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Managing soil fertility in eucalypt plantations in China

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Abstract

More than 1.5 M ha of eucalypt plantations have been established in south China, increasing by about 100,000 ha y^{-1}. Productivity is uneven and low, only about 25-50% of the world average for eucalypt plantations. Most land available for eucalypts are degraded oxisols and utilsols which also are acidic, highly leached and deeply weathered. Phosphorus deficiency is very severe and its availability is reduced because of limited compatible ectomycorrhizal fungi. Nitrogen supply is limited because of low organic matter content in the topsoil. This paper reviews a decade of field trials in the region concerning the use of fertilisers, harvest residue management and inoculation with ectomycorrhizal fungi. One of the key questions addressed is whether the productivity of plantation eucalypts in south China can be increased to the world average by nutrient management across a rotation. Some of the key findings are: Application of superphosphate at establishment substantially increased growth, tree survival and nutrient uptake. Coppice response to P was lower than the response to P in the first rotation. Inoculation with ectomycorrhizal fungi affected stand volume. Field effects were isolate-dependent, and poorly related to performance of isolates in the greenhouse. Reduction in the amount of residue removed during harvest increased tree growth by increasing available nutrient supply and reducing the loss of soil organic C. Intercropping with N-fixing trees enhanced tree growth. More than 80% of nutrient accumulation by trees was lost via harvesting practices. It is concluded that productivity of plantation eucalypts can be improved to 10-20 m^3 ha^{-1} y^{-1}, the average productivity in the world, by nutrient management. Harvest residue retention and coppice regeneration are recommended as operational practices in the second rotation. Research indicates that the productivity of well-managed plantations can be sustained whereas poor management practices result in dramatic yield declines across rotations.

Keywords: afforestation, sustainable forestry, nutrient management, mycorrhizal fungi

Introduction

Use of eucalypts, the main plantation genus in the tropics and warmer subtropics, is the most rapidly expanding sector in world forestry (Turnbull, 1999). Eucalypts are very popular for revegetation in many parts of south China because of their capacity to tolerate degraded sites and infertile soils, their fast growth potential and their multi-purpose use (Turnbull, 1994). One of the great advantages of eucalypts is their ability to coppice, thus generating new forests from the same plantation. More than 1.5 M ha of eucalypt plantations have been established in south China since the 1980s, mainly in Guangdong, Hainan, Guangxi, Fujian and Yunnan (Xu *et al.,* 2000), and the rate of establishment of new eucalypt plantations is more than 100,000 ha annually.

A common phenomenon of eucalypt plantations in south China is that the trees have small canopies and greatly reduced increment after 4 years (Xu *et al.,* 1996; Xu, 1997). Productivity appears to be declining with successive rotations in some areas (Yu *et al.,* 1999). What then are likely to be the main constraints for productivity of plantation eucalypts in south China? Most foresters in China take the low productivity of eucalypt plantations for granted, blaming either poor soil fertility or uneven precipitation. However, there is no evidence that precipitation is restricting productivity of plantation eucalypts in South China as most high-yielding eucalypt plantations (e.g. Leizhou, Dongmen and Hainan) occur in locations where precipitation is lower than in areas where productivity is low, such as Yangxi, Yangjiang and Guangzhou.

Productivity of eucalypt plantations in China is not only low but also uneven, from MAI 5 to 50 m^3 ha^{-1} y^{-1} (Xu *et al.,* 2000). Many eucalypt plantations reduce their leaf area, quickly followed by declines in tree growth rates, 3-4 years after planting (Xu *et al.,* 1996). Leaf biomass of fertilised plantations in south China (Table 1) is lower (<3 t ha^{-1}) than plantations in some other countries. Moreover, leaf biomass is further decreased when the land is used for successive rotations of eucalypt plantations (Yu *et al.,* 1999). Low biomass production and leaf area are indicative of limiting mineral nutrients.

Table 1 Leaf mass and aboveground N content of eucalypt plantations in China and selected locations in the world.

