EFFECTS OF PHOSPHORUS APPLICATION ON PRODUCTIVITY AND NUTRIENT ACCUMULATION OF A *EUCALYPTUS UROPHYLLA* PLANTATION

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XU, D., DELL, B., YANG, Z., MALAJCZUK, N. & GONG, M. 2005. Effects of phosphorus application on productivity and nutrient accumulation of a *Eucalyptus urophylla* plantation. Application of superphosphate at establishment as basal fertilizer increased tree growth and survival of *Eucalyptus urophylla* in a 4.5-year-old trial near Gaoyao, Guangdong, China. It also increased P and N concentrations in young fully expanded leaves at one year and biomass in all tree components. The addition of 20, 50 and 200 kg P ha^{-1} increased stand volume by five to seven times of the mean annual increment of trees without P. The more P applied, the higher the percentage of stemwood and the lower the relative allocation of biomass belowground. The low P concentrations in leaves and roots at 20 kg P ha^{-1} at year 4.5 suggested the withdrawal of P from the biomass, through internal cycling. The addition of P increased N, P, K, Ca and Mg uptake. The 200 kg P ha^{-1} treatment was optimal both for wood chip production and economic return.

Key words: Phosphorus fertilization – nutrient uptake – *E. urophylla* – utisols – southern China

XU, D., DELL, B., YANG, Z., MALAJCZUK, N. & GONG, M. 2005. Kesan fosforus terhadap produktiviti dan penumpukan nutrien di ladang *Eucalyptus urophylla*. Aplikasi superfostat sebagai baja pangkal yang dibubuh sewaktu penubuhan meningkatkan pertumbuhan pokok dan kemandirian *Eucalyptus urophylla* yang berusia 4.5 tahun di Gaoyao, Guandong, China. Baja itu juga meningkatkan kepekatan P dan N dalam daun muda yang kembang sepenuhnya pada usia satu tahun. Biojisim juga meningkat dalam semua komponen pokok. Penambahan P sebanyak 20, 50 dan 200 kg ha^{-1} meningkatkan isi padu dirian sebanyak lima hingga tujuh kali ganda berbanding min peningkatan tahunan pokok tanpa P. Lebih banyak P yang dibubuh, lebih tinggi peratusan kayu batang dan lebih rendah peruntukan relatif biojisim bawah tanah. Kepekatan P yang rendah dalam daun serta akar pada 20 kg P ha^{-1} dan usia 4.5 tahun mencadangkan perpindahan P daripada biojisim melalui kitaran dalaman. Penambahan P meningkatkan pengambilan N, P, K, Ca dan Mg. Rawatan 200 kg P ha^{-1} adalah optimum bagi penghasilan serpai kayu serta pulangan ekonomi.

Introduction

Eucalypts are very popular for revegetation of many parts of south China because of their capacity to tolerate degraded sites and infertile soils, their fast growth potential and their multiple use (Turnbull 1994). One of the great advantages of eucalypts is their ability to coppice, thus generating new forests from the same plantation without making large investment. *Eucalyptus urophylla* is the most widely planted eucalypt species for short rotation plantations in south China (Bai & Xu 1997). About half of the land available for eucalypt plantations in south China is classified as plain land (5–10° slope) with frequent human disturbance in the past and poor soil fertility. Phosphorus is often deficient in soils and is the key nutrient that constrains productivity of eucalypt plantations (Xu *et al.* 2001a). Application of superphosphate as basal fertilizer can dramatically increase growth of eucalypts in south China (He *et al.* 1999, Liang & Zhou 1999, Lin *et al.* 1999, Xu *et al.* 2001b). However, most of these reports were early tree responses to low rates of P application (less than 50 kg P ha^{-1}) combined with other nutrient treatments (nitrogen and potassium). There are very few reports on the effects of P application on productivity in a rotation and P application on nutrient partitioning and accumulation of eucalypt plantations in south China.

Site preparation for eucalypt planting in south China is very intensive (Wang & Zhou 1996). As soil tillage at plantation establishment has been shown to increase early tree growth (Yang *et al.* 1996), tractors are used to plough the topsoil to a depth of 20–30 cm where the slope is not too steep (less than 20°). Then pits (60 × 60 × 50 cm or 50 × 50 × 40 cm) are dug by hand. On some steep lands (more than 20°), strip terraces are prepared by hand before digging the pits. The most frequent spacing used for eucalypt plantations is 2 × 3 m (mainly for hilly land) or 3 × 1.5 m (mainly for plain land). Generally, one third of the pit is filled with topsoil. Fertilizer is then applied by hand and mixed with the soil. The hole is then filled with the remaining soil.

