

Site Classification and Evaluation of *Eucalyptus urophylla* × *Eucalyptus grandis* Plantation in Southern Yunnan, China

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Abstract: *Background and Objectives:* The site types of *Eucalyptus urophylla* × *Eucalyptus grandis* clonal plantations in southern Yunnan were compared, aiming to provide basis for site selection and scientific plantations management. *Materials and Methods:* In this study, 80 standard plots were set up in the 6–9-year-old Eucalypts plantations in Pu'er City and Lincang City. Furthermore, the quantitative theory I model and canonical correlation analysis were used to analyze the relationship between dominant tree growth traits and site factors, and evaluate the growth potential of *E. urophylla* × *E. grandis* plantation. *Results:* The multiple correlation coefficient between 8 site factors (altitude, slope, slope level, soil thickness, slope direction, texture, soil bulk density, and litter thickness) and the quantitative growth of the dominant wood was 0.825 ($P < 0.05$). According to the correlation coefficient of the quantitative regression model, slope, altitude, and soil thickness were the main factors for the classification of *E. urophylla* × *E. grandis* plantations in southern Yunnan. In addition, *E. urophylla* × *E. grandis* plantations grew best downhill and mid uphill at relatively low altitude, where the soil layer was thick and composed of weathered red soil. Contrastingly, *E. urophylla* × *E. grandis* plantation growth was extremely poor in uphill sites at higher altitude, where the soil layer was thin and composed of semi-weathered purple soil. Furthermore, total N, and available B, Cu, and Zn content, as well as soil organic matter content in the soil had a great influence on the growth of *E. urophylla* × *E. grandis*. *Conclusions:* Nitrogen and phosphate fertilizer as well as trace elements such as B, Zn, and Cu can be properly applied in middle- and low-yield forests to promote the growth and development of *E. urophylla* × *E. grandis* plantations.

Keywords: *E. urophylla* × *E. grandis*; plantation; forest yield

1. Introduction

Eucalypts has become the most important industrial raw material forest tree species in southern China due to its advantages of fast-growing, high-yield, wide-ranging and short-rotation [1]. By 2018, the area of Eucalypts plantations in China had reached 5.647 million ha, accounting for 2.5% and 6.8% of the total and planted forest area of the country, respectively. Moreover, the annual average wood production was 30 million m³, i.e., 25% of the country's commercial forest products, providing an important guarantee for the production of domestic wood and fiber raw materials.

Since 2004, the National Development and Reform Commission has promoted the "Tenth Five Year Plan of national forestry paper integration project construction and 2010 special plan," and large domestic and foreign paper-making industries have built large-scale Eucalypts forests for fiber

raw material in Hainan Island in South China, Leizhou Peninsula in Guangdong, Southern and Central Regions of Guangxi, and southern Yunnan.

The total area of Eucalypts plantations in Yunnan is 422,400 ha, and the plantation of *E. urophylla* × *E. grandis* in Pu'er City has reached 140,000 ha, accounting for 31.48% of the province area [2]. The planting area is located in the Lancang River Basin, which belongs to the subtropical low latitude mountain monsoon climate area. Affected by the warm and wet monsoon of the Indian Ocean, the dry and rainy seasons are distinct and rainfall is abundant, making it the best potential area for Eucalypts plantations. The introduction and cultivation of Eucalypts in China has a history of more than 100 years. In the past, differences in suitability of climatic zones and types of afforestation, as well as the lack of clear targeted cultivation materials for particular uses, resulted in a lack of standardized site type classification and quality evaluation of Eucalypts plantations. Relative to the study of *Cunninghamia lanceolata* and *Pinus massoniana*, only a few areas have carried out site type classification for *Eucalyptus* ABL No. 12 (W5 clone), *Eucalyptus urophylla* U6 clone, and *Eucalyptus grandis* plantation in Leizhou, Guangdong and Leshan, Sichuan [3–5].

However, there are several studies on classification and site quality evaluation of artificially planted Eucalypts abroad. For example, in a study of Eucalypts plantations in southeastern Brazil, Grant et al. [6] introduced climatic variables as covariates of the dominant wood height model and found that their impact on the classification of status index was usually only age-related. José et al. [7] used the Chapman-Richards model in northern Sumatra, Indonesia to parameterize the non-linear regression and determine the site index of *Eucalyptus grandis* with a reference age of 5 years. Sadono et al. [8] successfully predicted site index for soil and site parameters of *Eucalyptus dunnii* plantation in the subtropical region of eastern Australia.

In this study, 60,000 hm² of *E. urophylla* × *E. grandis* planted by Yunnan Yunjing Forestry and Pulp Mill Co., Ltd were taken as the research object. In this area, 130 standard plots were subjected to topographic factor investigation, per-wood detection, dominant wood trunk analysis, average wood pulpability sampling, understory vegetation growth survey, and soil chemical factor analysis. By means of quantitative models and canonical correlation analysis (CCA), the site factors, soil texture, soil nutrients, and understory vegetation were used to evaluate the relationship between the growth and site of *E. urophylla* × *E. grandis* plantations in the Lancang River Basin. Our aim is to provide a theoretical basis for the scientific management of *E. urophylla* × *E. grandis* pulp raw material forests in southern Yunnan, and a reference for the reasonable layout, planning, and adjustment of Eucalypts industrial raw material forests in this region.

2. Materials and methods

Eucalypts industrial raw material forest cultivation in southern Yunnan is mainly distributed in Pu'er City and Lincang City (22° 49'–23° 52' N, 100° 02'–101° 07' E). The annual rainfall and evaporation of this region is 1,354 and 1,916.4 mm, respectively. The rainy season extends from May to October and the average annual temperature ranges from 18.2 to 22.1 °C. Furthermore, the soil types are mainly lateritic red earths and humid-thermo ferralitic. Eucalypts forests are mainly composed of *Eupatorium adenophora*, *Microstegium vagans*, *Urena lobata*, and *Phyllanthus emblica*. Since 2011, Yunnan Yunjing Forestry and Pulp Mill Co., Ltd have developed the fiber raw material forest with *E. urophylla* × *E. grandis* DH series clones bred by the China-Australia Eucalypts Project in Dongmen Forest Farm of Guangxi. Afforestation technical measures included artificial hole digging and land preparation. The specification of the hole was 30 × 30 × 30 cm, and the afforestation density was 2,220 plants hm⁻². The base fertilizer was a special compound fertilizer for Eucalypts (10 : 16 : 7, N : P : K), with an effective nutrient of 33%. In the year of colonization, weeds were uprooted once, and according to the degree of weed exuberance, weeding was carried out at the appropriate time. The following year, the weeds were uprooted twice, and topdressing was done once at 0.5 kg plant⁻¹. In the third year, the weeds were uprooted once, and topdressing was done once at 0.7 kg plant⁻¹. In addition, the compound fertilizer N : P : K ratio was 18 : 12 : 10.

