EFFECTS OF SECOND ROTATION SEEDLINGS AND COPPICE ON UNDERSTOREY VEGETATION AND TIMBER PRODUCTION OF *EUCALYPTUS* PLANTATIONS

XG Zhou[1], D Ye[2], HG Zhu[1], XQ Li[1], Y Su[3], J Lan[3] & YG Wen[1, *]

[1]*Guangxi Key Laboratory of Forest Ecology and Conservation, Forestry College, Guangxi University, 100 Daxuedong Road, Nanning, Guangxi 530004, China*
[2]*College of Chemistry and Life Sciences, Zhejiang Normal University, 688 Yingbin Road, Jinhua, Zhejiang 321004, China*
[3]*Dongmen State Forest Farm of Guangxi, Fusui, Guangxi 532100, China*

**wenyg@263.net*

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Replanting with seedlings or regenerating with coppice in second rotation is a major forestry management regime in short rotation forestry (SRF), but little is known about its effects on understorey vegetation conservation, timber production and economic benefits. To evaluate the effects of second rotation seedlings and coppice regime on the composition, structure and biomass of understorey vegetation, timber production and economic benefits of *Eucalyptus* plantations, a long-term (14 years) comparative study was conducted using three rotation regimes: (1) the first rotation planted with seedlings (FRs), (2) second rotation replanted with seedlings (SRs) and (3) another second rotation regenerated with coppice (SRc). Both successive rotation regimes significantly decreased the species richness, diversity and evenness of the total understorey vegetation. SRs did not affect the abundance of understorey species but significantly decreased the coverage and biomass of understorey vegetation. SRc significantly increased the abundance of the understorey plant species and maintained the coverage and biomass of the understorey vegetation equivalent to FRs. SRs showed the highest stand volume and net present value, however the highest internal rate of return occurred in SRc due to the reduced establishment and management costs. This suggested regenerating with coppice should be a more suitable successive rotation regime for increasing economic benefits as well as biodiversity conservation in south China.

Keywords: Successive rotation, short rotation forestry, conservation, economic benefits, south China

INTRODUCTION

Short rotation forestry (SRF), especially under a successive rotation regime using fast-growing exotic species such as the *Eucalyptus* genus, is a major forestry practice in tropical and subtropical regions (Razakamanarivo et al. 2012). SRF of *Eucalyptus* provides significant carbon sequestration and has potential impact on native biodiversity (Fabião et al. 2002, Ryan et al. 2010, Wen et al. 2010, Drake et al. 2013). The establishment of single species stands and subsequent replanting or coppicing is the most common management regime in SRF (Fabião et al. 2002). However, the effects of different successive rotation regimes on understorey vegetation, timber production and economic benefits of *Eucalyptus* plantations are not well understood.

Previous studies have demonstrated that successive rotation regimes by planting new seedlings maintained timber production but caused the destruction of natural vegetation (Wen et al. 2005, Wen et al. 2010). Such management practice reduced the biodiversity of understorey vegetation and had a negative effect on the reestablishment of natural vegetation in the understorey (Bengtsson et al. 2000, Fabião et al. 2002, Hartley 2002, Wen et al. 2010). As for second rotation coppice, some studies have shown that sprout regeneration increased timber production (Wei et al. 2010, Crous & Burger 2015). However, other studies have conversely found that coppice decreased timber production and reduced the biodiversity of understorey vegetation (Proe et al. 2002, Whittock et al.

2004, Ye et al. 2007, Tang 2010, Lv et al. 2012). Difference of timber production between second rotation seedlings and coppice would result in different economic benefits. Unfortunately, few direct comparative studies of economic benefits between these two successive rotation regimes were conducted (Crous & Burger 2015). Hence, a comparison of the timber production and profitability of successive rotation regimes using seedlings or coppice need to be further examined.

Short rotation plantations of *Eucalyptus* have been expanding in south China during the last two decades. Currently there are 4.6 million hectares of *Eucalyptus* plantations in China, with 2.0 million of them in the Guangxi Zhuang Autonomous Region. Most of these *Eucalyptus* plantations (60–70%) are short rotation stands with 5–7 years per operating cycle. These *Eucalyptus* plantations primarily have been established using second rotations by replanting seedlings. In recent years, second rotation from coppice has been performed in short rotation plantations of *Eucalyptus* in south China, driven by the need to increase efficiency by reducing operation costs and minimising the disturbance of both soil and understorey vegetation in these plantations (Wen et al. 2010). However, previous research has not focused on the impact of management practices of successive rotation regimes in south China, especially the direct comparison between second rotation seedlings and coppice. Therefore, a long-term comparative study was conducted with the aim to compare the effects of second rotation seedlings and coppice on the composition, structure and biomass of understorey vegetation, timber production as well as economic benefits of *Eucalyptus* stands. This should provide additional useful information for evaluating suitable successive rotation regimes in tropical and subtropical regions in the world.

MATERIALS AND METHODS

Site characteristics

The study was performed in the Dongmen Forest Farm, south-western China (22°17'–22°30' N, 107°14'–108°00' E). This farm has a south subtropical monsoon climate, characterised by a wet summer and a dry winter. Annual rainfall is approximately 1300 mm, occurring primarily from April to September. Annual mean temperature is 22.3 °C with a mean monthly minimum temperature of 12.8 °C and maximum temperature of 28.6 °C. The soils were all latosolic red soil, developed from arenaceous shale parent materials with heavy texture, poor nutrients, pH values of 5.0–5.5 and soil depth > 1 m. The study site was previously occupied by a subtropical evergreen forest followed by a Chinese fir plantation in 1974 after clear cutting.

Plantation establishment

The first rotation of *Eucalyptus* hybrid (*E. urophylla* × *E. grandis*) was planted with seedlings (FRs) in 1998 after the 23-year-old Chinese fir plantation was harvested. Following harvest of FRs in October 2006, the second rotation stands replanted with seedlings (SRs) and regenerated with coppice (SRc) were established. For FRs and SRs, the site was prepared using a mechanical plow (depth 35–40 cm) after clear-cutting followed by prescribed burning. The plantations were established with a spacing of 3.4 m × 1.7 m. In SRc, the coppice was allowed to sprout from the harvested stumps to average heights of 5 cm above ground level. Sprout thinning treatments were applied in May 2007 and any excess sprouts were removed, leaving one dominant sprout per stump. The preservation density of coppice was 4.72% lower than that of the seedlings due to loss of stumps and mortality of the sprouts. During the first 3 years, all the stands were fertilised with 200 kg nitrogen, 150 kg phosphorus and 100 kg potassium per hectare and weeding was conducted in a 30 cm radius around each tree. The intensity of forest floor disturbance for the different rotation regimes during the experimental period was ranked as follows: SRs > SRc > FRs (Table 1).

Assessment of *Eucalyptus* tree aboveground biomass and stand volume

Eighteen 10 × 10 m fixed sampling plots were randomly established in each plantation and the tree height (H) and diameter at breast height (dbh) at 1.3 m above ground level of each *Eucalyptus* tree in each plot were measured every December from 1998 to 2005 for FRs and every December from 2007 to 2012 for SRs and SRc stands.

