Sustainable Forestry (2022) Volume 5 Issue 1
doi:10.24294/sf.v5i1.1620

ORIGINAL RESEARCH ARTICLE

Effects of interplanting native species of *Eucalyptus* on stand growth and soil physicochemical properties under different interplanting intensities

Muyi Huang[1], Yanfang Liang[2], Fucong Su[2], Yuanli Zhu[2], Zhihui Li[1*], Liling Liu[1], Suya Zhao[1], Yingyun Gong[1]

[1] *College of Forestry, Central South University of Forestry & Technology, Changsha 410004, China. E-mail: lzh1957@126.com*

[2] *Guangxi Qipo State Forestry Farm, Nangning 530003, China.*

ABSTRACT

Objective: To study the growth, accumulation and soil nutrient content of each overseeded species under different interharvesting intensity treatments of *Eucalyptus*, and to explore the best re-cultivation method suitable for mixed overseeded species after *Eucalyptus* interharvesting. **Methods:** In Guangxi state-owned Qipo forest, *Eucalyptus* tailorii with different planting densities (DH32-29) were mixed with *Castanopsis hystrix*, *Mytilaria laosensis* and *Michelia macclurei*, and four different treatments (CK, LT, MT and HT) were established for re-cultivation of *Eucalyptus* near-mature forests with different logging intensities, and the differences in growth conditions and soil physicochemical properties of each species were analyzed. **Results:** (1) As the proportion of *Eucalyptus* allocation decreased, the growth of *Eucalyptus* diameter at breast height, tree height and individual wood volume could be promoted; the growth of the three parameters of HT and MT *Eucalyptus* were significantly different from LT and CK. (2) The average wood volume per plant of the set species in the CK and LT treatments was *Mytilaria laosensis* > *Michelia macclurei* > *Castanopsis hystrix*, while in the MT and HT treatments it was *Mytilaria laosensis* > *Castanopsis hystrix* > *Michelia macclurei*. (3) The differences in soil aeration, total saturated water holding capacity, capillary water holding capacity, and field water holding capacity in soil layers of different depth varied. In the same soil layer, soil aeration, total porosity and capillary porosity were HT > CK > LT > MT; saturated water holding capacity and capillary water holding capacity were HT > CK > LT > MT, while field water holding capacity was CK > HT > LT > MT. (4) Organic matter, pH, total nitrogen, total phosphorus, total potassium, fast-acting nitrogen, fast-acting phosphorus, and fast-acting potassium changed with varying soil depth in each treatment.

Keywords: *Eucalyptus urophylla×E. grandis DH32-29*; Interplanting Setts; Stand Growth; Stand Structure; Soil Physicochemical Properties

ARTICLE INFO

Received: 20 March 2022
Accepted: 3 May 2022
Available online: 15 May 2022

1. Introduction

Eucalyptus is an important fast-growing and productive tree species in the world, with characteristics such as high adaptability, fast growth rate, high resistance, excellent material and wide use[1]. In recent years, in order to solve the problems of soil acidification, reduced enzyme activity, reduced biodiversity and decreased productivity caused by continuous planting of *Eucalyptus*[2-6], pure or mixed forests of *Eucalyptus* have been established to suit the characteristics of southern forest lands in China. *Eucalyptus* artificial mixed forests can make full use of the forest land, improve the forest environment, enhance resistance to resistance, promote the growth of forest trees, and improve the ecological and economic benefits of forest stands[7-9]. The cultivation mode of *Eucalyptus* intercalation with mixed species is the best way to re-cultivate *Eucalyptus* pure forests, and improving stand structure and regulating interspecific relationships through intercalation is the key to management[10]. The interplanting of near mature eucalypts with high quality broadleaf species to form a heterogeneous complex mixed forest can improve the yield per unit area, target the cultivation of *Eucalyptus* large-diameter timber, and make full use of the forest space, which is an ideal *Eucalyptus* mixed cultivation mode.

Eucalyptus urophylla×E. grandis DH32-29 is an excellent variety of *Eucalyptus tailorii*, which is fast-growing and productive with a straight and complete trunk, and is superior to *Eucalyptus caudatum* in terms of stand growth and economic benefits, and is commonly planted in Guangxi and Guangdong[11]. *Mytilaria laosensis*, *Castanopsis hystrix* and *Michelia macclurei* are excellent native species in Guangxi with strong adaptability and can also change the environment of the plantation site[12-15]. In order to explore the best mixed growth pattern of *Eucalyptus* near mature forests, transform *Eucalyptus* low-quality and inefficient forests, achieve precise quality improvement of *Eucalyptus* plantations and sustainable use of forest land in the future, and bring into play the multiple functions of *Eucalyptus* plantations. In this study, we selected *Mytilaria laosensis*, *Castanopsis hystrix* and *Michelia macclurei*, which have good shade tolerance in young age, as hybrid species to transform and cultivate *Eucalyptus* plantation hybrid forests, and explored the effects of different intercutting intensities of *Eucalyptus* on stand growth and soil quality in the conversion of *Eucalyptus* near mature forests in terms of the growth status, accumulation volume and soil nutrients of each species in different hybrid patterns, with a view to providing reference for the cultivation of *Eucalyptus* pure forests.

2. Materials and methods

2.1 Overview of the study area

The study area is located in the state-owned Qipo Forest Farm, Nanning City, Guangxi Zhuang Autonomous Region (22°41′–22°52′N, 108°02′–108°09′E). The area has a humid subtropical monsoon climate with sufficient sunshine, abundant precipitation, distinct dry and wet seasons, long summer rainfall, average annual precipitation of 1,300 mm, average annual relative humidity of 80%, and average annual temperature of 21.6 ℃. The soil type is mainly red loam with a thickness of 1 m or more; the surface vegetation is rich, It is mainly composed of *Verbenaceae*, *Araliaceae*, *Lauraceae*, *Moraceae*, *Dennstaedtiaceae*, *Euphorbiaceae*, and *Rutaceae*.