2.1. Standard ground survey and analysis of dominant tree trunks

From November to December 2017, standard sites were set according to site factors such as altitude, slope, slope position, and soil layer thickness, among others. A total of 130 standard plots (20 × 20 m) were set. Among them, 80 were selected from standard plots 6–9-year-old to construct quantitative regression models, and the other 50 plots were used for model testing. Standard surveys were performed by GPS to record geographic coordinates, altitudes, and measure diameter at breast height (DBH), and tree height for each tree of *E. urophylla* × *E. grandis*. Soil samples were collected by digging three soil sections at equal distances in the diagonal direction. Among them, 0.5 kg of mixed soil along 0–60 cm was used to analyze chemical composition, and soil sampled by 100-cm³ ring knife was used to measure soil bulk density and other physical properties.

The statistics of understory shrubs were recorded by setting five plots with an area of 2 × 2 m in the four corners and center of the standard plot. The highest single plant was selected as the dominant tree, one disk of 1.3 m was cut down at chest height, and a disk of 8–10 cm thick was cut at a length of 2 m to analyze the trunk. In addition, five cores with an average diameter of 5 mm were selected on the north and south side, with a core height of 1.3 m. The analysis of pulping test materials consisted on selecting a standard tree, removing the top 3 m and 1 m at the base, then slice the rest into 30–40-cm sections. The quantitative regression model formula was as follows [9]:

$$y = \sum_{i=1}^m \sum_{k=1}^{r_i} \delta_i(i, k) b_{ik} + \varepsilon_i, \quad (i = 1, \dots, n) \quad (1)$$

where b_{ik} is an unknown coefficient and ε_i is a random error. The least square estimate \hat{b}_{ik} for this is called the score of category k of item i , and the prediction equation was as follows:

$$\hat{y} = \sum_{i=1}^m \sum_{k=1}^{r_i} \delta_i(i, k) \hat{b}_{ik} + \varepsilon_i, \quad (2)$$

and the single timber volume of dominant trees was calculated as [10]:

$$V = \pi \times (\text{DBH} / 2)^2 \times H / 30,000, \quad (3)$$

where V represents the volume (m³) and H is the tree height (m).

2.2. Sample soil analysis

Soil analysis determined 11 indexes of soil, including pH, organic matter; total N, P, and K, as well as available N, P, K, B, Zn, and Cu. Soil pH was calculated with a soil:water mass ratio of 1:2.5 and measured by potentiometric method. Soil organic matter was measured by the potassium dichromate oxidation-capacity method. Total N was digested with H₂SO₄+ catalyst and measured by alkaline hydrolysis diffusion method, while P was determined by sodium hydroxide alkali melting-molybdenum antimony colorimetric method, and K was determined by sodium hydroxide alkali melting-atomic absorption spectrophotometer method. Available N, P and K were determined by the alkaline hydrolysis diffusion method, 0.05 mol L⁻¹ HCl-0.025 mol L⁻¹ H₂SO₄ extraction method, and 1 mol L⁻¹ ammonium acetate extraction-atomic absorption spectrometry, respectively. Effective B was determined by curcumin colorimetry, and effective Cu and Zn were extracted by 0.1 mol L⁻¹ hydrochloric acid and measured by atomic absorption spectrophotometry [11].

2.3. Data statistics and analysis methods

Quantitative theory I model was used to list each site factor by (0,1) and SPSS 13.0 for Windows (SPSS Inc., New York, NY, USA) was used for quantitative regression analysis. In addition, CCA of the dominant *E. urophylla* × *E. grandis* tree height and its single timber volume relative to soil chemical properties were performed in R Studio. Soil physical and chemical properties and the trends of productivity grade of *E. urophylla* × *E. grandis* were plotted in Excel 2016 (Microsoft, USA).

3. Results

3.1. Classification of site factors

Standard site factors and high average annual growth of dominant wood were listed in Table 1. The standard plot classification was performed (Table 2) according to the changes in site factors and growth factors of forest trees, combined with the principles and methods of site elements for classification and evaluation of forest sites.

Table 1. Site factors and mean annual increments of dominant tree height of different plots