Table 1 The intensity of the forest floor disturbance from site preparation to create *Eucalyptus* hybrid (*E. urophylla* × *E. grandis*) plantations from seedlings for the first and second rotation and from coppice for the second rotation at the Dongmen Forest Farm in Guangxi, China

Stand type	Burning frequency	Harrowing frequency	Weeding frequency	Fertilisation frequency
FRs	1.0	1.0	3.0	3.0
SRs	2.0	2.0	6.0	6.0
SRc	1.5	1.5	6.0	6.0

FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; frequency 0.5 of burning and harrowing in SRc stands show disturbance on 50% of stand area

Eighteen *Eucalyptus* trees representing the stand-specific dbh range were selected and destructively sampled in each plantation in July 2005 for FRs and July 2012 for FRs and FRc respectively. The aboveground parts of each sample tree were subdivided as stems, bark, branches and leaves and the total fresh weight of each part were determined in the field. Samples were dried at 85 °C until a constant weight was achieved to determine moisture content. The results of the biomass model indicated that the allometric relationship between the biomass of the tree components (W) and dbh (D) and height (H) was best fitted with the equations (Wen et al. 2005):

$$W = a \times (dbh^2 \times H)^b \qquad (1)$$

where dbh = diameter at breast height (cm) and H = tree height (m).

Biomass models of stems, bark, branches and leaves were separately built for each rotation regime (Table 2). The AGB of each tree was calculated as the sum of biomass of stems, bark, branches and leaves.

Stand volume (SV) was estimated by averaged experimental form factor method (Meng 1999):

$$SV = f_e \times (H + 3) \times \pi \times (1/4) \times dbh^2 \qquad (2)$$

where f_e = experimental form factor, π = ratio of circumference to diameter, H = tree height (m), dbh = diameter at breast height (cm). Since the tree form was similar in all three plantations, experimental form factor of the different rotation regimes were valued as 0.4, similar to other studies with *Eucalyptus* hybrid (Mu et al. 2006, Chen et al. 2008, Li et al. 2012).

Floristic surveys and biomass measurements of understorey vegetation

All the understorey plant species in each fixed sampling plot were measured according to species richness, abundance, height and coverage of shrub and herb layer in July 2005 for FRs and July 2012 for SRs and SRc. Species richness was estimated by tallying the number of plant species in each plot and abundance was calculated as the individual numbers of all species in each plot. Coverage was the ratio of the area of vertical projection of the aboveground part of the plants to the area of the plot. The important value (IV) of each species in the understorey plant community was calculated as follows:

$$IV = (Ra + Rf) / 2 \qquad (3)$$

where Ra = relative abundance, defined as the total number of individuals of a species as a percentage of the total number of individuals of all species, Rf = relative frequency, defined as the total frequency of a species as a percentage of the total frequency of all species.

The Shannon-Wiener index (H') was estimated for each stand using the equation (Magurran 1988):

$$H' = -\sum_{i=1}^{s} p_i \ln P_i \qquad (4)$$

where P_i = the ratio of the numbers of each species to the total numbers of all the species in each plot and s = the number of species in each plot. The Pielou's evenness index (E) was estimated for each stand using the equation (Pielou 1966):

$$E = H' / \ln S \qquad (5)$$

Table 2 The allometric equations of the components of aboveground tree biomass in three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China

Stand type	Component	Allometric equation	R^2	P
FRs	Stem	$W = 0.028\times(D^2H)^{0.932}$	0.987	0.000
	Bark	$W = 0.020\times(D^2H)^{0.696}$	0.973	0.000
	Branch	$W = 0.012\times(D^2H)^{0.719}$	0.661	0.031
	Leaf	$W = 0.00043\times(D^2H)^{1.087}$	0.686	0.026
SRs	Stem	$W = 0.013\times(D^2H)^{1.040}$	0.990	0.000
	Bark	$W = 0.009\times(D^2H)^{0.811}$	0.949	0.000
	Branch	$W = 0.00036\times(D^2H)^{1.216}$	0.905	0.001
	Leaf	$W = 0.0003\times(D^2H)^{1.181}$	0.915	0.000
SRc	Stem	$W = 0.037\times(D^2H)^{0.920}$	0.991	0.000
	Bark	$W = 0.002\times(D^2H)^{0.955}$	0.960	0.000
	Branch	$W = 0.000056\times(D^2H)^{1.472}$	0.888	0.001
	Leaf	$W = 0.000046\times(D^2H)^{1.472}$	0.888	0.001

FRs = first rotation planted with seedlings, SRs = second rotation planted with seedlings, SRc = second rotation regenerated with coppice; D = diameter at breest height, H = height

where H' = Shannon-Wiener index and S = the number of species in each plot. After floristic survey, two 2 × 2 m wooden quadrat frames were randomly placed within each plot for biomass sampling of woody and herbaceous understorey species. Aboveground and belowground biomass samples within the quadrat were collected and packed separately in labeled plastic bags. The samples were immediately dried in the lab at 85 °C to constant mass and weighed.

Economic benefits analysis

The standard total establishment and management cost (EMC) of *Eucalyptus* plantations in Dongmen Forest Farm in south China for FRs, SRs and SRc were 9450, 9450 and 7287 Yuan (RMB) hm^{-2}, respectively (Table 3). The standard cutting cost (CC) was 120 Yuan (RMB) m^{-3} including labor (50 Yuan m^{-3}), transportation (20 Yuan m^{-3}) and tax (50 Yuan m^{-3}). The unit price of timber was 600 Yuan (RMB) m^{-3}. The average out-turn rate of stand volume is 75% in *Eucalyptus* hybrid plantations (Qi 2002). The rotation length in the study was 6 years. Discount rate was defined as 12% following the forestry industry in China where *Eucalyptus* trees are logged from the third year after afforestation (Chen et al. 2008). Net cash flow (C_t) was calculated for each plantation from the third to the sixth year using the equation:

$$C_t = 600 \times (SV_t \times 75\%) - EMC_t - CC \times SV_t \quad (6)$$

where SV_t = stem volume at t year, EMC_t = establishment and management costs at t year and CC = cutting costs. The net present value (NPV) was determined for each stand using the equation (Khan 1999):

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \quad (7)$$

where n = rotation length, C_t = net cash flow at t year, i = discount rate. The internal rate of return (IRR) was calculated for each stand using the equation:

$$\sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} = 0 \quad (8)$$

where n = rotation length, C_t = net cash flow at the t year.

Data handling and statistical analysis

Data was expressed as mean ± SE. A one-way analysis of variance (ANOVA) was employed to compare serial changes among different plantation regimes in terms of composition,

Table 3 Establishment and management costs in three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China

Year	Components	Cost (Yuan ha^{-1})		
		FRs	SRs	SRc
0	Site preparation	800	800	400
	Base fertiliser	610	610	0
	Land rent	300	300	300
1	Seedling	870	870	0
	Plantation	1000	1000	0
	Fertilisation	600	600	600
	Weed control	720	720	730
	Land rent	300	300	300
2	Fertilisation	650	650	650
	Spout selection and control	0	0	707
	Weed control	725	725	725
	Land rent	300	300	300
3	Fertilisation	650	650	650
	Weed control	725	725	725
	Land rent	300	300	300
4	Land rent	300	300	300
5	Land rent	300	300	300
6	Land rent	300	300	300
Total		9450	9450	7287

FRs = first rotation planted with seedlings, SRs = second rotation planted with seedlings, SRc = second rotation regenerated with coppice

structure and biomass of understorey vegetation and timber production. LSD multiple comparison and Student Newman Keuls Test were conducted to examine differences among means of different rotations. All the analyses were performed using R version 2.15 and figures drawn in SigmaPlot 11.0 (Core Team, 2012).

