Effects of site preparation treatments before afforestation on soil carbon release

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ABSTRACT

Site preparation, as an important procedure before afforestation, can affect soil C release. However, the effect of site preparation on soil C release has not been sufficiently investigated. Two site clearing treatments (brush clearing and controlled burning) followed by three soil preparation treatments (overall soil preparation, spot soil preparation, and no soil preparation (control)) were carried out in subtropical China. Soil basal respiration (R_s) and C release of biomass burning were measured as soil C release on an area basis from March 2011 to March 2013. The site preparations changed the soil C release in the first year but had no effects in the second year. Compared with brush clearing (control), controlled burning (control) significantly increased the annual soil C release (decreased R_s but increased C release of biomass burning) during the first year. Within the brush clearing plots, overall soil preparation significantly increased the R_s rate over eight months and resulted in an increase in annual soil C release during the first year compared to the no soil preparation. In contrast, spot soil preparation increased the R_s rate only for three months and did not affect the annual soil C release during the first year relative to the no soil preparation. In the controlled burning plots, both overall and spot soil preparation increased the R_s rate across six months, but only overall soil preparation caused a significant increase in the annual soil C release. Our study suggests that minimizing the disturbance of the site preparation would decrease soil C release. Concluding, the spot soil preparation followed brush clearing is a good choice for site preparation in term of soil C storage.

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1. Introduction

In the context of global climate change, how to enhance C sequestration and reduce C emission are major subjects. The Kyoto Protocol and IPCC Report (2007) suggested that afforestation is a potentially useful approach to mitigate the increasing atmospheric CO₂ concentration (Berthrong et al., 2012), and the area of forest plantations is rapidly increasing throughout the world (Nouvellon et al., 2008). In China, forestation has been carried out as an effective measure against environment degradation since the 1970s and has brought a remarkable increase in the forest C stock of 0.45 Pg (Fang et al., 2001).

Apart from vegetation C stock, afforestation also influences the soil C stock. Approximately 75% of the total terrestrial C is stored in the world's soils, and forest soils hold approximately 40% of all

belowground C (Dixon et al., 1994; Huntington and Center, 1995). Therefore, even a small disturbance of the soil may result in a significant effect on the global C budget (Paul et al., 2002). Following afforestation, an initial decrease in soil C stock has been commonly observed (Trouvé et al., 1994; Paul et al., 2002, 2003) and a new soil C equilibrium is eventually reached after several years (Guo and Gifford, 2002). In recent years, a process-based model and a meta-analysis indicated that soil C stock decreased after afforestation, reached the minimum value after 5–10 years, and then recovered to pre-disturbance levels after approximately 20 years (Huang et al., 2007; Li et al., 2012). One possible reason was that the new C input from the young stands was too low to match the C decomposition (Vesterdal et al., 2002), and the plants-derived fresh organic matter (litter, root exudates, etc.) input may accelerate soil organic matter (SOM) decomposition due to the rhizosphere priming effects (Dijkstra et al., 2006). Another possible reason was the increase of soil C release caused by site preparation, because it can disturb soil structure, modify

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microclimate and enhance aeration (La Scala et al., 2005; Mallik and Hu, 1997). However, most researches did not investigate the effects of site preparation without plants on soil C release.

Site preparation is typical site treatment before afforestation to favor the survival and growth of planted trees by reducing competition from understory vegetation (Karlsson, 2002). Site preparation generally includes site clearing (brush clearing and controlled burning) and soil preparation (overall soil preparation, spot soil preparation and no soil preparation). The effect of controlled burning on soil C release is more complex than that of brush clearing. Compared to brush clearing, controlled burning can affect soil C release not only during the burning process but also during the post-burning period (Fernández et al., 1999). During the burning process, 60–80% of the surface organic materials are burned out and revert to the atmosphere as CO₂ (González-Pérez et al., 2004), leading to a remarkable decrease in soil C stock (Guo et al., 2006). The long-term impact of burning on the ecosystem-atmosphere C exchange has been reported, however, these results were inconsistent (Phillips et al., 2002; Wuthrich et al., 2002; Hubbard et al., 2004; Ma et al., 2004). These contradictory results may be attributed to the difference of the burning intensity, soil microclimate, topography, and vegetation (McCarthy and Brown, 2006). During the burning, the burning intensity determines the amount of ash (Certini, 2005), soil properties (Boerner et al., 2000), soil microbial and root mortality (Chapin et al., 2004). In addition, ash deposition can increase the soil respiration (R_s) through increased nutrient release and hence available C substrate for microbes (Fritze et al., 1994), whereas alterations in soil chemistry can reduce microbial activity (Pietikäinen and Fritze, 1995; Badía and Martí, 2003). However, the relative importance of each of these components of burning on R_s is largely unknown.

