Variations in biomass, nutrient contents and nutrient use efficiency among Chinese fir provenances

By Pengfei Wu[1], Mulualem Tigabu[2], Xiangqing Ma[1],[*], Per Christer Odén[2], Youlan He[1], Xintuo Yu[1] and Zhiying He[1]

Abstract

A provenance trial involving 16 Chinese fir provenances was established in southern China in 1979, and biomass, nutrient content and nutrient use efficiency were assessed at the age of 23. One-way analysis of variance revealed significant inter-provenance variation ($p < 0.0001$) in measured variables. The mean total biomass ranged from 98.8 ± 5.3 to 163.3 ± 4.2 t ha^{-1}, and the stemwood accounted for 47–65% of the total biomass, followed by roots (11–24%), stembark (7.4–13.7%), and needles and branches (<10%). Much of the nitrogen, phosphorus and potassium were stored in the needles, although the concentration varies among provenances. Whole-tree nutrient use efficiency varied from 115.4 ± 2.1 to 180.2 ± 1.02 g g^{-1}, while efficiency in stemwood production ranged from 53.9 ± 3.1 to 106.3 ± 1.1 g g^{-1}. Provenances did not display consistent variation in all measured variables, suggesting the need for multiple criteria for selection in future tree improvement program. In conclusion, the study reveals the existence of considerable variation in biomass production and nutrient use efficiency among Chinese fir provenances that can be exploited for selecting desirable genotypes for enhancing productivity of Chinese fir plantations.

Key words: Biomass production; *Cunninghamia lanceolata*; Tree improvement; forest nutrition.

Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is a fast-growing evergreen coniferous tree with high yield and excellent wood quality. Its natural distribution ranges from 34°03'N to 20°41'N latitude, distribute among 16 Provinces in China. The planting history of Chinese fir extends over more than 1000 years (Wu, 1984), but the area under Chinese fir plantations has expanded rapidly since the 1980s (Zhang et al., 2004). Chinese fir plantations are usually established for industrial timber production with a short rotation period of 20–25 years. Many short rotation plantations that couple intensive management may lead to high rates of nutrient removal during harvesting, thus raising concerns about tree nutrient utilization efficiencies (Wang et al., 1991).

The decline in yield of Chinese fir over successive rotations has been recognized and become a major concern among forest managers and scientists (Ma et al., 2000a, 2002, 2003; Tian et al., 2002). The standing wood volume of the second and third rotations of Chinese fir plantation decreased by 30% and 47%, respectively, compared to the first rotation (Chen, 1983). The dominant tree height of the second and third rotation of Chinese fir was reduced by 7% and 23%, respectively compared to the first rotation (Fang, 1987). In addition, degradation in soil physical, chemical, biological and biochemical properties under successive rotations of Chinese fir have been widely reported (Yang et al., 1996; Ying, 1997; Ma et al., 2000b; Yu et al., 2000; Sun et al., 2003; Zhang et al., 2004).

The traditional provenance trial for timber plantation mainly focused on tree growth and biomass productivity, but paid little attention to nutrient use efficiency of trees (Anonymous, 1991, 994; Li et al., 1993). A range wide provenance variation in growth, photosynthesis, and transpiration of Chinese fir has been observed (Yu, 1997; Shen et al., 1994). The patterns of biomass distribution in Chinese fir stands and the magnitude of nutrient loss associated with harvesting method have also been characterized (Li et al., 1994; Ying, 2004; Yang, 1999; Yang, 2000). However, these studies have rarely continued beyond comparison of total stand yield or conclusion of the order of biomass in tree components. Detailed information about biomass productivity and nutrient use efficiency of different provenances is still scarce. Thus, this study was carried out to characterize variations in biomass distribution and nutrient use efficiency among 16 Chinese fir provenances to identify fast-growing genotypes that have good nutrient-use efficiency and woody biomass productivity.

Materials and Methods

Study site

The study was carried out in a Chinese fir plantation established at the Xiqin Teaching Forest Farm (26°40'N, 118°10'E) of Fujian Agriculture and Forestry University, Nanping city in central Fujian Province, southern China. The climate of the study site is subtropical monsoon type, with an annual average temperature of 19.4°C and an annual average rainfall of 1786 mm. The average annual relative humidity is 81%, mean length

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Table 1. – Geographic locations and climatic conditions (mean annual rainfall and mean annual temperature) of the different provenances of Chinese fir included in the trial.

latitudinal zone		Provenance	Latitude (°N)	Longitude (°E)	Rainfall (mm)	Temperature (°C)
I	South Subtropic	Pubei, Guangxi	22.25	109.52	1804.3	21.4
		Wenshan, Yunnan	23.38	104.25	962.2	17.8
		Huaiji, Guangdong	23.93	112.18	1713.2	20.9
		Changtai, Fujian	24.62	110.73	1469.2	21.0
		Rongshui, Guangxi	25.13	109.23	1769.1	19.3
II	Middle Subtropic	Quannan, Jiangxi	24.76	114.52	1515.6	18.9
		Nanping, Fujian	26.67	118.17	1679.2	19.3
		Jinping, Guizhou	26.68	108.18	1375.3	16.5
		Chenxi, Hunan	28.02	110.18	1401.3	16.9
		Enshi, Hubei	30.27	109.37	1518.8	16.3
		Xuyong, Sichuan	28.14	105.47	1175.8	18.0
III	North Subtropic	Kaihua, Zhejiang	29.03	118.42	1704.1	16.4
		Jiande, Zhejiang	29.55	118.27	1440.4	17.0
		Xiuning, Anhui	29.77	118.18	1642.8	16.3
		Luoshan, Henan	32.22	114.55	1032.3	15.2
		Shangcheng, Henan	34.78	115.42	1197.5	15.5

of the growing season (sum of days with a daily mean temperature >5°C) is 300 days, and the frost season begins from the first ten days of November to early March of the second year. The stands are located at 150–200 m altitude on a slope of 25°. The soils were classified as mountainous red clay loam covered with thin humus, acidic oxisols. The Chinese fir plantation was established in 1979 using seeds obtained from 16 provenances in 13 provinces (*Table 1*). Pubei, Wenshan, Huaiji, Changtai and Rongshui represent the southern range of distribution of the species, Quannan, Nanping, Jinping, Chenxi, Enshi and Xuyong represent the central range, and Kaihua, Jiande, Xiuning, Luoshan and Shangcheng represent the northern distribution range (*Figure 1*). The planting site was divided into four blocks and with each block 16 plots were laid. Within a block, provenances were randomly assigned to the plots and 21 seedlings from each provenance were planted in each plot.