2.2 Sample plot setting and management design

The target of re-cultivation is near-mature *Eucalyptus urophylla×E. grandis clone DH32–29*. All the *Eucalyptus* plantations plot in the study area were planted in 2010 with a planting density of 1,667 plants /hm^2 and all the interplanting measures were carried out in 2012. The thinning method adopts the lower layer thinning method. According to the thinning intensity, the trees with poor growth and poor dry shape are preferentially felled, and at the same time, the uniformity of the space position of the reserved wood is taken into account. In October 2014, plots with the same elevation, slope and orientation were selected to investigate the species, diameter at breast height, height and crown width of each tree in the sample plots before the mixed forest conversion operation. Each sample plot was set up with an area of 20 m × 20 m. A total of 12 sample plots, including control plots, were set up. The sample plots were investigated for stand diameter at breast height, tree height, height under branches, crown width, stem shape quality, stand composition, stand structure, understory regeneration and its soil nutrients. The stands were divided into four different re-cultivation types for the re-cultivation operation in October 2015: HT (400–450 plants/hm^2 retained after thinning), MT (750–800 plants/hm^2 retained after thinning), LT (1,200–1,250 plants/hm^2 retained after thinning) and CK (1,500–1,550 plants/hm^2). After clearing the felling residue properly, blocks were prepared and then planted with high quality trees, such as *Mytilaria laosensis*, *Castanopsis hystrix* and *Michelia macclurei*, using

Table 1. General situation and management operation of each sample plot

Stand	Sample plot	Slope/(°)	Altitude/m	Pre-thinning density/(plant·hm^{-2})	Planed density/(plant·hm^{-2})	Post-thinning density/(plant·hm^{-2})	(2020) average DBH/cm	(2020) average tree height/m
HT	QP–1	15–20	140	1,061	400–450	411	24.75	30.30
MT	QP–2	15–20	160	1,042	750–800	731	24.53	28.91
LT	QP–3	15–20	170	1,326	1200–1250	1,224	20.53	25.65
CK	QP–4	15–20	155	1,512	1,512	1,512	17.46	24.10

1-year old live seedlings, and planting holes were dug in the planting zone with the specifications of 50 cm × 50 cm × 30 cm, where the planting density ratio of each treatment of *Mytilaria laosensis*, *Castanopsis hystrix* and *Michelia macclurei* was 1:1:1 for 375 plants/hm^2 per hectare. The sample plot setup and management design are shown in **Table 1**.

2.3 Data survey

2.3.1 Soil nutrient survey

Soil sampling and determination soil samples were selected by randomly laying 3 points in each sample plot diagonally from the lower to upper slope of the microtopography, digging the soil profile and taking soil samples at 3 levels: upper, middle and lower. 2 kg of soil samples were taken from each level at each point in plastic bags and brought back to the room. The samples were manually ground after 14 days of air-drying to remove plant residues and gravels, sieved, and mixed with the soil samples at the same level by the same weight. The mixed soil samples were divided by the method of quartering and sealed in a cool and ventilated place for storage. The physical properties of soil water holding capacity and aeration are determined by the ring knife method; the pH of soil is determined by the potentiometric method; the organic matter content is determined by the potassium dichromate volumetric method; the total nitrogen is determined by the selenium powder—potassium sulfate—sulfuric acid digestion distillation titration method; the total potassium is determined by the flame photometer method; the total phosphorus is determined by the sulfuric acid—perchloric acid digestion—molybdenum. The total phosphorus was determined by sulfuric acid—perchloric acid digestion—molybdenum antimony anti-colorimetric method; the fast-acting nitrogen was determined by alkaline solution diffusion boric acid absorption method; the fast-acting potassium was determined by flame photometer method; the effective phosphorus was determined by hydrochloric acid—sulfuric acid leaching method, and the determination method was referred to "Methods for Agricultural Chemical Analysis of Soil"[16].

2.3.2 Investigation of growth indicators

In June 2020, a random sampling method was used to conduct a per-wood survey in each *Eucalyptus* mixed forest sample plot separately, and the neighboring *Eucalyptus* trees with different sets of species in each row were tracked and recorded. The diameter at breast height of each individual plant was measured with a perimeter ruler with an accuracy of 0.1 cm, the height of the tree and the height under the branch were measured with a laser height meter (Nikon Rangefinder Ruihao 1000aS) with an accuracy of 0.1 m, and the crown width was measured in both east-west and north-south directions using a tape measure, and the average value was taken. Crown length = the height of the tree – the height under the branch. The wood volume was calculated as[17,18]:

$$V_{\text{eucalyptus}} = 0.0000628767d^{1.821621}H^{0.96436}$$

$$V_{\text{Rice Lao Pai}} = 0.0000683297d^{1.926256}H^{0.8840614}$$

$$V_{\text{red vertebra}} = 0.000052764d^{1.88216}H^{1.00931}$$

$$V_{\text{Fire Nan}} = 0.000052764291d^{1.8821611}H^{0.931923697}$$

2.4 Data processing

The experimental data were statistically and analytically analyzed using Excel 2007 and SPSS 23.0 software, and one-way ANOVA was performed for the main growth parameters and soil physical and chemical properties.