In China, it was only in the 1990s that inorganic fertilizers were used in forestry (Wang & Zhou 1996). This is because fertilizer production in China was, until recently, not able to meet the agricultural demand for food production. Currently, most forest farmers apply 50 g urea, 150 g superphosphate and 30 g KCl into the planting hole at establishment. Some farmers reapply 50 g urea and 30 g KCl at one year. Very few farmers apply fertilizers to trees that are more than one year old. Weed control is only carried out by a small number of farmers. Usually, a 1 m^2 area (1 × 1 m, 0.5 m from each side of tree) is cleaned by hand and then fertilizers are applied.

Xu *et al.* (2001b) has shown that P application significantly increased tree growth, biomass production, and N, P and K uptakes of a clonal plantation of *E. grandis* × *E. urophylla* hybrid on a terraced hilly site in south China. However, the plain land (5–10° slope) in south China has been subjected to much more human disturbance in the past than hilly sites and the soils thus are more infertile. For this reason, trials were established in 1996 on a plain near Gaoyao. Earlier studies at this site by Xu *et al.* (2001a) showed a large response of *E. urophylla* to P application and only a small response to ectomycorrhizal fungi inoculation. Under tropical conditions, changes in soil fertility may occur over periods of just a few years, with feedback effects on stand productivity (Fisher 1995). This paper, therefore, reports on follow-up investigations at the plantation up to age 4.5 years. This information will be essential for nutrient management in the second rotation of the eucalypt plantation at this site as rotation period of most eucalypt plantations in south China has been reduced to 3.5–5.5 years.

Materials and methods

The experiment has been described in detail in Xu *et al.* (2001a). The site is typical of land available for eucalypt plantations in Guangdong Province. Soil properties of the site is given in Table 1. The climate is tropical with an annual rainfall of 1870 mm, of which more than 70% is concentrated during the summer wet season (April to September). The dry season extends from October to March and the rainfall is less than 120 mm a month. The annual mean temperature is 22.0 °C; 31.2 °C in the hottest month (July) and 13.4 °C in the coolest month (January). The soil is a lateritic red soil (Ultisol) over granite and maximum P adsorption of this soil is 1040 mg P kg^{-1} (Xu *et al.* 2001a). A naturally regenerated forest of *Pinus massoniana* (about 30 years old) at the site near Gaoyao was clearfelled three months before planting and the residue was burnt on site. The site was prepared by tillage (0–20 cm topsoil) and planting pits (0.5 × 0.5 × 0.4 m) were dug by hand at a spacing of 1.5 × 3.0 m. A randomized block split-plot design was used in which four ectomycorrhizal fungi treatments (uninoculated control and three inoculation treatments) were established in subplots randomised within the main P plots. There were four replicates in the experiment. The four P treatments (0, 20, 50 and 200 kg P ha^{-1}, referred to as P0, P20, P50 and P200 respectively) in each replicate were applied in a band, 0.8 m wide at planting (April 1996). Each P treatment had 40 measurement trees spaced at 1.5 × 3.0 m. In addition, 156 kg $CaSO_4$ ha^{-1} and 55.6 kg ha^{-1} micronutrient mix (5.0% Cu, 5.0% Zn, 12.5% Fe, 3.0% B and 0.15% Mo) were applied into the planting pits before they were backfilled. Urea and KCl were applied on three occasions (at 0, 15 and 27 months after planting; total amount was 444 kg urea and 378 kg KCl ha^{-1}).

Table 1 Properties of soil profile of the *Eucalyptus urophylla* plantation in Gaoyao, Guangdong, China

	Layer and depth (cm)		
Soil property	A (0–23 cm)	AB (24–58 cm)	B(59–100 cm)
pH[1]	3.2	3.2	3.4
Organic C (g kg^{-1})[2]	6.85	3.00	1.98
Total N (g kg^{-1})[3]	0.62	0.33	0.31
Total P (g kg^{-1})[4]	0.16	0.15	0.16
Bray 1-P (mg kg^{-1})[5]	1.53	0.48	0.24
Total K (g kg^{-1})[6]	5.80	5.74	7.49
Exchangeable K (mg kg^{-1})[7]	12.34	18.00	14.26
Exchangeable Ca (mmol kg^{-1})[8]	1.02	0.39	0.29
Exchangeable Mg (mmol kg^{-1})[9]	0.19	0.11	0.09
Stone (%, > 2 mm)	8.00	2.91	5.64
Sand (%, 2–0.05 mm)	51.45	52.88	40.11
Silt (%, 0.05–0.002 mm)	21.85	18.00	13.03
Clay (%, < 0.002 mm)	26.70	29.12	46.86

[1] 1:5 soil/1M KCl suspension; [2] dichromate oxidation procedure; [3] automated colorimetric method following Kjeldahl digestion; [4] fusion method and determined by colorimetric molybdate blue method; [5] 1:50 soil:Bray No.1 reagent and automated colorimetric determination; [6] fusion method (same as total P) and determined by flame photometer method; [7] extracted by 1 mol l^{-1} NH_4OAc and determined by flame photometer method; [8] and [9] extracted by 1 mol l^{-1} NH_4OAc and determined by atomic absorption spectrometry method (Rayment & Higginson 1992).