Soil preparation, such as ploughing, ripping or disking, enhances soil C release (Post and Kwon, 2000; McLaughlin et al., 2000; Bernoux et al., 2006) by several mechanisms. Soil preparation mixed the organic surface layer with mineral soil, which created new conditions for organisms and may enhanced the decomposition rates of the buried organic matter (Johansson, 1994). In addition, soil preparation could disrupt soil aggregates and transfer labile organic matter to soil microorganisms (La Scala et al., 2008), resulting in a reduction in the amounts of intra-aggregate soil organic C. Soil preparation also affects soil C release by modifying the soil surface microclimate, e.g., the soil water content and temperature (Mallik and Hu, 1997). Enhanced R_s after soil preparation has been demonstrated (La Scala et al., 2005; Mallik and Hu, 1997), but the effects varied with on soil texture, initial soil C stocks and climate (Post and Kwon, 2000; Six et al., 2002). However, few studies have assessed the soil preparation effects on R_s in subtropical soils (Feller and Beare, 1997). Compared with the overall soil preparation, spot soil preparation affects the soil microclimate and properties with a relatively lower intensity. However, few studies have assessed the effects of spot soil preparation on R_s (Pumpanden et al., 2004; Strömberg and Mjöfors, 2012).

In subtropical China, forests encompass a total area of approximately 53 million hectares, of which approximately 41% are young plantations. Brush clearing, controlled burning and soil preparation before planting are traditional silvicultural practices to improve the survival rate and growth in South China (Yang et al., 2005). However, these measures can cause substantial loss and redistribution of organic matter (Johnson and Curtis, 2001; Certini, 2005). Furthermore, subtropical forests are characterized by the East Asian monsoon climate with a clear wet season and dry season and approximately 60% of precipitation occurred during the short rainy season from March to June (Wang et al., 2012a). Such higher rainfall, not only advantaged of moister soil for decomposition (Post et al., 1982), but also accelerated the soil surface

compaction because of the rain splash (Mataix-Solera et al., 2011), and then may influence the duration of soil preparation on R_s . However, there is very little information available regarding the effect of site preparation on soil C release in this area (Guo et al., 2010). Especially, with climate-change-induced changes in precipitation amount and patterns, we need a better understanding to the impacts of site preparation on soil C release in subtropical China.

The main objectives of the present study were to assess the effects of different site preparation treatments before afforestation on soil C release. Based on previously documented R_s after similar site preparation (Guo et al., 2010; Mallik and Hu, 1997) and soil C stock change after afforestation in the same area (Huang et al., 2007), we hypothesize that (1) compared with brush clearing, controlled burning would decrease the annual cumulative R_s because litter and organic carbon are consumed in burning; (2) overall soil preparation increases the annual cumulative R_s , but spot soil preparation has less effects on the annual cumulative R_s due to the small disturbance area; and (3) site preparation effects on R_s may decline gradually over time, because of its direct effect on soil physical property might be weakened and lack of fresh organic matter input.

2. Materials and methods

2.1. Experimental site

The experiment was carried out at the Qianyanzhou Ecological Research Station (26°44'39"N, 115°03'33"E) in subtropical China. The site is controlled by a warm and humid monsoon climate and is characterized by a clear summer drought due to the unevenly distributed rainfall. The annual mean air temperature was 17.9 °C, and the precipitation was 1469 mm yr⁻¹ from 1985 to 2008 (Wang et al., 2011). The soil was iron-rich red soil and classified as Typic Dystrudepts Udepts Inceptisols according to U.S. soil taxonomy (Wang et al., 2013). This study was conducted in an abandoned orange orchard. The vegetation was predominated by *Loropetalum chinensis* (R. Br.) Oliv, Cogon grass (*Imperata cylindrica* (L.) Beauv.) and Canadian Fleabane (*Conyza canadensis* (L.) Cronq.).

2.2. Experimental design

The experiment used a paired, nested design with site clearing (brush clearing and controlled burning) as primary treatments and soil preparation (overall soil preparation, spot soil preparation and no soil preparation) as secondary treatments. Three blocks of 14 m × 9 m were established for brush clearing and controlled burning treatments. Each block was placed about 1 m apart and was divided into six 4 m × 4 m subplots (Fig. 1). In two subplots of each block, sites were fully ploughed (brush clearing + overall soil preparation, BCOP; controlled burning + overall soil preparation, CBOP) with a depth of 30 cm or patch scarified (brush clearing + spot soil preparation, BCSP; and controlled burning + spot soil preparation, CBSP) with a size of 50 × 50 × 40 cm³ (Length × Width × Depth). The two remaining subplots acted as no soil preparation controls (brush clearing control, BCCT; controlled burning control, CBCT). Further descriptions of site preparation were listed in Table 1.

2.3. Measurement of soil basal respiration

After site preparation, polyvinyl chloride (PVC) collars (11 cm in diameter, 6 cm in height) were immediately placed. In each subplot for BCCT, BCOP, CBCT and CBOP, four PVC collars were pressed

Fig. 1. A sketch map of the experimental design (a total of three duplicated blocks were designed for this study). BCCT = brush clearing + no soil preparation (control of brush clearing), BCOP = brush clearing + overall soil preparation, BCSP = brush clearing + spot soil preparation, CBCT = controlled burning + no soil preparation (control of controlled burning), CBOP = controlled burning + overall soil preparation, CBSP = controlled burning + spot soil preparation.

Table 1

Summary of site preparation treatments applied at Qianyanzhou (LFH = Litter, Fermentation and Humus subhorizons).