Plot	Elevation /m	Slope degree	Slope position	Thickness of soil/cm	Aspect	Texture	Soil density /g*cm ⁻³	Thickness of litter/cm	Annual average high growth of dominant tree/m
1	994	16	Lower slope	40~80	Sunny slope	Middle loam	1.57	<5	3.02
2	1592	23	Lower slope	40~80	Half-sunny slope	Middle loam	0.93	5-10	3.04
3	1591	30	Upper slope	>80	Sunny slope	Middle loam	1.64	5-10	3.67
4	1532	25	Upper slope	<40	Sunny slope	Heavy loam	1.14	<5	3.18
5	1607	27	Upper slope	40~80	Sunny slope	Heavy loam	1.16	<5	3.73
6	1355	13	Upper slope	<40	Sunny slope	Heavy loam	1.44	>10	3.58
7	1400	14	Upper slope	<40	Half-shady slope	Heavy loam	1.23	>10	3.69
8	1132	23	Lower slope	>80	Half-shady slope	Middle loam	1.41	5-10	3.51
9	1468	22	Upper slope	<40	Sunny slope	Middle loam	1.06	<5	3.03
10	1272	30	Lower slope	>80	Shady slope	Middle loam	1.14	5-10	3.45
11	1167	32	Upper slope	<40	Half-sunny slope	Sandy loam	1.22	5-10	2.87
12	1140	18	Upper slope	>80	Half-sunny slope	Sandy loam	1.30	>10	3.82
13	1409	39	Upper slope	<40	Half-sunny slope	Middle loam	1.83	5-10	3.09
14	1392	28	Lower slope	>80	Half-sunny slope	Middle loam	1.42	5-10	3.76
15	1435	0	Flat ground	40~80	Flat slope	Heavy loam	1.11	5-10	3.15
16	1462	0	Flat ground	40~80	Flat slope	Heavy loam	1.25	5-10	3.18
17	1228	16	Lower slope	>80	Half-shady slope	Middle loam	1.40	<5	3.98
18	1628	29	Upper slope	<40	Half-shady slope	Middle loam	1.22	<5	3.24
19	1594	17	Upper slope	<40	Sunny slope	Heavy loam	1.45	<5	3.13
20	969	25	Lower slope	40~80	Sunny slope	Middle loam	1.42	<5	2.87
21	1095	16	Upper slope	<40	Half-shady slope	Middle loam	1.46	<5	2.91
22	1364	13	Middle slope	40~80	Half-sunny slope	Heavy loam	1.57	5-10	3.68
23	1137	26	Middle slope	>80	Half-sunny slope	Heavy loam	1.38	>10	3.82
24	1257	17	Lower slope	>80	Half-sunny slope	Heavy loam	1.58	5-10	4.34
25	1192	27	Lower slope	>80	Half-sunny slope	Heavy loam	1.19	5-10	4.36
26	1165	10	Middle slope	>80	Half-sunny slope	Heavy loam	1.49	5-10	3.67
27	1149	18	Middle slope	40~80	Half-shady slope	Heavy loam	1.34	5-10	3.20
28	1140	19	Middle slope	40~80	Shady slope	Heavy loam	1.42	5-10	3.36
29	956	10	Lower slope	>80	Half-sunny slope	Sandy loam	1.65	5-10	3.56
30	1080	26	Middle slope	<40	Half-sunny slope	Middle loam	1.72	5-10	2.76
31	1137	26	Middle slope	<40	Half-sunny slope	Sandy loam	1.67	5-10	2.78
32	1157	26	Middle slope	40~80	Half-sunny slope	Heavy loam	1.52	5-10	3.22
33	1281	13	Middle slope	40~80	Half-sunny slope	Middle loam	1.35	5-10	3.21
34	1303	12	Upper slope	<40	Half-shady slope	Middle loam	1.36	5-10	3.26
35	1301	23	Upper slope	40~80	Half-sunny slope	Middle loam	1.57	5-10	3.47
36	1305	22	Lower slope	>80	Shady slope	Middle loam	1.43	5-10	4.16
37	1348	23	Middle slope	40~80	Sunny slope	Middle loam	1.75	5-10	3.43
38	1345	15	Middle slope	40~80	Half-sunny slope	Middle loam	1.54	<5	3.41
39	1217	16	Lower slope	>80	Half-shady slope	Middle loam	1.32	5-10	3.76
40	1268	6	Upper slope	<40	Half-sunny slope	Middle loam	1.14	<5	3.11
41	1339	28	Upper slope	<40	Sunny slope	Middle loam	1.44	<5	3.15
42	1238	22	Middle slope	40~80	Half-sunny slope	Middle loam	1.23	5-10	3.23
43	1308	25	Upper slope	40~80	Half-sunny slope	Sandy loam	1.12	5-10	3.69
44	1089	28	Middle slope	40~80	Half-shady slope	Heavy loam	1.48	5-10	3.21
45	1497	27	Upper slope	40~80	Half-sunny slope	Middle loam	1.50	<5	3.58
46	1654	15	Upper slope	>80	Half-sunny slope	Middle loam	1.10	<5	3.73
47	1055	27	Middle slope	>80	Half-sunny slope	Sandy loam	1.14	<5	3.76
48	1005	28	Middle slope	>80	Half-sunny slope	Light loam	1.17	5-10	3.58

49	1375	20	Upper slope	<40	Half-shady slope	Middle loam	1.21	<5	3.21
50	1217	23	Middle slope	40~80	Half-shady slope	Light loam	1.30	<5	3.67
51	1413	18	Upper slope	40~80	Sunny slope	Middle loam	1.12	<5	3.38
52	1625	14	Upper slope	40~80	Sunny slope	Middle loam	1.28	<5	3.38
53	1309	19	Middle slope	40~80	Shady slope	Middle loam	1.34	<5	3.37
54	1786	34	Upper slope	40~80	Half-sunny slope	Middle loam	1.12	<5	3.57
55	1663	35	Upper slope	<40	Half-shady slope	Middle loam	1.12	<5	3.10
56	1020	32	Lower slope	>80	Half-sunny slope	Sandy loam	1.27	<5	4.20
57	1214	20	Upper slope	40~80	Half-shady slope	Middle loam	1.25	<5	3.54
58	1190	3	Upper slope	<40	Half-sunny slope	Middle loam	1.27	<5	3.10
59	1545	35	Middle slope	40~80	Half-sunny slope	Middle loam	1.20	<5	3.10
60	1385	15	Upper slope	>80	Half-shady slope	Middle loam	1.24	<5	3.93
61	1693	8	Middle slope	40~80	Half-shady slope	Sandy loam	1.03	<5	3.33
62	1736	15	Middle slope	>80	Half-sunny slope	Light loam	1.04	5-10	3.90
63	995	32	Lower slope	>80	Sunny slope	Middle loam	1.12	<5	3.51
64	1227	28	Middle slope	40~80	Half-shady slope	Middle loam	1.08	<5	3.24
65	1538	25	Upper slope	<40	Half-shady slope	Light loam	1.17	<5	3.58
66	1573	19	Upper slope	<40	Shady slope	Middle loam	1.14	5-10	3.13
67	1334	30	Upper slope	<40	Half-shady slope	Middle loam	1.11	5-10	3.23
68	1127	25	Upper slope	<40	Half-sunny slope	Middle loam	1.30	<5	3.03
69	1262	31	Middle slope	40~80	Shady slope	Middle loam	1.12	5-10	3.05
70	1335	21	Upper slope	40~80	Half-sunny slope	Middle loam	1.14	5-10	3.68
71	1550	34	Upper slope	<40	Half-shady slope	Middle loam	1.29	<5	2.89
72	1502	40	Upper slope	<40	Half-shady slope	Middle loam	1.58	<5	3.06
73	1057	29	Upper slope	40~80	Shady slope	Sandy loam	1.20	5-10	3.39
74	1595	20	Middle slope	40~80	Half-sunny slope	Middle loam	1.32	5-10	3.13
75	1055	12	Middle slope	>80	Sunny slope	Middle loam	1.20	5-10	3.26
76	1123	24	Middle slope	40~80	Sunny slope	Middle loam	1.20	<5	3.16
77	1177	31	Upper slope	<40	Half-sunny slope	Middle loam	1.38	5-10	3.15
78	1064	20	Middle slope	>80	Half-shady slope	Middle loam	1.28	<5	3.52
79	1074	10	Middle slope	40~80	Sunny slope	Middle loam	1.19	<5	3.19
80	1207	13	Middle slope	>80	Sunny slope	Middle loam	1.26	5-10	3.65