Diameter at breast height (dbh, 1.3 m) was measured 54 months after planting. Height was estimated by an equation (Table 2) developed from 18 trees cut for biomass investigation because it was impossible to see the apex of trees after canopy closure, i.e. height measurements could not be determined accurately (Xu *et al.* 2001b). Tree volume was calculated by the formula developed for eucalypts growing in China (Simpson *et al.* 1997):

$$V = 0.4 \times \text{height} \times \text{basal area}$$

Data obtained at 54 months after planting are reported in this paper, whereas the earlier results for the previous measurements were reported in Xu *et al.* (2001a). A mixed sample of topsoil (0–20 cm), collected from 10 random points in each plot, was used to measure available P at years 2 and 4.5.

At age 4.5 years, estimates of dry matter production in each plot were obtained using allometric functions relating dry matter to diameter. Allometric functions were derived by destructively sampling trees in all plots covering a wide range of tree sizes. A total of 18 trees (16 trees from experimental main plots, one per plot, and an additional of one small and one large tree, covering all diameter classes and P treatment plots) were selected according to the mean tree diameter in a plot

Table 2 Constants used for estimation of dry weight of components in *Eucalyptus urophylla*

Tree component	a	b	r^2
Stem-wood	- 3.7078	3.0167	0.98
Stem-bark	- 4.4483	2.4559	0.98
Branch	- 4.8592	2.3552	0.86
Leaf	- 3.3579	1.5730	0.72
Taproot (> 5 cm)	- 4.9804	2.7221	0.89
Large root (2–5 cm)	- 4.6544	2.0056	0.56
Small root (< 2 cm)	- 2.6631	2.7343	0.59
Tree height	0.5021	3.0167	0.98

for biomass investigation before harvesting. After measuring felled tree height, the components of each tree was sorted into leaves, branches, stem-bark, stem-wood, taproot, large roots (> 2 cm) and small roots (< 2 cm). The equation used to fit each tree component was:

$$\ln(Y) = a + b \ln(X),$$

where
Y = biomass (oven dry basis)
a, b = constants and
X = dbh over bark

The equations (i.e. for each component) were used to predict tree biomass of each plot from the tree diameters (Table 2).

During the biomass investigation, the fresh weights of stem and other aboveground components (leaf, branch and the few fruits available at the time of harvest) were measured in the field immediately after tree felling. Discs (2 cm thick) were removed from each 3 m of stem and the bark and wood were separated, weighed, and broken into small pieces and dried at 75 °C to constant dry weight (approximately for 48 hours). The canopy was partitioned into two equal strata. Samples consisting of 10% of the total other aboveground components (leaf, branch and fruit) were taken, weighed, and subsamples (approximately 500 g) of each component were removed for determination of dry weight. Samples of leaf, branch, stem-bark and stem-wood from each of the 16 harvested trees in the experimental plots were taken for chemical analyses.

The taproot of each tree was excavated by hand. Half of the root system (0.75 × 3 m) of each tree was excavated to 80 cm depth by hand, and roots were sampled for dry weight determination after taproot excavation. Half of the dried samples were washed and re-dried to estimate the amount of soil covering the root.

In each plot, five 1 m^2 sample plots were used to collect the understorey and litter on soil surface. Roots were excavated by hand to a depth of 0.5 m. Fresh weights of understorey shoots and roots were obtained on site. A sample (approximately 500 g) of each component was dried at 75 °C for 48 hours to constant weight. Bulk samples from the five sample plots in the main P treatment plots were processed for chemical analyses (Chen *et al.* 1994).

Nutrient accumulation was estimated by the equation:

Nutrient content = biomass (different components of tree or understorey) × nutrient concentration from the sample trees in the plot

Nutrient recovery is the percentage of nutrient applied taken up by trees or by trees and vegetation compared with the control without P application (Fernandez *et al.* 2000). Nutrient use efficiency represents the mean quantity of biomass produced by one unit of nutrient (Herbert 1996). Since the main product of eucalypt plantation is the stem-wood, the mean quantity of biomass produced by one unit of nutrient in total tree biomass is also a useful indicator for growth.

Methods used for plant analysis were:

(1) N by H_2SO_4 ($ZnSO_4$, $FeSO_4$) digestion and Kjeldahl method (Anderson & Ingram 1993)

(2) P by HNO_3 and $HClO_4$ digestion and molybdate blue colorimetry (Murphy & Riley 1962)

(3) K by HNO_3 and $HClO_4$ digestion and flame photometry and

(4) Ca and Mg, by HNO_3 and $HClO_4$ digestion and atomic absorption spectroscopy

For soil analysis, available P was extracted by 0.5 M $NaHCO_3$ for Olsen-P, 0.03 M NH_4F in 0.025 M HCl for Bray 1-P, 0.03 M NH_4F in 0.1 M HCl for Bray 2-P and 0.05 M HCl and 0.025 M H_2SO_4 for Mehlich 1-P (Bray & Kurtz 1945, Olsen & Sommers 1982) and measured by molybdate blue colorimetry (Murphy & Riley 1962).