3. Results and analysis

3.1 Growth of *Eucalyptus* trees

We conducted variance analysis on growth indicators such as average tree height and average diameter at breast height of *Eucalyptus* after stand replanting, and the results showed that there was no significant difference in average diameter at breast height, average tree height and average volume per plant of *Eucalyptus* between HT and MT treatments., but the differences between HT and MT, LT and CK were significant and increased with decreasing density of *Eucalyptus* trees, which indicated that as the density of *Eucalyptus* trees decreased in the stand, the space for growth of *Eucalyptus* trees in the stand increased substantially. Sufficient light reduces soil nutrient pressure, which is conducive to the growth of *Eucalyptus* DBH and tree height; the mean branch height of *Eucalyptus* does not differ significantly between MT and LT treatments, but MT and LT differ significantly from HT and CK, and increases with the decrease of *Eucalyptus* density; the canopy width of *Eucalyptus* does not differ significantly between the stands in each treatment, which indicates that the change of *Eucalyptus* density has little effect on the growth of canopy width under the reasonable structure of stand level (**Table 2**).

Table 2. The effect of different cultivation methods on the growth of *Eucalyptus*†

Stand	DBH/cm	Tree height/m	Height under branches/m	Crown width/m	Individual volume/m^3
CK	17.46 ± 0.34 c	24.10 ± 0.36 c	16.71 ± 0.26 c	3.02 ± 0.04 a	0.2570 ± 0.0116 c
LT	20.53 ± 0.39 b	25.65 ± 0.39 b	17.98 ± 0.25 b	3.04 ± 0.09 a	0.3649 ± 0.0161 b
MT	24.53 ± 0.56 a	28.91 ± 0.55 a	18.99 ± 0.44 b	3.13 ± 0.06 a	0.5650 ± 0.0319 a
HT	24.75 ± 1.13 a	30.30 ± 1.04 a	20.66 ± 0.44 a	3.22 ± 0.10 a	0.6184 ± 0.0610 a

† The letters in each column indicate significant differences ($P < 0.05$).

Table 3. Effects of different cultivation methods on the growth of interplanting trees†

Stand	Varieties of trees	Existing density/(plant·hm^{-2})	Survival rate/%	Average DBH/cm	Average tree height/m	Average individual volume/m^3
CK	*Mytilaria laosensis*	323	86.1	7.67 ± 0.29 aC	7.44 ± 0.28 aC	0.0236 ± 0.0024 aC
	Castanopsis hystrix	302	80.5	3.21 ± 0.20 cC	4.32 ± 0.17 bD	0.0028 ± 0.0005 bC
	Michelia macclurei	332	88.4	3.95 ± 0.13 bC	4.28 ± 0.16 bB	0.0031 ± 0.0003 bC
LT	*Mytilaria laosensis*	335	89.3	8.32 ± 0.26 aC	8.12 ± 0.24 aC	0.0283 ± 0.0020 aC
	Castanopsis hystrix	316	84.3	3.79 ± 0.17 cC	4.92 ± 0.19 bC	0.0039 ± 0.0004 bC
	Michelia macclurei	345	92.0	5.19 ± 0.15 bB	4.68 ± 0.11 bB	0.0058 ± 0.0007 bB
MT	*Mytilaria laosensis*	340	90.7	9.12 ± 0.27 aB	9.13 ± 0.20 aB	0.0366 ± 0.0026 aB
	Castanopsis hystrix	345	92.0	5.51 ± 0.24 bB	6.39 ± 0.21 bB	0.0101 ± 0.0011 bB
	Michelia macclurei	342	91.3	6.01 ± 0.21 bA	5.86 ± 0.20 bA	0.0091 ± 0.0008 bA
HT	*Mytilaria laosensis*	344	91.7	10.11 ± 0.25 aA	10.95 ± 0.33 aA	0.0526 ± 0.0040 aA
	Castanopsis hystrix	349	93.0	9.46 ± 0.27 aA	9.41 ± 0.23 bA	0.0378 ± 0.0030 bA
	Michelia macclurei	346	92.3	6.48 ± 0.21 bA	6.07 ± 0.17 cA	0.0105 ± 0.0009 cA

† a: lowercase letters indicate significant differences ($P < 0.05$) among different tree species with the same treatment. b: capital letters indicate that there are significant differences ($P < 0.05$) among the same tree species with different treatments.

3.2 Growth of the crop species

3.2.1 Growth of diameter at breast height

As shown in **Table 3**, the diameter at breast height of each tree species increased as the density of *Eucalyptus* decreased. Among them, the diameter at breast height of *Mytilaria laosensis* and *Castanopsis hystrix* did not differ significantly between CK and LT, and differed significantly between LT, MT and HT; while the diameter at breast height of *Michelia macclurei* did not differ significantly between MT and HT, and differed significantly between CK, LT and MT. In CK and LT, the growth of diameter at breast height of each tree species showed *Mytilaria laosensis* > *Michelia macclurei* > *Castanopsis hystrix*, and in MT and HT, it showed *Mytilaria laosensis* > *Castanopsis hystri* > *Michelia macclurei*, which indicated that in this indicates that the diameter at breast height of *Mytilaria laosensis* is larger than that of the other two species in each treatment, and as the density of the native species of *Eucalyptus* continues to decrease, the diameter at breast height of *Mytilaria laosensis* and *Castanopsis hystrix* changes more and more obviously, while the opposite is true for *Michelia macclurei*.

3.2.2 Growth of tree height

As seen in **Table 3**, the tree height of each set of tree species increased with decreasing density of *Eucalyptus* in different transformation treatments. The height of *Mytilaria laosensis* was higher than that of *Castanopsis hystrix* and *Michelia macclurei* in all treatments and the difference was significant; the height of *Castanopsis hystrix* and *Michelia macclurei* differed significantly only under HT treatment among treatments; the difference between CK and LT under different treatments of *Mytilaria laosensis* was not significant, while the difference between LT, MT and HT was significant, the height of *Castanopsis hystrix* trees differed significantly between CK, LT, MT and HT, the height of *Michelia macclurei* trees differed significantly between CK and LT, MT and HT treatments The differences between CK and LT, MT and HT treatments were not significant, but the differences between LT and MT treatments were significant, which indicated that the tree height of each species responded to the continuous reduction of *Eucalyptus* density, but the response rhythm of different species was different, with *Castanopsis hystrix* responding the most strongly, followed by *Mytilaria laosensis*, and *Michelia macclurei* the least.