RESULTS

Composition, structure and biomass of understorey vegetation

Across the plots, there were 66 plant species from 31 families in the understorey with 50 species from 25 families in FRs (35 species from 20 families in shrub layer and 15 species from 5 families in herb layer), 30 species from 16 families in SRs (16 species from 12 families in shrub layer and 14 species from 4 families in herb layer) and 42 species from 28 families in SRc (31 species from 22 families in shrub layer and 11 species from 6 families in herb layer) (Table 4). A total of 23 species including one dominant species (IV ≥ 5) and 19 rare species (IV < 1.5) in shrub layer and 2 species in herb layer disappeared in SRs, while 5 rare species absent in FRs appeared in SRs. A total of 12 rare species (IV < 1.5) in shrub layer and 7 species in herb layer disappeared in SRc but 10 rare species in shrub layer and 3 rare species in herb layer absent in FRs appeared in SRc. Ten species were unique to FRs, 3 to SRs and 10 occurred exclusively in SRc. *Litsea glutinosa, Rhus chinensis, Clerodendrum cyrtophyllum, Miscanthus floridulus* and *Eupatorium odoratum* were the co-dominant species (IV ≥ 5) in the three plantations. Four invasive species, *Sida acuta, Bougainvillea glabra, Eupatorium odoratum* and *Bidens pilosa* (Yan et al. 2014, Jin et al. 2015) were detected and the mean

Table 4 Relative abundance, relative frequency and important value (mean ± SE) of understory plant species in three *Eucalyptus (E. urophylla × E. grandis)* plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China

Species	FRs			SRs			SRc		
	Ra	Rf	IV	Ra	Rf	IV	Ra	Rf	IV
Shrub layer									
Litsea glutinosa	39.36	9.42	24.39	2.76	10.96	6.86	16.67	10.61	13.64
Rhus chinensis	11.99	9.42	10.71	55.80	24.66	40.23	8.88	9.09	8.99
Clerodendrum cyrtophyllum	10.14	9.42	9.78	32.78	23.29	28.03	4.78	7.58	6.18
Cajanus scarabaeoides	6.42	10.99	8.71	1.29	5.48	3.38	4.51	8.33	6.42
Mallotus repandus	4.56	6.28	5.42	0.37	1.37	0.87	10.11	9.85	9.98
Breynia fruticosa	4.56	5.76	5.16	0.00	0.00	0.00	2.73	5.30	4.02
Streptocaulon griffithii	2.03	4.71	3.37	0.55	4.11	2.33	0.27	0.76	0.52
Berchemia lineata	1.69	4.71	3.20	0.00	0.00	0.00	4.10	6.06	5.08
Cipadessa cinerascens	1.86	3.66	2.76	0.00	0.00	0.00	0.68	1.52	1.10
Urena lobata	2.70	2.62	2.66	0.37	2.74	1.55	0.14	0.76	0.45
Mallotus philippensis	1.35	3.66	2.51	0.00	0.00	0.00	0.41	0.76	0.58
Grewia biloba var. *Parviflora*	2.03	1.57	1.80	0.00	0.00	0.00	0.00	0.00	0.00
Broussonetia kazinoki	1.35	2.09	1.72	0.00	0.00	0.00	10.38	4.55	7.46
Sageretia theezans	1.18	2.09	1.64	0.37	2.74	1.55	14.89	9.09	11.99
Mallotus barbatus	0.84	2.09	1.47	4.05	12.33	8.19	0.96	0.76	0.86
Trema cannabina var. *dielsiana*	0.68	2.09	1.38	0.00	0.00	0.00	2.60	1.52	2.06
Cudrania fruticosa	0.68	2.09	1.38	0.55	4.11	2.33	0.00	0.00	0.00
Cunninghamia lanceolata	0.68	2.09	1.38	0.00	0.00	0.00	0.55	1.52	1.03
Sida acuta	0.68	1.57	1.12	0.00	0.00	0.00	0.00	0.00	0.00
Symplocos laurina	0.51	1.57	1.04	0.00	0.00	0.00	0.00	0.00	0.00
Trachelospermum jasminoides	0.51	1.57	1.04	0.00	0.00	0.00	0.27	0.76	0.52
Rhodomyrtus tomentosa	0.51	1.05	0.78	0.00	0.00	0.00	0.68	0.76	0.72
Grewia abutilifolia	0.34	1.05	0.69	0.00	0.00	0.00	0.00	0.00	0.00
Camellia oleifera	0.34	1.05	0.69	0.18	1.37	0.78	0.82	3.03	1.92
Flueggea virosa	0.34	1.05	0.69	0.00	0.00	0.00	0.00	0.00	0.00
Embelia laeta	0.34	1.05	0.69	0.00	0.00	0.00	0.00	0.00	0.00
Millettia nitida	0.34	1.05	0.69	0.00	0.00	0.00	0.00	0.00	0.00
Melia azedarach	0.68	0.52	0.60	0.00	0.00	0.00	0.00	0.00	0.00
Cocculus sp.	0.34	0.52	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Flemingia macrophylla	0.17	0.52	0.35	0.00	0.00	0.00	0.00	0.00	0.00
Glochidion puberu	0.17	0.52	0.35	0.00	0.00	0.00	0.00	0.00	0.00
Desmodium caudatum	0.17	0.52	0.35	0.00	0.00	0.00	0.00	0.00	0.00
Bridelia tomentosa	0.17	0.52	0.35	0.00	0.00	0.00	1.50	3.03	2.27
Mallotus paniculatus	0.17	0.52	0.35	0.18	1.37	0.78	0.14	0.76	0.45
Atalantia buxifolia	0.17	0.52	0.35	0.00	0.00	0.00	0.00	0.00	0.00
Ficus hirta	0.00	0.00	0.00	0.18	1.37	0.78	2.19	1.52	1.85
Evodia lepta	0.00	0.00	0.00	0.18	1.37	0.78	2.19	3.03	2.61
Pericampylus glaucus	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.76	0.52
Cinnamomum camphora	0.00	0.00	0.00	0.18	1.37	0.78	0.00	0.00	0.00
Symplocos chinensis	0.00	0.00	0.00	0.18	1.37	0.78	0.00	0.00	0.00
Murraya paniculata	0.00	0.00	0.00	0.00	0.00	0.00	2.46	0.76	1.61
Clematis chinensis	0.00	0.00	0.00	0.00	0.00	0.00	4.10	2.27	3.19
Cudrania cochinchinensis	0.00	0.00	0.00	0.00	0.00	0.00	1.78	2.27	2.02
Vitis heyneana	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.76	0.45

Table 4 (continued)

