Site Management and Productivity in Tropical Plantation Forests

Workshop Proceedings
7-11 December 1999
Kerala, India

Editors

E.K.S. Nambiar
A. Tiarks
C. Cossalter
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A Progress Report

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Introduction to Third Workshop in Kerala, India

E.K.S. Nambiar[1]

It has been widely recognised that an increasing proportion of the demand for wood supply should be met by timber harvest from planted forests rather than native forests. This is particularly so in many tropical and subtropical countries which have either established large areas of plantation forests (e.g., Brazil, India) or have embarked upon plantation forestry at a significant scale (e.g., Vietnam, Uruguay). Investors in these plantations seek to benefit from their short rotation resources, largely facilitated by industrial scale operations.

The strong need for growing plantation forests is evident in Kerala, where this workshop took place. Booth and Nambiar (2000) discussed the scenario in Kerala, which was once endowed with rich forests and abundant supply of tropical timber, and supported a major inter-state timber trade. Deforestation has brought this to a halt. Despite the diminishing use of timber for house construction (because of prohibitive price and scarcity) the current consumption is estimated to be between 2.6 and 3.0 million m^3 for a population of more than 29 million. More than half of this volume is taken from trees felled from homestead plantings, an unsustainable practice. India has an estimated area of about 4.8 million ha of eucalypt plantations, one of the largest areas under this genus in any one country. However, productivity of these plantations is low, less than 10 m^3 ha^{-1} yr^{-1} and frequently too low to be commercially viable. However, as the workshop field visit to experimental sites showed, the potential for increasing productivity by improved management is high. Acute shortage in wood supply (industrial, pole, structural and fuel wood) is endemic in India where harvesting of timber from native forests is illegal. Indian pulp and paper industries have pointed out that the establishment of well-managed plantation forests in 1% of the estimated 130 million hectares of ‘degraded forest land’ would alleviate the current resource constraint on their development.

Large areas of planted forests are reaching harvestable age and will go into second rotation in ecosystems where there are risks to sustainability. An example of this is the *Acacia mangium* plantations in Sumatra and Kalimantan in Indonesia which are managed on a 8-10-year rotation. Information for developing management options for maintaining and enhancing the productivity of successive crops is urgently needed, a point strongly made by several papers in this proceedings.

Since we began this network project the potential role of planted forests for providing ecosystem services including carbon sequestration for partly offsetting net greenhouse gas emissions, biodiversity enhancements in the landscape and mitigation of land and water degradation have been receiving renewed interest in several countries (Booth and Nambiar 2000). Soekartiko *et al.* (2000) have estimated that in South East Asia over two million hectares of land could be planted to eucalypt plantations through carbon investments within the next decade, sequestering about 10 million tonnes of carbon dioxide per year. Such development indeed requires major considerations on many complex issues including investments, community participation, balanced land use policies and capacity to generate and apply knowledge.

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Sustained productivity of plantation forests is the foundation of successful forestry which can provide diverse benefits. Sustained productivity is not a result of any single management practice but a single adverse practice such as poor harvesting practice can degrade soil to the detriment of long-term productivity. Sustainability is achieved incrementally, through all management practices applied throughout the rotation and between rotations (Nambiar and Brown 1997). The phase between the harvesting of one crop and the establishment of the next is a window of considerable risk as well as opportunity to set the course of successful forestry with little or no risk to environmental values. Managers have great flexibility for judicious application of technology for achieving their goals at this phase. Therefore the focus of the project is on the inter-rotation management phase.

Tiarks *et al.* (1998) have described the rationale of the project, including the concept of treatments, network arrangements and mutual obligations for partners. The key principles are:

- Evaluate the impact of soil and site management practices on the productivity of successive rotations of plantations;
- Develop management options for maintaining or increasing productivity;
- Strengthen local institutional capacity to respond to new problems and opportunities; and
- Establish close participation with local managers and foster appropriate mechanisms for technology transfer.

We reported on locations of sites, progress in installations, methods and of experimental results from a number of sites in the previous proceedings (Nambiar *et al.* 1999). The contents of the proceedings of the Kerala workshop build on that information. There has been further progress on new sites and more detailed results from sites where the study has been in progress for more than four years are available. Some sites are already providing highly relevant information, while others are at an early stage. The strength of the network lies in its unique opportunity to share knowledge (empirical and mechanistic) and management experience among scientists and managers working at 15 sites in seven countries. Partners in the network include researchers from research organisations operating at local, state or national levels, private companies, universities, forest managers and staff of international agencies supporting research. The papers presented in the new proceedings highlight the scientific progress achieved so far. Information in them, discussions and field visits are the conduits for achieving the project's goals.

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2

Effects of Site Management in a *Eucalyptus grandis* Plantation in the Humid Tropics: São Paulo, Brazil

J.L.M. Gonçalves[1], M.I.P. Serrano[2], K.C.F.S. Mendes[3] and J.L. Gava[3]

Abstract

This paper reports the effect of site management practices of minimum and intensive cultivation of the soil on the growth of a stand of *Eucalyptus grandis* and on N mineralisation. The study site is a commercial plantation of *E. grandis* in Itatinga district, São Paulo State, Brazil. At 39 months of age, the height growth among the treatments where the residues were retained, incorporated or burnt did not differ from each other. The height differences among these treatments decreased with time. These results highlight the temporary effect on initial growth promoted by the large availability of nutrients released by burning and from mineralisation of incorporated residues. The largest N-mineralisation rates were in the standing crop treatment, 44 kg ha^{-1} yr^{-1} of N, followed by the treatments where the residues were incorporated, 35 kg ha^{-1} yr^{-1} of N, and where slash and litter were retained with minimum site disturbance, 33 kg ha^{-1} yr^{-1} of N. Removal or burning of the residues inhibited N-mineralisation with only 26 and 16 kg ha^{-1} yr^{-1} of N, respectively in these treatments. The high rates of N-mineralisation in some treatments show why most of Brazilian eucalypt plantations have little or no response to N fertilisation.