Treatment	Description	Illustration
Brush clearing	Clear-cutting all of the aboveground plants, clipping the grass 3 cm above the ground, all aboveground plants were removed and weighed after oven drying at 65 °C. Soil exposure was minimal	
Controlled burning	All of the aboveground plants burned out in situ, all brushes and grass were fully consumed, leaving an ash layer over mineral soil. Soil exposure was minimal	
Overall soil preparation	The organic matter and mineral soil were thoroughly mixed to a depth 30 cm. In order to reducing the spatial heterogeneity, all clods were broken into pieces and avoid the formation of furrow. Mineral soil exposure was 100%	
Spot soil preparation	Taken a soil core with a size of 50 × 50 × 40 cm ³ (Length × Width × Depth), thoroughly mixed organic matter and mineral soil and backfilled to the cave. Each spot was distributed 2 m apart (with an assumed planting density of 2500 seedling per ha). This spot soil preparation raised the bed approximately 3–5 cm than surround soil surface. Mineral soil exposure was 100%	

into the soil at randomly selected positions (approximately 2 m apart). In each BCSP or CBSP subplot, six PVC collars were inserted into soil. Three PVC collars were inserted in spot, one of them was inserted in the center of spot, and others were inserted around approximately 10 cm. The other three collars were in the non-spot place at randomly selected positions. Soil collars were inserted at 3 cm depth carefully to avoid disturbing soil, and the soil around the collars was pressed slightly to avoid air leakage and the underestimation of the R_s .

The R_s was measured from March 2011 to March 2013 in different frequencies as follows: once daily during the first week after site preparation, every other day in the following month, and weekly from the second month after site preparation to the end. The LI-8100 portable soil CO₂ flux system (Li-Cor, Inc., Lincoln, NE, USA) was used to measure the R_s . We used a 10 cm respiration chamber, in which the increase in CO₂ concentration was recorded at 1 s intervals by the LI-8100's infrared gas analyser. The length of measurement was limited to 2 min, in order to avoid important chamber CO₂ concentration changes (Davidson et al., 2002). All measurements were made between 9:00 and 11:00 am, because the R_s measured in this time were close to daily means (Wang et al., 2012a). At least 2 days before each measurement the living plants inside the soil collars were removed by hand to eliminate aboveground plant respiration.

2.4. Measurement of soil properties

The soil temperature (T_s) and soil water content (SWC) at 10 cm below soil surface were monitored at each chamber. T_s was measured using a portable temperature probes (JM624 digital thermometer, Living-Jinming Ltd., China). Volumetric soil moisture

(m³ m⁻³) was measured using a moisture probe meter (TDR100, Spectrum, USA). In block 2, continuous measurements of the T_s and SWC were taken every 30-min using thermocouples (ST-100, Campbell Inc.) and TDR sensors (CS616, Campbell Inc.) at 10 cm depth. These data were then used to estimate cumulative R_s .

Soil was collected before and after (7 days) site preparation, we used a 45-mm-diameter hand auger to take soil samples at depths of 0–10 cm and 10–20 cm. Three soil cores were taken and combined into a composite soil samples in each plot. Soil samples were divided into two parts, one part was air-dried and used for soil chemical analyses and the other was used to assess the microbial biomass C. At each sampling location, soil bulk density was determined by use of the high stainless steel cutting ring core with a 5 cm diameter and 5 cm at the depth of 0–10 cm and 10–20 cm, soil samples in the rings were dried in the laboratory at 105 °C for 48 h for calculating soil bulk density.

Soil samples used to measure soil organic carbon (SOC), total nitrogen (TN) and pH were passed through a 0.25 mm sieve and then measured with a CN-element analyzer (Elementar VarioMax CN, Mt. Laurel, NJ). The soil pH was measured potentiometrically in a 1: 2.5 soil: water suspension. Samples for microbial biomass C analysis were sieved (2 mm) and estimated by chloroform fumigation-extraction (Vance et al., 1987).

2.5. Statistical analysis

An exponential equation (Eq. (1)) was used to simulate the relationship between the T_s and R_s rate. To understand the dependence of the R_s rate on SWC, all of the observed R_s rates were normalized to 15 °C ($R_{s,15}$) using Eq. (2). The relationship between $R_{s,15}$ and SWC was determined with Eq. (3). Eq. (4) was used to model the

responses of the R_s rate to both T_s and SWC (Xu and Qi, 2001). The annual mean and monthly mean R_s rates were the weighted averages of the observed R_s rate. The annual cumulative R_s was extrapolated with fitted models as generated by Eq. (4) and the continuous T_s and SWC datasets (Wang et al., 2012a). Eq. (5) was used to calculate the annual cumulative R_s of spot soil preparation, which was the sum of the R_s of 2500 spots (the planting density was assumed to be 2500 trees ha^{-2}) and no-spot area.

$$R_s = a * e^{bT_s} \quad (1)$$

$$R_{s,15} = R_s * e^{b(15-T_s)} \quad (2)$$

$$R_{s,15} = a * SWC^b \quad (3)$$

$$R_s = a * e^{bT_s} * SWC^c \quad (4)$$

$$\sum R_s = \sum R_{s(\text{spot})} + \sum R_{s(\text{no-spot})} \quad (5)$$

where R_s is the soil basal respiration ($\mu\text{mol m}^{-2} \text{s}^{-1}$), $R_{s,15}$ is the normalized soil basal respiration at a reference temperature of 15 °C (283.15 K), T_s is the soil temperature (°C), and SWC is the volumetric soil water content ($\text{cm}^3 \text{cm}^{-3}$). a , b and c are the fitted parameters.