Results

Whilst ectomycorrhizal fungal inoculation affected tree height growth over the first three years (Xu *et al.* 2001a), there was no significant difference between fungal treatments at 4.5 years after planting. Furthermore, fungal inoculation only had an impact on tree diameter growth of one-year-old trees. As there was no significant difference between fungal treatments in tree biomass at 4.5 years and there was no interaction between ectomycorrhizal fungal inoculation and P application, this paper only examines the effects of P application.

Phosphorus application significantly increased P ($p < 0.001$) and N ($p = 0.042$) concentrations in young fully expanded leaves one year after planting (Figure 1). The P concentration in leaves of P0 trees was in the deficient range and that in P20 trees was intermediate between the deficient and adequate ranges according to Dell *et al.* (2001). The N concentration in the young fully expanded leaves in P200 trees was higher than in other treatments. Regardless of the P rate, all foliar N concentrations were in the adequate range (Dell *et al.* 2001). There was no significant difference in foliar K concentration with P treatment.

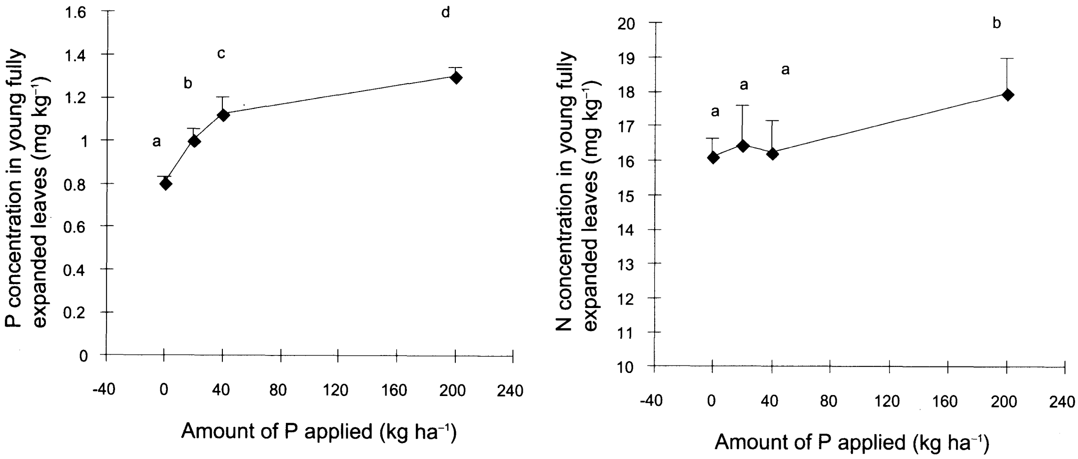

Figure 1 Phosphorus and nitrogen concentrations in the young fully expanded leaves of *E. urophylla* at one year after planting. Means of the treatments with the same letter are not significantly different at p = 0.05 using Newman-Keuls Critical Range Test. Bars = one standard deviation.

Phosphorus application significantly increased available P in the topsoil at 2 ($p < 0.001$) and 4.5 ($p = 0.023$) years after planting (Table 3). The trend of available P increasing with the amount of fertilizer P applied was similar across all four extraction methods. However, among the different extraction methods for available P in soil, the difference between treatments using Bray 2 extraction was the largest at 2 years followed by Bray 1 method. Therefore, Bray 1 extraction method was used at year 4.5 as this method is widely used for tropical soils and it gave satisfactory results in this study. Mehlich 1-P and Olsen P were lower than Bray 1-P and Bray 2-P. Olsen P was lower at high P treatments (P50 and P200) and higher at low P treatments (P0 and P20) compared with Mehlich 1-P. Bray 2-P was higher than Bray 1-P in all P application treatments. At 2 and 4.5 years of age, available P in the P200 plots was significantly higher than in the rest of the treatments but the difference between treatments was smaller at year 4.5 than that at year 2.

Phosphorus significantly ($p = 0.042$) increased tree survival at 3 and 4.5 years after planting (Table 4). However, there was no significant difference between P treatments at 1 and 2 years after planting.

Phosphorus application significantly ($p < 0.001$) increased the biomass of all tree components, total biomass and stand volume. However, the difference between P20 and P50 was not significant (Table 5). The application of P changed the proportion of biomass of different tree components to total biomass. It increased the proportion of stem-wood to total biomass and reduced branch and leaf biomass, stem-bark biomass and belowground root biomass to total biomass.