Estimation of tree biomass and nutrient analyses

The trial was assessed at the age of 23 years for height and diameter at breast height (DBH) of every tree in each plot. The mean average tree was used to estimate stand biomass as DBH and height did not vary much within each stand (MA et al., 2007). The average trees were felled at the ground level using a mechanical

chain saw and the roots carefully dug out from the different soil layers and washed with water. Aboveground part of sample tree was classified as stemwood, stembark, live branches, dead branches and needles. Fresh weights of all the tree components were weighed in the
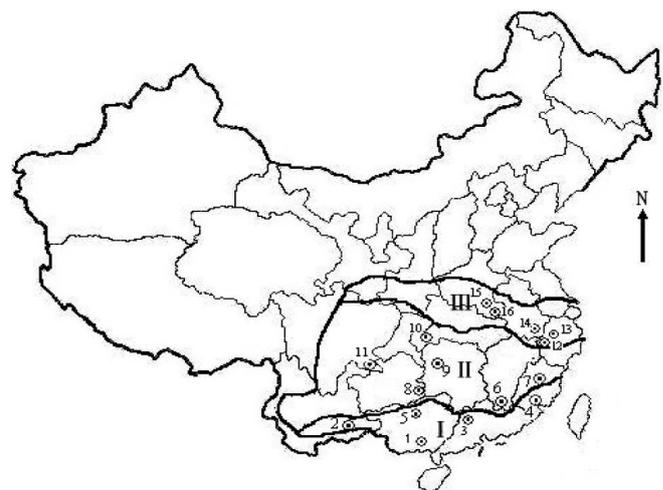
Figure 1. – Natural distribution of Chinese fir (I, II, III) and provenances represented in the trial (1: Pubei, 2: Wenshan, 3: Huaiji, 4: Changtai, 5: Rongshui, 6: Quannan, 7: Nanping, 8: Jinping, 9: Chenxi, 10: Enshi, 11: Xuyong, 12: Kaihua, 13: Jiande, 14: Xiuning, 15: Luoshan, 16: Shangcheng).

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field and then sub-sampled for determination of the dry mass and nutrient concentrations. All samples were dried at 80 °C to constant weight to determine the biomass. Biomass of all tree components was summed to obtain the mean tree biomass. It was then multiplied by the number of trees per plot and extrapolated to a hectare (KUMAR et al., 1998; SHUJAUDDIN et al., 2003).

Following dry weight determination, plant tissue samples were ground to pass a 1 mm mesh prior to chemical analyses. Triplicate samples were analyzed for N, P and K. Total nitrogen was determined by micro-Kjeldahl technique (PEACH and TRACY, 1956; MISRA, 1968). Phosphorus and potassium were extracted by wet ashing of 0.5 g plant material in an acid mixture consisting of 10 ml H_2SO_4, 3 ml HNO_3 and 1 ml $HClO_4$, following the method of LACKSON (1958). Phosphorus was determined following the molybdenum-blue method and potassium by flame photometry.

Data analysis

Nutrient contents of plant parts were calculated as the product of nutrient concentrations and plant dry matter. The stand nutrient content was obtained by multiplying each biomass fraction by the respective nutrient concentration and finally summing the contents of the individual fractions. The nutrient use efficiency (NUE) was calculated by two different equations based on the total amount of nutrient content in the stand biomass for whole tree as a quantity of total biomass built per unit of the nutrient in the biomass (WANG et al., 1991; VITOUSEK, 1982), and stem wood as a quantity of stem wood biomass produced per unit of nutrient in the biomass (HERBERT, 1996; AERTS, 1989) as follows:

$$\text{Whole-tree NUE} = \text{dry biomass of stand}/\text{nutrient content of stand} \qquad (1)$$

$$\text{Stem wood NUE} = \text{stem wood biomass of stand}/\text{nutrient content of stand} \qquad (2)$$

Table 2. – Estimates of variance components as percentage of the total variation, and phenotypic coefficient of variation (PCV) for biomass, nutrient content (Nitrogen, Phosphorus and Potassium) and nutrient use efficiency (NUE).

Trait	Grand Mean	Provenance	Error	PCV (%)
Biomass (t ha⁻¹)				
Needle	7.6	95.1	4.9	40.1
Live branch	10.3	93.1	6.9	37.3
Dead branch	3.4	95.8	4.2	48.6
Bark	13.1	87.1	12.9	25.7
Stem wood	75.8	56.5	43.5	13.3
Root	21.3	89.3	10.7	30.4
Total	131.5	88.2	11.8	15.8
Nitrogen content (g kg⁻¹)				
Needle	14.9	79.7	20.3	14.0
Live branch	7.6	91.7	8.3	31.0
Dead branch	4.0	93.3	6.7	32.9
Bark	6.7	94.5	5.5	36.6
Stem wood	2.5	80.5	19.5	46.1
Root	7.6	88.3	11.7	24.3
Phosphorus content (g kg⁻¹)				
Needle	1.1	96.2	3.8	43.4
Live branch	0.8	97.2	2.8	49.6
Dead branch	0.2	98.1	1.9	127.9
Bark	0.6	96.7	3.3	58.0
Stem wood	0.2	99.8	0.2	119.3
Root	0.5	97.3	2.7	57.1

Table 2. – Continued.

Trait	Grand Mean	Variance component (%)		PCV (%)
		Provenance	Error	
Potassium content (g kg⁻¹)				
Needle	5.3	87.0	13.0	18.7
Live branch	3.4	89.1	10.9	22.1
Dead branch	0.9	96.6	3.4	41.8
Bark	2.5	95.4	4.6	36.2
Stem wood	0.9	97.3	2.7	43.4
Root	3.3	83.0	17.0	19.7
NUE-whole tree (g g⁻¹)				
Nitrogen	211.3	96.5	3.5	15.9
Phosphorus	3573.4	99.2	0.8	46.3
Potassium	548.1	97.0	3.0	18.4
Overall NUE	143.6	95.5	4.5	13.9
NUE-stem wood (g g⁻¹)				
Nitrogen	123.6	90.2	9.8	21.5
Phosphorus	2086.5	97.4	2.6	48.8
Potassium	319.9	90.9	9.1	23.4
Overall NUE	83.9	88.2	11.8	19.6

One-way Analyses of variance was used to determine whether biomass, nutrient content and nutrient utilization efficiency differ significantly among provenances using SPSS Statistical Package (SPSS 13.0, SPSS Inc., IL, U.S.A.). Means that exhibited significant differences were compared using Tukey's test at 5% level of significance. The magnitude of variation, as percentage of the total variation, due to provenance or environment (error) was quantified for each trait using the restricted maximum likelihood method, and the phenotypic coefficient of variation was computed based on the overall mean and the total variance for each trait.