Species	FRs			SRs			SRc		
	Ra	Rf	IV	Ra	Rf	IV	Ra	Rf	IV
Bougainvillea glabra	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.76	0.58
Cratoxylum cochinchinense	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.76	0.52
Pavetta arenosa	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.76	0.45
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Herb layer									
Miscanthus floridulus	95.89	22.22	59.06	90.44	18.75	54.59	89.97	31.58	60.77
Eupatorium odoratum	1.66	19.75	10.71	4.39	20.00	12.20	3.40	19.30	11.35
Neyraudia reynaudina	0.33	11.11	5.72	0.86	11.25	6.06	0.00	0.00	0.00
Arthraxon hispidus	0.26	9.88	5.07	0.69	10.00	5.34	0.40	3.51	1.95
Imperata cylindrical	0.42	7.88	4.15	1.12	10.00	5.56	1.67	10.53	6.10
Scleria elata	0.23	6.17	3.20	0.60	6.25	3.43	0.00	0.00	0.00
Pteris semipinnata	0.13	4.94	2.53	0.34	5.00	2.67	0.66	3.51	2.09
Lygodium japonicum	0.52	4.48	2.50	0.00	0.00	0.00	2.20	17.54	9.87
Microstegium sp.	0.16	4.17	2.17	0.43	6.25	3.34	0.00	0.00	0.00
Cymbopogon goeringii	0.13	2.73	1.43	0.34	3.75	2.05	0.00	0.00	0.00
Pteridium aquilinum var. *latiusculum*	0.07	2.47	1.27	0.17	2.50	1.34	0.08	3.51	1.79
Hyparrhenia bracteata	0.03	1.23	0.63	0.09	1.25	0.67	0.00	0.00	0.00
Paspalum orbiculare	0.03	1.23	0.63	0.09	1.25	0.67	0.00	0.00	0.00
Dicranopteris linearis	0.03	1.23	0.63	0.09	1.25	0.67	0.82	3.51	2.17
Senecio scandens	0.10	0.50	0.30	0.00	0.00	0.00	0.00	0.00	0.00
Adiantum flabellulatum	0.00	0.00	0.00	0.00	0.00	0.00	0.13	1.75	0.94
Sorghum nitidum	0.00	0.00	0.00	0.34	2.50	1.42	0.00	0.00	0.00
Ottochloa nodosa var. *micrantha*	0.00	0.00	0.00	0.00	0.00	0.00	0.27	1.75	1.01
Bidens pilosa	0.00	0.00	0.00	0.00	0.00	0.00	0.40	3.51	1.95
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

FRs = first rotation planted with seedlings, SRs = second rotation planted with seedlings, SRc = second rotation regenerated with coppice, Ra = relative abundance, Rf = relative frequency, IV = important value

total number of invasive species per plot had no significant difference in the three plantations (Figure 1). FRs and SRc had a significantly higher number of constant species in shrub layer (IV ≥ 5) than SRs ($p < 0.01$). SRs and SRc had lower number of rare species in shrub layer (IV < 1.5) than FRs. The mean number of constant species (IV ≥ 10) and rare species (IV < 2.5) per plot in herb layer was not significantly different in all the plantations.

Compared with the first rotation stands, both second rotation seedlings and coppice had remarkable effects on understorey vegetation (Figure 2). Both seedlings and coppice regimes of the second rotation significantly decreased the total species richness, total Shannon-Wiener index and total Pielou's evenness index of understorey vegetation, with richness and Shannon-Wiener index of the woody species decreasing significantly ($p < 0.01$, Figure 2a, c). Replanting with seedlings had no effects on richness, abundance, Shannon-Wiener index and Pielou's evenness index of the herb species (Figure 2), but significantly decreased the coverage of the understorey vegetation ($p < 0.001$, Figure 3). Coppice regime significantly decreased richness, Shannon-Wiener index and Pielou's evenness index of the herbaceous species ($p < 0.01$, Figure 2a, c, d), but significantly increased the abundance of the understorey vegetation ($p = 0.001$, Figure 2b) and had no effects on the coverage of the understorey vegetation (Figure 3).

Within the two successive rotation regimes, there were no significant differences in the total species richness of understorey vegetation, although herbaceous species richness significantly decreased in the coppice plantations ($p < 0.001$, Figure 2a). Compared to the seedlings regime,

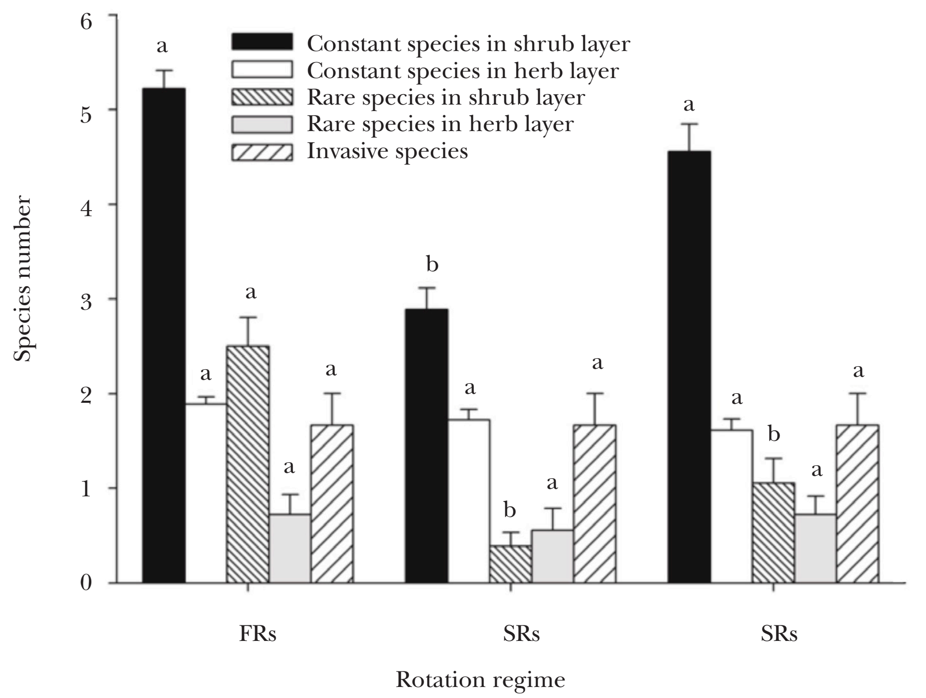

Figure 1 Constant, rare and invasive species of understorey vegetation in three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China; FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; vertical bars indicate standard errors of means (n = 18); different lowercase letters indicate statistically significant differences between rotation management regime groups ($p < 0.05$)

coppice significantly decreased the abundance of woody plants ($p < 0.001$, Figure 2b), but increased the abundance of the herbaceous plants and the understorey vegetation ($p < 0.001$, Figure 2b). The Shonnon-Wiener index and Pielou's evenness index of woody, herbaceous layers and total understorey vegetation in the two second successive rotations showed the same patterns with Shonnon-Wiener index and Pielou's evenness index, markedly higher in shrub layer but lower in herb layer and total understorey in the coppice stands ($p < 0.01$, Figure 2c, d). In the coppice stands, the coverage of shrub and herb layer was significantly higher than seedlings stands ($p < 0.001$, Figure 3). The biomass of shrub layer, herb layer and total understorey vegetation in second rotation seedlings plantations was significantly lower ($p < 0.01$) than the first rotation seedlings plantations (Figure 4). Biomass of shrub layer in second rotation coppice was markedly higher ($p < 0.001$) than the first rotation seedlings plantations, while variation in biomass of herb layer and total understorey between these two plantations was no significant.

Dbh, height, AGB and stand volume of *Eucalyptus* plantations

There were no differences in DBH, tree height and AGB among three regimes (Figure 5a, b and c). However, significant differences were found in stand volume among the three regimes ($p < 0.01$, Figure 5d). SRs showed the highest stand volume (126.1 m^3 ha^{-1}) followed by FRs (114.0 m^3 ha^{-1}) and SRc (100.4 m^3 ha^{-1}).

Economic benefits

The highest net present value at the end of the rotation occurred in SRs with significant difference from FRs and SRc ($p < 0.001$, Figure 6a). However, in the 6th year the highest internal rate of return was shown in SRc (47.8%) followed by SRs (45.1%) and FRs (36.7%) with significant difference between each other ($p < 0.001$, Figure 6b).