Table 3 Available P in the topsoil (0–20 cm) at years 2 and 4.5 after P application

Treament	Year 2				Year 4.5
	Mehlich 1	Bray 1	Bray 2	Olsen	Bray 1
P0	0.92 ± 0.26a	1.71 ± 0.12a	1.85 ± 0.14a	1.69 ± 0.19a	1.85 ± 0.14a
P20	1.90 ± 0.42a	3.09 ± 0.82a	3.91 ± 1.14a	2.27 ± 0.43a	2.19 ± 0.11a
P50	5.06 ± 0.86a	7.38 ± 1.74a	10.25 ± 1.821a	3.70 ± 0.83a	2.86 ± 0.61a
P200	22.71 ± 4.33b	40.24 ± 3.28b	56.91 ± 6.94b	7.45 ± 2.42b	10.54 ± 1.94b

*Means in columns with the same letter are not significantly different at p = 0.05 using the Newman-Keuls Critical Range Test. At planting, the topsoil had 1.53 mg Bray 1-P kg^{-1}

Table 4 Effects of phosphorus application on mortality of *E. urophylla* at 1–4.5 years after planting *

Treament	Age (year since planting)			
	1.0	2.0	3.0	4.5
P0	8.8 a	18.1 a	33.1 b	46.9 b
P20	15.6 a	15.6 a	17.5 a	22.5 a
P50	15.6 a	17.5 a	17.5 a	24.4 a
P200	16.9 a	19.4 a	19.4 a	25.6 a

*Means in columns with the same letter are not significantly different at p = 0.05 using the Newman-Keuls Critical Range Test.

Table 5 Effects of phosphorus application on biomass and volume of *E. urophylla* components and proportion of tree component biomass to total biomass*

Treatment	Stem-wood	Stem-bark	Branches	Leaves	Roots	Total	Volume ($m^3 ha^{-1}$)
P0	8.56 a	1.31 a	0.71 a	0.71 a	2.07 a	13.36 a	16.2 a
	(64.09)	(9.78)	(5.32)	(5.34)	(15.47)		
P20	51.70 b	6.28 b	3.26 b	2.25 b	9.87 b	73.36 b	97.1 b
	(70.48)	(8.55)	(4.44)	(3.07)	(13.46)		
P50	49.36 b	6.06 b	3.15 b	2.20 b	9.52 b	70.28 b	92.9 b
	(70.23)	(8.62)	(4.49)	(3.12)	(13.54)		
P200	72.46 c	8.30 c	4.27 c	2.69 c	13.09 c	100.82 c	134.2 c
	(71.88)	(8.24)	(4.23)	(2.67)	(12.98)		

* biomass is in t ha^{-1}; values in parentheses are percentages of biomass to total biomass; means of treatments with same letter are not significantly different at p = 0.05 using Newman-Keuls Critical Range Test.

Phosphorus application significantly affected N (p = 0.041) and P (p = 0.004) concentrations in tree components at 4.5 years after planting (Table 6). Generally, P application decreased N concentrations in all tree components. The P concentrations in stem-wood, stem-bark, leaves and litter of trees in P0 were higher than those in P20. Also, the P concentration in leaves of trees in P0 was higher than that in P50.

Phosphorus application significantly (p < 0.001) increased uptake of N, P, K, Ca and Mg (Table 7) by all tree components in the plantation. It also changed the proportions of N, P, K, Ca and Mg uptake between tree components. At P0, the amounts of N uptake by stem-wood and leaves were 29.6 and 25.8% of total N uptake by trees respectively, and 40.7 and 20.3% at P200 respectively. At P0, the values for P uptake by stem-wood and leaves were 26.2 and 29.1% of total uptake by trees respectively, whereas they were 33.6 and 18.7% at P200 respectively. The uptake of K in the treatments with P application was much higher than in P0. At P0, K uptake values by stem-wood and leaves were 48.5 and 19.7% of total uptake by trees respectively. They were 28.9 and 14.2% respectively at P200. Across all treatments, about 45.3% of Ca uptake was in stem-bark. At P0, Ca uptake values by

Table 6 Effects of P fertilization on N and P concentrations in tree components of *E. urophylla* 4.5 years after planting