Introduction

Brazilian eucalypt plantations have been established in areas originally covered by climax vegetation known as 'Cerrado' (savanna) and Atlantic forest. In the long term there are serious risks to sustainability, because of the low fertility and low reserves of primary minerals in the soils, commonly, medium textured latosols and quartzipsamments. Little is known about potential impacts caused by different site management practices on yield sustainability over successive rotations of eucalypt stands, particularly the relationship to nitrogen dynamics in these ecosystems.

Extensive eucalypt plantations rarely respond to N fertilisation under tropical and subtropical conditions (Barros *et al.* 1990, Herbert and Schönau 1990, Gonçalves *et al.* 1997). This is because the several natural sources of N, mainly the organic N mineralisation during the rotation, are enough to meet tree demands (Gonçalves and Barros 1999). However, due to the high outputs of N (Bellote *et al.* 1980, Poggiani 1985, Reis *et al.* 1987, Gonçalves 1995) and due to the possible exhaustion of mineralisable organic N reserves, intensively managed forests may respond to N fertilisation after successive rotations. The deficiency of N is closely related to exhaustion of mineralisable C sources, since the N dynamics are closely related to C (McGill and Christie 1983). There has been little research on this topic in Brazil.

This study aims to evaluate and compare the potential of N mineralisation in eucalypt stands established under different systems of soil preparation and forest residues management. Results presented here build on those reported by Gonçalves *et al.* (1999).

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Material and Methods

Description of the Experimental Area

The study is located in a commercial plantation of *Eucalyptus grandis* Hill ex Maiden, Itatinga district, São Paulo state, Brazil. It is located at $23^0$00'S and $48^0$52'W at an altitude of 750 m. The site is representative of extensive areas planted with eucalypts on the São Paulo plateau. Before plantation establishment the site was occupied by 'Cerrado', the native vegetation typical of the area. At the beginning of the study the stand was 7-year-old *E. grandis*. The climate of the area is Köeppen type Cwa, characterised by a dry winter with mean temperature for the coldest month (July) less than 18^0C, and a wet summer with the hottest month (January) above 22^0C. The annual mean precipitation is about 1580 mm, 57% of which falls during December to March. There is no pronounced water deficit. The soil type is characterised as a red-yellow latosol (oxisol), medium texture, dystrophic, and the topography flat to gentle relief. The physical and chemical characteristics of the soil are presented in the Tables 1 and 2.

Site Preparation

The experimental treatments are operational practices designed to provide a range of disturbances of different intensities for the soil and harvest residues. The first set of four treatments parallel the core treatments of the CIFOR Network trials (Tiarks *et al.* 1998; Gonçalves *et al.* 1999).

BL_0	All aboveground biomass, including the crop trees, understorey, slash and litter, removed.
BL_1	All stemwood harvested. All bark, understorey, slash and litter were retained with minimum disturbance to site (Note that in BL_1 treatment of the CIFOR Protocol aboveground parts, including bark of the commercial-sized crop stems, are removed).
BL_2	Stemwood with bark harvested. All slash, understorey and litter retained with minimum disturbance.
SC	Standing crop left intact.
SL_p	Harvest all stemwood. All residue (bark, slash, litter and understorey) incorporated in the soil with a heavy harrow.
SL_b	Harvest stemwood. All residue distributed on the soil and burnt.
CP	Clear-cut the stand and harvest stemwood. All residue retained on the soil. Cut stumps allowed to coppice.

The stand was clear-cut in July 1995 and treatments were applied by August 1995. Treatments BL_0, BL_1, BL_2, SL_p and SL_b were completed after the clearcutting and seedlings for the new plantation were planted in September 1995 at a spacing of 3 x 2 m. *Eucalyptus grandis* of Coffs Harbour provenance was used. Seedlings were planted in furrows and fertilised at planting with 15, 13 and 12 kg ha^{-1} of N, P and K, respectively, and a basal dressing of 250 kg ha^{-1} of KCl was applied in May 1996. Weeds were controlled manually.

Experimental Design

The plots were established in a randomised complete block design, with seven treatments and four replicates. Each plot consisted of 121 trees (11 x 11) and the total trial occupied 1.75 ha.

Table 1. Some physical characteristics of the soil

Depth	Sand	Silt	Clay	Bulk density	Particle density
(cm)		%		($g\ cm^{-3}$)	
0-20	77	3	20	1.25	2.22
20-50	76	2	22	1.30	2.25

Table 2. Some chemical characteristics of the soil

Depth	pH	C	N	C:N	P	K	Ca	Mg	H	Al	BS[1]	CEC[2]
(cm)	$CaCl_2$	($g\ dm^{-3}$)		($mg\ dm^{-3}$)			($cmol_c\ dm^{-3}$)					
0-10	3.7	14.5	1.2	12	4.0	0.04	0.4	0.1	6.0	1.7	0.5	2.2
10-20	3.8	9.9	0.9	11	4.3	0.03	0.5	0.1	5.5	1.5	0.6	2.1
20-30	3.8	9.3	0.9	10	3.0	0.03	0.2	0.1	3.8	1.5	0.3	1.8
30-50	3.9	4.7	0.5	9	3.0	0.02	0.1	0.1	3.0	1.3	0.2	1.5

[1] Sum of bases (K + Ca + Mg); [2] CEC at pH 7.0.

N Mineralisation

Rates of N mineralisation were measured in treatments SC, BL$_0$, BL$_1$, SL$_p$ and SL$_b$, using methodology of Raison *et al.* (1987). Soil cores were contained *in situ* in six PVC tubes (40 cm long and 5 cm diameter). Soil was incubated (*ca* 50 days), sequentially sampled and mineral N measured. The soil cores were divided at the following depths: 0-5, 5-15 and 15-30 cm.