The main and interactive effects of site clearing and soil preparation treatments on R_s , T_s and SWC were determined with repeated measures analysis of variance (RM-ANOVA). Between subject effects were evaluated as treatments and within subject effects were time-of-month. A General Linear Model (GLM) with a least significant difference (LSD) test was used to examine the effects of soil preparation on the monthly mean values within the brush clearing and controlled burning. Regression analyses were used to test the associations among R_s , T_s and SWC. To examine which variable had a more important effect R_s , simple

and multiple nonlinear regression analyses were applied between R_s and these measured variables under the different site preparation treatments. SPSS software (SPSS 16, SPSS Inc., Illinois, Chicago, USA) was used to perform all analyses. The standard 0.05 level was used throughout as a cutoff for statistical significance.

3. Results

3.1. Soil physicochemical properties

Compared with brush clearing (control), controlled burning (control) significantly decreased soil total nitrogen (TN) by 15.4% in 10–20 cm depth ($P < 0.05$), but significantly increased microbial biomass C by 28.0% in 0–10 cm depth ($P < 0.05$). No other distinguished differences were detected in soil physicochemical properties between brush clearing and controlled burning. Soil preparation significantly affected soil physicochemical properties. Within brush clearing plots, BCOP significantly decreased soil organic C (SOC) and TN in 0–10 cm depth and significantly decreased microbial biomass C and soil bulk density in two depths compared with BCCT. BCSP significantly decreased bulk density in two depths, but no significant difference in SOC, TN and microbial biomass C were found at any of the soil depths, compared to BCCT (Table 2). In the controlled burning plots, CBOP significantly decreased SOC, TN and microbial biomass C in 0–10 cm depth, and significantly decreased bulk density in all the depths compared to CBCT. CBSP significantly decreased bulk density in two depths compared with CBCT.

3.2. Soil microclimate

The T_s exhibited a similar seasonal variation trend and peaked in July and August in all treatments (Fig. 2). No distinguished difference in T_s was detected at all treatments (Table 3). SWC

Table 2
Soil physicochemical properties before and after site preparation. Note: Mean $\pm$ standard deviation (SD), $n = 3$. SOC = Soil organic carbon, TN = Total nitrogen, MBC = Microbial biomass carbon, BD = Soil bulk density.

Depth (cm)	Treatments	SOC (g kg^{-1})	TN (g kg^{-1})	MBC (mg kg^{-1})	BD (g cm^{-3})
0–10	Before site preparation	13.02 $\pm$ 0.16	1.33 $\pm$ 0.02	113.38 $\pm$ 10.55	1.41 $\pm$ 0.01
10–20		7.89 $\pm$ 0.21	0.85 $\pm$ 0.01	40.73 $\pm$ 6.34	1.40 $\pm$ 0.01
7 days after site preparation					
0–10	BCCT	15.14 $\pm$ 1.27a	1.39 $\pm$ 0.10a	74.84 $\pm$ 3.27b	1.40 $\pm$ 0.02a
	BCOP	8.37 $\pm$ 2.40b	0.92 $\pm$ 0.18b	64.03 $\pm$ 9.25b	1.18 $\pm$ 0.04b
	BCSP	13.11 $\pm$ 2.25a	1.26 $\pm$ 0.20ab	119.01 $\pm$ 10.06a	1.18 $\pm$ 0.02b
	CBCT	14.42 $\pm$ 5.05a	1.23 $\pm$ 0.44a	95.86 $\pm$ 8.72a	1.43 $\pm$ 0.02a
	CBOP	6.75 $\pm$ 0.95b	0.78 $\pm$ 0.11b	36.23 $\pm$ 7.95b	1.04 $\pm$ 0.05b
	CBSP	13.34 $\pm$ 0.52a	1.21 $\pm$ 0.12a	88.34 $\pm$ 14.33a	1.01 $\pm$ 0.12b
10–20	BCCT	9.84 $\pm$ 2.00a	0.97 $\pm$ 0.08a	34.19 $\pm$ 10.50ab	1.38 $\pm$ 0.01a
	BCOP	9.14 $\pm$ 1.48a	0.96 $\pm$ 0.08a	26.82 $\pm$ 3.14b	1.13 $\pm$ 0.04b
	BCSP	10.67 $\pm$ 1.84a	1.07 $\pm$ 0.16a	50.87 $\pm$ 13.82a	1.18 $\pm$ 0.05b
	CBCT	8.63 $\pm$ 3.30a	0.82 $\pm$ 0.34a	31.54 $\pm$ 12.58b	1.39 $\pm$ 0.03a
	CBOP	7.80 $\pm$ 1.83a	0.87 $\pm$ 0.12a	48.51 $\pm$ 16.93ab	1.10 $\pm$ 0.07b
	CBSP	10.31 $\pm$ 2.18a	0.95 $\pm$ 0.19a	64.82 $\pm$ 11.63a	1.21 $\pm$ 0.11b
Analysis of variance					
Site clearing (C)		ns	*	***	*
Soil preparation (P)		***	***	***	***
Depth (D)		***	***	***	ns
C $\times$ P		ns	ns	ns	ns
C $\times$ D		ns	ns	**	*
P $\times$ D		***	**	***	*
C $\times$ P $\times$ D		ns	ns	**	ns