Country/Source	Species	Leaf mass (t ha^{-1})	N applied (kg ha^{-1})	N content (kg ha^{-1})	Age (year)
China/Xu *et al.* (unpub)	*E. urophylla*	2.7	444	162	4.6
China/Xu *et al.* (2002)	*E. grandis x E. urophylla*	1.9	194	96.1	6.3
China/Xu *et al.* (1996)	*E. grandis x E. urophylla*	2.8	393	129	3.5
China/Simpson *et al.* (1997)	*E. grandis*	2.5	100	74	4.8
Australia/Birk and Turner (1992)	*E. grandis*	3.1	0	246	9.5
Australia/Birk and Turner (1992)	*E. grandis*	5.0	2180	331	9.5
Brazil/Harrison *et al.* (2000)	*E. urophylla*	10.6	11	371	3.5
India/Hunter (2001)	*E. grandis*	5.9	0	185	3.0
India/Hunter (2001)	*E. grandis*	7.2	320	203	3.0

Soil Phosphorus Supply and Productivity of Plantation Eucalypts

First rotation

The soils available for eucalypt plantations in south China are generally lateritic and lateritic red earths (Oxisols and Ultisols) which are acidic in reaction (pH_{water} 4-6), highly leached, often heavy-textured and deeply weathered (Li, 1983; Wang and Zhou, 1996). Phosphorus may be the primary macronutrient limiting the growth of eucalypts in south China, since, without P application, *E. urophylla* did not respond to N fertiliser at Dongmen and Enping (Chen *et al.*, 1996; Wang and Zhou, 1996). Similar data are available for Yangxi (Li *et al.*, 1995), Yangdong (Wu *et al.,* 1996) and Leizhou (Lin *et al.,* 1999; Liang and Zhou, 1999) in Guangdong, and Baoshan (He *et al.,* 1999) in Yunnan. From these studies, it can be concluded that fertilisation with P is essential (Table 2). In general, low soil pH and high concentrations of Al^{+3} and Fe^{3+} in South China soils greatly reduce the availability of P to trees through adsorption processes (Li, 1983).

Our studies show the addition of 300 kg P ha^{-1} increased stand volume by 66%, at age 3 years on a site with a mildly P-deficient red ultisol at Chuxiong, Yunnan (Xu *et al.,* 2001). Application of 40 kg P ha^{-1} was sufficient to maintain marginal growth in the short-term. The addition of 200 kg P ha^{-1} increased stand volume by 7 times the MAI at P0, at age 4.5 years on a site with a severely P-deficient oxisol at Gaoyao, Guangdong. The addition of 208 kg P ha^{-1} increased stand volume by 4 times the MAI at P0, respectively, at age 6.3 years on an oxisol at Kaiping, Guangdong.

Table 2 Summary of the results of P application in South China.

Location	Species and age (year)	P applied (kg ha^{-1})	Increment over control	Soil pH	Notes
Baoshan (1)*	*E. globulus*, 5	31-62	39-64%	5.8 (H_2O)	Factorial with N and K
Chuxiong (2)	*E. globulus*, 3	13-300	15-66%	4.8 (KC1)	P rates trial
Dongmen (3)	*E. grandis x E. urophylla*, 6-8	50	40-67%	5.7 (H_2O)	Factorial with N and K
Leizhou (4)	*E. urophylla*, 4.6	15-58	160-320%		Factorial with N and K
Gaoyao (5)	*E. urophylla*, 4.5	20-200	470-740%	3.2 (KC1)	P rates trial
Yangxi (6)	*E. urophylla*, 3.7	32.5-65	130-460%	4.4 (H_2O)	With N and K
Kaiping (7a)	*E. grandis x E. urophylla*, 6.3	13-312	160-370%	3.3 (KCl)	P rates trial
Kaiping (7b)	*E. urophylla*, 4.5	43-130	130-210%	4.6 (H_2O) 3.6 (KCl)	Factorial with N and K

*(1) He *et al.,* 1999; (2) Xu *et al.,* 2001; (3) Simpson *et al.,* 1997; (4) Xu *et al.,* 2001; (5) Lin *et al.,* 1999; (6) Xu *et al.,* 2000b; (7) Xu *et al.,* 2000a; (8) Liang and Zhou, 1999.

Second rotation

On infertile soils in China, coppice grew faster than replants at low fertilisation and the gap became smaller as the amount of fertiliser applied increased (Table 3, Xu *et al.,* 2000). By contrast, coppice is generally poorer than replanted trees in the Congo and Brazil because P is not a limitation to tree growth in most parts of these countries (Bouillet *et al.,* 1998; Gonçalves *et al.,* 2000). Whether the improved growth of coppice is due to P storage in roots of the first rotation trees or whether the large root system has better access to soil P reserves has yet to be determined.