3.2.3 Growth of wood volume and accumulation

Table 4 shows that the different transformation modes had significant effects on the three tree species; the accumulation volume of *Mytilaria laosensis* was the largest in all treatments, and its total accumulation volume was 2.54 times that of the total accumulation volume of *Castanopsis hystrix* and 4.87 times that of *Michelia macclurei*. As the proportion of *Eucalyptus* in the stand decreased, the increase in the accumulation of rice old row compared to the previous treatment was 0.24%, 31%, and 45%, respectively; 46%, 182%, and 279% for red spine; and 94%, 56%, and 17% for *Mytilaria laosensis*. This indicates that HT treatment is the best choice if the main purpose is to operate *Mytilaria laosensis*, *Castanopsis hystrix*, and *Michelia macclurei*r after *Eucalyptus* near maturity forest conversion.

Table 4. Average stand stock volume and total stand stock volume of different interplanting trees $m^3 \cdot hm^{-2}$†

Stand	*Mytilaria laosensis* stock volume	*Castanopsis hystrix* stock volume	*Michelia macclurei* stock volume	Total stock volume
CK	7.6228 d	0.8456 d	1.0292 d	9.4976 d
LT	9.4805 c	1.2324 c	2.0010 c	12.7139 c
MT	12.4440 b	3.4845 b	3.1122 b	19.0407 b
HT	18.0944 a	13.1922 a	3.6330 a	34.9196 a

†The letters in each column indicate significant differences ($P < 0.05$).

3.3 Stand structure and stand quality status

The distribution of stand diameter order can reflect the growth condition of the stand and the competition between stands, which is an important indicator of the stability of stand structure[19]. From **Table 5**, it can be seen that: the skewness of the diameter order frequency distribution plot of *Mytilaria laosensis* becomes smaller as the density of *Eucalyptus* in the stand decreases, and the diameter order distribution under HT and MT treatments is closest to normal distribution; the skewness of the diameter order frequency distribution plot of *Castanopsis hystrix* is significantly higher under CK and LT treatments than the other two types of trees, indicating that the stand growth is abnormal under these two treatments and the competition among trees is highly differentiated, and gradually tends to the skewness of the diameter distribution diagram of *Michelia macclurei*r was not significantly different among the treatments, but the kurtosis was significantly higher than the other two species in each treatment, indicating that the diameter distribution deviated from the normal distribution, and the main feature was that there was greater differentiation between stands smaller than the mean diameter and stands larger than the mean diameter. The vertical and horizontal structure of the stand did not adversely affect the trees in each diameter class.

3.4 Effect of different re-cultivation treatments on changes in physical properties of soil in forest stands

Roots can improve physical properties such as soil structure, porosity and permeability and help the soil to form agglomerate structure[20]. Soil porosity and soil water content reflect the water holding and water supply capacity of the soil and are important indicators of soil structure; the larger the value, the stronger the ability of the soil to contain water and maintain water and soil. As can be seen from **Table 6**, soil venting quality, total porosity, capillary porosity, saturated water holding capacity, capillary water holding capacity, and field water holding capacity of 0–20 cm soil layer in each model were greater than those of 20–40 cm soil layer; in the same soil layer, soil aeration, total porosity, and capillary porosity all showed HT > CK > LT > MT; in 0–20 cm soil layer, saturated water holding capacity, capillary water holding capacity, and field water holding capacity showed HT > CK > LT > MT, but in 20–40 cm soil layer, saturated water holding capacity, capillary water holding capacity showed HT > CK > LT > MT, and field water holding capacity showed CK > HT > LT > MT. The differences between the groups were not significant, but in the 20–40 cm soil layer, the saturated water holding capacity and capillary water holding capacity were HT > CK > LT > MT, and the field water holding capacity was CK > HT > LT > MT, and the differences were significant. This indicates that in the 20–40 cm soil layer, the physical properties of soil in the mixed forests tended to decrease and then increase with the decreasing proportion of *Eucalyptus*. HT and CK were generally better than the LT and MT treatments. HT and CK were more advantageous than LT and MT in improving the internal soil structure and increasing soil permeability.

Table 5. Diameter class distribution of interplanting trees in different cultivation methods

Stand	Varieties of Trees	Number of plants	Average DBH/cm	Coefficient of variation/%	Skewness	Kurtosis	Minimum DBH/cm	Maximum DBH/cm
CK	*Castanopsis hystrix*	39	3.21 ± 0.196	40.94	0.850	0.505	1.3	6.7
	Mytilaria laosensis	36	7.67 ± 0.287	25.08	0.070	-0.421	3.1	11.3
	Michelia macclurei	40	3.95 ± 0.135	22.83	-0.107	-0.828	2.1	5.7
LT	*Castanopsis hystrix*	40	3.79 ± 0.167	29.58	0.329	0.153	1.6	6.8
	Mytilaria laosensis	38	8.32 ± 0.280	23.57	0.029	-0.278	4.1	12.6
	Michelia macclurei	41	5.19 ± 0.150	19.40	0.061	-0.722	3.2	7.2
MT	*Castanopsis hystrix*	41	5.51 ± 0.242	29.42	0.129	0.076	1.9	9.5
	Mytilaria laosensis	40	9.11 ± 0.265	9.51	-0.019	0.154	4.4	12.8
	Michelia macclurei	41	6.01 ± 0.219	24.42	0.196	-0.841	3.6	8.9
HT	*Castanopsis hystrix*	41	9.46 ± 0.270	19.14	0.088	0.066	5.0	13.5
	Mytilaria laosensis	42	10.11 ± 0.252	6.73	-0.020	0.097	6.3	13.8
	Michelia macclurei	42	6.48 ± 0.213	22.01	0.085	-0.844	3.8	9.1