Small letters indicate the significant differences among the three soil preparation methods within brush clearing and controlled burning. ($P < 0.05$, randomized complete block design ANOVA followed by multiple comparison tests). ns indicates not significant.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Fig. 2. Monthly variations in the soil temperature (T_s), soil water content (SWC) and basal soil respiration rate (R_s) during the experiment period in each treatment (control, closed circle; overall soil preparation, open circle; spot soil preparation, close triangle) under brush clearing (a, c and e) and controlled burning (b, d and f). The values are mean $\pm$ SD, ($n = 3$). * and ** are statistically significantly different among three levels soil preparation treatments at $P < 0.05$ and 0.01 , respectively.

experienced a reversed trend, which in the wet season was higher than that in the dry season. There was no significant difference in SWC between BCCT and CBCT, over the two years experiment period. However, soil preparation significantly decreased SWC. Within brush clearing plots, the mean SWC decreased by 39.2% and 38.8% for the BCOP and BCSP across the two years experiment period, respectively, compared to the BCCT. Within controlled burning plots, a significant reduction was observed in SWC for both CBOP and CBSP by 45.0% and 35.0% (Table 3) compared with CBCT, respectively.

3.3. The response of basal soil respiration to site preparation

All site preparation treatments showed a strong seasonal pattern of R_s with maximum rates from June to August (Fig. 2). Compared with brush clearing (control), controlled burning (control) significantly decreased monthly mean R_s rate from July to September in the first year. However, no significant difference in the R_s rate was found between the two treatments in the second year. The annual cumulative R_s was also calculated and found that controlled burning significantly decreased the annual cumulative R_s by 12.4% ($P < 0.05$) compared to the brush clearing in the first year. In the second year, however, no significant decrease in the annual cumulative R_s for the controlled burning treatment was detected.

In the brush clearing plots, compared with BCCT, BCOP significantly increased the monthly mean R_s rate during the first eight months (Fig. 2a), thereby increasing the annual mean R_s rate by

25.3% ($P < 0.05$) and annual cumulative R_s increased by 23.9% ($P < 0.05$) in the first year, but there was no obvious difference during the second year (Fig. 3). For BCSP, the monthly mean R_s rate also significantly increased compared to the BCCT in the first three months after site preparation (Fig. 2a), but no significant enhancement was detected in the annual mean R_s rate and cumulative R_s over the two years (Fig. 3).

In the controlled burning plots, compared with CBCT, the monthly mean R_s rate of CBOP and CBSP significantly increased within the first six months, except for a small disturbance (Fig. 2b). For the first year, CBOP and CBSP significantly increased the annual mean R_s rate by 20.0% and 21.0% ($P < 0.05$), compared CBCT, respectively. The annual cumulative R_s significantly increased by 19.7% ($P < 0.05$) for CBOP, but no obvious changes were observed for CBSP (Fig. 3). During the second year, however, there was no significant difference in the monthly or annual mean R_s rate among the three treatments.

3.4. The dependence of soil respiration on soil temperature and soil water content

The relationship between T_s and R_s rate for each treatment was fitted with an exponential model over the two years experiment period and results are given in Table 4. T_s explained more than 40% of R_s variation (Table 4). Unlike the relationship between R_s and T_s , $R_{s,15}$ and SWC had no significant relationship over the two years experiment period (Table 4). However, when the

Table 3

Annual mean soil temperature (T_s), soil water content (SWC) and soil respiration (R_s) influenced by site preparation treatments at Qianyanzhou Ecological Research Station in subtropical China (mean $\pm$ SD, $n = 3$).

Time/Treatments	T_s		SWC		R_s	
<i>1st year</i>						
BCCT	19.29a	0.58	29.70a	2.27	1.98b	0.09
BCOP	18.84a	0.45	18.40b	1.84	2.47a	0.20
BCSP	18.98a	0.29	18.06b	1.12	2.18b	0.02
CBCT	19.65a	0.24	29.15a	2.53	1.77b	0.06
CBOP	18.90a	0.55	16.06b	1.94	2.14a	0.10
CBSP	19.27a	0.37	18.46b	2.06	2.13a	0.07
<i>2nd year</i>						
BCCT	19.56a	0.54	32.23a	2.13	1.39a	0.14
BCOP	19.16a	0.48	19.30b	1.91	1.48a	0.28
BCSP	19.34a	0.37	19.71b	1.18	1.49a	0.11
CBCT	20.05a	0.29	31.48a	2.00	1.35a	0.15
CBOP	19.34a	0.69	17.15b	2.08	1.45a	0.23
CBSP	19.76a	0.47	20.69b	1.90	1.32a	0.10
<i>Analysis of variance</i>						
<i>1st year</i>						
Site clearing (C)	ns		ns		**	
Soil preparation (P)	ns		***		***	
C $\times$ P	ns		ns		ns	
<i>2nd year</i>						
C	ns		ns		ns	
P	ns		***		ns	
C $\times$ P	ns		ns		ns	

Different letters on means indicates significant difference at $P < 0.05$ between soil preparation treatments within brush clearing and controlled burning treatments. ns indicates not significant.

*Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Fig. 3. Annual cumulative R_s (mean $\pm$ SD, $n = 3$) in control, overall and spot soil preparation in brush clearing and controlled burning plots. Different small and capital letters indicate the significant differences among three levels of soil preparation and between two site clearing treatments, respectively.

observation period was separated into dry and wet seasons, significant relationships between $R_{s,15}$ and SWC were detected (Table 4). Although the relationships between $R_{s,15}$ and SWC were weaker than those between R_s and T_s , they were significant ($P < 0.05$), explaining 11–23% of R_s variations (Table 4). We combined T_s and SWC to examine the interactive effects of these factors on R_s by Eq. (4). The results indicate that T_s and SWC together contributed 39–60% (two years) of the variation in R_s .

Compared to brush clearing (control), controlled burning (control) had no significantly effect on the relationship between R_s and T_s , as well as the interactive effects of T_s and SWC on R_s . However, soil preparation significantly weakened these relationships. In the brush clearing treatments, the correlation of seasonal R_s with T_s

was best in BCCT ($R^2 = 0.62$, $P < 0.05$), followed by BCOP ($R^2 = 0.49$, $P < 0.05$) and BCSP ($R^2 = 0.47$, $P < 0.05$). The T_s and SWC together explained 48% and 43% of the variation in R_s rate during the two years for BCOP and BCSP, respectively. In the controlled burning plots, we found that T_s explained 46% and 42% variation of R_s in CBOP and CBSP, respectively, which is lower than that in CBCT (58%). T_s and SWC together explained 45% and 39% of the variation in the R_s rate for CBOP and CBSP, respectively (Table 4).

4. Discussion

4.1. Effect of controlled burning on soil C release

Controlled burning significantly decreased the annual cumulative R_s by 12.4% (Fig. 3) compared with brush clearing in the first year. These results support our first hypothesis. Decreases in R_s after controlled burning have also been found by other studies (Guo et al., 2010; Pietikäinen and Fritze, 1995). Based on a meta-analysis of burning experimental data on globe, Wang et al. (2012b) concluded that burning significantly decreased R_s by 13.5%. These results may be explained by several factors. First, controlled burning induced a decrease in soil organic matter by rapid oxidation (Guo et al., 2006). Organic carbon may losses higher than 50% under pine forest after a burning (Fernández et al., 1997). In addition, the burning may change the quality of SOC (Certini, 2005). González-Pérez et al. (2004) believed that burning led to soil humus transformed into a new particulate C forms highly resistant to oxidation and biological degradation. In our study, the SOC decreased by 6% for the controlled burning treatments compared to brush clearing (Table 1). Therefore, the decreased R_s could be due to the reduction of soil C substrate in the controlled burning treatment. Second, compared to brush clearing, controlled burning may change the soil microclimate. Treseder et al. (2004) found that after burning T_s changes temporarily because of the disappearing of the litter mantle and the darkening of ground. In addition, burning can yield hydrophobic hydrocarbons that, together with the layer of ashes, could limit the soil's water infiltration capacity and hence its moisture content (Neary et al., 1999). Third, controlled burning may affect soil aeration. Because of burning may deteriorate soil structure by affecting aggregate stability and soil sealing can occur as a result of aggregate breakdown by the rain splash (Mataix-Solera et al., 2011). Moreover, soil pores were reported to be blocked by burning ashes (Neary et al., 1999; Martin and Moody, 2001). In our study site, there is abundant precipitation, which may lead to the breakdown of soil aggregates and redistribution of ashes to block the macro-pores (Lavee et al., 1995). Therefore, decreases in R_s could be due to decreased soil aeration in the controlled burning treatment. Last, controlled burning can lead to a significant reduction in microbial biomass C (Pietikäinen and Fritze, 1995). This decline in microbial biomass C after controlled burning has either a direct effect or indirect effect on decreasing the soil moisture content, destroying soil structure or increasing soil pH (Fritze et al., 1994). However, in our study, microbial biomass C did not change with the controlled burning compare to the brush clearing. Hamman et al. (2007) observed that microbial biomass C did not change with burning, but there was a shift in soil microbial community structure. Sun et al. (2011) observed the soil microbial community structure by total phospholipid fatty acids (PLFAs), and found that the ratios of fungi PLFAs to bacteria PLFAs were low in the burned plots. This result suggests that only measurement on microbial biomass C could not discover the effect on burning and merit further investigation.

Though controlled burning diminished cumulative R_s in the first year, the released CO_2 from the above ground plants burning must be considered. The C release of biomass burning in the experiment

Table 4Models for the relationship between the soil respiration (R_s), soil temperature (T_s) in °C and soil water content (SWC, cm³ cm⁻³).