To obtain the extracts, 10 g of fresh soil and litter was shaken with 50 ml of KCl (2M) for one hour (Bremner 1965). The extracts were centrifuged to 2000 rpm for 15 minutes; and 20 ml of aliquots collected, and treated with 1 ml of the microbial inhibitor. Concentration of NH_4^+-N and NO_3^--N was measured in the aliquot. Soil and litter subsamples were dried at 105ºC for 24 hours to determine moisture content.

Results and Discussion

Tree Growth under Different Systems of Site Management

Tree growth data at 6, 15 and 39 months are shown in the Fig. 1. At 6 months, the coppiced trees (CP) were the tallest (4.4 m; $p < 0.05$). This high initial growth of the eucalypt coppice compared to planted seedlings is observed frequently in plantations, partly due to the effect of nutrient reserves in the stumps and root system, and the ability of an established root system to uptake water and nutrients. The trees in SL$_b$, where the residues (litter and slash) were burned, had the second largest height growth in this age, which was significantly larger than the other treatments. The BL$_1$, BL$_2$ and SL$_p$ treatments (minimum site disturbance, all residues retained and residues incorporated respectively) were not significantly different from each other at 6 months, neither were BL$_2$ and BL$_0$ treatments (litter retained and all the residues removed, respectively). It is clear that BL$_0$ treatment resulted in the smallest trees. This highlights the effect of forest residues management and nutrient removal on initial growth.

At 15 months, tree height in SL$_b$ differed significantly ($p<0.05$) from BL$_1$, BL$_2$ and SL$_p$ treatments (Fig. 1). At this age, the height growth in BL$_1$ and SL$_p$ was the same as in the coppice (CP). Treatment BL$_0$ had the smallest average height. At 39 months, the height growth among BL$_1$, SL$_p$ and SL$_b$ was the same. Height differences among these treatments have diminished with time (Fig. 1). The basal area growth of BL$_1$ was not significantly different from SL$_b$, but was higher for SL$_p$ (Table 3). These results emphasise the temporary effect on early tree growth of the high amounts of nutrients released by burning and mineralisation. However, these treatments probably have undesirable effects such as loss of nutrients by volatilisation, leaching and erosion in the long term. The poorest growth was found in CP and BL$_0$ treatments (Fig. 1 and Table 3). Overall, the growth of the coppice was poorer than in replanted plots (except BL$_0$). This may be partly due to the better genetic quality of the seedlings.

Figure 1. Height growth of *E. grandis* at 6, 15 and 39 months of age in relation to treatments

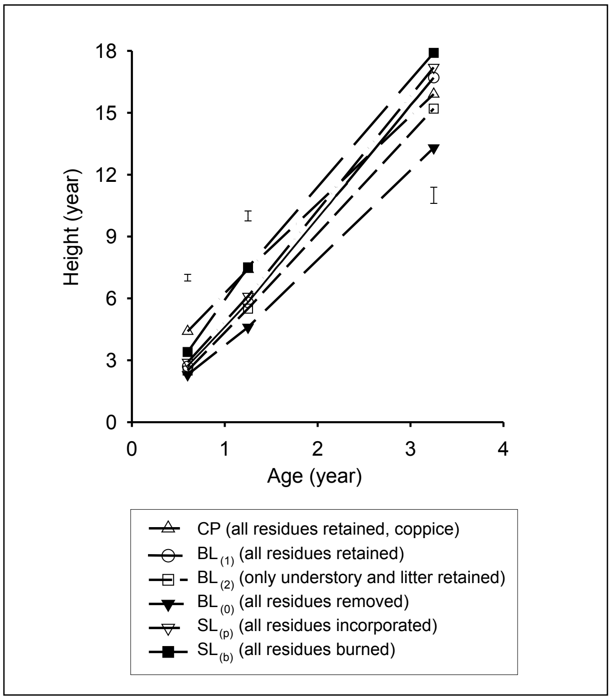


Table 3. Diameter and basal area at age 39 months

Treatment	dbh(1) (cm)	Basal area(1) ($m^2 ha^{-1}$)
CP	9.4 c	9.4 c
BL$_{(0)}$	8.5 d	9.2 c
BL$_{(1)}$	10.6 b	14.7 a
BL$_{(2)}$	9.8 c	12.4 b
SL$_{(p)}$	11.2 a	12.0 b
SL$_{(b)}$	11.2 a	15.7 a

(1) Mean followed by different letters are significantly different by Tukey test (p = 0.05).