Table 6. Soil physical properties of different soil layers in different cultivation methods

Soil layers/cm	Stand	Venting quality/%	Total porosity/%	Capillary porosity/%	Saturated water holding capacity/%	Capillary water holding capacity/%	Field water holding capacity/%
0–20	CK	24.61 ± 0.37 ab	24.78 ± 0.38 ab	23.85 ± 0.73 a	35.73 ± 1.14 a	34.36 ± 0.88 a	23.31 ± 0.37 a
	LT	24.04 ± 0.38 ab	24.17 ± 0.23 ab	22.60 ± 1.09 a	36.98 ± 1.50 a	34.52 ± 1.58 a	19.58 ± 0.61 a
	MT	23.07 ± 1.18 b	23.22 ± 1.19 b	22.43 ± 1.16 a	35.10 ± 3.96 a	33.92 ± 3.83 a	22.26 ± 2.01 a
	HT	26.44 ± 0.90 a	26.60 ± 0.90 a	25.27 ± 1.03 a	41.64 ± 3.61 a	39.67 ± 4.06 a	24.62 ± 3.79 a
20–40	CK	24.12 ± 1.21 ab	24.30 ± 1.21 ab	23.53 ± 0.67 ab	32.65 ± 2.74 ab	31.58 ± 2.03 ab	23.90 ± 1.65 a
	LT	23.01 ± 0.48 b	23.14 ± 0.82 b	22.12 ± 0.37 b	32.47 ± 0.52 ab	31.03 ± 0.37 ab	18.56 ± 1.77 b
	MT	22.30 ± 0.81 b	22.44 ± 1.39 b	21.20 ± 1.19 b	29.30 ± 1.24 b	27.69 ± 1.72 b	18.18 ± 0.06 b
	HT	26.46 ± 0.33a	26.62 ± 0.59 a	26.07 ± 1.06 a	37.02 ± 0.80 a	36.25 ± 1.64 a	21.72 ± 1.88 ab

†The letters in each column indicate that there are significant differences between different treatments in the same soil layer ($P < 0.05$).

3.5 Changes in soil nutrient content under different re-cultivation methods

3.5.1 Changes in soil ph and organic matter content under different cultivation methods

The pH of the soil can affect some chemical reactions in the soil and is a response to the different free ion ratios in the soil. As seen in **Table 6**, there were different degrees of differences in ph between different patterns of the same soil layer, which showed that HT > MT > LT > CK, indicating that the acidity of the soil in the stand diminished as the density of *Eucalyptus* in the stand decreased. Soil organic matter is one of the important indicators for evaluating soil properties and can improve the effectiveness of soil nutrients. As shown in Figure 1, the soil organic matter of 0–20 cm was significantly higher than that of 20–40 cm in each model. The differences in soil organic matter content among different treatments in the same soil layer all reached significant levels. It showed a trend of increasing and then decreasing with the decrease of *Eucalyptus* density, which showed MT > LT > HT > CK. It can be seen that the HT and LT models have higher soil organic matter content and better fertilizer retention and supply capacity, which may be related to the reasonable mix of stand structure, which can produce more dead leaves and higher fern cover in the forest understory.

3.5.2 Changes in soil total N, total P, and total K contents under different re-cultivation methods

The content of soil total N, total P and total K is an important indicator to respond to the long-term fertility level of soil. From **Figure 1**, it can be seen that the contents of total N, total P and total K per unit soil volume in the same soil layer differed to different degrees among different modes. The contents of total N, total P, and total K in the 0–20 cm soil layers were greater than those in the 20–40 cm soil layer in each model. In the 0–20 cm soil layer, the performance of soil total N was MT > LT > HT > CK, which was similar to the performance of organic matter content, while in the 20–40 cm soil layer, LT was better than other treatments, and there was no significant difference in total N content among other treatments; in terms of total P content, it was MT > HT > LT > CK in the 0–20 cm soil layer, and in the 20–40 cm In terms of total K content, CK > MT > LT > HT in the 0–20 cm soil layer and CK > LT > MT > HT in the 20–40 cm layer, and the total K content showed a trend of decreasing with decreasing density of *Eucalyptus* in the stand. The results of the analysis of the total N, P and K contents of different soil layers in different treatments showed that the conversion treatments with smaller *Eucalyptus* densities were favorable to the increase of total N and P nutrients, while the conversion treatments with higher *Eucalyptus* densities were favorable to the increase of total K nutrients.

3.5.3 Changes of soil fast-acting N, fast-acting P and fast-acting K contents under different cultivation treatments

Soil fast-acting nutrients are the guarantee of high crop yield and can be directly absorbed and used by crops. The results of **Figure 1** show that the content of fast-acting nutrients in the 0–20 cm soil layer of each model is higher than that in the 20–40 cm soil layer. In terms of fast-acting N, HT > LT > MT > CK in the 0–20 cm soil layer, LT was significantly higher than other treatments in the 20–40 cm soil layer, and there was no significant difference among other treatments; in terms of fast-acting P, the effect among soil layers was: HT > MT > LT > CK in the 0–20 cm, MT > HT > LT > CK in the 20–40 cm, and the fast-acting P content in all soil layers continued to increase with decreasing density of *Eucalyptus*. In terms of fast-acting K, the differences among soil layers were not significant, with LT significantly higher than other treatments in the 0–20 cm soil layer and no significant differences among other treatments. The results of the analysis showed that the effect of soil fast-acting nutrient content was better in the treatments with smaller *Eucalyptus* density.