Component	N concentration (g kg^{-1})				P concentration (g kg^{-1})			
	P0	P20	P50	P200	P0	P20	P50	P200
Stem-wood	1.505 b	1.249 ab	0.998a	1.073 a	0.064 b	0.047 a	0.060 ab	0.063 ab
	0.071*	0.170	0.180	0.280	0.009	0.010	0.007	0.013
Stem-bark	5.413 b	4.071 ab	3.153 a	3.657 a	0.372 b	0.235 a	0.330 ab	0.333 ab
	1.374	1.126	0.335	0.780	0.048	0.030	0.081	0.093
Branch	5.663 b	3.640 a	3.628 a	3.500 a	0.377	0.336	0.325	0.391
	1.236	1.195	0.962	1.084	0.058	0.040	0.076	0.086
Leaf	16.203b	15.207 ab	14.043 a	14.306 a	0.975 c	0.820 a	0.847 ab	0.938 bc
	1.007	0.894	0.572	1.011	0.085	0.082	0.035	0.728
Large-root	4.005 b	2.911 ab	2.131 a	2.034 a	0.120 ab	0.095 a	0.126 b	0.125 b
	0.581	1.176	0.817	0.358	0.007	0.020	0.004	0.027
Small-root	5.053 a	4.233 bc	3.641 ab	3.155 a	0.230ab	0.190 a	0.264 b	0.253 b
	0.474	0.825	0.581	0.533	0.035	0.031	0.037	0.032
Branch-litter	4.734 b	2.953 a	3.160 a	3.049 a	0.189 b	0.083 a	0.112 a	0.122 a
	0.922	0.445	0.443	0.499	0.039	0.027	0.029	0.017
Leaf-litter	9.645 b	8.813 ab	8.775 ab	8.731 a	0.396 b	0.337 a	0.369 ab	0.366 ab
	0.746	0.728	0.188	0.392	0.040	0.021	0.038	0.029

Means in rows with the same letter are not significantly different at p = 0.05 using the Newman-Keuls Critical Range Test. * Standard deviation

Table 7 Effects of P fertilization on N, P, K, Ca and Mg uptake (kg ha^{-1}) in *E. urophylla* 4.5 years after planting

Treatment	Element	Stem-wood	Stem-bark	Branch	Leaf	Taproot	Large root	Small root	Total
P0	N	12.80 a	6.87 a	3.91 a	11.18 a	5.18 a	1.73 a	1.60 a	43.27 a
	P	0.60 a	0.49 a	0.27 a	0.67 a	0.16 a	0.04 a	0.07 a	2.29 a
	K	5.36 a	10.40 a	3.56 a	7.82 a	1.80 a	0.60 a	0.87 a	30.40 a
	Ca	4.18 a	17.07 a	4.24 a	6.40 a	3.87 a	1.24 a	1.24 a	38.22 a
	Mg	0.51 a	0.07 a	0.24 a	0.89 a	0.20 a	0.07 a	0.09 a	2.07 a
P20	N	64.40 c	25.40 c	11.93 b	34.22 bc	20.13 c	4.98 c	4.64 c	165.71 c
	P	2.42 b	1.47 b	1.13 b	1.84 b	0.67 b	0.16 b	0.20 b	7.89 b
	K	48.53 b	44.33 c	16.96 c	19.67 b	8.71 c	2.13 c	2.40 b	142.73 b
	Ca	30.24 b	73.71 c	16.96 c	19.29 b	9.40 b	2.31 b	3.09 b	155.02 b
	Mg	3.13 b	0.38 b	1.11 c	2.62 b	0.76 b	0.18 b	0.22 b	8.42 b
P50	N	48.40 b	19.16 b	11.38 b	30.78 b	14.31 b	3.53 b	3.89 b	131.44 b
	P	2.96 b	2.00 c	0.98 b	1.87 b	0.84 c	0.22 c	0.29 c	9.16 b
	K	42.29 b	38.71 b	13.47 b	22.24 bc	6.33 b	1.58 b	2.11 b	126.73 b
	Ca	38.98 b	62.31 b	13.47 b	19.27 b	9.20 b	2.27 b	3.53 b	147.02 b
	Mg	4.51 c	0.56 c	0.78 b	2.78 b	0.67 b	0.16 b	0.22 b	9.67 bc
P200	N	77.64 d	31.04 d	14.89 c	38.60 c	19.62 c	4.44 c	4.29 c	190.53 c
	P	4.56 c	2.89 d	1.73 c	2.53 c	1.22 d	0.27 d	0.33 d	13.53 c
	K	51.60 b	64.56 d	19.33 c	25.42 c	12.24 d	2.78 d	2.84 c	178.78 c
	Ca	38.60 b	89.53 d	19.33 c	22.38 b	15.00 c	3.42 c	4.24 c	192.51 c
	Mg	4.18 c	0.49 c	1.09 c	3.58 c	0.78 b	0.18 b	0.27 b	10.56 c

Means of the same element in columns with the same letter are not significantly different between the same element at p = 0.05 using the Newman-Keuls Critical Range Test.

stem-wood and leaves were 10.9 and 16.7% of total uptake by trees respectively. The values were 20.1 and 11.6% respectively at P200. Accumulation of Mg in stem-wood was the largest pool and the second largest was in leaves. At P0, the values for Mg uptake by stem-wood and leaves were 24.6 and 43.0% respectively of total uptake by trees.