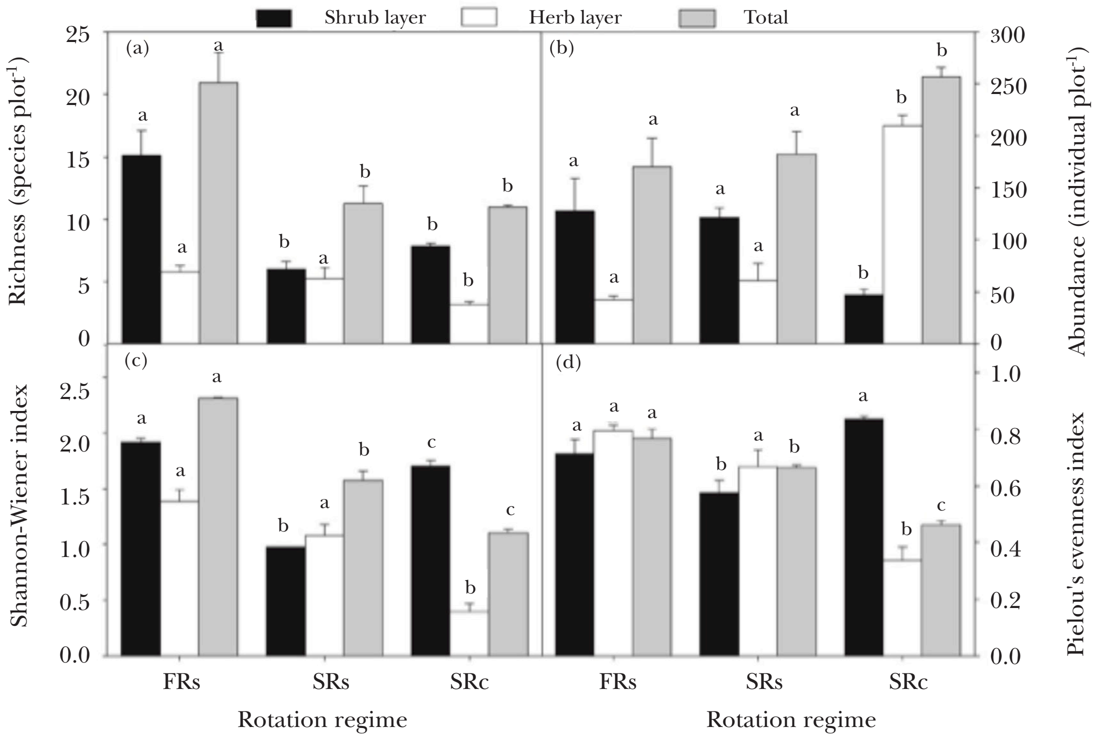

Figure 2 Three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China, (a) species richness, (b) abundance, (c) shannon-Wiener index and (d) Pielous's evenness index of understorey vegetation; FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; vertical bars indicate standard errors of means (n = 18); different lowercase letters indicate statistically significant differences between rotation management regime groups ($p < 0.05$)

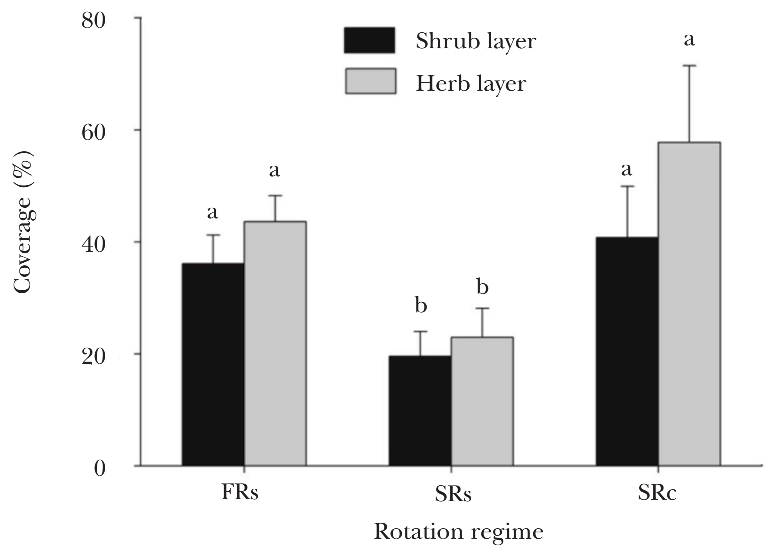

Figure 3 Coverage of understory vegetation in three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China; FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; vertical bars indicate standard errors of means (n = 18); different lowercase letters indicate statistically significant differences between rotation management regime groups ($p < 0.05$)

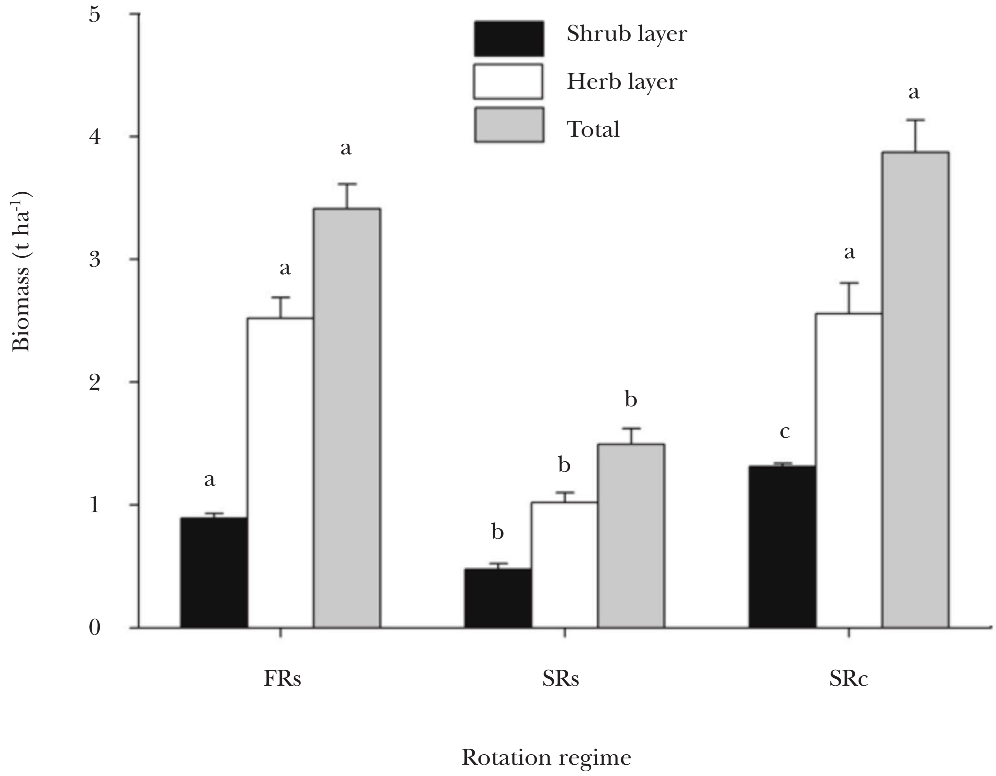

Figure 4 Biomass of understorey vegetation in three *Eucalyptus* (*E. rophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China; FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; vertical bars indicate standard errors of means (n = 36); different lowercase letters indicate statistically significant differences between groups ($p < 0.05$)