Nitrogen Mineralisation

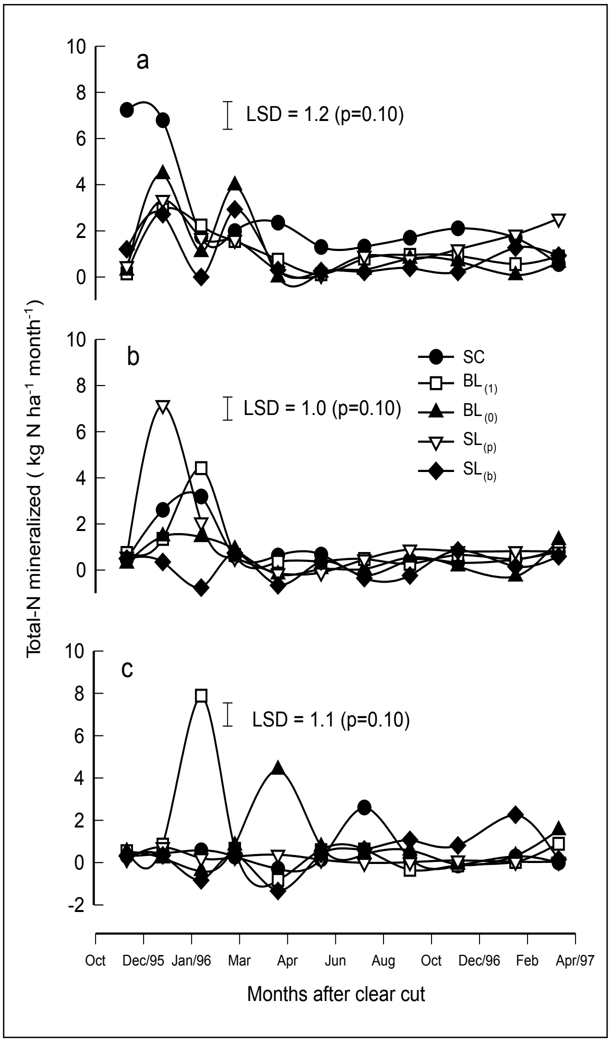
Over a 21 month period, the highest rates of N mineralisation (ammonification and nitrification) were found in SC (77 kg ha^{-1}), followed by SL$_p$ (61 kg ha^{-1}) and BL$_1$ treatments (58 kg ha^{-1}). In BL$_0$ 45 kg ha^{-1} of N was mineralised, and in SL$_b$ only 28 kg ha^{-1}. The contribution of litter was very small, less than 5% of the total N mineralised (Table 4 and Fig. 2). The largest amount of mineralised N was in the treatments where the soil microorganisms had more access to substrate. The removal or burning of forest residues considerably inhibited the N mineralisation rates. In the first case, the soil was exposed to the sterilising and drying effects of the sun, and so experienced high temperature and humidity fluctuations (Gonçalves *et al.* 1999), besides the reduction of substrate quality for the soil microorganisms. In the second case, the greater surface soil temperatures would have caused considerable reduction of microbial biomass. The residue incorporation (SL$_p$) increased N mineralisation by accelerating residue decomposition. So in this treatment, unlike BL$_1$, a large part of the mineralised N may have come from residue decomposition and soil organic matter.

Table 4. Total-N mineralised (NH_4^+ + NO_3^-) over the first 21 months after planting. The values in brackets are the percentages in relation to the total N

Treatment	Total-N mineralised				
	Litter	0-5 cm	5-15 cm	15-30 cm	Total
	(kg ha^{-1})				
SC	3 (4)	49 (64)	17 (22)	8 (10)	77
BL$_1$	3 (5)	20 (35)	18 (31)	17 (29)	58
BL$_0$	-	20 (44)	9 (20)	16 (36)	45
SL$_p$	-	26 (43)	23 (38)	12 (19)	61
SL$_b$	-	16 (57)	3 (11)	9 (32)	28

The high N mineralisation, 32 to 44 kg ha^{-1} yr^{-1}, in some treatments, explains the small or no response to N fertilisation in Brazilian eucalypt plantations (Barros *et al.* 1990 and Gonçalves and Barros 1999). The annual demand of N measured in young eucalypt stands is in the range of 20 to 50 kg ha^{-1} yr^{-1} as observed at this site (Gonçalves *et al.* 1999) and reported by Bellote *et al.* (1980), Poggiani (1985), Reis *et al.* (1987) and Gonçalves (1995).

Figure 2. Total-N mineralised (NH_4^+-N - NO_3^--N) in different soil layers, (a) 0-5 cm, (b) 5-15 cm, (c) 15-30 cm



The treatments where all (BL$_0$) or part of the residues (BL$_2$) were removed had smaller growth rates (Fig. 1 and Table 3). The removal of residues very much reduced the rates of N mineralisation in BL$_0$ (Table 5). However, this was not the main cause of the growth reduction, otherwise, growth would also have been low in SL$_b$, where all residues were burned and the rates of N mineralisation were very low (Table 5). The ashes of the residues produced in this treatment also did not constitute a good source of N for the trees, because most N is volatilised to the atmosphere during burning. Similarly, in the Brazilian savannas, Maluf (1991) reported losses of 88% of N from the residues of a eucalypt stand after harvesting. Comparing treatments BL_0 and SL_b, it appears that the more limiting nutrients were present in abundance in the residue ashes, and that it was probably P and K that stimulated much of the growth increase. Gava (1997) observed a strong response to K fertilisation in eucalypt plantations in similar climatic and edaphic conditions. All eucalypt plantations near the research site are given a large amount of P and K fertilisers at planting time (*ca* 35 kg ha^{-1} P and 8.5 kg ha^{-1} K) and in basal dressing (*ca* 90 kg ha^{-1} K). When these fertilisers are not applied, the growth is drastically reduced and economical wood production is not feasible.

Table 5. Amount of NH_4^+-N and NO_3^--N mineralised (0-30 cm) over the first 21 months after site preparation

Treatment	NH_4^+-N	NO_3^--N
	(kg ha^{-1})	
SC	60	17
BL_1	38	20
BL_0	32	13
SL_p	48	13
SL_b	10	18

Generally, the largest N mineralisation occurred in the 0-15 cm soil layer (> 65%) and in the old stand (SC), mineral N in this layer was about 90% of the total N (Table 4).

The highest N mineralisation rates and treatment differences were found in the first 8 months after clear-cut as a direct effect of the treatments in exposing soil (Fig. 2). Similar trends were also found for the soil temperature and moisture (Gonçalves *et al.* 1999). After this time, the fluctuations in mineralised amounts in each treatment and the differences among treatments were small. The superiority of the SC, SL_p and BL_1 over other treatments can be seen in Fig. 2.

The fluctuations of N mineralised with time were very small after the third measurement in the SC treatment (Fig. 2). Probably it would also have been small in the previous evaluations if the eucalypt stand had not been cleared to set up the adjacent plots of the other treatments. Because of the clear-cutting around the SC treatment plots, lateral solar radiation penetrated the SC plots, for about 8 to 12 months until the adjacent trees grew up. This caused a temperature increase (Gonçalves *et al.* 1999) and one of the possible causes of the high rates of N mineralisation in this period. After the rates stabilised the average N mineralisation rates were 2 kg ha^{-1} $month^{-1}$ at 0-5 cm, 1 kg ha^{-1} $month^{-1}$ at 5-15 cm and 0.4 kg ha^{-1} $month^{-1}$ at 15-30 cm. The mean N mineralisation rate was about 41 kg ha^{-1} yr^{-1} in the 0-30 cm layer (Fig. 2).