Table 2. Category division of site factors

Item	Category				
Elevation	<1000 m	1000~1200 m	1200~1400 m	1400~1600 m	1600~1800 m
Slope degree	Conservative	Gentle Slope	Slope	Steep slope	
	Slope(0~5°)	(6~15°)	(16~25°)	>25°	
Slope position	Upper slope	Middle slope	Lower slope	Flat ground	
Thickness of soil/cm	Thin: <40 cm	Medium: 40-80	Thick: >80 cm		
	cm				
Parent rock	Shale and Sand Shale	Purple Sand Shale	Sandstone		
Aspect	Sunny slope	Half-sunny slope	Half-shady slope	Shady slope	Flat slope
Texture soil density	Sandy loam	Light loam	Middle loam	Heavy loam	
	>1.4 g·cm ⁻³	1.2~1.4 g·cm ⁻³	1.0~1.2 g·cm ⁻³	<1.0 g·cm ⁻³	
Thickness of litter/cm	Thin: <5.0 cm	Medium: 5.0~10.0	Thick: >10.0		
	cm				

3.2. Building a quantitative regression model

By combining site factor classification with standard survey information (Table 2), each site factor of the plot was listed in (0,1). Quantitative theory I was used for site index modeling, and the site factor categories were obtained by fitting regression coefficients and related parameters of annual average height growth of the dominant species, i.e., *E. urophylla* × *E. grandis* (Table 3).

The quantitative regression equation was as follows: $Y = 3.412 - 0.509 X_{11} - 0.112 X_{12} + 0.055 X_{13} - 0.024 X_{14} - 0.059 X_{15} - 0.054 X_{21} + 0.093 X_{22} + 0.052 X_{23} - 0.190 X_{32} + 0.145 X_{33} - 0.469 X_{34} + 0.218 X_{42} + 0.522 X_{43} - 0.109 X_{51} - 0.124 X_{53} - 0.070 X_{54} + 0.162 X_{61} + 0.373 X_{62} + 0.290 X_{64} - 0.277 X_{71} - 0.217 X_{72} - 0.208 X_{73} - 0.546 X_{74} + 0.070 X_{81} + 0.103 X_{83}$.

According to the scores of each site factor, slope position > altitude > soil layer thickness > soil texture > soil bulk density > slope > slope direction > litter thickness (Table 3), and the proportion of the first three site factor scores was 61.04%. Among site factors, the effect of slope position and altitude on the growth of *E. urophylla* × *E. grandis* plantation was stronger than that of slope and slope-exposure. The results of t-test showed that the partial correlation between the eight site factors and the annual average height increment of *E. urophylla* × *E. grandis* was significant ($P < 0.05$). Furthermore, the regression model complex correlation coefficient was $R = 0.825$ and statistically significant ($F_{(8,71)} = 24.137 > F_{0.05(8,71)} = 2.072$). Thus, the eight selected site factors were closely related to the average annual growth of dominant trees, and this equation is theoretically reliable to evaluate the site quality of *E. urophylla* × *E. grandis* plantations.

Table 3. Quantity regression result of site factors

Item	Category	Code	Score	Score range and Proportion	Coefficient of partial correlation	t-test
constant			3.412			
Elevation X ₁	<1000 m	X ₁₁	-0.509	0.564 (20.25%)	0.324**	3.124
	1000~1200 m	X ₁₂	-0.112			
	1200~1400 m	X ₁₃	0.055			
	1400~1600 m	X ₁₄	-0.024			
	1600~1800 m	X ₁₅	-0.059			
Slope degree X ₂	Conservative Slope	X ₂₁	-0.054	0.147 (5.28%)	0.157*	2.316
	Gentle Slope	X ₂₂	0.093			
	Slope	X ₂₃	0.052			
	Steep slope	X ₂₄	0			
	Upper slope	X ₃₁	0			
Slope position X ₃	Middle slope	X ₃₂	-0.190	0.614 (22.05%)	0.536**	5.283
	Lower slope	X ₃₃	0.145			
	Flat ground	X ₃₄	-0.469			
	Thin: <40 cm	X ₄₁	0			
Thickness of soil/cm X ₄	Medium: 40~80 cm	X ₄₂	0.218	0.522 (18.74%)	0.494**	3.837
	Thick: >80 cm	X ₄₃	0.522			
	Sunny slope	X ₅₁	-0.109			
Aspect X ₅	Half-sunny slope	X ₅₂	0	0.124 (4.45%)	0.254*	2.206
	Half-shady slope	X ₅₃	-0.124			
	Shady slope	X ₅₄	-0.070			
	Flat slope	X ₅₅	0			
	Sandy loam	X ₆₁	0.162			
Texture X ₆	Light loam	X ₆₂	0.373	0.373 (13.39%)	0.403*	3.294
	Middle loam	X ₆₃	0			
	Heavy loam	X ₆₄	0.290			
	>1.4 g·cm ⁻³	X ₇₁	-0.277			
Soil density X ₇	1.2~1.4 g·cm ⁻³	X ₇₂	-0.217	0.338 (12.14%)	0.367*	3.514
	1.0~1.2 g·cm ⁻³	X ₇₃	-0.208			
	<1.0 g·cm ⁻³	X ₇₄	-0.546			
	Thin: <5.0 cm	X ₈₁	0.070			
Thickness of litter/cm X ₈	Medium: 5.0~10.0	X ₈₂	0	0.103 (3.70%)	0.194*	2.257
	cm	X ₈₃	0.103			

 Thick: >10.0 cm

 Note:** Statistical significance at $P < 0.01$, * Statistical significance at $P < 0.05$.

3.3. Site Classification and evaluation

Eighty plots were divided into 13 different site types (Table 4). Among the four site types on upper slope, the average site index value of "upper slope, medium-low altitude, medium-thick soil layer" was 3.61 m, while that of the "upper slope, low elevation, thin soil layer" was 3.01 m. Among the four site types of the middle slope position, the average site index value of the "middle slope, medium-low altitude, medium-thick soil layer" was 3.41 m, while that of the "middle slope, medium-low altitude, thin soil layer" was 2.77 m. Among the four site types of the lower slope, the average site index value on the "lower slope, low elevation, medium-thick soil layer" was 4.02 m, while that of "lower slope, medium elevation, middle-thick soil layer" was 3.04 m. In the flat site type, the average site index of the "flat slope, medium-high altitude, medium soil layer" was 3.16 m.