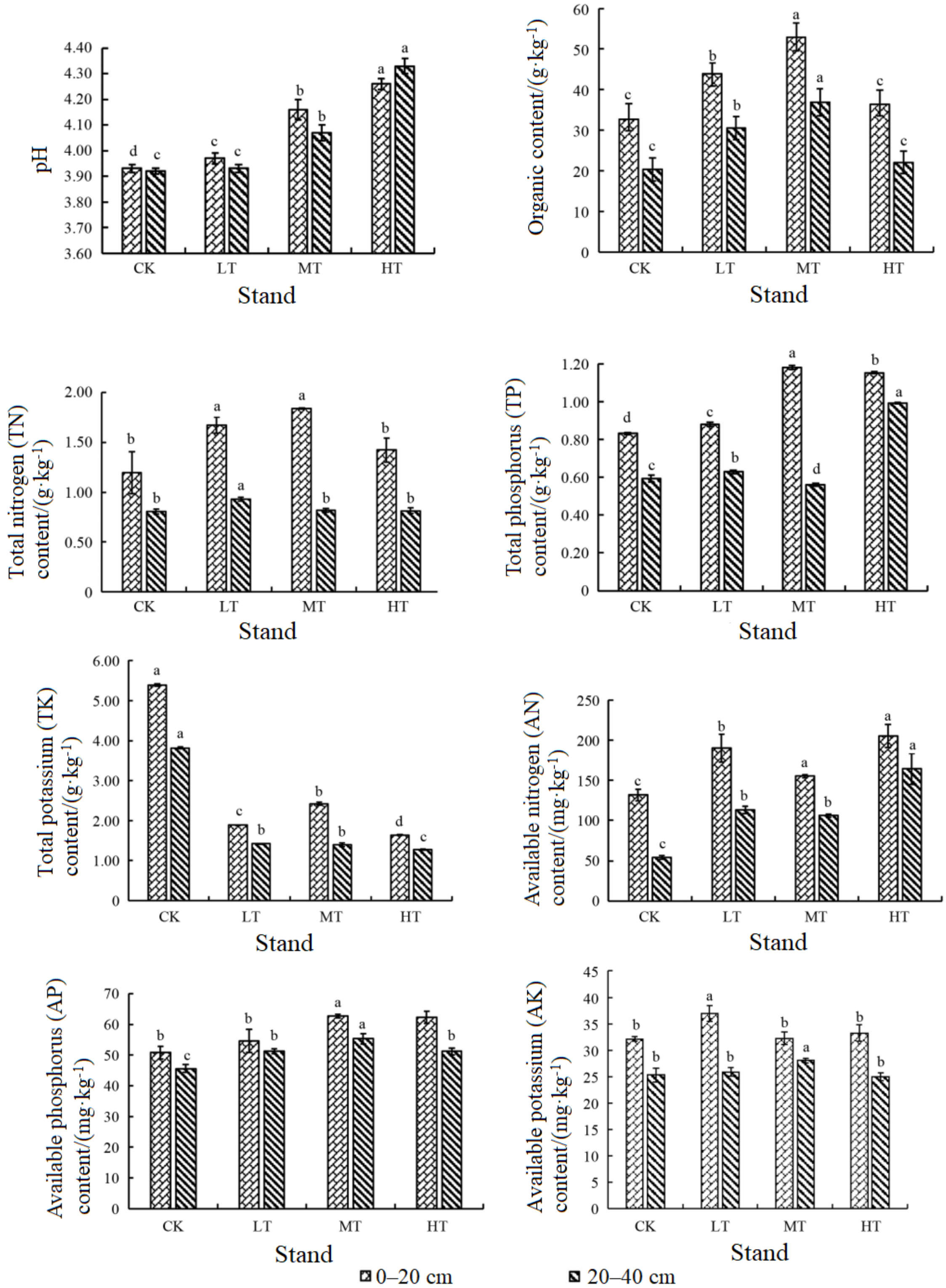

Figure 1. Soil chemical properties of different soil layers in different cultivation methods.

Note: The letters on the column indicate that there are significant differences ($P < 0.05$) between different treatments in the same soil layer.

4. Conclusion and discussion

The present study showed that the diameter at breast height, tree height and individual wood volume of *Eucalyptus* in mixed stands increased with decreasing density in mixed stands, which is similar to the results of previous studies[20]. *Eucalyptus* is a former silvicultural species, which has been above the canopy for a long time, and the reduced density of silviculture and reduced competition among individuals, together with the increased light penetration in the forest, lead to a great advantage in resource acquisition and thus changes in growth. The differences in diameter at breast height and tree height between MT and HT eucalypts are not significant, and the reasons for this are: first, after the eucalypts grow to a certain age, the respiratory consumption of the tree increases and the supply of nutrients required for tree height growth decreases; second, during the growth of *Eucalyptus* stands, the available soil nutrients are reduced due to the overgrowth of other mixed species, which eventually limits the growth of tree height; third, Chen mentioned in his study that understory ferns would Third, Chen mentioned in his study that understory ferns promote the growth of *Eucalyptus*[21], and it was observed that the greater depression of the stand at MT and the wetter soil surface layer than HT resulted in ferns being the dominant ground cover plant in its understory, which indicates that the growth of *Eucalyptus* near mature age is influenced by its biology.