Phosphorus application significantly (p = 0.014) increased P uptake by understorey and litter (Table 8). Phosphorus application increased the use efficiency of N, P, K, Ca and Mg in terms of stem-wood production or tree biomass (Table 9). However, the highest P use efficiency occurred when a small amount of P was applied.

Discussion

Without P application, the mean annual increment (MAI) of the *E. urophylla* plantation was only 3.6 m^3 ha^{-1}, lower than the average productivity of other eucalypt plantations in south China (Xu *et al.* 2000a). The MAI increased to 29.8 m^3 ha^{-1} at P200, similar to the average for commercial eucalypt plantations in Brazil (Brown *et al.* 1997). Phosphorus application also changed the proportion of tree components to total biomass. The more P that was applied, the higher the percentage of stem-wood (wood chip) and the lower the percentage of biomass allocated to roots. In the early stages, greater development of tree roots in the fertilized plots resulted in higher foliar N concentration, and also higher accumulation of other nutrients. Over time, trees in P0 distributed a higher percentage of biomass production to root development presumably to facilitate uptake of P from the soil. In spite of this, by the end of the study, more trees in P0 died than those given P at establishment.

Tree response to P application in this study was much higher than the response to P with N and K (14–45% increment in stand volume) reported in Dongmen, Guangxi (Simpson *et al.* 1997). The highest P treatment in this study , 200 kg P ha^{-1}, exceeded rates used by most previous workers in south China. For example, 88.8 kg P ha^{-1} was the maximum rate used by Liang and Zhou (1999) in Kaiping in an

Table 8 Effects of P fertilization on P uptake and P recovery by trees, understorey and litter

Treatment	P uptake				P recovery (%)	
	Tree	Understorey	Litter	Total	Tree	Total
P0	2.29 a	0.98 a	1.65 a	4.92 a	–	–
P20	7.89 b	1.13 a	1.81 ab	10.83 b	28.0	29.6
P50	9.16 b	1.09 a	1.86 ab	12.11 b	13.7	14.4
P200	13.53 c	1.35 b	2.00 b	16.88 c	5.6	6.0

Means in columns with the same letter are not significantly different at p = 0.05 using the Newman-Keuls Critical Range Test.

Table 9 Effects of P fertilization on nutrient use efficiency (NUE) of 4.5-year-old *E. urophylla* for stem-wood and total tree biomass

Treatment	NUE of stem-wood (t kg^{-1})					NUE of tree (t kg^{-1})				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
P0	0.20	3.74	0.28	0.22	4.14	0.31	5.83	0.44	0.35	6.45
P20	0.31	6.55	0.36	0.33	6.14	0.44	9.30	0.51	0.47	8.71
P50	0.38	5.39	0.39	0.34	5.10	0.53	7.67	0.55	0.48	7.27
P200	0.38	5.36	0.41	0.38	6.86	0.53	7.45	0.56	0.52	9.55

N-P-K factorial experiment (300% increment in stand volume compared with treatment with no fertilizer), and 13.3 kg P ha^{-1} was the best treatment of an N-P-K factorial experiment in Leizhou with 302% increment in stand volume over the treatment without application of fertilizer (Lin *et al.* 1999). The lower tree response in the these two studies, compared with our results, could be due to induced deficiencies of other nutrients, such as N, K and trace elements, which have been commonly observed in the region (Dell *et al.* 2001). In their best treatment, Liang and Zhou (1999) did not use any trace elements and application of N and K were only at 75 and 40 kg ha^{-1} respectively. Lin *et al.* (1999) observed the best growth when 30 kg ha^{-1} N and 24 kg ha^{-1} were applied. In a previous study, we suggested that 208 kg P ha^{-1} was adequate for an *E. grandis* × *E. urophylla* hybrid plantation at a more fertile site (> 1% organic C) in Zhenghai (Xu *et al.* 2001b). This rate is similar to P200 used in the present investigation. However, productivity of the former is lower than the latter. The better growth at Gaoyao was probably due to the reduced competition from understorey vegetation due to soil cultivation after plantation establishment. The understorey biomass was only one-tenth of that in Zhenghai. Furthermore, the amount of N and K fertilizer applied at Gaoyao was more than double the amount used in Zhenghai. Therefore, neither N nor K was likely to be limiting for early growth. Foliar analysis, one year after tree planting, showed that trees had adequate levels of N and K at that stage. Since maximum P adsorption capacity of the topsoil at this site was very high, available P from 2 to 4.5 years decreased substantially. The low Bray 1-P at P0, P20 and P50 suggested that P may limit tree growth if the trees are not harvested at year 5. Furthermore, in the next rotation, it is expected that trees in P200 will grow faster than trees in P20. This is because litter at the plot was richer in P and release of this element could maintain tree growth rate even if soil extractable P was reduced.