Regarding the average site index of *E. urophylla* × *E. grandis* at different slopes, lower slope > medium slope > upper slope > flat ground, and in the same slope, the average site index of "medium-low altitude, medium-thick soil layer" was higher than that of "medium-high altitude, thin soil layer." *E. urophylla* × *E. grandis* enjoyed a warm climate, and site productivity level was the highest at the "lower slope, medium-low altitude, thick soil layer."

Table 4. Site Classification of *E. urophylla* × *E. grandis* Plantation in southern Yunnan

Number	Basis of division			Site type	site index		
	Slope position	Altitude /m	Thickness of soil/cm		Average value	Range of change	Sample plot
1	Upper slope	1000~1200	>40	Upper slope、mid-low altitude、medium-thick soil	3.61	3.39~3.82	12、73
2		1000~1200	<40	Upper slope、medium-low altitude、Thin soil	3.01	2.87~3.15	11、21、58、68、77
3		1200~1400	*	Upper slope、medium altitude、total soil	3.43	3.11~3.58	6、34、40、41、43、49、57、60、67、70
4		1400~1800	*	Upper slope、medium-high altitude、total soil	3.35	2.93~3.73	3、4、5、7、9、13、18、19、45、46、51、52、54、55、65、66、71、72
5	Middle slope	1000~1200	>40	Middle slope、medium-low altitude、medium-thick soil	3.41	3.16~3.82	27、28、32、44、76、79、23、26、47、48、75、78
6		1000~1200	<40	Middle slope、medium-low altitude、Thin soil	2.77	2.76~2.78	30、31
7		1200~1400	>40	Middle slope、medium altitude、medium-thick soil	3.40	3.05~3.68	22、33、37、38、42、50、53、64、69、80
8		1400~1800	>40	Middle slope、medium-high altitude、medium-thick soil	3.37	3.10~3.90	59、61、62、74
9	Lower slope	900~1000	>40	Lower slope、low altitude、medium-thick soil	4.02	3.51~4.36	8、25、56
10		1000~1200	>80	Lower slope、medium-low	3.85	3.45~4.34	10、14、17、24、35、36、39

			altitude、thick soil			
11		1200~1400	>40	Lower slope、medium altitude、medium-thick soil	3.04	— 2
12		1400~1600	40~80	Lower slope、medium-high altitude、medium soil	3.24	2.87~3.56 1、20、29、63
13	Flat slope	1400~1600	40~80	Flat slope、medium-high altitude、medium soil	3.16	3.15~3.18 15、16

Note: "*" indicates that the soil layer covers three levels of thickness: thin, medium and thick.

Following the site factor regression model (Table 5), and the principle that the model's predicted value was close to the measured value, sample plots were divided into three productivity levels (high-, medium-, and low-yield), and each level was divided into thirteen site types in conformity with the difference in slope, altitude, and soil thickness.

The high-yield group was mainly located downhill, where the soil layer was medium-thick and the elevation was 1,000–1,400 m. The average annual height growth, DBH, and accumulation growth of *E. urophylla* × *E. grandis* were 2.71 m, 2.11 cm, and 32.84 m³ hm⁻², respectively.

The middle-yield group was mainly located in the middle and upper slope, where the soil layer was not that thick, and its elevation was 900–1,800 m. The average annual height growth, DBH, and accumulation growth of *E. urophylla* × *E. grandis* were 2.32 m, 1.93 cm, and 23.5 m³ hm⁻², respectively.

The low-yield group was mainly located on the upper slope, where the soil layer was thin and the elevation was 1,000–1,600 m. The average annual height growth, DBH, and accumulation growth of *E. urophylla* × *E. grandis* were 1.98 m, 1.82 cm, and 17.94 m³ hm⁻², respectively.

Table 5. Site evaluation of *E. urophylla* × *E. grandis* plantation in southern Yunnan

Site productivity groups	Site type	Mean annual increment of dominant height predicted / m	Mean annual increment of dominant height measured / m	Sample plot
High production group I	I ₁ Lower slope、1000~1200 m、>80 cm	3.98	4.02	8、25、56
	I ₂ Lower slope、1200~1400 m、>40 cm	3.87	3.85	10、14、17、24、35、36、39
	I ₃ Upper slope、1000~1200 m、>40 cm	3.66	3.61	12、73
Middle production group II	II ₁ Upper slope、1200~1400 m	3.45	3.43	6、34、40、41、43、49、57、60、67、70
	II ₂ Middle slope、1000~1200 m、>40 cm	3.42	3.41	27、28、32、44、76、79、23、26、47、48、75、78
	II ₃ Middle slope、1200~1400 m、>40 cm	3.40	3.40	22、33、37、38、42、50、53、64、69、80
	II ₄ Middle slope、1400~1800 m、>40 cm	3.44	3.37	59、61、62、74
	II ₅ Upper slope、1400~1800 m	3.34	3.35	3、4、5、7、9、13、18、19、45、46、51、52、54、55、65、66、71、72
	II ₆ Lower slope、900~1000 m、>40 cm	3.22	3.24	1、20、29、63
Low production group III	III ₁ Flat ground、1400~1600 m、40~80cm	3.17	3.16	15、16
	III ₂ Lower slope、1400~1600m、40~80cm	3.04	3.04	2
	III ₃ Upper slope、1000~1200 m、<40	3.09	3.01	11、21、58、68、77

	cm			
III ₄	Middle slope, 1000~1200 m, <40 cm	2.92	2.77	30, 31

3.4. Relationship between the growth of *E. urophylla* × *E. grandis* and soil chemical properties

To explore the effect of soil chemical properties on the growth of *E. urophylla* × *E. grandis*, the tree height and single timber volume of dominant trees, and soil chemical properties were used as two sets of variables for CCA (Table 6). From the scatter plot (Figure 1), it can be seen that the first and second canonical variables of *E. urophylla* × *E. grandis* were distributed near a straight line, and the statistically significant correlation coefficients were 0.8045 and 0.8263, respectively.

In the first canonical variable, owing to the analysis of soil chemical properties, the load of the total N content was 0.1362. The remaining five factors were available B content, organic matter content, available Zn, Cu, and P content in turn, and the loads were 0.0961, 0.0924, 0.0858, 0.0673, and 0.0582, respectively. Regarding growth parameters, the trait with the maximum load was the height of dominant trees followed by the single timber volume of dominant trees, with loads of 0.1393 and 0.0605, respectively.