The amount of NH_4^+-N mineralised was higher than NO_3^--N in SC, BL_1, BL_0 and SL_p. The opposite only occurred in the SL_b treatment (residue burned) (Table 5). These results confirm that larger amounts of N are absorbed in the NH_4^+-N form. The total amount of NH_4^+ and NO_3^- mineralised in 0-30 cm soil in SC and SL_p were similar, NH_4^+ was lower than NO_3^- in BL_1, BL_0 and especially in SL_b treatment the differences were very high (Table 6). This means that the nitrification rates were higher than ammonification rates in all clearfelled treatments where the residues were burned, removed or maintained on the soil. The incorporation of the residues stimulated the nitrification. The burning of residues and the ash deposition on soil surface stimulated the activity of the nitrifier bacteria, probably due to increasing pH and soil fertility (Gonçalves *et al.* 1999), which can increase their competitive ability with other microorganisms. The burning effect on NO_3^- mineralisation was observed mainly in the 0-15 cm layer over the first 6 months. Similar results were found by Theodorou and Bowen (1982) when evaluating the effects of a bushfire on the microbiology of a dystrophic planosol under eucalypt forests. They found that the largest changes occurred in the 0-2 cm layer, with the effect still being observed about 2 months after burning.

The NH_4^+ mineralised in SC in the 0-5 cm layer was much higher than NO_3^- (Table 6). This indicates an inhibiting effect of the stand on the nitrification process. According to Carlyle (1986), the magnitude of the nitrification in forest stands is low relative to that observed in most agricultural lands due to great uptake of NH_4^+ (substrate of the nitrifier bacteria) and the adverse conditions of many soils used for forestry, such as low natural fertility and high acidity. In most of forest soils the N demand for heterotrophic organisms (arboreal, herbaceous species and microorganisms) is so high that little NH_4^+ remains for nitrifiers (Jansson 1958; Paul and Juna 1981; Attiwill and Leeper 1987). Most of the NH_4^+ is either taken up or immobilised.

Table 6. Nitrogen mineralisation in the form NH_4^+ and NO_3^-, and NH_4^+ : NO_3^- ratio during the first 21 months of measurement in the litter and soil

Treatment	N form	N mineralised				
		Litter	0 - 5 cm	5 - 15 cm	15 - 30 cm	Total
		(kg ha^{-1})				
SC	NH_4^+	0.4	57.2	11.3	5.2	74.1
	NO_3^-	0.1	19.2	34.9	16	70.2
	NH_4^+: NO_3^-	4	3	0.3	0.3	1.1
BL_1	NH_4^+	3.3	17.7	10.6	18.4	50.0
	NO_3^-	0.9	29.1	43.3	13.3	86.6
	NH_4^+: NO_3^-	3.6	0.6	0.3	1.4	0.6
BL_0	NH_4^+	-	19.2	5	17	41.2
	NO_3^-	-	22.5	22.8	12.1	57.4
	NH_4^+: NO_3^-	-	0.9	0.2	1.4	0.7
SL_p	NH_4^+	-	29.1	21.9	11.4	62.4
	NO_3^-	-	15.5	28.2	15	58.7
	NH_4^+-N: NO_3^--N	-	1.9	0.8	0.8	1.1
SL_b	NH_4^+	-	11.9	-5.2	6.3	13.0
	NO_3^-	-	29.6	30.2	17.8	77.6
	NH_4^+-N: NO_3^--N	-	0.4	-0.2	0.4	0.2

Conclusions

At 6 months, height growth of the coppice (4.4 m) exceeded that of the seedlings. The higher initial growth of *E. grandis* coppice shoots compared with planted seedlings is frequently observed in commercial plantations. However, by 39 months the growth of coppice was substantially poorer than all treatments except where all residue and litter was removed.

Burning the residues stimulated height growth up to 6 months of age. Where litter was retained (BL_2) or all the residues removed (BL_0) height growth was poorest. This highlights the effect of the forest residues and nutrient management on the initial tree growth. There was a temporary stimulating effect on height growth due to the high initial availability of nutrients released by burning and incorporation of residue.

The highest rates of N mineralisation (44 kg ha^{-1} yr^{-1}) were found in the standing crop. Other treatments (residues were incorporated in the soil, and slash and litter retained with minimum disturbance of the site) gave values of 35 and 33 kg ha^{-1} yr^{-1} respectively.

The removal or burning of the residues inhibited N mineralisation; only 26 and 16 kg ha^{-1} yr^{-1} of N, respectively, were produced in these treatments.

The largest N mineralisation rates and differences among treatments were observed over the first 8 months after clear-cutting. Subsequently fluctuations of mineralisation rates were low in and among treatments.

The mineralisation rates of NH_4^+-N were much higher than NH_3^+-N for all treatments, except for where the residues were burned. The NH_4^+-N mineralised in the standing crop (SC) in the 0-5 cm layer was much higher than NH_3^+-N. This indicates a strong inhibiting effect of the stand on the nitrification process.

The high rates of N mineralisation in the best treatments provide a basis for one of the reasons why most Brazilian eucalypt plantations have little or no response to N fertilisation.