After thinning of *Eucalyptus* trees, 3 kinds of broad-leaved trees, namely *Mytilaria laosensis*, *Castanopsis hystrix* and *Michelia macclurei*, were interplanted in a strip-like pattern of *Eucalyptus* and broadleaf. The three broad-leaved trees are shade-tolerant when young, neutral shade after middle age, prefer a warm and humid environment, and have high preservation rates in all treatments. Among them, *Mytilaria laosensis* has the best growth status and stand structure in all treatments. *Castanopsis hystrix* growth was significantly suppressed in CK and LT treatments, but improved in MT treatment and reached the optimum in HT treatment. *Michelia macclurei*, on the other hand, responded least to different density configurations of *Eucalyptus* in the stand. In terms of stocking volume of each tree species in the set, the treatments with different intercutting intensities of *Eucalyptus* did not significantly increase the woody growth of *Michelia macclurei*, but the treatments with smaller *Eucalyptus* densities had a significant effect on the woody growth of *Mytilaria laosensis* and *Castanopsis hystrix*. This indicates that to transform *Eucalyptus* near-mature forests into multi-species mixed forests and to cultivate *Eucalyptus* large-diameter timber at the same time, the small density of *Eucalyptus* in a stand can have better ecological and economic benefits.

Eucalyptus mixed with the above three broad-leaved trees can improve the nutrient content of soil in *Eucalyptus* succession stands to a certain extent, among which pH, organic matter, total phosphorus, total nitrogen, fast-acting phosphorus, fast-acting nitrogen, and fast-acting potassium perform better in the conversion stands with smaller *Eucalyptus* densities. However, in terms of soil physical properties, the MT and LT treatments performed significantly worse than the HT and CK treatments, which may be due to the poor root development caused by the growth inhibition of the overseeded native species in the CK treatment, which occupied less space horizontally and had less contact area with the root system of *Eucalyptus* and no obvious growth competition, resulting in a more reasonable horizontal distribution of the root system in the mixed forest. In contrast, in LT and MT treatments, the growth of the set species gradually tends to normalize, the root system is well developed, the horizontal occupation of space gradually increases, there is horizontal overlap, and the roots mostly cross each other, causing root fracture and division, distortion or even necrosis, and the soil subsurface structure is damaged to some extent, which is similar to Farooq's study[22]; Sarto and Sudmeyer, on the other hand, both found in their studies[23,24] that the number of *Eucalyptus* roots decreases significantly with increasing forest composition, while with the appearance of its lateral extent of roots and maximum root density within 0.5 m of the soil surface will be in fierce competition with other species, and because of these reasons dead and untimely decayed vegetation may cause short-term deterioration of soil physical properties. In the HT treatment, the soil structure was rationalized again and soil physical properties were significantly improved due to the significant reduction of *Eucalyptus* density in the stand, which led to an increase in the distance between the root system of *Eucalyptus* and the root system of the overgrown broadleaf forest. This aspect may also be related to the chemosensory effect of plants, where mutual constraints between plants may switch to mutual facilitation with the decrease in the number of one of them[25,26].

The differences in growth and various indicators of soil physicochemical properties in the mixed forests with different conversion methods are mainly caused by different treatments of *Eucalyptus* intercalation intensity, while the ecological differences in the mixed forests are amplified by the biological ecological properties of *Mytilaria laosensis*, *Castanopsis hystrix* and *Michelia macclurei* themselves. For soil improvement, it is generally believed that mixed forests affect soil microbiological traits and root secretions through decomposition of apoplastic material[27]. It has been shown that *Castanopsis hystrix* with high amount of apoplastic material and short decomposition cycle of apoplastic material has a great effect on soil improvement and water conservation[28]. The results of this experiment showed that the physical properties of the soil in the HT treatment where *Castanopsis hystrix* grew better were significantly better than those in the other stands, which may be related to this reason. In the case of *Mytilaria laosensis*, some studies showed that its promotion of soil sucrase, protease and acid phosphatase were all significantly higher than that of *Eucalyptus*, *Castanopsis hystrix* and *Michelia macclurei*[29,30], as well as significant enhancement of soil microbial biomass carbon, nitrogen and phosphorus[12]. The strength of soil enzyme activity and the content of microbial biomass carbon, nitrogen and phosphorus will directly affect the soil nutrient content, which may lead to the results of this experiment in which LT, MT and HT soil nutrient content, except for total potassium, were significantly better than CK in the better growing *Mytilaria laosensis*.

In this paper, we conducted a study on the experiment of planting native species under different intercutting intensities, focusing on the selection of the best conversion treatment for the conversion of *Eucalyptus* near-mature forest to multi-species mixed forest, and we observed and analyzed the growth and accumulation of *Eucalyptus* and three native species, and measured and analyzed a series of soil physical properties and nutrient contents, which are of guiding significance for production. Throughout the paper, the HT treatment was evaluated highly in terms of the growth performance of each species, stand structural performance, and soil physical and chemical properties in the transition period of the conversion of *Eucalyptus* near-mature forests to multi-species mixed forests. However, due to the large number of tree species involved in this trial, there are limitations in the study of the specific effects of chemosensory effects and root distribution patterns among tree species on the growth and soil physicochemical properties of mixed forests. In addition, the experiment was conducted for a short period of time, and there was a lack of comparison between different years for each index, so further research is needed on the growth of mixed stands, changes in understory vegetation diversity, dynamic changes in soil physicochemical properties, and changes in soil enzyme activity and soil microbial diversity.

Acknowledgements

This work was supported by National "Thirteenth Five-Year Plan" key R&D project "Integration and Demonstration of *Eucalyptus* High Yield and Efficiency Technology" (2017YFD06010202).

Conflict of interest

The authors declared no conflict of interest.