Results

Biomass production

Significant differences ($p < 0.001$) among Chinese fir provenances were detected for total biomass and biomass of various tree components. The magnitude of variation due to provenance was higher for total biomass and biomass of various tree components except stemwood biomass, although its phenotypic coefficient of variation was comparable to that of total biomass (*Table 2*). The mean total biomass ranged from 98.8 ± 5.3 t ha⁻¹ to 163.3 ± 4.2 t ha⁻¹. The highest mean total biomass was recorded for Changtai and Xiuning while the lowest value was recorded for Kaihua and Jiande (*Figure 2*). For needles, the mean biomass varied from 2.8 ± 0.2 t ha⁻¹ to 12.5 ± 0.8 t ha⁻¹, and Changtai, Shangcheng and Chenxi recorded the highest value while Xuyong, Kaihua and Huaiji recorded the lowest. The mean biomass of live branches ranged from 4.9 ± 0.4 t ha⁻¹ to 17.3 ± 1.4 t ha⁻¹, and Changtai recorded the highest while Xuyong and Kaihua the least values for this trait. For dead branches, the mean biomass varied from 0.9 ± 0.1 t ha⁻¹ (Shangcheng) to 5.9 ± 0.3 t ha⁻¹ (Enshi). For stembark, the mean biomass ranged from 9.0 ± 0.9 t ha⁻¹ to 19.1 ± 1.9 t ha⁻¹. Wenshan, Xiuning and Pubei had the highest value for this trait while the lowest value was recorded for Kaihua, Huaiji and Quannan. The mean stemwood biomass varied between 58.3 ± 5.8 t ha⁻¹ (Jiande) and 87.2 ± 6.9 t ha⁻¹ (Xiuning). The mean root biomass varied between 14.2 ± 0.7 t ha⁻¹ and 39.4 ± 4.7 t ha⁻¹; Changtai had the highest value while Rongshui, Kaihua and Huaiji had the lowest value for this trait. Ranking of provenances did not show a consistent trend for all biomass estimates. However, Kaihua, Xuyong and Jiande ranked the lowest for most biomass estimates while Xiuning, Changtai and Wenshan recorded the highest values.

In all provenances, much of the biomass was accumulated in the stem wood, which accounted for 46.6% to

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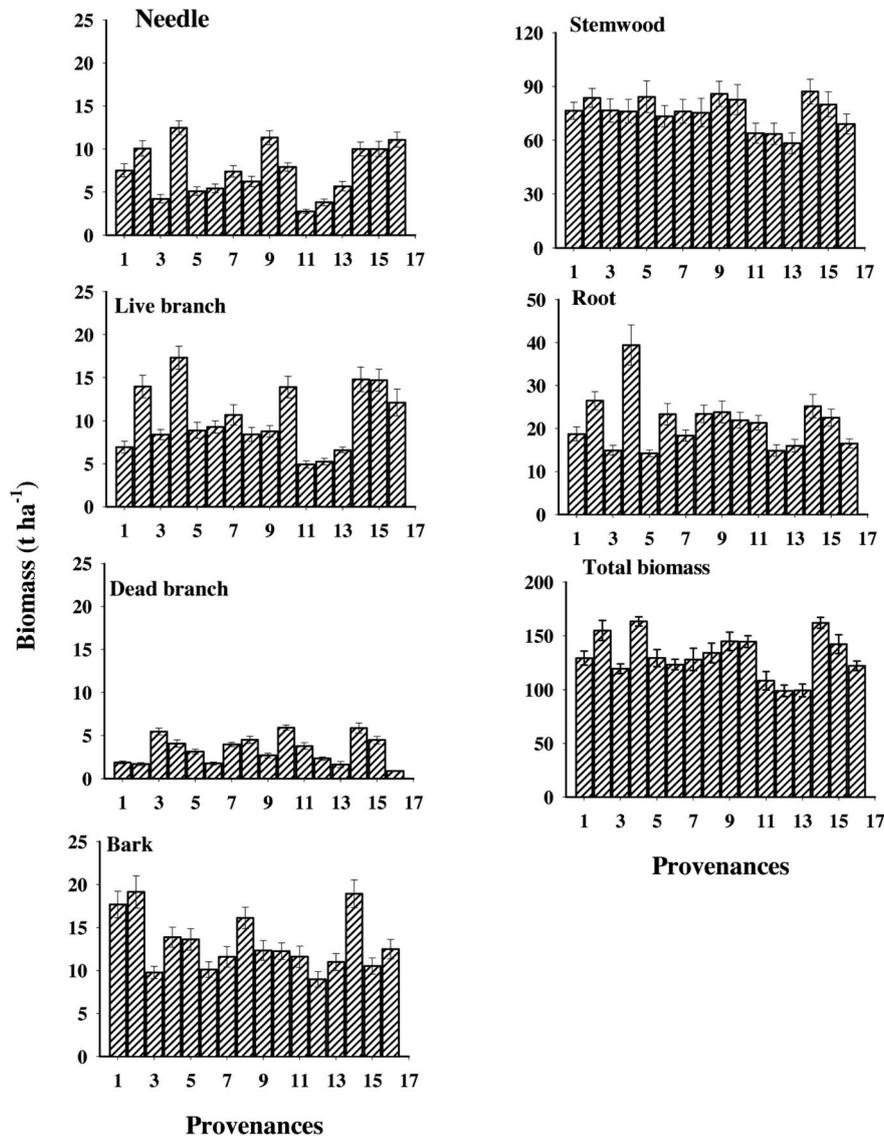
Figure 2. – Total biomass accumulation (t ha⁻¹) and biomass of various tree components for 16 Chinese fir provenances (mean ± se).
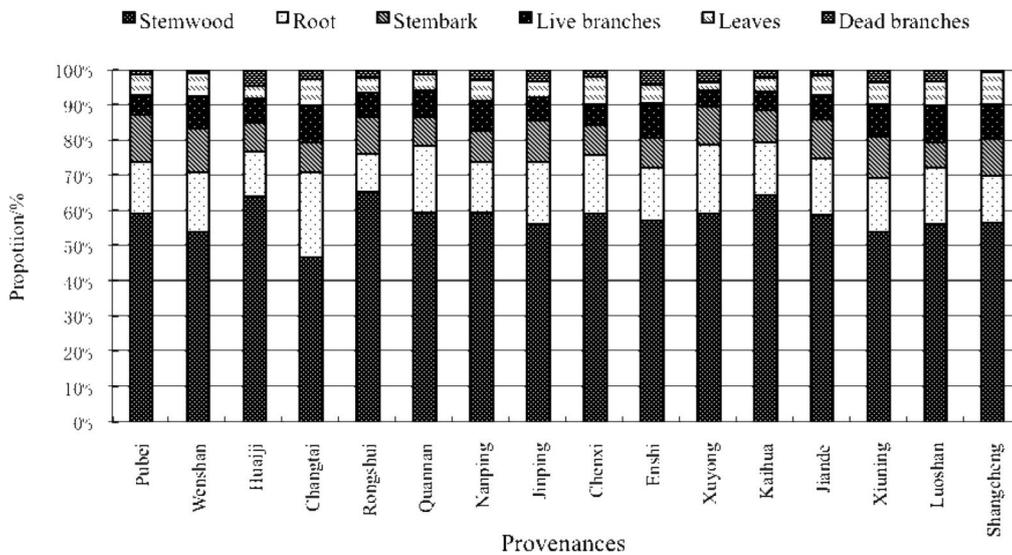
Figure 3. – Biomass distribution patterns among various tree components for 16 Chinese fir provenances.