DISCUSSION

Successive rotation regimes had negative effects on understorey plant diversity

The results suggested that successive rotation regimes in SRF, whether replanted with seedlings or regenerated with coppice, had significantly negative effects on the diversity of understorey vegetation (Figure 2). These findings were consistent with a previous study where successive rotation regimes reduced understorey plant richness and diversity (Wen et al. 2010). Newmaster et al. (2007) suggested that repetitive prescribed burning and mechanical site preparation resulted in decreased species diversity in the understory. In this study, only one round of disturbance was performed in the first rotation stands including prescribed burning, mechanical site preparation and fertilisation (Table 1). In contrast, second rotations suffered more disturbance than the first rotation and subsequently had a marked impact on the understorey vegetations. SRs suffered two rounds of prescribed burning, mechanical site preparation, weeding and fertilisation and lost more than half of the woody species. SRc undertook fewer disturbances and lost less species in shrub layer, but almost half of the herbaceous species disappeared in SRc. Actually, the significantly lower species richness and evenness in the herb layer and total understorey led to significantly lower diversity index in SRc than in SRs. This difference in diversity in SRs and SRc should be due to the different efficiency of soil seed bank. In SRs, some species, sensitive to fire, disappeared. But in SRc, the increasing coverage of woody species inhibited the growth of light-demanding herbaceous species, thus more species were lost in the herb layer. Previous studies also found that management practices, such as cutting, prescribed burning, site preparation, weeding and fertilisation drive the variation in the composition and biomass of understorey

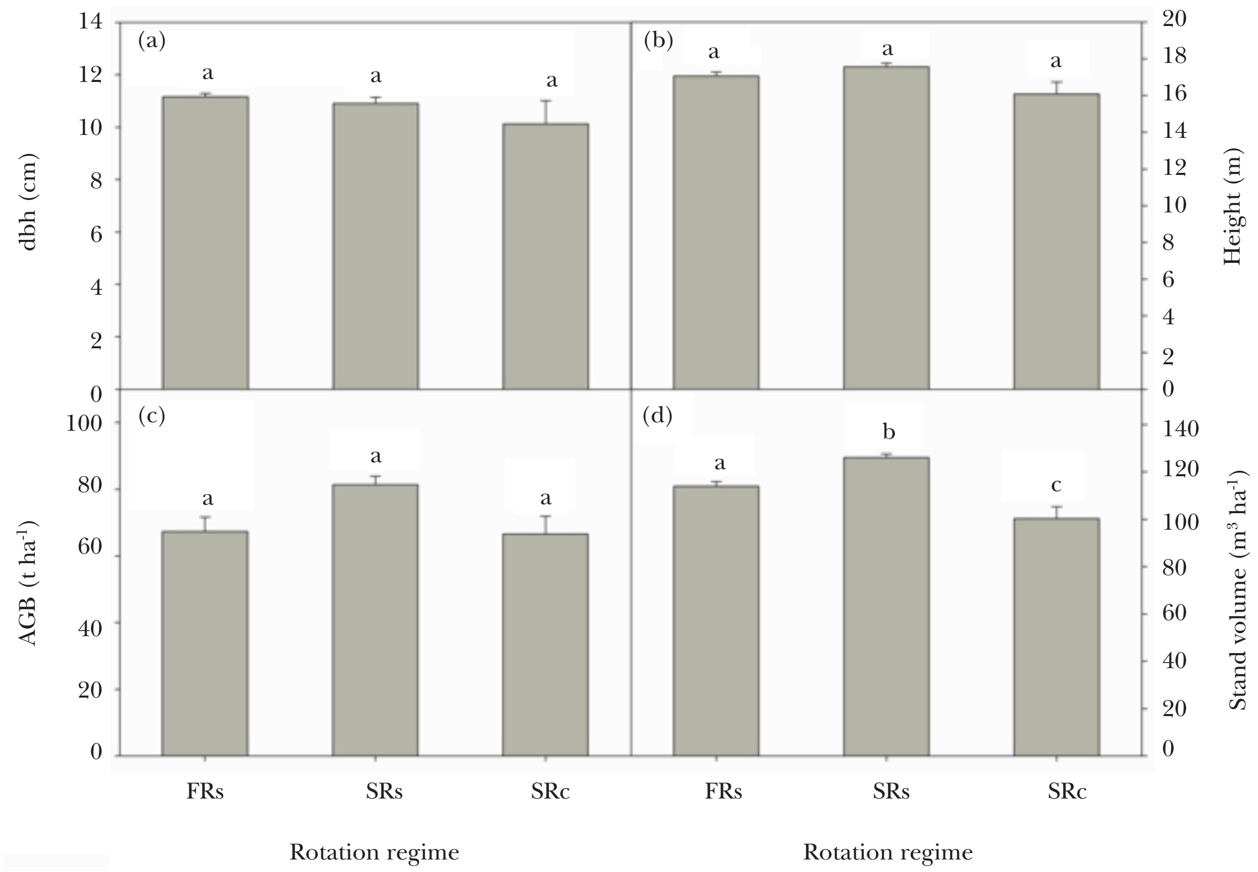

Figure 5 Three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China, (a) diameter at breast height, (b) tree height, (c) aboveground biomass and (d) stand volume; FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; DBH = diameter at breast height, H = tree height, AGB = aboveground biomass; vertical bars indicate standard errors of means (dbh and H: FRs and SRs, n = 101, SRc, n = 95, AGB and stand volume, n = 18); different lowercase letters indicate statistically significant differences between groups ($p < 0.05$)

vegetation by acting as disturbances (Fabião et al. 2002, Ramovs & Roberts 2003, Carneiro et al. 2008). These disturbances decrease the efficiency of soil seed banks and vegetative portions of native plant pools (Sakai et al. 2010, Otto et al. 2012).

Coppice regime promoted the restoration of understorey vegetation

In this study, coppice regime had positive effects on the abundance coverage and biomass of understorey species. In this regime, the abundance of the herbaceous plants and the total understorey vegetation was significantly higher than FRs. The coverage and biomass of both shrub and herb layer in SRc was higher than FRs and the difference of the biomass of shrub layer was significant. The result revealed that the abundance of herbaceous species and coverage and biomass of understorey vegetation in coppice regime recovered to the level of first rotation. When coppice stands were established, controlled burning, mechanical site preparation and replanting practices were not performed. The coppice stands therefore suffered fewer disturbances than seedling stands. This was beneficial to the restoration of understorey vegetation (Fabião et al. 2002, Newmaster et al. 2007, Carneiro et al. 2008, Zhu et al. 2014, Müllerová et al. 2015).