Table 3 Comparison between tree growth in the first rotation and coppice growth in the second rotation of *E. grandis x E. urophylla* with re-fertilisation of N, K and B. The P treatments were applied at establishment of the first plantation.

Rotation	Tree height (m)				Tree diameter (cm)			
Age (month)	1st	1st	2nd	2nd	1st	1st	2nd	2nd
	19	75	17	30	19	27	17	30
P0	3.6	10.6	6.9	10.2	2.25	3.68	5.0	7.4
P13	6.9	14.2	7.8	11.1	5.06	7.13	5.6	8.6
P52	8.9	16.0	7.9	11.9	7.09	8.67	6.0	9.3
P104	8.8	15.7	7.9	11.4	7.14	8.67	5.7	8.7
P208	9.6	16.6	8.2	11.8	8.09	9.29	6.0	9.1
P312	9.4	16.8	8.1	11.2	8.45	9.71	6.0	8.9

Ectomycorrhizal fungi

It has been suggested that the low productivity of plantation eucalypts in China is due to the absence of symbiotic, ectomycorrhizal fungi (ECMF) that are normally associated with eucalypts in their native habitat (Malajczuk *et al.,* 1994). Therefore, ECMF inoculation may be essential for the success of eucalypts introduced to places where indigenous fungi are unable to form effective associations. Although many studies have established the potential of ECMF inoculation to increase growth of eucalypts in glasshouse experiments under conditions of limiting P availability (Burgess *et al.,* 1990; Xu *et al.,* 1994), few workers have followed up these studies in the field.

A small number of field experiments have quantified effects of ectomycorrhizal fungi inoculation on growth of plantation eucalypts (Table 4). Although inoculation with some species/isolates of eucalypt-compatible ectomycorrhizal fungi increased tree growth by 15-33% in south China, many fungi were not effective in the field. In several field trials, where over 50 fungi were compared in Yunnan and Guangdong, only a few fungi lifted tree productivity in spite of the fact that the fungi were efficient in providing eucalypt seedlings with P under P-limiting conditions in glasshouse and nursery trials. Much further work is required to better match fungi with site and soil conditions. The challenge in future is to manage fertiliser regimes to ensure that the beneficial fungi remain effective in nutrient capture and cycling in plantations. How well these fungi survive perturbations, such as coppicing and clear-felling, has yet to be determined.

Other Nutrients and Productivity of Plantation Eucalypts

Because organic matter (SOM) in the topsoil is usually low, N uptake by eucalypts in south China is also increased by N fertilisation. Several experiments have demonstrated that N fertilisation combined with phosphorus increased tree growth in south China (Chen *et al.,* 1996; Wu *et al.,* 1996; He *et al.,* 1999). After P, N supply is usually the factor constraining leaf area of plantation eucalypts in south China. It is important that the OM content and N:C ratio of soils are increased so as to promote adequate N supplies in the future. These are discussed further below. Further, the data on timing and rates of N fertiliser application required in first rotation eucalypt plantations in south China are insufficient to enable operational prescriptions to be formulated at this time.

Table 4 Published accounts of field trials where eucalypts have been inoculated in the nursery with ectomycorrhizal fungi and then out-planted.

Country	Eucalypt species	% increase in tree growth over control	Reference
Australia	*E. diversicolor*	50%	Malajczuk 1987
Congo	*E. urophylla x E. tereticornis*	26-30%	Garbaye *et al.* 1988
China	*E. urophylla*	33%	Zhong *et al.* 2000 b
China	*E. grandis x E. urophylla*	18%	Huang and Liang, 2000
China	*E. globulus*	15%	Xu *et al.* 2001
China	*E. urophylla*	27%	Xu *et al.* 2001
Philippines	*E. urophylla*	21-31%	Aggangan *et al.,* 1999
Philippines	*E. deglupta*	40-52%	Dela Cruz *et al.* 1988

Regarding other nutrients, so far, only a few unpublished trials have demonstrated positive responses to K fertilisation for first rotation plantations. However, as about 133 kg K ha^{-1} can be lost by erosion in the year after site preparation (Xu *et al.,* 1999), the change in soil K status across successive rotations should be monitored. Boron deficiency has been found after adequate fertilization with N, P and K (Dell and Malajczuk, 1994). It is prevalent on sandy soils where the organic topsoil has been eroded. In Yunnan, there are sites where B is the primary limiting nutrient. As symptoms of B deficiency can be seasonally expressed (Dell *et al.,* 2001), they are often overlooked. In conclusion, refertilisation with N, K and B (and P where not provided in the previous rotation) should be routinely undertaken for coppice.