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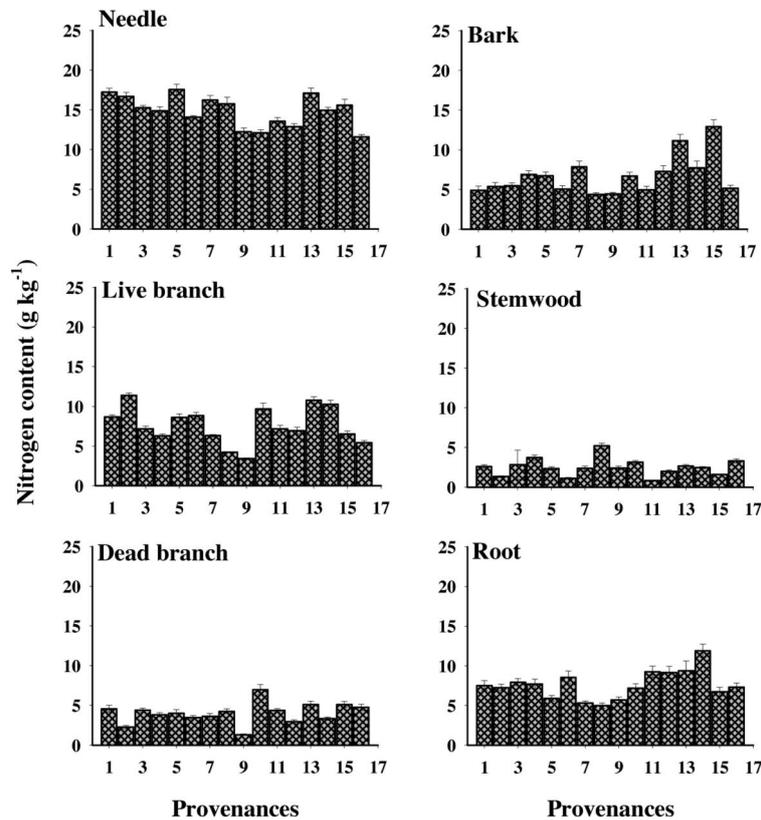
Figure 4. – Nitrogen content (g kg⁻¹) of various tree components for 16 Chinese fir provenances (mean ± se).

65.2% of the total biomass (*Figure 3*). Percentage contribution of roots to the total biomass ranged from 11.0% to 24.1%, while that of bark was generally low, 7.4–13.7%. The contribution of either branches or needles to the total biomass was ≤10%. As a whole, the biomass distribution among different tree components was as follows stemwood > root > stembark > live branches > needle > dead branches.

Nutrient content

The concentration of nitrogen, phosphorus and potassium in various tree components varied significantly among provenances ($p < 0.0001$), and more that 79% of the variation was due to provenance (*Table 2*). The PCV was considerably higher for phosphorus content than the corresponding nitrogen and potassium contents in various tree components. Unlike other tree components, stemwood and dead branches had the highest PCV in phosphorus content. Much of the nitrogen was stored in the needles followed by root, live branches, stembark, dead branches and stemwood, respectively. The mean nitrogen content of needles ranged from 11.6 ± 0.5 to 17.5 ± 0.7 g kg⁻¹; of live branches from 3.4 ± 0.1 to 11.4 ± 0.3 g kg⁻¹; of dead branches from 1.3 ± 0.1 to 7.0 ± 0.4 g kg⁻¹; of stembark from 4.4 ± 0.1 to 12.9 ± 0.5 g kg⁻¹; of stemwood from 0.8 ± 0.03 to 5.2 ± 0.2 g kg⁻¹; of root from 5.0 ± 0.2 to 11.9 ± 0.5 g kg⁻¹ (*Figure 4*). Ranking of provenances with respect to nitrogen content of various tree components was not consistent. Shangcheng, Chenxi, Jinping, and Xuyong had the lowest nitrogen content in needles, branches, stembarks, and stemwood,

respectively. Jinping also recorded the lowest value for root nitrogen content. The nitrogen content was the highest in needles for Rongshui, in live branches for Wenshan, in dead branches for Enshi, in stembark for Luoshan, in stemwood for Jinping and in roots for Xiuning.

Much of the phosphorus was stored in the needles, live branches, stembark and root while it was much less in the dead branches and stemwood. The mean phosphorus content ranged between 0.4 ± 0.01 and 2.0 ± 0.1 g kg⁻¹ for needles; $0.2 \pm 0.01 - 1.4 \pm 0.1$ g kg⁻¹ for live branches; $0.04 \pm 0.003 - 0.9 \pm 0.04$ g kg⁻¹ for dead branches; $0.2 \pm 0.004 - 1.5 \pm 0.1$ g kg⁻¹ for stembark; $0.04 \pm 0.001 - 0.7 \pm 0.02$ g kg⁻¹ for stemwood; and $0.2 \pm 0.01 - 1.2 \pm 0.1$ g kg⁻¹ for root. Luoshan consistently recorded the highest value for this trait in various tree components while Xiuning, Chenxi, Jiande and Nanping recorded the lowest phosphorus content in needles, dead branches, stemwood and roots, respectively while Quannan had the lowest phosphorus content in live branches and stembark.

The potassium content of the various tree components also varied significantly among provenances, and much of it was stored in the needles followed by live branches, roots and barks while dead branches and stemwood were relatively poor in potassium content. The mean potassium content ranged from 3.4 ± 0.1 to 7.1 ± 0.2 g kg⁻¹ for needles; $2.2 \pm 0.1 - 5.3 \pm 0.2$ g kg⁻¹ for live branches; $0.2 \pm 0.02 - 1.8 \pm 0.1$ g kg⁻¹ for dead branches; $1.4 \pm 0.1 - 4.7 \pm 0.2$ g kg⁻¹ for stembark; $0.6 \pm 0.02 -$

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Table 3. – N, P, K and overall nutrient use efficiency of 16 Chinese fir provenances based on whole tree estimate (Mean ± se).