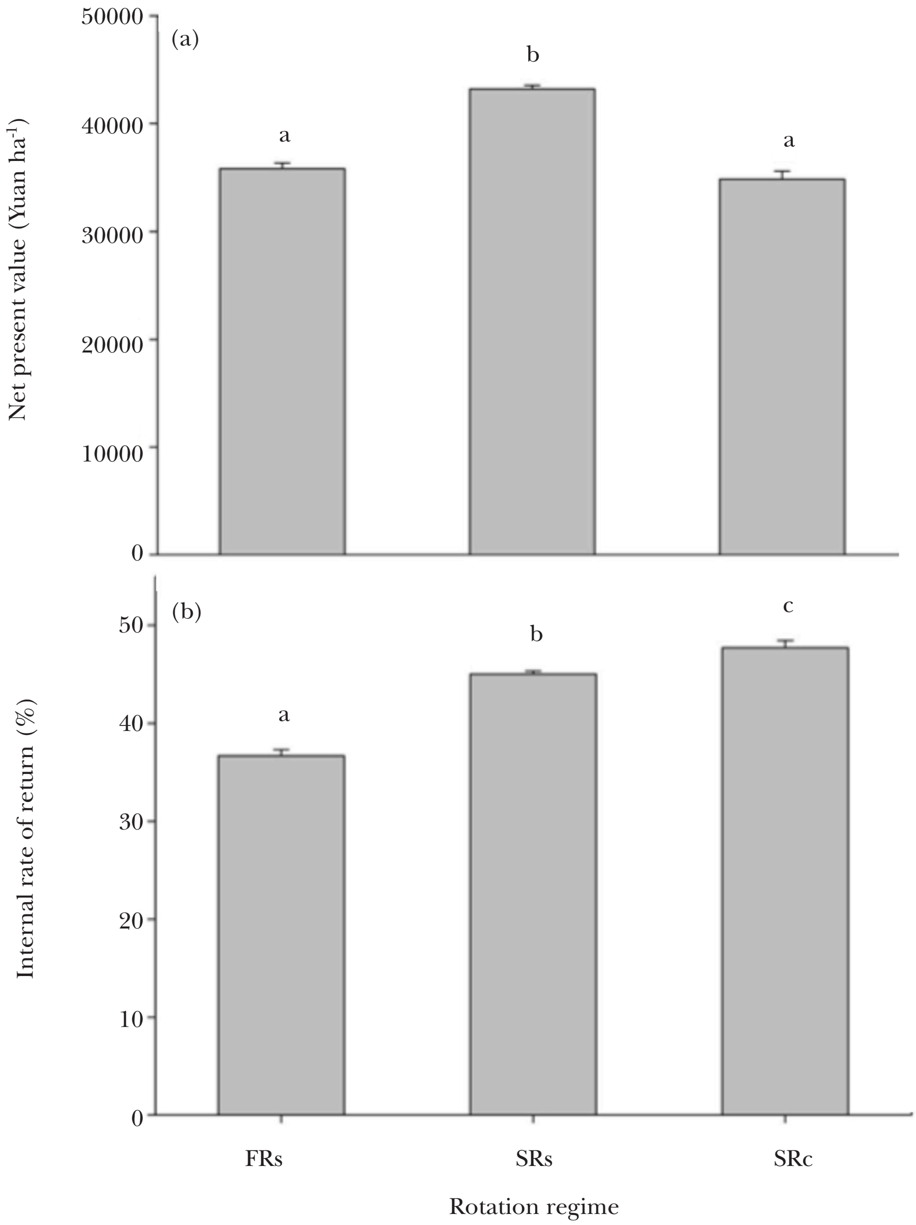

Figure 6 Three *Eucalyptus* (*E. urophylla* × *E. grandis*) plantation management regimes of first rotation planted with seedlings, second rotation replanted with seedlings and second rotation regenerated with coppice methods at the Dongmen Forest Farm in Guangxi, China, (a) net present value and (b) internal rate of return at the end of rotations; FRs = first rotation planted with seedlings, SRs = second rotation replanted with seedlings, SRc = second rotation regenerated with coppice; vertical bars indicate standard errors of means (n = 18); different lowercase letters indicate statistically significant differences between groups ($p < 0.05$)

Coppice regime decreased timber production but maintained economic benefits

Previous studies have revealed that successive rotations decreased the AGB and productivity of stands (Keeves 1966, Zhang et al. 2004, O'Hehir & Nambiar 2010). However, seedling and coppice re-establishment had different effects on timber production. Second rotation seedlings had higher DBH, height and AGB than the other two plantations, although these differences were not statistically significant (Figure 5). Compared with the first rotation, timber production increased significantly in seedling regime but decreased significantly in coppice regime. This should be due to the growth decline of the coppices and the lower preservation density caused by stump loss and shoot mortality. Assisted by the established root system, coppice grew rapidly in the early 2 years but became consenescence and grew slowly in the following years (Blake 1983, Tang 2010). Several authors also found that coppice regime reduced timber production (Whittock et al. 2004, Ye et al. 2007, Tang 2010, Drake et al. 2012). Whittock et al. (2003) found that stump mortality following harvest significantly reduced the productivity of *E. globulus* coppice plantation. Loss of stumps is a common cause of reduced mean annual increment (merchantable volume) in coppice crops (Mattews 1991). In our coppice stands, stump loss and sprout mortality led to a lower preservation density than the first rotation (4.72%) which was consistent with the findings in *E. camaldulensisi* copice and *E. grandis* × *E. urophylla* coppice plantations (Sesbou & Nepveu 1991, Tang 2010).

In the study, SRs had the highest net present value at the current discount rate of 12% in forestry industry in China (Chen et al. 2008). Although SRc had the lowest net present value due to lower timber production, the value was not significantly different from FRs. The highest internal rate of return occurred in SRc due to the reduced establishment and management costs. In previous studies related to economic analysis of second rotation seedlings and coppice in *Eucalyptus* plantations, Whittock et al. (2004) used a discounted cash flow model with incremental net present value to compare the profitability of coppice and seedling crops in second rotation *E. globulus* pulpwood plantations. It was found that, at a discount rate of 12%, the reduction in cost of management combined with similar yields in a second rotation coppice crop, when compared to a first rotation seedling crop, drove the economics of plantation production towards using coppice in the second rotation. Similar results were observed from a comparison study of planting and coppice regeneration of *E.grandis* × *E. urophylla* clones in South Africa in which the benefit of coppicing was also mainly related to a reduction in the temporary unplanted period and reduced establishment cost (Crous & Burger 2015). This suggested that second rotation regenerated with coppice was more profitable.

Implications for the second rotation management

Seedling re-establishment in second rotation increased productivity. In the seedlings plantations, tree height and DBH grew rapidly at 2 years and stem volume accumulated rapidly at 2.5 years after replantation (Tang 2010). The productive potential of the seedlings was greater than that of the coppice plantations. Subsequently replanting with seedlings could facilitate cultivation of large diameter timber and to obtain considerable net present value. While replanting increased disturbance severity in the plantations, it also resulted in biodiversity decrease and soil erosion (Wen et al. 2005, Williams 2015). The ability of *Eucalyptus* to sprout and reduced establishment and management costs made regeneration with coppice very popular in the successive rotation of *Eucalyptus* plantations in south China (Zhu et al. 2014). The results indicated that although timber production and net present value in the coppice stands were markedly lower than replanted seedlings stands, the internal rate of return in the coppice stands was significantly higher than the first rotation. Meanwhile, the abundance of herbaceous species and coverage and biomass of understorey vegetation in the coppice stands was restored to the level of the first rotation. This suggested coppice regime should be a more suitable successive rotation regime that could conserve biodiversity as well as maintain economic benefits with achieving a better return from less investment.

CONCLUSIONS

The two successive rotation regimes evaluated had significant effects on the understorey vegetation, timber production and economic benefits of *Eucalyptus* plantations. The second rotation seedlings increased timber production and net present value in spite of decreasing the diversity of understorey vegetation and increasing management investment. Thus the practice of replanting with seedlings was more attractive for timber production. However, since the second rotation coppice increased the abundance and maintained coverage and biomass of understorey vegetation equivalent to the first rotation, and achieved a better return from less investment, it is recommended that coppice regime should be a more sustainable forest management practice for second rotation in south China.

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REFERENCES

Bengtsson J, Nilsson SG, Franc A & Menozzi P. 2000. Biodiversity, disturbances, ecosystem function and management of European forests. *Forest Ecology and Management* 132: 39–50.

Blake TJ. 1983. Coppice systems for short rotation intensive forestry: the influence of cultural, seasonal and plant factors. *Austrian Journal of Forest Science* 13: 279–291.

Carneiro A, Fabião A, Martins MC, Fabião A, Da Silva MA, Hilário L, Lousa M & Madeira M. 2008. Effects of harrowing and fertilisation on understorey vegetation and timber production of a *Eucalyptus globulus* Labill. plantation in Central Portugal. *Forest Ecology and Management* 255: 591–597.