References

1. Xie Y. The real *Eucalyptus*. Beijing: China Forestry Publishing House; 2015.
2. Wen Y, Liu S, Chen F. Effects of continuous cropping on understory species diversity in *Eucalyptus* plantations. Chinese Journal of Applied Ecology 2005; 16(9): 1667–1671.
3. Wang Z, Duan C, Qi L, *et al.* A preliminary investigation of ecological issues arising in the man-made forest of *Eucalyptus* in China. Chinese Journal of Ecology 1998; 17(6): 65–69.
4. Yu F, Huang X, Wang K, *et al.* An overview of ecological degradation and restoration of *Eucalyptus* plantation. Chinese Journal of Eco-Agriculture 2009; 17(2): 393–398.
5. Jurskis V. Eucalypt decline in Australia, and a general concept of tree decline and dieback. Forest Ecology and Management 2005; 215(1/2/3): 1–20.
6. Robinson N, Harper RJ, Smettem KRJ. Soil water

depletion by *Eucalyptus* spp. Integrated into dryland agricultural systems. Plant and Soil 2006; 286(1/2): 141–151.

7. Santos FM, Chaer GM, Diniz AR, *et al.* Nutrient cycling over five years of mixed-species plantations of *Eucalyptus* and Acacia on a sandy tropical soil. Forest Ecology and Management 2017; 384: 110–121.
8. Le Maire G, Nouvellon Y, Christina M, *et al.* Tree and stand light use efficiencies over a full rotation of single- and mixed- species *Eucalyptus* grandis and Acacia mangium plantations. Forest Ecology and Management 2013; 288: 31–42.
9. Bristow M, Vanclay JK, Brooks L, *et al.* Growth and species interactions of *Eucalyptus* pellita in a mixed and monoculture plantation in the humid tropics of north Queensland. Forest Ecology and Management 2006; 233(2/3): 285–294.
10. Important progress and results achieved in 2018 of the National Key R & D Program “Research on Efficient Cultivation Technology of *Eucalyptus*”. Eucalypt Science & Technology 2018; 35(4): 33–60.
11. Lu D, Cai H, Zhang X, *et al.* Growth and economic evaluation of *Eucalyptus* clones plantation. Journal of Zhejiang A & F University 2008; 25(1): 65–68.
12. Li Z, Li B, Qi C, *et al.* Studies on the importance of valuable wood species resources and its development strategy. Journal of Central South University of Forestry & Technology 2012; 32(11): 1–8.
13. Wang T, Wan X, Cheng L, *et al.* Effects of broadleaf tree species on soil microbial stoichiometry in a reforested Cunninghamia lanceolata woodland. Chinese Journal of Applied Ecology 2020; 31(8): 1–9.
14. Pang S, Zhang P, Jia H, *et al.* Effects of different afforestation modes on diversity of undergrowth plants in *Eucalyptus* plantation. Journal of Northwest A & F University (Natural Science Edition) 2020; 48(9): 44–52.
15. Jiang Q, Li Q, Zhong C. The cultivation and comprehensive utilization of Michelia macclurei Dandy. Forest Science and Technology 2017; 63(8): 3–7.
16. Lu R. Methods for agricultural chemical analysis of soil. Beijing: China Agricultural Science and Technology Press; 2000.
17. Mo X, Yu X, Zhu C, *et al.* Theory and method of *Eucalyptus* plantation cultivation. Beijing: China Forestry Publishing House; 2005.
18. Liu Q. Chinese standing timber volume table. Beijing: China Forestry Publishing House; 2017.
19. Jiang J. Study on the effect of mixed afforestation of Castanopsis hystrix and Cunninghamia lanceolata. Journal of Forest and Environment 2002; 43(4): 329–333.
20. Wang Z. The research on monitoring and evaluation of ecological benefit of national non-commercial forest in Hunan Province [PhD thesis]. Changsha: Central South University of Forestry & Technology; 2013.
21. Chen J. The understory fern Dicranopteris dichotoma facilitates the overstory *Eucalyptus* trees in subtropical plantations. Ecosphere 2014; 5(5): 1–12.
22. Farooq T, Wu W, Tigabu M, *et al.* Growth, biomass production and root development of Chinese fir in relation to initial planting density. Forests 2019; 10(3): 1–15.
23. Sarto MVM, Borges WLB, Sarto JRW, *et al.* Root and shoot interactions in a tropical integrated crop-livestock-forest system. Agricultural Systems 2020; 181(6): 2–11.
24. Sudmeyer RA, Speijers J, Nicholas BD. Root distribution of *Pinus pinaster*, *P. Radiata*, *Eucalyptus globulus* and *E. Kochii* and associated soil chemistry in agricultural land adjacent to tree lines. Tree Physiology 2004; 24(12): 1333–1346.
25. Lin W, Zhan C, Chen H. Effects of allelopathy among tree species. World Forestry Research 2011; 24(5): 13–17.
26. Ping X, Wang T. Ecological significance of plant allelopathy and progress in allelopathy research in grassland ecosystems. Acta Prataculturae Sinica 2018; 27(8): 175–184.
27. Wu W. Plant diversity, soil microbial diversity and ecosystem multifunction in pure and mixed plantations [PhD thesis]. Nanning: Guangxi University; 2019.
28. Liu E, Wang H, Liu S. Characteristics of carbon storage and sequestration in different age beech (Castanopsis hystrix) plantations in south subtropical area of China. Chinese Journal of Applied Ecology 2012; 23(2): 335–340.
29. Zhu C. Soil fertility comprehensive evaluation of five broad-leaved trees plantations [PhD thesis]. Nanning: Guangxi University; 2015.
30. Huang H. Study on soil physical and chemical properties and enzyme activities of different species plantation in southwest Guangxi [PhD thesis]. Nanning: Guangxi University; 2017.