Provenance	Whole-tree NUE (g g⁻¹)			
	N	P	K	Overall
Pubei	207.10 ± 1.02d	1751.51 ± 6.02b	538.42 ± 0.89d	137.81 ± 0.36c
Wenshan	210.15 ± 1.80de	3599.71 ± 43.51ef	590.57 ± 3.51ef	148.60 ± 1.20de
Huaiji	223.21 ± 4.42ef	1735.19 ± 22.96b	780.02 ± 12.53h	157.77 ± 2.91ef
Changtai	164.86 ± 2.67a	2711.91 ± 83.48c	448.16 ± 9.00bc	115.39 ± 2.06a
Rongshui	233.79 ± 4.19fg	3896.06 ± 136.58fg	613.74 ± 13.87fg	162.25 ± 3.23f
Quannan	248.56 ± 8.19gh	5990.31 ± 119.31i	560.13 ± 19.29de	167.35 ± 5.53f
Nanping	224.80 ± 0.53ef	7011.28 ± 16.59j	629.79 ± 3.46fg	161.84 ± 0.51f
Jinping	183.31 ± 1.34b	3462.52 ± 106.44e	641.27 ± 9.66g	136.91 ± 1.32c
Chenxi	254.07 ± 3.80h	3612.59 ± 124.85ef	489.58 ± 7.17c	159.86 ± 2.51f
Enshi	187.33 ± 3.86bc	1724.37 ± 16.95b	463.93 ± 14.09bc	123.85 ± 2.78ab
Xuyong	273.12 ± 1.64i	3243.64 ± 31.51de	633.22 ± 2.70fg	180.21 ± 1.02g
Kaihua	235.32 ± 6.19fg	5306.86 ± 95.79h	387.22 ± 4.96a	142.43 ± 3.01cd
Jiande	164.26 ± 2.53a	2955.75 ± 105.85cd	543.08 ± 14.62d	120.95 ± 2.27ab
Xiuning	165.22 ± 2.67a	4988.05 ± 77.06h	431.55 ± 3.83b	116.68 ± 1.65a
Luoshan	206.30 ± 1.39d	1042.69 ± 4.56a	552.95 ± 3.53de	131.32 ± 0.83bc
Shangcheng	199.62 ± 2.61cd	4142.37 ± 111.55g	465.73 ± 13.97bc	135.15 ± 2.47c
Mean	211.32 ± 4.74	3573.43 ± 233.73	548.09 ± 14.26	143.65 ± 2.82

2.1 ± 0.1 g kg⁻¹ for stemwood; and $2.5 \pm 0.1 - 4.3 \pm 0.2$ g kg⁻¹ for root. Ranking of provenances according to potassium content of various tree components was not consistent. Huaiji recorded the lowest values in needles and stembark, Luoshan in stemwood and roots, Chenxi in live branches, and Jiande in dead branches. The highest values for this trait was recorded for Shangcheng in needles, Enshi in live branches, Xuyong in dead branches, Luoshan in stembark, Kaihua in stemwood and Quannan in the roots.

Nutrient-use efficiency

Nutrient use efficiency for N, P, K and total NUE, based on both whole-tree and stem wood estimates, varied significantly (p<0.0001) among provenances, and much of the variation was attributed to provenances (*Table 2*). The PCV was higher for P use efficiency than N and K use efficiencies. In terms of whole-tree nutrient use efficiency, Xuyong was the most efficient provenance for N, and Xiuning and Changtai were the least (*Table 3*). Most efficient provenances for P and K uses were Nanping and Huaiji, respectively while Loshan and Kaihuan were the least efficient provenances (*Table 3*). While Xuyong was the most efficient in overall NUE,
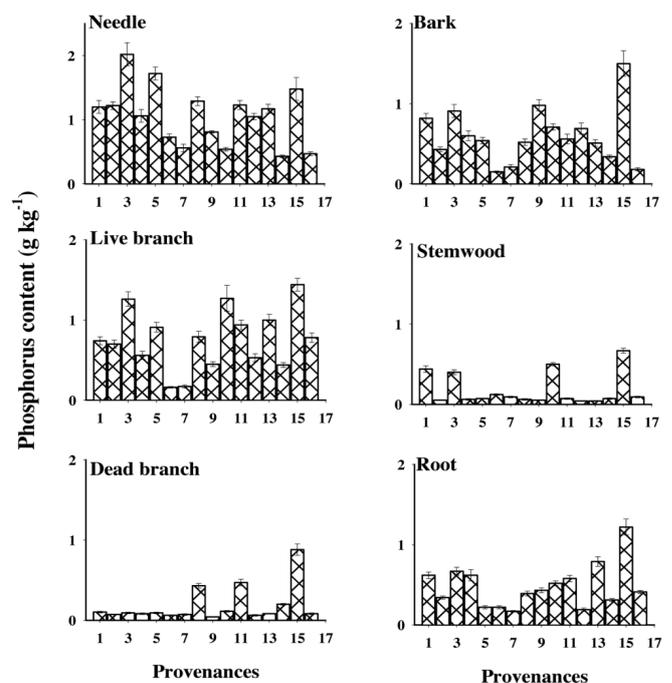
Figure 5. – Phosphorus content (g kg⁻¹) of various tree components for 16 Chinese fir provenances (mean ± se).

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Table 4. – N, P, K and overall nutrient use efficiency of 16 Chinese fir provenances based on stem wood estimate (Mean ± se).