Treatment	Period	$R_s = a * e^{bT_s}$				$R_{s,15} = a * SWC^b$				$R_s = a * e^{bT_s} * SWC^c$				
		a	b	R ²	P	a	b	R ²	P	a	b	c	R ²	P
BCCT	Wet season	0.46	0.07	0.53	<0.01	11.26	-0.61	0.23	<0.01	5.86	0.05	-0.62	0.67	<0.01
	Dry season	0.40	0.07	0.76	<0.01	0.29	0.39	0.14	<0.01	0.17	0.07	0.23	0.77	<0.01
	Two years	0.51	0.06	0.62	<0.01	0.72	0.13	0.02	0.16	0.60	0.06	-0.03	0.60	<0.01
BCOP	Wet season	0.80	0.05	0.44	<0.01	8.70	-0.51	0.11	0.01	4.78	0.05	-0.54	0.50	<0.01
	Dry season	0.49	0.06	0.65	<0.01	0.22	0.62	0.16	<0.01	0.07	0.07	0.62	0.72	<0.01
	Two years	0.80	0.05	0.49	<0.01	0.59	0.33	0.06	0.01	0.49	0.05	0.16	0.48	<0.01
BCSP	Wet season	0.81	0.05	0.38	<0.01	7.79	-0.50	0.18	<0.01	6.64	0.05	-0.65	0.55	<0.01
	Dry season	0.49	0.06	0.76	<0.01	0.38	0.39	0.12	0.03	0.11	0.07	0.51	0.82	<0.01
	Two years	0.82	0.04	0.47	<0.01	0.93	0.14	0.02	0.15	0.81	0.04	0.02	0.44	<0.01
CBCT	Wet season	0.42	0.07	0.58	<0.01	11.19	-0.63	0.17	<0.01	5.65	0.06	-0.69	0.66	<0.01
	Dry season	0.42	0.06	0.73	<0.01	0.44	0.27	0.16	<0.01	0.19	0.06	0.21	0.75	<0.01
	Two years	0.53	0.05	0.59	<0.01	0.82	0.08	0.01	0.30	0.30	0.06	0.15	0.58	<0.01
CBOP	Wet season	0.78	0.05	0.47	<0.01	4.92	-0.34	0.14	<0.01	2.54	0.05	-0.35	0.55	<0.01
	Dry season	0.37	0.07	0.77	<0.01	0.32	0.46	0.17	<0.01	0.10	0.07	0.46	0.83	<0.01
	Two years	0.80	0.04	0.46	<0.01	0.68	0.28	0.06	0.01	0.52	0.05	0.15	0.45	<0.01
CBSP	Wet season	0.83	0.05	0.32	<0.01	5.55	-0.38	0.11	0.01	3.50	0.04	-0.42	0.39	<0.01
	Dry season	0.38	0.07	0.71	<0.01	0.25	0.56	0.20	<0.01	0.07	0.07	0.60	0.79	<0.01
	Two years	0.76	0.04	0.42	<0.01	0.78	0.20	0.04	0.05	0.68	0.04	0.05	0.39	<0.01

was calculated by equation: $C = A \times B \times \alpha \times \beta$ (Seiler and Crutzen, 1980), where C is C release of biomass burning (t C ha⁻¹), A is the total land area that was burned (ha), B is the average aboveground biomass per unit area (t ha⁻¹), α is the C concentration of the aboveground biomass (%), and β is the burning efficiency of the aboveground biomass (%). In this experiment, B was measured at brush clearing plots, as the biomass was relatively uniform among the plots. All of the aboveground plant in brush clearing plots were cut, removed and weighed after oven drying at 65 °C. α and β are 45% and 90% according to Andreae (1991), respectively. The C release of biomass burning was approximately 5.21 ± 0.74 t C ha⁻¹ in this study. Therefore, compared with brush clearing, controlled burning significantly increased the annual soil C release by 57.8% in the first year. However, C release of biomass burning in this study would be underestimated since the biomass calculation does not include the slash residues and the litters.

4.2. Effect of overall and spot soil preparation on soil C release

Overall soil preparation increased the annual R_s compared with the control in the first year. These results support our second hypothesis. Both Mallik and Hu (1997) and Pumpanen (2003) reported that mixing organic matter with mineral soil significantly increased R_s rate. In detail, the organic matter decomposition rate was faster in buried sites than left on soil surface (Johansson, 1994; Lundmark-Thelin and Johansson, 1997). Lundmark-Thelin and Johansson (1997) found that burying needle litters and slash needle litters resulted in accelerated mass loss rates and increased nutrient availability as compared with litters decomposed on soil surface after three years. Accelerated decomposition rates are probably related to enhanced microbial activity and increased microbial population (Salonius, 1983), because soil mixing might improve substrate availability to soil microbial of deep soils (Thorburn et al., 2001) and habitat accessibility for the microbial in each layer. Furthermore, soil preparation may influence decomposition rate by modifying the soil microclimate, e.g., SWC and T_s (Mallik and Hu, 1997; Pérez-Batallón et al., 2001). By burying organic matter under mineral soil, SWC and T_s are like fluctuated less with depth, because having a buffering mineral layer above them creates a more stable environment (Bulmer et al., 1998). In our study, soil preparation significantly decreased SWC (0–10 cm). The relationship between the $R_{s,15}$ rate and SWC was