Surprisingly, even small amounts of P increased stand biomass; in our study 20 kg P ha^{-1} increased stand biomass by 449%. Hence, only a small amount of P was sufficient to improve short-term growth from severe deficiency to a marginal condition (MAI = 21.6 m^3 ha^{-1}, 73% of maximum yield at P200). The low P concentrations in leaves and roots in P20 at year 4.5 suggested the withdrawal of P from the biomass through efficient internal cycling, thus making effective use of limited P pools for growth. There was no difference in available P in topsoil of the P0, P20 and P50 plots at year 4.5. This indicated that the initial high growth response to small amounts of P fertilizer cannot be sustained. In similar commercial cases, it is recommended that plantations be harvested early and additional superphosphate be applied for the next rotation to improve site productivity. It remains to be determined how productivity will change in different P treatments when the rotation period is increased from 4–6 to 6–8 years, which is the rotation for saw wood. Further study is needed to determine if adequate fertilization can extend the rotation without loss of productivity.

At ages of 3 and 4.5 years, the survival of P0 trees was much lower than trees treated with superphosphate. Other studies in south China (Simpson *et al.* 1997; Liang & Zhou 1999, Lin *et al.* 1999) have not reported any significant difference in survival after fertilization. Unlike trees supplied with adequate P, untreated trees growing on high P-fixing soil are small and weak, and are more sensitive to stress.

It is clear that P application increased nutrient uptake and use efficiency of all elements analysed in this study. With regard to the nutrient budget, retention of harvest residue on site is an important factor in nutrient conservation between rotations. In this study, the mean N, P, K, Ca and Mg contents in leaves across all P rates were 23, 23, 18, 14 and 34% of the total tree accumulation respectively, even though leaves were only 3–5% (0.7–2.7 t ha^{-1}) of total tree biomass in different P treatments. At P0, the percentage of nutrients (N, P, K, Ca and Mg) in leaves was higher than that in trees supplied with additional P. This indicates that leaf harvesting on poor sites exacerbates the negative nutrient budget. Across all P treatments, N, P, K, Ca and Mg contents in bark were 16, 21, 31, 45 and 5% of total tree accumulation respectively. Debarking on site will be very important for Ca and K. Stem-bark had 35% of the K content of aboveground uptake across the four P treatments. This value is also higher than the 17% reported by Jade (1996) for aboveground uptake in a 20-year-old *E. grandis* plantation, and the 28% reported by Hunter (2001) for a 3.5-year-old *E. camaldulensis* plantation. This indicates that young eucalypt trees store more K in bark than old trees. Stem-bark had 53% of the Ca content of aboveground uptake across all P treatments. This is lower than values reported by Xu *et al.* (1996). This shows that eucalypts may accumulate relatively more Ca in their bark as they age. Therefore, debarking on site is very important for Ca recycling.

Further, P application increased the amount of P uptake by stem-wood. This means that P loss from such plantation through harvest will be higher than the plantation without P fertilization. In south China, two common scenarios for harvesting eucalypt plantations are total aboveground tree harvesting or total aboveground tree plus taproot harvesting (Table 10). It will be beneficial if bole

Table 10 Comparison of nutrient loss (kg ha^{-1}) from 4.5-year-old *E. urophylla* trees with or without phosphorus fertilizer with four harvesting strategies

Harvest strategy [a]	P200					P0				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Scenario 1	77.6	4.6	51.6	38.6	4.2	12.8	0.6	5.4	4.2	0.5
	41*	34	29	20	40	30	26	18	11	25
Scenario 2	108.7	7.4	116.2	128.1	4.7	19.7	1.1	15.8	21.3	0.6
	57	54	65	67	44	45	48	52	56	28
Scenario 3	162.2	11.7	160.9	169.8	9.3	34.8	2.0	27.1	31.9	1.7
	85	86	90	88	88	80	88	89	83	83
Scenario 4	181.8	12.9	173.2	184.8	10.1	39.9	2.2	28.9	35.8	1.9
	95	95	97	96	96	92	95	95	94	92

* Percentage of total tree accumulation

[a] Scenario 1 = stem wood harvesting only, Scenario 2 = bole harvesting only, Scenario 3 = total aboveground harvesting (including leaves and branches), Scenario 4 = total aboveground plus taproot harvesting

harvesting or stem-wood harvesting (debarking on site) can be adopted in the future. Nutrient loss in these scenarios is very different. More than 80% of nutrient accumulation by trees will be lost by the two harvesting scenarios that are now widely used in China, i.e. scenarios 3 and 4. The management of harvest residue is very useful to increase available nutrient supply to the trees in following rotation (Xu *et al.* 2000b).

From the view of the forest farmers, P200 was the best treatment both for wood chip production and economic return, since the price of 27 t ha^{-1} wood chip (stem-wood difference between P20 and P200) was much higher than the price of 2.8 t ha^{-1} superphosphate (fertilizer difference between P20 and P200). At the moment, the price of wood chip is almost the same as that of superphosphate per dry tonne.

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