Chen SX, Li ZH, Li TH, Zhou GF, Wu ZH & Zhou QY. 2008. Economic analysis of *Eucalyptus* with different initial spacing. *Forest Research* 21: 1–6. (In Chinese)

Crous JW & Burger L. 2015. A comparison of planting and coppice regeneration of *Eucalyptus grandis* × *Eucalyptus urophylla* clones in South Africa. *Southern Forests* 77: 277–285.

Core Team R. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing. http://www.r-project.org.

Drake PL, Mendham DS, White DA, Ogden GN & Dell B. 2012. Water use and water-use efficiency of coppice and seedling *Eucalyptus globulus* Labill.: a comparison of stand-scale water balance components. *Plant Soil* 350: 221–235.

Drake PL, Mendham DS & Ogden GN. 2013. Plant carbon pools and fluxes in coppice regrowth of *Eucalyptus globulus*. *Forest Ecology and Management* 306: 161–170.

Fabião A, Martins MC, Cerveira C, Santos C, Lousã M, Madeira M & Correia A. 2002. Influence of soil and organic residue management on biomass and biodiversity of understorey vegetation in a *Eucalyptus globulus* Labill. plantation. *Forest Ecology and Management* 171: 87–100.

Hartley MJ. 2002. Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecology and Management* 155: 81–95.

Jin DM, Huang Y, Zhou XL, Chen B, Ma JS & Yan YH. 2015. High risk of plant invasion in the understorey of eucalypt plantations in south China. *Scientific Report* 5: 18492. doi: 10.1038/srep18492.

Keeves A. 1966. Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. *Australian Forestry* 30: 51–63.

Khan MY. 1999. *Theory and Problems in Financial Management*. McGraw Hill Higher Education, Boston.

Li CW & Liu BY. 2012. Research on the experimental form factor of fast-growing Eucalyptus. *Inner Mongolia Forestry Investigation and Design* 35: 72–74. (In Chinese)

Lv S, Lu CY, Lai JY, Jiang GX & Niu H. 2012. Analysis on understorey vegetation diversity of *Eucalyptus* sprout forest in Qibo Forestry of Guangxi. *Journal of Southern Agriculture* 43: 1534–1538. (In Chinese)

Magurran AE. 1988. *Ecological Diversity and Its Measurement*. Princeton University Press, Princeton.

Matthews JD. 1991. *Silvicultural Systems*. Clarendon Press, Oxford.

Meng XY. 1999. *Forest Mensuration*. China Forestry Publishing House, Beijing. (In Chinese)

Mu HT, Wei RP & Zhang WY. 2006. Characteristics of short rotation Eucalyptus individual trees and stands. *Guangdong Forestry Science and Technology* 22: 17–22. (In Chinese)

Müllerová J, Hédl R & Szabó P. 2015. Coppice abandonment and its implications for species diversity in forest vegetation. *Forest Ecology and Management* 343: 88–100.

Newmaster SG, Parker WC, Bell FW & Paterson JM. 2007. Effects of forest floor disturbances by mechanical site preparation on floristic diversity in a central Ontario clearcut. *Forest Ecology and Management* 246: 196–207.

O'hehir JF & Nambiar EKS. 2010. Productivity of three successive rotations of *P. radiata* plantations in South Australia over a century. *Forest Ecology and Management* 259: 1857–1869.

Otto R, Garcia-Del-Rey E, MÉndez J & Fernández-Palacios JM. 2012. Effects of thinning on seed rain, regeneration and understorey vegetation in a *Pinus canariensis* plantation (Tenerife, Canary Islands). *Forest Ecology and Management* 280: 71–81.

Pielou E. 1966. The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology* 13: 131–144.

Proe MF, Griffiths JH & Craig J. 2002. Effects of spacing, species and coppicing on leaf area, light interception and photosynthesis in short rotation forestry. *Biomass and Bioenergy* 23: 315–326.

Qi SX. 2002. *Eucalyptus in China*. China Forestry Publishing House, Beijing. (In Chinese)

Ramovs BV & Roberts MR. 2003. Understory vegetation and environment responses to tillage, forest harvesting, and conifer plantation development. *Ecological Applications* 13: 1682–1700.

Razakamanarivo RH, Razakavololona A, Razafindrakoto MA, Vieilledent G & Albrecht A. 2012. Below-ground biomass production and allometric relationships of eucalyptus coppice plantation in the central highlands of Madagascar. *Biomass and Bioenergy* 45: 1–10.

Ryan MG, Stape JL, Binkley D et al. 2010. Factors controlling *Eucalyptus* productivity: How water availability and stand structure alter production and carbon allocation. *Forest Ecology and Management* 259: 1695–1703.

Sakai A, Sakai T, Kuramoto S & Sato S. 2010. Soil seed banks in a mature Hinoki (*Chamaecyparis obtusa* Endl.) plantation and initial process of secondary succession after clearcutting in southwestern Japan. *Journal of Forest Research* 15: 316–327.

Sesbou PA & Nepveu G. 1991. Viabilité infraspécifique et effet du receépage sur la densité du bois, le rendement papetier et la longueur des fibres chez *Eucalyptus camaldulensis* traité en taillis. *Silvae Genetica* 40: 173–179.

Tang JF. 2010. Effects and benefits analysis of different regeneration patterns of Eucalyputs. *Journal of Fujian Forestry Science and Technology* 37: 93–97. (In Chinese)

Wei YW, Qin ZH, Yang KT & Huang JS. 2010. Comparison of growth in *Eucalyptus* planted and coppice plantations. *Guangxi Forestry Science* 39: 223–225. (In Chinese)

Wen YG, Liu SR & Chen F. 2005. Effects of continuous cropping on understorey species diversity in *Eucalyptus* plantations. *Chinese Journal of Applied Ecology* 16: 1667–1671. (In Chinese)

Wen YG, Ye D, Chen F, Liu SR & Liang HW. 2010. The changes of understorey plant diversity in continuous cropping system of *Eucalyptus* plantations, South China. *Journal of Forest Research* 15: 252–258.

Whittock SP, Apiolaza LA, Kelly CM & Potts BM. 2003. Genetic control of coppice and lignotuber development in *Eucalyptus globulus. Australian Journal of Botany* 51: 57–61.

Whittock SP, Greaves BL & Apiolaza LA. 2004. A cash flow model to compare coppice and genetically improved seedling options for *Eucalyptus globulus* pulpwood plantations. *Forest Ecology and Management* 191: 267–274.

Williams RA. 2015. Mitigating biodiversity concerns in Eucalyptus plantations located in South China. *Journal of Biosciences and Medicines* 3: 1–8.

Yan XL, Liu QR, Shou HY, et al. 2014. The categorization and analysis on the geographic distribution patterns of Chinese alien invasive plants. *Biodiversity Science* 22: 667–676. (In Chinese)

Ye SM, Zeng XX, Xie WD & Zhao LJ. 2007. Sprout regeneration and plant regeneration influences on *Eucalyptus urophylla* × *grandis* plantation yield. *Journal of Nanjing Forestry University (Natural Sciences Edition)* 31: 43–46. (In Chinese)

Zhang XQ, Kirschbaum MUF, Hou ZH & Guo ZH. 2004. Carbon stock changes in successive rotations of Chinese fir (*Cunninghamia lanceolata* (Lamb) Hook) plantations. *Forest Ecology and Management* 202: 131–147.

Zhu HG, Xiong JB, You YM, Lan BG, Wen YG, Yang YQ, Liu ZF & Yang JQ. 2014. Changes in understorey plant community of *Eucalyptus grandis* × *E. urophylla* plantation in different regeneration modes and associated environmental explanations. *Guangxi Sciences* 21: 469–476. (In Chinese)