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3

Effects of Site Management on *Eucalyptus* Plantations in the Equatorial Zone, on the Coastal Plains of the Congo

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Abstract

Sustainability is a research priority for clonal eucalypt plantations planted on very sandy and poor soils in the Congo. Results from a study using cloned *Eucalyptus* hybrids conducted since 1997 show: (1) a marked depressive effect on tree growth of removing slash and tree biomass after harvest; (2) a high risk of nutrient leaching in the first year after harvesting linked to the high rate of litter decomposition; (3) a temporary starter effect of litter burning but a depressive effect in the medium term; and (4) a slow but lasting impact of burying litter. It is concluded that site management must conserve a maximum amount of organic matter to ensure a sustainable production system. Debarking and retention on site of the upper stem and other harvesting slash without burning is recommended.

Introduction

Since 1978, 42 000 ha of clonal *Eucalyptus* plantations have been established around Pointe Noire by ECO sa (Eucalyptus du Congo Société Anonyme). These plantations are based on two natural hybrids (*Eucalyptus* PF1 and *E. tereticornis* x *E. grandis*) and, increasingly, on the artificial hybrid *E. urophylla* x *E. grandis*. The plantations consist of 9000 ha of first rotation planted trees, 18 000 ha of coppice and 15 000 ha of replanted sites. They are on sandy, acidic soils with small reserves of available nutrients. Potential risks of nutrient and water deficiencies exist in the medium or long term. The sustainability of these plantations has therefore been identified by UR2PI, an association of the Congo government, CIRAD and ECO sa for research and development, as a priority for research. Complementary studies focusing on this goal have been conducted since 1997.

A long-term field study has been set up in a savanna and in a planted crop of *E*. PF1 clone 1-41 to quantify the main fluxes through the two ecosystems, and to establish comparative water balances and nutrient budgets. First results relating to accumulation of nutrients in the stands, atmospheric inputs, and chemistry of through fall and soil solutions are already available (Laclau *et al*. 1999, 2000).

Other work has focused on the influence of successive rotations on changes in soil biological fertility (IRD 1999). The main changes likely in biological factors as plantations get older are: higher litter fall and increase of litter decomposition rate leading to enhanced nutrient cycling; increase of soil organic matter in the top layer which may induce a higher Cation Exchange Capacity; increase of parasitic nematode density with probable injurious effect on cuttings planted on former *Eucalyptus* areas; increase in abundance of earthworms and termites leading to improved soil properties. The CIFOR/UR2PI experiment includes two complementary trials, set up to assess harvesting methods and soil preparation for sustainable management of the replanted sites. The aim of this paper is to present the current results obtained and the potential consequences for the silvicultural practices.

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Location and Site Description

The general plantations are established on coastal plains around Pointe-Noire (latitude 4°48'S, longitude 11°5'E) with an elevation varying between 40 m and 180 m. The climate is subequatorial with an annual rainfall of 1200 mm, a rainy season from October to May (90% of the annual precipitation) and a dry season from June to September. Climatic conditions and soils have been described in detail in Bouillet *et al*. (1999). The soils, developed on very deep continental detritic material, are arenosols. They are characterised by homogeneous sandy texture, limited available nutrients, very low levels of exchangeable cations, organic matter and small cation exchange capacity, and are highly erodible. The soils on the trial sites share these general characteristics.

Stand Description

Experiment 1

Experimental details have been described previously in Bouillet *et al.* (1999). Before planting, the original savanna vegetation was burnt, regrowth controlled and the site ripped along the planting lines. The original stand was *E.* PF1 clone 1-41 planted in 1990 at a spacing of 4.0 x 4.7 m. NPK fertiliser was applied at the base of each tree at a rate of 13.8 kg ha^{-1} N, 13.8 kg ha^{-1} P and 22.3 kg ha^{-1} K. A further 26.0 kg ha^{-1} N, 26.0 kg ha^{-1} P and 42.0 kg ha^{-1} K was applied after three years. At harvesting in 1997, the stand had a mean height of 26.1 m, basal area of 12.9 m^2 ha^{-1} and standing volume under bark of 129 m^3 ha^{-1}. The stumps were weakened with glyphosate.

The second rotation trial was planted in 1998 with clone *E.* PF1 1-41. Spacing was 2.7 x 4.7 m (800 stems ha^{-1}). NPK fertiliser (15.6 kg ha^{-1} N, 15.6 kg ha^{-1} P and 25.2 kg ha^{-1} K). was applied at the base of each tree soon after planting. At 8 months, weeds were controlled with herbicide between the rows and manually in the rows.

Experiment 2

The stand was originally planted with *E.* PF1 clone 1-60 in October 1981. The area was ploughed with a disc harrow and then ripped along each planting row. Tree spacing was 4.0 x 6.0 m (417 stems ha^{-1}). Fertiliser, 100 g NPK (13-13-21), was applied in the planting hole (5.4 kg ha^{-1} N, 5.4 kg ha^{-1} P and 8.8 kg ha^{-1} K). Weeding was carried out mechanically with a disc harrow between the rows and manually in the rows. Five passes were necessary during the first three years. The first harvest was in August 1988. During the second rotation weeding was carried out mechanically. No fertiliser was applied. The second harvest was in November 1994. At the end of this first coppice rotation, the yield was low (10 m^3 ha^{-1} yr^{-1}) and the plot had to be replanted.

After harvesting, the stumps were treated with triclopyr and in April 1995 weeds were sprayed with glyphosate. In July and August 1995 the treatments including burning, ploughing or ripping were established. Cuttings were planted in October 1995 at a density of 800 stems ha^{-1}. The blocks were monoclonal; *E.* PF1 clones 1-87 and 1-131, *E. tereticornis* x *E. grandis* clones 2-6, 2-45 and L2-123 and *E. urophylla* x *E. grandis* clone 18-52 were used. Weed control was at 3, 6 and 19 months using glyphosate.