Provenance	Stem wood-NUE (g g⁻¹)			
	N	P	K	Overall
Pubei	122.55 ± 0.32def	1036.44 ± 11.29b	318.60 ± 2.91cde	81.54 ± 0.40cdef
Wenshan	113.41 ± 1.15cde	1942.54 ± 25.70cd	318.69 ± 2.54cde	80.19 ± 0.78cde
Huaiji	143.21 ± 6.69fgh	1112.92 ± 44.37b	500.38 ± 21.52g	101.22 ± 4.59g
Changtai	76.96 ± 4.31a	1267.41 ± 88.97b	209.27 ± 12.51a	53.87 ± 3.10a
Rongshui	152.32 ± 6.56gh	2540.60 ± 151.86ef	399.96 ± 19.04f	105.72 ± 4.75g
Quannan	147.98 ± 8.47gh	3563.90 ± 157.13g	333.50 ± 19.59de	99.63 ± 5.71g
Nanping	133.55 ± 1.07efg	4165.08 ± 32.46h	374.15 ± 4.23ef	96.14 ± 0.85fg
Jinping	102.98 ± 2.91bcd	1947.12 ± 102.07cd	360.38 ± 13.21ef	76.92 ± 2.38bcd
Chenxi	150.58 ± 4.32gh	2142.19 ± 103.38cde	290.15 ± 8.23bcd	94.74 ± 2.79efg
Enshi	107.14 ± 6.61bcd	985.41 ± 50.03b	265.56 ± 18.98abc	70.85 ± 4.49bc
Xuyong	161.09 ± 1.71h	1913.23 ± 27.71cd	373.48 ± 3.27ef	106.29 ± 1.09g
Kaihua	151.43 ± 7.39gh	3413.67 ± 138.69g	249.02 ± 8.82ab	91.63 ± 4.00defg
Jiande	96.50 ± 3.69abc	1738.09 ± 102.02c	319.22 ± 15.89cde	71.07 ± 3.00bc
Xiuning	88.95 ± 4.09ab	2685.24 ± 121.69f	232.23 ± 8.99ab	62.81 ± 2.76ab
Luoshan	115.98 ± 2.61cde	586.16 ± 11.89a	310.87 ± 6.89cde	73.83 ± 1.64bc
Shangcheng	112.86 ± 4.76cde	2343.64 ± 128.72def	263.56 ± 15.43abc	76.43 ± 3.62bcd
Mean	123.59 ± 3.76	2086.48 ± 143.87	319.94 ± 10.57	83.93 ± 2.33
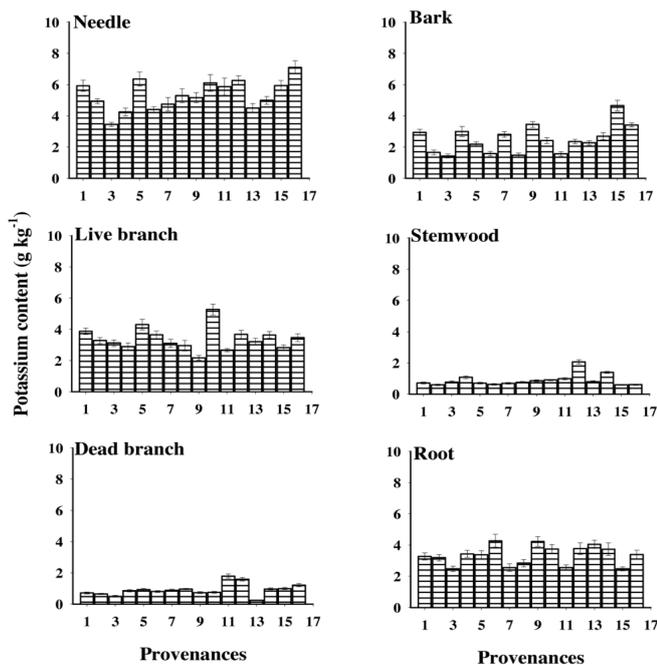
Figure 6. – Potassium content (g kg⁻¹) of various tree components for 16 Chinese fir provenances (mean ± se).

Xiuning and Changtai were the two least efficient provenances (*Table 3*). It is interesting to note that the overall NUE followed a similar order as that of nitrogen use efficiency, implying the leading role of nitrogen use in deciding total nutrient use efficiency, as N accounted approximately 62–75 % of the total nutrient content.

Viewed from the point of stem wood nutrient use efficiency, Xuyong again ranked the best in nitrogen use efficiency followed by Quannan, Wenshan and Luoshan, while Changtai was the least efficient provenance (*Table 4*). With regard to P use efficiency, Nanping appeared to be the most efficient while Luoshan, a provenance from the most northern, represented the least P use efficiency. The K use efficiency was the greatest in Huaiji, but the least in Changtai.

Discussion

In general, determinants of patterns of genetic variation in plant populations are extremely varied and involve complex interactions between plant attributes, such as life form, floral architecture, modes of reproduction, mating system, and ecological and environmental factors that may influence pollination events, population

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size and isolation (HAMRICK et al., 1992; PROBER and BROWN, 1994; COATES and BYRNE, 2005). In addition, the large heterogeneity in environmental conditions within the natural range of distribution of the species would favor monomorphic, specialized and genetically different populations while heterogeneity in time of reproductive events may lead to polymorphy within populations. In fact, a range wide provenance variation observed in growth, photosynthesis, and transpiration of Chinese fir (YU, 1997; SHEN et al., 1994) is an indicator for the existence of genetic variation for a number of other traits. Substantial genetic variation among natural populations for a variety of quantitative traits has been documented for economically useful tropical plantation species such as *Cordia africana* Lam. (LOHA et al., 2006, 2009), *Millettia ferruginea* (Hochst.) Baker (LOHA et al., 2008), *Vitellaria paradoxa* C.F. Gaertn. (LAMIEN et al., 2007), *Gmelina arborea* Roxb. (LAURIDSEN, 2004; HODGE and DVORAK, 2004), *Tectona grandis* L.f. (JAYASANKAR et al., 1999) and *Hevea brasiliensis* (Willd. ex Adr. de Juss) Muell.-Arg. (ALIKA, 1980).

The occurrence of Chinese fir over a wide geographical range, encompassing a great diversity in edapho-climatic conditions of its habitat, is expected to be reflected in the genetic constitution of its diverse populations. In the present study, a considerable variation in biomass, nutrient content and NUE was observed among provenances, and most of the total variation was a provenance effect (*Table 2*). Differences in local topography and regional environment as well as geographical and ecological isolations generally account for variation in biomass productivity among Chinese fir provenances (ANONYMOUS, 1994). Within the provenance region, the growth and productivity of Chinese fir declines gradually from central habitat to boundary area with varied geography and eco-climatic conditions, thus lead to quantitative and qualitative differences in biomass and wood production among provenances within the region. As a whole, the variation among provenances indicates that there is a great scope for further selection of genotypes to enhance productivity of Chinese fir in short-rotation plantations.

From total biomass production viewpoint, Changtai and Wenshan from the southern range and Xiuning from the northern range of distribution of Chinese fir performed best. Generally, growth of Chinese fir declines towards the northern range of its distribution. However, provenances from the south and north performed well in terms of biomass production when planted in the central distribution region. This is in line with the fact that when species move to a "new" environment, they express their full genetic potential for growth. However, the prime goal in short-rotation forestry is to produce a good quality timber in the shortest possible time. In this regard, Xiuning, Chenxi, Rongshan and Wenshan would be the target provenances for future planting on sites similar to the study area, as they have the highest stemwood biomass.