In the second canonical variable, regarding soil chemical properties, the maximum load was N content (0.0902). The remaining five factors were effective B and Zn content, organic matter content, and effective Cu and P content in turn, with loads of 0.0752, 0.0671, 0.0528, 0.0503, and 0.0459, respectively. Regarding growth parameters, the trait with the maximum load was the height of dominant trees (0.1046), followed by the single timber volume of dominant trees (0.0857).

Results indicated that during the growth process of *E. urophylla* × *E. grandis*, total N content, trace elements B, Zn, and Cu content, and organic matter content had the greatest influence on the tree height and single timber volume of dominant trees of *E. urophylla* × *E. grandis*.

Table 6. Canonical correlation analysis between trait (tree height and single timber volume of dominant trees) and soil chemical property of *E. urophylla* × *E. grandis*

		First canonical variable	Second canonical variable
		$r_1=0.8045$ ($F=0.0135^*$)	$r_2=0.8263$ ($F=0.0127^*$)
Soil chemical property	pH	0.0446	-0.0314
	Organic matter	0.0924	0.0528
	Total N content	0.1362	0.0902
	Total P content	0.0286	0.0325
	Total K content	0.0559	0.0436
	Available N content	0.0109	0.0235
	Available P content	0.0582	0.0459
	Available K content	0.0406	0.0352
	Available Cu content	0.0673	0.0503
	Available Zn content	0.0858	0.0671
Trait	Available B content	0.0961	0.0752
	The height of dominant trees	0.1393	0.1046
	Single timber volume of dominant trees	0.0605	0.0857

Note:* Statistical significance at $P < 0.05$. r_1 represents the correlation coefficients between soil chemical property and the height of dominant trees. r_2 represents the correlation coefficients between soil chemical property and single timber volume of dominant trees.

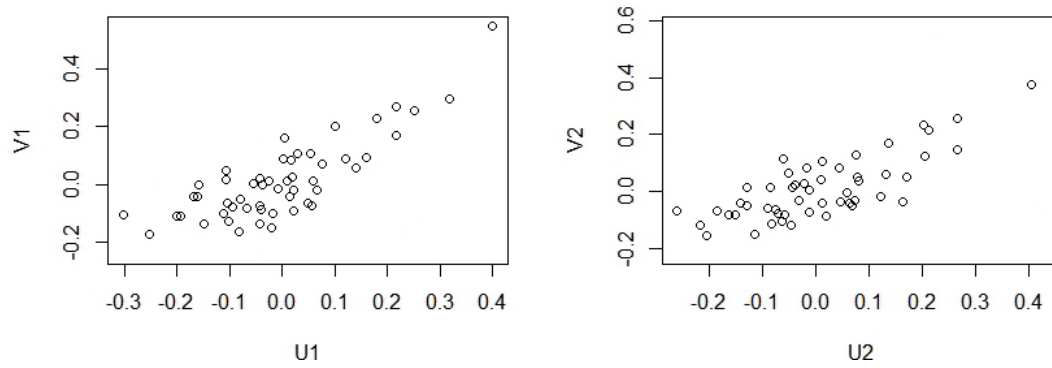
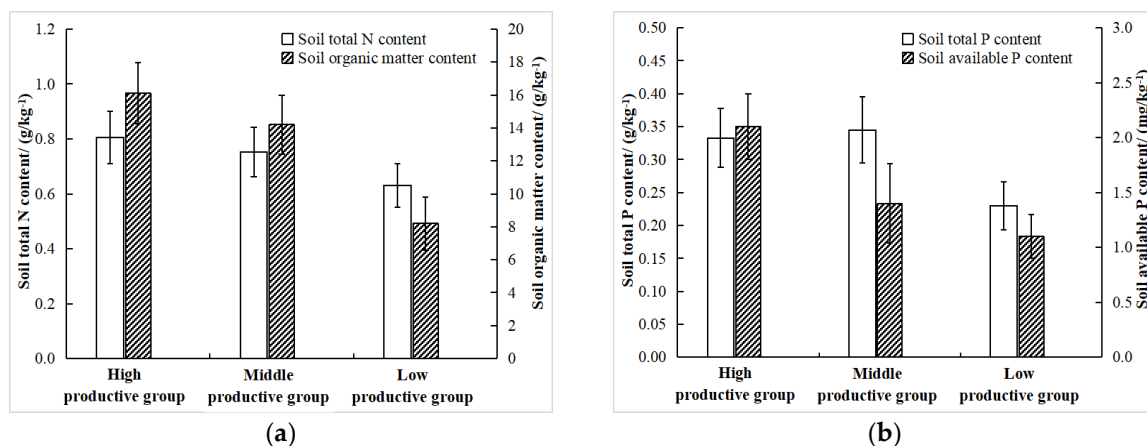


Figure 1. Scatter figure on canonical variable of trait and soil chemical property. In the first canonical variable, U1 is the index of soil chemical properties, and V1 is the height of dominant trees, because $r_1 = 0.8045$, it shows that there is a high correlation between U1 and V1; In the second canonical variable, U2 is the index of soil chemical properties, and V2 is the single timber volume of dominant trees, because $r_2 = 0.8263$, it shows that there is a high correlation between U2 and V2.

3.5. Relationship between soil chemical properties and productivity of *E. urophylla* × *E. grandis*

CCA results of *E. urophylla* × *E. grandis* growth and soil chemical properties, the effects of the first six factors (total N content, effective B content, soil organic matter content, and effective Zn, Cu, and P content) had a great impact on the growth of *E. urophylla* × *E. grandis*. As can be seen in Figure 2, through the analysis of all soil chemical factors and *E. urophylla* × *E. grandis* productivity, the total N content of soil in the high-yield group was 8.0% and 28.6% higher than that in the middle- and low-yield group, respectively. The content of soil alkalized N in the high-yield group was 11.1% and 42.9% higher than that in the middle- and low-yield groups, respectively. Soil effective P content of the high-yield group was 50.2% and 94.4% higher than that of the middle- and low-yield group, respectively. Total K content of the soil in the high- and middle-yield groups was slightly different, but it was 20.2% and 23.5% higher than that in the low-yield group, respectively. The soil available K content in the high- and middle-yield groups were 14.8% and 13.7% higher than that of the low-yield group, respectively. The effective B content of the high-yield group was 29.4% and 57.1% higher than that of the middle- and low-yield groups, respectively. The effective Zn content of the high-yield group was 25.3% and 59.3% higher than that in the middle- and low-yield groups, respectively. The effective Cu content of the high-yield group was 23.4% and 61.2% higher than that of the middle- and low-yield groups, respectively. The soil organic matter content of the high-yield group was 16.5% and 90.9% higher than that of the middle- and low-yield groups, and that of the middle-yield group was 64% higher than that of the low-yield group.