Experimental Design and Methods

Experiment 1

The experimental design is a complete randomised block with four replications. A unit plot has a gross area of 0.26 ha and an inner plot of 0.11 ha (88 trees) with two border rows (112 trees). Harvest residue treatments were:

BL$_0$	All above-ground residues removed from the plot.
BL$_1$	Whole-tree harvest. All above-ground components of the commercial trees (stem diameter at breast height > 11cm) were removed.
BL$_2$	Stemwood + bark harvested. Only the commercial-sized boles (top-end over-bark diameter > 2 cm) and associated bark was removed.
BL$_3$	Double slash. All the trees werere logged as in the BL$_2$ treatment. The residue of the treatment and that from BL$_1$ were distributed on the ground.
BL$_4$	Stemwood harvested. Only the commercial-sized boles, debarked, were removed.
BL$_5$	BL$_4$ + residue burned.

Litter samples were collected before harvesting the stand. Litter decomposition was assessed as follows: samples were collected every three months from September 1998 to December 1999, from blocks 1 and 3, for BL$_1$, BL$_2$, BL$_3$ and BL$_4$ treatments. For each of the three inter-row types, four samples were collected to quantify remaining biomass, and pooled for mineral content estimation. Litterfall was collected weekly using traps 50 cm square, for each treatment of block 1. These samples were used to estimate biomass and pooled at the end of each month for mineral content determination.

Two hundred soil samples were taken before stand harvesting from depths of 0-10, 10-20, 20-50, 50-70 and 70-100 cm. One year after planting (April 1999) samples were collected again in the same way. Since November 1998, N mineralisation by *in situ* methods (Raison *et al.* 1987) was measured every two weeks for BL_0, BL_3 and BL_4 of block 1. However it must be stressed that all the tubes were open, with cationic or anionic resins placed at the bottom of each to retain leached mineral-N (Jussy 1998).

Weed development was estimated as an index at eight months. A rope was put along the two diagonals of each inner plot and the weed re-establishment rate was defined as the ratio between the length of the rope resting on weeds and the length of the two diagonals expressed as a percentage.

Twelve trees were sampled to quantify above ground biomass and nutrient content of the stand before harvesting. Regression equations relating biomass and nutrient content of each tree component to the girth at breast height were developed (Bouillet *et al.* 1999). These tables were applied to the inventory data to estimate the biomass of the stands. The same approach was used to estimate the above ground biomass and nutrient content for BL_0, BL_3, BL_4 and BL_5 of block 1 one year after planting (end of the rainy season).

Experiment 2

The experimental design was a composite of three litter treatments and three site preparation treatments. The gross experimental unit is 0.42 ha and the inner plot 0.13 ha with four border rows.

Litter and soil preparation treatments were:

C	undisturbed (control)
D	incorporated with a disc harrow
B	controlled burn
NS	no subsoiling
1T	subsoiling using one tine
3T	subsoiling using three tines

Fifty-four litter samples were collected, five months after the coppice harvesting. At the same places, soil samples were taken at 0-10 cm and 10-20 cm (54 samples for each level). Thirty-six other soil samples were taken for the treatment NS x B, immediately after burning. Samples were taken again, one year after planting.

Results

Experiment 1

Biomass and nutrient content

The aboveground biomass and nutrient content of the trees before clearfelling were reported by Bouillet *et al.* (1999). The average biomass of the stand was *ca* 118 t ha^{-1} corresponding to 316 kg ha^{-1} N, 48 kg ha^{-1} P, 199 kg ha^{-1} K, 74 kg ha^{-1} Ca and 48 kg ha^{-1} Mg. The biomass, one year after planting, of the stands for BL_0, BL_3, BL_4 and BL_5, is given in Table 1. Determination of the corresponding nutrient content is still in process.

Table 1. Biomass of the aboveground components of the trees for BL_0, BL_3, BL_4 and BL_5 at 12 months in Experiment 1

Components	Treatments			
(t ha^{-1})	BL_0	BL_3	BL_4	BL_5
Wood (diameter >1 cm o.b.)	2.07 a	2.69 a	2.28 a	2.61 a
Bark (diameter > 1 cm o.b.)	1.13 a	1.46 b	1.50 b	1.82 c
Live leaves	0.64 a	3.29 bc	2.93 b	3.56 c
Branches + top stem	2.07 a	2.28 ab	2.38 ab	2.70 b
Total stand	5.91 a	9.71 b	9.09 b	10.68 b

Letters a and b indicate significant differences between treatments according to Bonferroni test (threshold : 5%).

BL_0 had a significantly lower total biomass and a very poor crown development (0.64 t ha^{-1} of leaves compared with an average of 3.26 t ha^{-1} for the other treatments). Conversely the highest biomass was in BL_5, where litter was burnt.

Tree growth

Up to 12 months, there were no significant differences in height and diameter between treatments, but at 18 months tree growth in BL_0 was significantly lower than in BL_3. There is also a tendency to a better growth for treatments with an initial higher amount of organic matter (BL_3 and BL_4) and for BL_5 (Table 2).

Table 2. Height and circumference of trees at 18 months in Experiment 1

Parameters	Treatments					
	BL_3	BL_5	BL_4	BL_2	BL_1	BL_0
Height (m)	8.64 a	8.49 ab	8.31 ab	8.28 ab	7.99 ab	7.72 b
Circumference (cm)	26.36 a	25.17 ab	24.85 ab	24.14 abc	22.48 bc	21.37 c

Letters a, b, c indicate significant differences between treatments according to Bonferroni test (threshold: 5%).

Understorey development

The understorey is mainly monocotyledons (*Loudetia arundinacea* and *Panicum maximum*), except in block 2 which was invaded by *Chromolaena odorata*. Weed regrowth indices at eight months are given in Table 3. There were significant differences between treatments with more weeds where there was less slash retained.

Table 3. Weed regrowth index (WRI) at 8 months in Experiment 1

Treatments	BL_0	BL_2	BL_1	BL_5	BL_4	BL_3
WRI (%)	86 a	78 a	77 ab	67 ab	56 b	42 c

Letters a, b, c indicate significant differences between treatments according to Bonferroni test (threshold: 5%).

