics over time after treatments could not be evaluated. Besides, the effect of prescribed burning on forest C storage was only investigated in a *Eucalyptus* plantation and a naturally recovered shrubland, whether or not it can be applied to other forests needs more investigation.

Conclusions

In subtropical plantations, we found that prescribed burning significantly increased herb biomass C storage and total plant biomass C storage in the naturally recovered shrubland, and slightly increased tree biomass C storage and total plant biomass C storage in the *Eucalyptus* plantation. However, SOC storage and ecosystem C storage were not significantly affected by prescribed burning in two vegetation types. Consequently, we conclude that prescribed burning has little impact on overall C storage of forest ecosystems, and could be an option for forest site preparation in subtropics.

Abbreviations

BEU: burned *Eucalyptus urophylla* plantation; BNS: burned naturally recovered shrubland; C: carbon; EU: *Eucalyptus urophylla* plantation; N: nitrogen; NS: naturally recovered shrubland; SOC: soil organic carbon.; UEU: unburned *Eucalyptus urophylla* plantation; UNS: unburned naturally recovered shrubland

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions
SF and LZ designed and supervised the research. YC, JC and FL carried out the field and laboratory works. YC analyzed data and wrote the manuscript. SF improved the manuscript. All authors read and approved the final manuscript.

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Not applicable.

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Competing interests
The authors declare that they have no competing interests.

Author details
[1]Hunan Province Key Laboratory of Coal Resources Clean-utilization and Mine Environment Protection, Hunan University of Science and Technology, Xiangtan 411201, China. [2]Key Laboratory of Ecological Remediation and Safe Utilization of Heavy Metal-polluted Soils, College of Hunan Province, School of Life Science, Hunan University of Science and Technology, Xiangtan 411201, Hunan, China. [3]Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China. [4]University of Chinese Academy of Sciences, Beijing 100049, China. [5]Key laboratory of Geospatial Technology for the Middle & Lower Yellow River Regions, Ministry of Education, College of Environment and Planning, Henan University, Kaifeng 475004, China.

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