positive in the dry season but negative in the wet season (Table 2). High SWC may inhibit the diffusion of O₂ and impede the development of aerobic microorganisms, which can decrease R_s (Davidson et al., 1998; Ellert and Janzen, 1999). In addition, soil preparation significantly decreased soil bulk density (Table 2). Soils under plough generally have lower soil bulk density and associated higher total porosity within the plough layer than under no plough (Lipiec et al., 2006). In these iron-rich red soils, soil texture is divided into 2.0–0.05 mm (17%), 0.05–0.002 mm (68%), and <0.002 mm (15%) (Wen et al., 2010), soil aeration might be an important limiting factor.

In this study, the annual mean R_s rate and annual cumulative R_s per hectare of spot soil preparation treatment were significantly lower than those of the overall soil preparation treatment and were not significantly different from those of the control. Laganière et al. (2010) analyzed the experienced low and high intensity pre-planting disturbance and found that minimizing the disturbance associated with the preparation of the plantation site can increase the soil C stock by 15%. Bulmer et al. (1998) and Prescott et al. (2000) suggested that site preparation affects soil C stock not only by the intensity of soil preparation but also by the total disturbed area. Although the plough depth of spot soil preparation was deeper than that of overall soil preparation, the disturbed area for spot soil preparation was only 625 m² for 1 ha of forestation area under the assumption of a planting density of 2500 trees ha⁻¹. Thus, it is reasonable to have less of an effect of spot soil preparation than overall soil preparation on the soil annual cumulative R_s .

4.3. Temporal dynamics in soil C release after site preparation

When the R_s was compared between controlled burning and brush clearing, no obvious differences were found during the first four months, which is inconsistent with our third hypothesis. This phenomenon has also been reported in other studies. For example, Guo et al. (2010) found no significant differences of R_s during the first 3–4 months after clear-cutting and controlled burning. In our experiment, controlled burning generally lasted less than 20 min because large shrubs and trees were removed from the experimental plots. Therefore, the root system of plants should not be significantly affected because we had to remove the regenerated grasses frequently to keep it clean for the controlled burning plots during

the initial stage experimental period. In addition, there was no difference in the microbial biomass C of the soil surface between the two treatments (Table 2) due to the relatively short heat exposure. Meanwhile, ash deposition following burning increases the availability of inorganic nutrients in soil, which could stimulate microbial growth (Peay et al., 2009). However, ash deposition had only a relatively short-term effect on the microbial community (Zimmermann and Frey, 2002). Therefore, the R_s in the controlled burning treatment decreased markedly and maintained a significantly lower level for three months compared to brush clearing (Fig. 2) from the fifth month.

R_s increased by soil preparation during the initial stage of treatment and maintained a significantly higher level compared to that of the control in the first year. However, there were no significant differences in the R_s among the soil preparation treatments in the second year. These results support our third hypothesis. Consistent with our findings, Mallik and Hu (1997) reported that the effects of site preparation on R_s lasted 5 months. However, some studies have suggested that the effects of site preparation on R_s last shorter or longer than in our study (Guo et al., 2010; Zummo and Friedland, 2011). These contradictory results may be attributed to the difference of the soil slope, soil type, climate, and decomposition rate. For example, Guo et al. (2010) found that site preparation significantly decreased the R_s during a two-year experiment that was conducted in widespread steep slopes with heavy rainfall. Soil erosion is the main path of soil C loss during site preparation (Black and Harden, 1995). In this study, the experiment was conducted on a flat area in which soil C may not be affected by soil erosion after soil preparation.

In subtropical, the litter decomposition rate is fast due to the high temperatures and abundant precipitation (Wang et al., 2009). Wang et al. (2010) found that about 75% of initial leaf litter masses and 55% of initial fine root masses were lost after one year. Site preparation buries litters in the soil, which may increase the decomposition rate (Kuzakov, 2006). In our study, the amount of residues was not quantified, but we removed all of the aboveground plants, just left some slash residues and litters. In addition, there was no fresh organic matter input after treatment because regenerated plants were cleared frequently. Therefore, the contribution of organic matter decomposition to the R_s decreased to almost zero and no significant differences were found among treatments in the second year.

5. Conclusions

The site preparation treatments affected R_s and thus the soil C stock. However, significant effects of site preparation on R_s were only observed in the first year. For site clearing processes, controlled burning significantly decreased the annual cumulative R_s , but the total C release (R_s and C release of biomass burning) was significantly higher than that of brush clearing. The overall soil preparation treatment stimulated annual cumulative R_s compared to that of the control in both brush clearing and controlled burning plots. The spot soil preparation had no significant effect on the annual cumulative R_s due to the small area of disturbed soil. We also found the relationships between R_s and soil environmental variables varied among the different treatments. In addition, our observations indicate that the relationships between R_s and T_s can be weakened by soil preparation. Based on our results, brush clearing following spot soil preparation might be a good choice for site preparation in reducing soil C loss before afforestation.

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