Weed Management and Productivity of Plantation Eucalypts

Where nutrients are limiting, competition from weeds can be intense. In a P fertilisation trial in Zhenghai, Guangdong without good weed control, the proportion of P, N and K uptake by the understorey and litter increased as the quantity of superphosphate applied decreased (Table 5). Further, the percentage of N uptake by the trees to total N uptake was much lower than the percentage of P and K uptake by the trees to total uptake. Even in P312, N uptake by the trees was less than 50% of total N uptake.

Slash Management and Productivity of Plantation Eucalypts

A common practice by rural people in south China is to harvest litter and understorey from forests to meet their fuel needs. The average amount collected is 3.3 t ha^{-1} y^{-1}, which can be as much as 55% of litter and understorey production (Brown *et al.,* 1995). It has been calculated that harvesting removes a substantial quantity (about 44-73%) of the nutrients that could be potentially recycled (Mo *et al.,* 1995).

As the soils under eucalypt plantations in China are mostly nutrient poor, the retention of unburnt harvest residue on site should increase nutrient supply to trees in the following rotation. Slash retention has other advantages such as reducing nutrient loss from wind and water erosion, improving soil properties, and weed suppression. Slash retention had a large impact on eucalypt performance in infertile sandy soils at Yangxi, China (Figure 1; Xu *et al.,* 2000). In this region, the decline in yield across rotations is marked. Although removal of all organic material improved tree growth in the early stage of the second rotation, compared to whole tree harvest, growth could not be sustained as soil fertility declined. As intercropping with N-fixing trees enhanced tree growth and increased litterfall, the option of mixed plantations should be explored. So far, only early growth responses have been measured and further research should monitor long-term changes in soil fertility and site productivity in relation to OM management. There are only a few studies on slash management for second rotation eucalypts. Gonçalves *et al.* (2000) observed a significant improvement in tree growth in second rotation *E. grandis* at age 4 years following slash retention in the humid tropical climate in Brazil. However, Jones *et al.* (1999) reported only a small, but insignificant, positive response to slash retention for a second rotation plantation of *E. globulus*. Intercropping with N-fixing trees enhanced tree growth and increased litterfall treatments at Yangxi at 46 months. BL0, All aboveground organic residue removed and regrowth cleared early in year 2; BL1, Whole tree harvest, slash relocated to BL3; BL2, Bole (bark and wood) harvest, slash distributed evenly over plot; BL3, Double slash; BL4, Bole harvest and intercropping with *Acacia holosericea*. Means of the treatment with same letter are not significantly different at p=0.05. Bars = one standard deviation.

Table 5 Nutrient accumulation of a 75 months-plantation of *Eucalyptus grandis* x *E. urophylla* in Kaiping, fertilised with six levels of superphosphate at establishment.

(kg P ha^{-1})	Tree			Understorey			Litterfall		
	P	N	K	P	N	K	P	N	K
P0	2.5 a*	38.7 a	44.9 a	4.2 a	93.6 bc	84.4 bc	2.1 ab	55.2	14.7bc
P13	5.1 b	79.1 b	95.3 b	5.0 ab	104.4 c	91.5 c	1.9 a	55.2	12.2 ab
P52	10.4 c	109.9 d	119.9 c	6.3 bc	102.7 c	81.0 bc	2.2 ab	57.2	10.4 a
P104	12.7 d	102.0 c	114.4 c	5.3 ab	76.8 ab	68.5 a	3.2 c	63.2	18.6 c
P208	21.9 e	119.4 e	152.9 e	7.3 c	100.7 c	77.8 ab	2.5 b	49.6	16.7 c
P312	23.2 f	119.4 e	140.7 d	6.8 c	75.3 a	68.7 a	2.4 b	47.6	11.4 ab

* Means in columns with the same letter are not significantly different at p=0.05