High biomass production obviously is an important consideration in all commercial tree-planting programs. However, provenances should not be selected only on growth traits but also on the nutrient cost of biomass removed by harvesting (KUMAR et al., 1998). Nutrient use efficiency provides a good measure to evaluate the differences in nutrient costs of biomass production (WANG et al., 1991; KUMAR et al., 1998). Provenance selection that considers nutrient use efficiency, therefore, is a potential tool available to the forest managers to limit the cost of fertilizing needed to maintain stand growth and soil fertility. There is also growing evidence pointing to yield reduction and carbon stock change in successive rotation of Chinese fir plantations due to depletion of the soil fertility (e.g. CHEN, 1983; FANG, 1987; MA et al., 2003; ZHANG et al., 2004). Thus, provenances that are not only yielding good stemwood but also efficient in their nutrient use should be considered in future planting. For this purpose, Rongshui and Chenxi appear to be the best candidate in terms of both overall nutrient use efficiency and stemwood production. Xuyong is, however, the most efficient of all provenances in terms of nitrogen use efficiency and overall nutrient use efficiency, thus it can be planted on poor sites despite its low biomass and stemwood production.

Given their high nitrogen use efficiency, Chenxi, Quannan, Rongshui and Kaihua can be suitable provenances for planting on nitrogen-deficient sites while Hauiji, Jinping, Rongshui and Nanping are suitable for potassium-limited sites. Available phosphorus is the major growth limiting factor in Chinese fir plantation areas (WU et al., 2001). For such areas, Nanping, Quannan, Kaihua and Xiuning would be the target source of planting materials, as they are the most efficient in their phosphorus use. On the contrary, Luoshan exhibited the greatest concentrations of P in various tree components despite better NUE for N and K. Consequently, choosing Luoshan to plant in the south subtropic zone where the soil is limited in phosphorus availability would aggravate/accelerate depletion of soil P.

Stemwood has made up the main part of the total stand biomass in all provenances, thus nutrients stored in the stemwood could not be small. Hence, the current harvesting practices for Chinese fir plantations of clear-cutting all trees at the same time and removing the stems (and bark), which contain 68% of the tree biomass nutrient store, may cause nutrient depletion of the site. It is therefore recommended that the harvest residues (needles, branches and roots) are retained on the site (as is currently practiced) in order to maximize the retention of nutrients at the site. It should be noted that a considerable amount of nutrients (N, P, and K) is stored in the needles, branches and roots irrespective of the provenances. Nutrient turnover time (the time taken for 95% of the litter to decompose) of Chinese fir litter is slow and hence the nutrients in litterfall are not instantly available to the tree (MA et al., 2007). Thus proper management of harvest residue for enhanced recycling of nutrients back to the soil should be designed.

Conclusions

The study reveals the existence of considerable variation in biomass, nutrient content and nutrient use effi-

ciency among Chinese fir provenances, which can be exploited further for selecting desirable genotypes for enhancing productivity of Chinese fir plantations. The fact that none of the provenances displayed consistent variation for biomass, nutrient content and NUE suggests the need for multiple criteria for selection in future tree improvement program. As this study is based on single planting site, further genotype × location study is recommended to select genotypes suitable for different purposes and site conditions.

Acknowledgements

References

AERTS, R. (1990): Nutrient use efficiency in evergreen and deciduous species from heathlands. Oecologia **84**: 391–397.

ALIKA, J. E. (1980): Genetic variation among Nigerian Havea provenances. Silvae Genetica **29**: 201–205.

ANONYMOUS (1991): Selecting and applying fine strain origins of *Cunninghamia lanceolata* in afforestation districts of Zhejiang province. Cooperative group of Cunninghamia lanceolata research in Zhejiang. Journal of Zhejiang Forest Science & Technology **11**: 31–38 (in Chinese, with English abstract).

ANONYMOUS (1994): Study on division of Chinese fir provenance. National Cooperative Group of Chinese fir Provenance Test. Forest research – memoir of Chinese fir provenance test **7**: 130–144 (in Chinese, with English abstract).

CHEN, L. (1983): Effects of successive rotation on the growth of Chinese fir and soil fertility in Yongshui of Guangxi Province. Guangxi Journal of Forestry Invention **12**(1): 17–25 (in Chinese).

COATES, D. J. and M. BYRNE (2005): Genetic variation in plant populations: assessing cause and pattern, pp. 139–164. *In:* Plant Diversity and Evolution: Genotypic and phenotypic variation in Higher Plants, edited by R. J. HENRY, CABI Publishing, Wallingford / Massachusetts.

FANG, Q. (1987): Influences of continuous cropping on soil fertility and stand growth in Chinese fir plantation. Scientia Silvae Sinicae **23**(4): 389–397 (in Chinese, with English abstract).

HAMRICK, J. L., M. J. GODT and S. L. SHERMAN-BROYLES (1992): Factors influencing levels of genetic diversity in woody plant species. New Forests **6**: 92–124.

HERBERT, M. A. (1996): Fertilizers and Eucalypt plantations in South Africa, pp. 303–325. *In:* Nutrition of Eucalypts, edited by P. M. ATTIWILL and M. A. ADAMS, CSIRO, Australia.

HODGE, G. R. and W. S. DVORAK (2004): The CAMCORE international provenance/progeny trials of *Gmelina arborea*: genetic parameters and potential gain. New Forests **28**: 147–166.

JACKSON, M. L. (1958): Soil Chemical Analysis. Prentice-Hall, Englewood Cliffs, NJ.

JAYASANKAR, S., L. C. BABU, K. SUDHAKAR and V. K. G. UNNITHAN (1999): Provenance variation in seed and germination characteristics of teak (*Tectona grandis* L.F.). Seed Science and Technology **27**: 131–139.

KUMAR, B. M. S. J. GEORGE, V. JAMALUDHEEN and T. K. SURESH (1998): Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. Forest Ecology and Management **112**: 145–163.

LAMIEN, N., M. TIGABU, S. GUINKO and P. C. ODEN (2007): Variations in dendrometric and fruiting characters of *Vitellaria paradoxa* populations and multivariate models for estimation of fruit yield. Agroforestry Systems **69**: 1–11.

LAURIDSEN, E. B. (2004): Features of some provenances in an international provenance experiment of *Gmelina arborea*. New Forests **28**: 127–145.

LI, X., L. HUANG, L. SUN, K. FAN, X. DU, Y. JIN, J. LV, Z. HUA, H. LU, C. SUN and G. XIE (1993): Study on elite provenance selection of *Cunninghamia lanceolata* for short rotation timber. Journal of Jiangsu Forestry Science & Technology **3**: 1–7 (in Chinese, with English abstract).

LI, X., L. HUANG, Y. LI, Z. HUA and Y. WU (1994): Geographic variation in trunk wood and aboveground biomass among various Chinese fir provenances, J Jiangxi Forestry Science & Technology **149**(3–4): 128–133 (in Chinese, with English abstract).