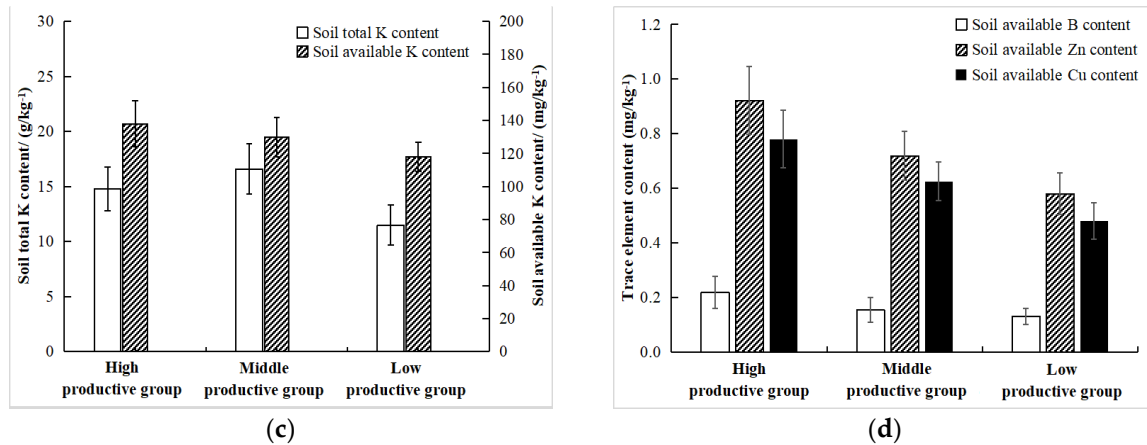


Figure 2. Main chemical and physical properties for each productivity group. (a) Performance of soil total N content and soil organic matter content under different productivity group, (b) Performance of soil total P content and soil available P content under different productivity group, (c) Performance of soil total K content and soil available K content under different productivity group, (d) Performance of soil available B content, soil available Zn content and soil available Cu content under different productivity group.

4. Discussion

4.1. Differences between site types of *E. urophylla* × *E. grandis* in southern Yunnan and other regions

Since the 1950s, Leizhou Forestry Bureau has had more than 60 years of Eucalyptus cultivation history, with several varieties planted such as *Eucalyptus exserta*, *Eucalyptus leizhou* No.1, *Eucalyptus urophylla*, *Eucalyptus ABL* No.12, *Eucalyptus urophylla* U6 clone, and TH and LH series clones of *Eucalyptus urophylla* × *Eucalyptus tereticornis*, etc. Zhang et al. [12] conducted a site index model study on *Eucalyptus ABL* No. 12 (W5 clone). Zhen et al. [13,14] adopted successive generations of continuous crop farming, and found that soil organic matter decreased significantly. The average single plant biomass decreased with the increase of continuous cropping [15], and there was a fertility decline phenomenon. At the same time, summer typhoons were frequent in the coastal areas of southern China, which was a major threat to the growth and cultivation of Eucalypts [16]. The survey period was relatively short, approximately 4 to 5 years, so it is difficult to classify site types in the Leizhou Peninsula, and Eucalypts cultivation in southern Yunnan has developed since the 1990s [17]. Since 2001, Yunnan Yunjing Forestry and Pulp Mill Co., Ltd and Leizhou Forestry Bureau have carried on the cooperative introduction and scale planting DH clones of *E. urophylla* × *E. grandis*. As this is relatively new, reforestation has not yet started. Therefore, the stand of the raw forest belongs to the first generation forest and first generation with 2–3 times sprouting forest, with no decline in soil fertility caused by continuous planting of multiple generations. In addition, there are no meteorological factors such as typhoons, and the survey period is mainly from 6 to 9 years, which can better reflect the site productivity of forest land. The excellent clones represented by *E. urophylla* × *E. grandis* DH clones were screened out, and their average annual accumulated growth was more than 30 m³ hm⁻², which basically was in accordance with the site production potential of this study [18]. Hence, the reliability of site type division of *E. urophylla* × *E. grandis* plantations in southern Yunnan has been further improved. However, the paper-wood properties and pulp yield of *E. urophylla* × *E. grandis* plantations will be analyzed in a later stage.

4.2. Main impact factors on site types of *E. urophylla* × *E. grandis* in southern Yunnan

Site type division and evaluation are the basis of scientific afforestation, and particularly important to evaluate the potential of site production [19]. Slope position, elevation, and slope direction are the dominant factors for site type classification of birch plantations in the southwestern

Daqing Mountains of Guangxi [20]. Meanwhile, soil nutrients, density, and texture are the dominant factors for the site types of teak plantations in Xishuangbanna, Yunnan [21], while slope position, altitude, and soil thickness are the dominant factors for the site types of *E. urophylla* × *E. grandis* plantations in southern Yunnan. Moreover, the growth of Eucalypts is greatly affected by the soil physical and chemical properties at different slopes. The soil layer downhill was more loose than that of the middle and upper slopes, and the ventilation, water permeability and conservation, as well as fertilizer retention ability downhill are better than those uphill, which is beneficial to promote root growth and normal development [22]. With decreasing slope, the soil layer thickness and soil moisture content have an increasing trend, which is related to the physical and chemical properties of the soil, and has a great impact on soil nutrition [23]. Furthermore, the conservation rate of Eucalypts plantations is little affected by different slope levels, but the annual average height and single timber volume of dominant trees increase with the decrease of slope position. In this study, the maximum value of annual average growth of the dominant trees at the lower slope was 4.02 m, while that at the top of the hill was 3.16 m. Such differences may be caused by the presence of certain shade between stands affecting photosynthesis or associated with drainage factors [24].

Additionally, some studies have shown that the biomass of Eucalypts plantation is significantly negatively correlated with the increase of elevation gradient, which changes the hydrothermal conditions, affecting the growth and development of stand, and reducing the biomass [25–28]. In this study, the elevation of *E. urophylla* × *E. grandis* in the high-yield group was generally below 1,400 m, while the altitude of the middle- and low-yield groups was more than 1,400 m. Therefore, at higher altitudes, sites were less suitable for the growth of *E. urophylla* × *E. grandis*.