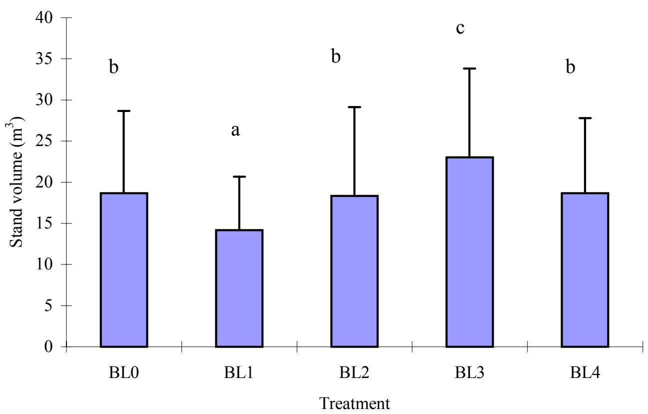

Figure 1 Stand volume of *E. urophylla* plantation with different slash retention.

A survey by Yu *et al.* (1999) in Leizhou, revealed that with the same clone and fertiliser rates, the yield of fourth rotation eucalypt plantations was only 50% of the yield of first rotation plantations. Soil fertility of the first rotation site was much higher than that of the fourth rotation site on the same soil.

At harvest, the current practice in China is for all of the aboveground biomass to be removed from the site. If the trees are not coppiced, the large roots are dug-out and removed for fuel. This results in significant loss of inorganic (Table 6) and organic nutrients. Retention of harvest residues, including bark, on-site is therefore recommended.

Table 6 Comparison of nutrient loss (kg ha^{-1}) from 4.5 year-old *E. urophylla* trees with or without phosphorus fertiliser with four harvesting strategies.

Harvest treatment	Rate of P applied = 200 kg ha^{-1}					Rate of P applied = 0 kg ha^{-1}				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
scenario 1[a]	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 only harvesting, Scenario 2 = bole only harvesting, Scenario 3 = all aboveground harvesting (including leaves and branches), Scenario 4 = all above ground plus tap-root harvesting.

Conclusions

Results from trials in Guangdong and Yunnan show that MAI can readily be increased to 20 m^3 ha^{-1} y^{-1} by better nutrient management. On a typical plain site where the soil was cultivated and P was not applied, the MAI of a 4.5 years-old *E. urophylla* plantation was only 4 m^3 ha^{-1} and was increased to 22 m^3 ha^{-1} by the application of 20 kg P ha^{-1}, and to 30 m^3 ha^{-1} by the application of 200 kg P ha^{-1} (Xu *et al.,* 2001). Similarly, on a relatively fertile hilly site (less disturbed topsoil) without P fertilisation, the MAI of a 6.3 years-old *E. grandis x E. urophylla* plantation was only 4 m^3 ha^{-1} and was increased to 16 m^3 ha^{-1} by the application of 52 kg P ha^{-1} and to 19 m^3 ha^{-1} by the application of 209 kg P ha^{-1} (Xu *et al.,* 2002). The application of 52 kg P ha^{-1} in the previous rotation lifted the MAI of 2.5 years-old coppice from 9 to 18 m^3 ha^{-1}. Re-fertilisation with N, K and B in the second rotation further increased the MAI to 23 m^3 ha^{-1}. Even on a degraded site, the MAI of a 3.7 years-old second rotation *E. urophylla* plantation was increased from 1 to 7 m^3 ha^{-1} with replanted trees, and from 11 to 14 m^3 ha^{-1} with coppice. Therefore, it is possible to increase the average MAI of eucalypt plantations in south China from 5-10 (current situation) to 10-20 m^3 ha^{-1} in the near future, and to >20 m^3 ha^{-1} in the future.

Following the previous discussion on productivity increase by fertilisation, organic material management and ectomycorrhizal fungi inoculation, there is no doubt that the productivity of plantation eucalypts can be improved. However, the cost of plantation establishment is the largest cost for plantation eucalypts in south China. If the rotation period can be extended from the current 4-6 to 6-8 years without a decline in MAI, this will benefit both the economic position of the forest farmers and the maintenance of site fertility because there will be less disturbance to the soil if the rotation is longer. Therefore, more research effort should be placed on managing nutrients so as to extend the length of the rotation period without a decline in bole-wood production.

Results from our, and other studies, suggest the low productivity of eucalypt plantations in south China is a consequence of poor management of forest soil fertility in the past, including the over-harvesting of organic matter, and nil to inadequate fertilisation. It is predictable that better management of eucalypt plantations today will improve soil fertility and this will lead to higher productivity in the future. However, this requires underpinning by further research and monitoring.

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