LOHA, A., M. TIGABU, D. TEKETAY, K. LUNDKVIST and A. FRIES (2006): Provenance variation in seed morphometric traits, germination and seedling growth of *Cordia africana* Lam. New Forests **32**: 71–86.

LOHA, A., M. TIGABU and A. FRIES (2008): Variability in seed- and seedling-related traits of *Millettia ferruginea*, a potential agroforestry species. New Forests **36**: 67–78.

LOHA, A., M. TIGABU and A. FRIES (2009): Genetic variation among and within populations of *Cordia africana* in seed size and germination responses to constant temperatures. Euphytica **165**: 189–196.

MA, X., A. LIU, Z. MA and S. FAN (2000a): A comparative study on nutrient accumulation and distribution of different generations of Chinese fir plantation. Chinese Journal of Applied Ecology **11**(4): 501–506 (in Chinese, with English abstract).

MA, X., S. FAN, A. LIU, S. CHEN and S. LIN (2000b): A comparison on soil fertilities of Chinese fir plantations of different generations. Forestry Research **13**(6): 577–582 (in Chinese, with English abstract).

MA X., S. KANG, Y. HUANG, K. LIN and S. FAN (2002): Effects of multi-rotation of Chinese fir plantations on granite sites. Journal of Fujian College of Forestry **22**(4): 289–294 (in Chinese, with English abstract).

MA, X., K. V. HEAL, A. LIU and P. G. JARVIS (2007): Nutrient cycling and distribution in different-aged plantations of Chinese fir in southern China. Forest Ecology and Management **243**: 61–74.

MISRA, R. (1968): Ecology Work Book. Oxford and IBH Publishing, Calcutta.

PEACH, K. and M. V. TRACY (1956): Modern Methods of Plant Analysis. Springer/Verlag, Berlin.

PROBER, S. M. and A. H. D. BROWN (1994): Conservation of the grassy white box woodlands: Population genetics and fragmentation of *Eucalyptus albens*. Conservation Biology **8**: 1003–1013.

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SHEN, X., C. HONG, J. XU, Y. WU, G. XIA and G. XU (1994): Study on geographic variability of *Cunninghamia lanceolata* provenance. Journal of Zhejiang Forestry Science & Technology **14**: 20–24 (in Chinese, with English abstract).

SHENG, W. and S. FAN (2005): Long term productivity of Chinese fir plantations. Science press, Beijing (in Chinese).

SHUJAUDDIN, N. and B. M. KUMAR (2003): *Ailanthus triphysa* at different densities and fertilizer regimes in Kerala, India: growth, yield, nutrient use efficiency and nutrient export through harvest. Forest Ecology and Management **180**: 135–151.

SUN, Q., C. YANG and R. JIAO (2003): The changes of soil properties of the successive Chinese fir plantation in Dagang Mountain of Jiangxi Province. Scientia Silvae Sinicae **39**(3): 1–5 (in Chinese, with English abstract).

TIAN, D., W. XIANG, W. YAN and W. KANG (2002): Effect of successive rotation on productivity and biomass of Chinese fir plantation at fast growing stage. Scientia Silvae Sinicae **38**(4): 14–18 (in Chinese, with English abstract).

VITOUSEK, P. M. (1982): Nutrient cycling and nutrient efficiency. The American Naturalist **119**(4): 553–572.

WANG, D., F. H. BORMANN, A. E. LUGO and R. D. BOWDEN (1991): Comparison of nutrient-use efficiency and biomass production in five tropical tree taxa. Forest Ecology and Management **46**: 1–21.

WU, Z. (1984): Chinese Fir. Chinese Forestry Press, Beijing (in Chinese).

WU, W., T. ZHANG, C. GAO, B. SUN, B. PENG and Q. ZHAO (2001): Changes of soil fertility quality properties under artificial Chinese fir forest in red soil region. Acta Pedologica Sinica **38**(3): 285–294.

YANG, C., X-Q ZHANG and R. JIAO (1996): Variations of chemical properties, biochemical, microorganism activities and function in soil of successive rotation of Chinese fir and their influences on growing. Scientia Silvae Sinicae **32**(2): 175–181 (in Chinese, with English abstract).

YANG, Y., G. CHEN, J. XIE and X. YU (2000): Effect of harvesting and cleaning on nutrition in Chinese fir plantation. Journal of Natural Resources **15**: 133–137 (in Chinese, with English abstract).

YANG, Y., D. YE, X. YU and G. CHEN (1999): Stand biomass in different rotations of Chinese fir. Journal of Northeast Forestry University **27**: 9–12 (in Chinese, with English abstract).

YING, J. (1997): Comparative study on the growth and soil properties under different successive rotation of Chinese fir. Journal of Jiangsu Forestry Science and Technology **24**(1): 31–34 (in Chinese, with English abstract).

YING, J., Z. HE, S. FAN, H. SU and H. LIAN (2004): Research on biomass and its distribution of a 29-year-old, first rotation Chinese fir plantation, Journal of Fujian Forestry College **21**: 339–342 (in Chinese, with English abstract).

YU, X. (1997): Chinese Fir Silviculture. Fujian Science and Technology Press, Fuzhou (in Chinese).

YU, X. and Q. ZHANG (1989): Study on soil biochemical character and its fertility in the successive planting site of Chinese fir plantation. Journal of Fujian Forestry College **9**: 263–271 (in Chinese, with English abstract).

YU, Y., X. DENG, W. SHENG, S. FAN, Q. LIN and L. LEI (2000): Effects of continuous plantation of Chinese fir on soil physical properties. Journal of Nanjing Forestry University **24**(6): 36–40 (in Chinese, with English abstract).

ZHANG, X-Q., M. U. F. KIRSCHBAUM, Z. HOU and Z. GUO (2004): Carbon stock changes in successive rotations of Chinese fir (*Cunninghamia lanceolata* (Lamb) Hook) plantations. Forest Ecology and Management **202**: 131–147.

Genetic parameter estimates and parental selection in *Eucalyptus longirostrata* and *Corymbia henryi* populations tested in South Africa

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Abstract

The sub-tropical species, *Eucalyptus longirostrata* (formerly *E. punctata* var *longirostrata*) and *Corymbia henryi* were investigated as alternative species for growth on the Zululand coastal plain in South Africa. Provenance/progeny trials were established in 2001 at two sites, namely, Nyalazi and Kwambonambi. The seed material purchased from the Commonwealth Scientific and Industrial Research Organization in Australia in 2000 included six provenances of *E. longirostrata* and five provenances of *C. henryi*. Six-year diameter at breast height measurements were completed in 2007. Individual narrow-sense heritability coefficients for diameter growth varied from 0.30 to 0.58 for both species, with heritabilities being higher at the drier

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