4.3. Physical and chemical properties of soil and productivity

Nitrogen fertilizer can increase plant chlorophyll content and photosynthetic rate, and promote the growth of plant stems and leaves [29]. B, Zn, and Cu are essential trace elements for plant growth and development, and the lack of three trace elements is extremely detrimental to the growth of young Eucalypts forests and it will inhibit growth and cause physiological diseases [30–32]. When elements such as B, Zn, Cu, and Mn were applied alone, the production of *Eucalyptus* ABL No. 12 (W5 clone) and *Eucalyptus urophylla* exceeded that of unfertilized sites in three years [33]. B participates in the metabolism and transportation of carbohydrates in plants, and promotes the growth and development of the root system. B deficiency will lead to thin, curly, dark, and dull leaves, and the tip growth will be inhibited or withered shoots and branches will be produced. The lack of Zn results in shortened node spacing, smaller leaves, clusters of tender shoots, reddish leaves and their edges, or withered leaves, while Cu deficiency causes deformed leaves and young shoots. Furthermore, the texture of the leaves will become thicker, crisper, and dull or produce tip shoot [34].

Moreover, soil organic matter content represents soil fertility, and is an important source of various nutrients such as nitrogen, phosphorus, and trace elements required by plants. Increasing organic matter content plays an important role in high and stable yield of Eucalypts trees, and thus forest litter should be kept as much as possible [35]. Total N in soil has a great impact on the productivity level of *Eucalyptus grandis*, and ethanol deficiency can inhibit the growth of above-ground parts and roots of Eucalyptus, affect chlorophyll synthesis, cause leaf yellowing, and may cause spot blight [36].

According to our results and the soil nutrient grading standards of the second national soil census [37] (Table 7). the average content of soil organic matter and total N in the three productivity levels of *E. urophylla* × *E. grandis* plantations in southern Yunnan were 8.41–16.06 and 0.63–0.81 g kg⁻¹ respectively, both belong to lower middle level; Available P was 1.12–2.13 mg kg⁻¹, belonging to extremely level; Available K was 117.3–138.4 mg kg⁻¹, belonging to upper middle level; Available B was 0.14–0.22 mg kg⁻¹, between extremely low and low level; Available Zn was 0.59–0.91 mg kg⁻¹, belonging to upper middle level, and available Cu was 0.49–0.79 mg kg⁻¹, belonging to upper middle level. Available Zn and available Cu were 0.59–0.91 and 0.49–0.79 mg kg⁻¹ respectively, both belong to upper middle level. Therefore, for medium- and low-yield groups, N and P fertilizer should be

appropriately added, and at the same time, trace elements such as B, Zn, and Cu should be added to promote the growth and development of forests. The logging operations should keep the dead branches, fallen leaves, and harvested residues in the forest land to increase soil organic matter, thus providing a guarantee for later nutrient recycling.

Table 7. Standard for nutrient classification of the second National Soil Census

Soil chemical property		level					
		I	II	III	IV	V	VI
Organic matter	g/kg	>40	30–40	20–30	10–20	6–10	<6
Total N	g/kg	>2.0	1.5–2	1–1.5	0.75–1	0.5–0.75	<0.5
Available P	mg/kg	>40	20–40	10–20	5–10	3–5	<3
Available K	mg/kg	>200	150–200	100–150	50–100	30–50	<30
Available B	mg/kg	>2.0	1.0–2.0	0.5–1.0	0.2–0.5	<0.2	
Available Zn	mg/kg	>3.0	1.0–3.0	0.5–1.0	0.3–0.5	<0.3	
Available Cu	mg/kg	>1.8	1.0–1.8	0.2–1.0	0.1–0.2	<0.1	

Note: I represents extremely high level; II represents high level; III represents upper middle level; IV represents lower middle level; V represents low level; VI represents extremely low level.

Additionally, the soil of high-yield group was composed of red soil developed by the weathering of argillaceous rocks, which was intact and deep, thus ensuring that fertility lasted for a long time and Eucalypts grew vigorously. Therefore, proper tending and scientific management can give full play to the potential of site production, which is the best site for cultivation of *E. urophylla* × *E. grandis* with high pulp ratio and large diameter plywood. The soil of middle-yield group was mainly composed of lateritic red soil and natural red soil with deep development, i.e., good site conditions and production potential. Therefore, it is an ideal site to cultivate *E. urophylla* × *E. grandis* with high pulp ratio under proper management. The soil of low-yield group was mainly composed of purple sandy shale semi-weathered purple soil, where the biological accumulation effect was weak, soil development was not deep, water retention ability was low, and the site condition was poor. Thus, it is not suitable to cultivate fast-growing and high-yielding Eucalypts. However, it can be reformed to cultivate native tree species such as *Pinus kesiya* var. *langbianensis*, so as to avoid great loss.

5. Conclusion

Slope position, soil bulk density, and altitude were the dominant factors for the site types of *E. urophylla* × *E. grandis* plantations in southern Yunnan. *E. urophylla* × *E. grandis* grew best in the downhill, with relatively low elevation and thick soil layer composed of red soil developed by weathering of argillaceous rocks. *E. urophylla* × *E. grandis* grew relatively well on the middle and upper slopes, with slightly higher elevation and moderate soil bulk density, composed of red soil formed by the development of sandstone and shale and sandstone. *E. urophylla* × *E. grandis* grew comparatively less gently on the uphill and hilltops, with higher elevation and thinner soil layer than those of other sites, composed of purple semi-weathered soil of purple sandy shale rocks. Besides, total N, available B, soil organic matter, available Zn and Cu, and available P content had a significant effect on the growth of *E. urophylla* × *E. grandis*. However, the soils of this study were deficient in organic matter, total N, available P, B, Zn, K, and Cu. Hence, according to the above-mentioned site conditions and to achieve the full production potential of the forest stand, the selection of forest land should be combined with the actual situation, and a scientific and reasonable

management mode should be adopted to create a broader prospect for the development of *E. urophylla* × *E. grandis* plantation in southern Yunnan.

Author Contributions: H.L. organized the available literature and data, and subsequently developed the original draft of the manuscript. H.L., Y.W., Y.Z., J.B., G.S., C.J. and W.L. felled dominant trees and collected the soil samples. J.X. and H.L. planned and designed the research. J.X. and G.L. developed the original concept for the project, co-authored the proposal to fund the research and edited all subsequent drafts of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: Project supported by the National Key Research and Development Program of China “Eucalyptus high fiber pulpwood directional cultivation technology”(No. 2016YFD0600503).

Conflicts of Interest: The authors declare no conflict of interest.

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