Nitrogen mineralisation

There is no significant difference between treatments on net N mineralisation. However higher values were observed in BL_3: amounts produced in BL_0, BL_3, and BL_4, between 7 and 19 months, are 49.1 kg ha^{-1}, 57.8 kg ha^{-1}, and 45.5 kg ha^{-1} respectively (Figure 1). The trend to a greater mineral-N production for the double slash treatment is due to a higher nitrification rate: NO_3^--N production is significantly larger in BL_3 than in BL_0 (Table 4). We emphasise that net nitrification represents respectively 63%, 76% and 69% of net N mineralisation for BL_0, BL_3 and BL_4.

Figure 1. Changes in net N mineralisation from November 1998 to November 1999. Quantities produced during two weeks in 0-15 cm soil layer in Experiment 1

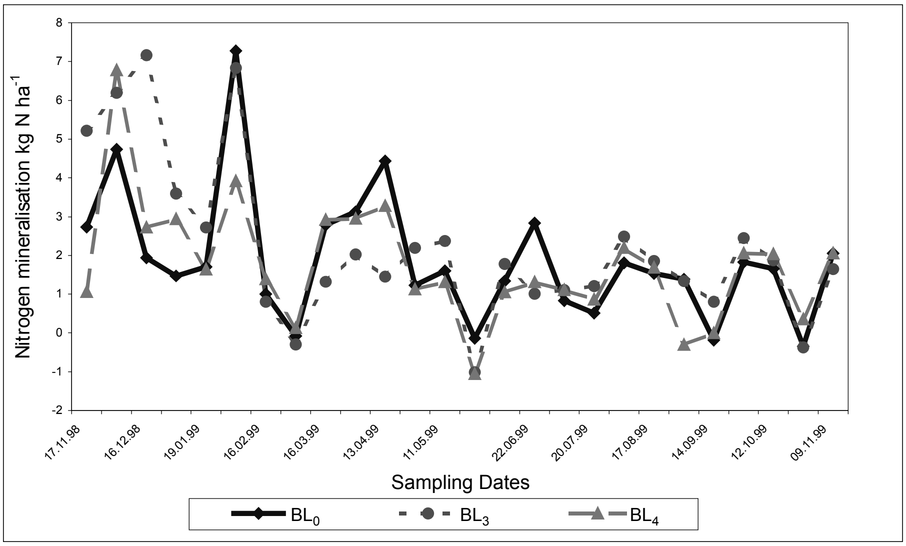

Table 4. Mean net nitrification and ammonification. Quantities produced during two weeks in 0-15 cm soil layer, between ages 7 and 19 months in Experiment 1

Treatments	$N\text{-}NO_3^-$	$N\text{-}NH_4^+$
	(kg ha^{-1})	
BL_3	1.70 a	0.53 a
BL_4	1.20ab	0.54 a
BL_0	1.18 b	0.70 a

Letters a and b indicate significant differences between treatments according to Bonferroni test (threshold: 5%).

Litter decomposition

Initially, the amount of slash in BL_1 was half that of BL_2 and BL_4 and a third of BL_3 (Table 5), but at 15 months the differences between treatments were much less. Almost all leaves and bark were decomposed and the slash remaining made up mainly of dead branches already fallen at the end of the previous rotation or broken during harvesting. Their amounts were similar in the different treatments.

Experiment 2

Tree growth

Litter treatments

Litter burning induced better growth during the first year, but this effect disappeared during the second year. In the third year, average growth in undisturbed litter and buried litter treatments was significantly better than in the litter burning treatments: 16.1 m^3 ha^{-1} yr^{-1} compared to 14.2 m^3 ha^{-1} yr^{-1}.

Soil preparation treatments

Significant differences on total volume increment between subsoiling with three tines (9.2 m^3 ha^{-1} yr^{-1}) and no subsoiling (7.6 m^3 ha^{-1} yr^{-1}) were found at 11 months but at 21 months and 36 months these treatments were no longer significantly different.

Growth of trees in different rows within plots

In logged areas, three types of interrows can be identified (Bouillet *et al.* 1999):

- slash interrows well stocked with leaves, bark, branches and twigs;
- log interrows used to store debarked wood; and
- haulage interrows (used by machines collecting the crop) contain a small amount of litter and have compacted soil.

At 36 months, production on haulage interrows (14.2 m^3 ha^{-1} yr^{-1}) was lower than on log interrows (15.4 m^3 ha^{-1} yr^{-1}) and slash interrows (16.7 m^3 ha^{-1} yr^{-1}). The changes of main effects are comparable, for each type of interrow, to those observed previously on the entire plots. It must be stressed that significant differences between subsoiling with three tines and no subsoiling still exist at 36 months on slash interrows, but not on the other interrows (Table 6). Hence, subsoiling effect is mainly linked to a better organic matter mineralisation, but not to the decompaction of the soil: a higher increase of production is thus observed on slash interrows, characterised by an abundant litter. Therefore, the differences of production between interrows can be explained by the amounts of organic matter and biological activity but not due to soil compaction.

Table 5. Changes in slash quantity (S) in t ha^{-1} and decomposition rate (D) as a proportion of initial weight (%) in Experiment 1

Treatment	Before harvest	After harvest	6 months		9 months		12 months		15 months	
	S	S	S	D	S	D	S	D	S	D
BL_1	12.66	16.07	9.99	37.8	7.44	53.7	5.91	63.2	5.14	68.0
BL_2	14.81	30.22	14.23	52.9	9.33	69.1	6.78	77.6	5.48	81.9
BL_3	13.08	49.38	17.11	65.4	13.75	72.2	9.47	80.8	6.08	87.7
BL_4	13.04	33.93	14.38	57.6	9.03	73.4	7.02	79.3	5.61	83.5

Table 6. Comparison of the mean annual increment on different subsoiling treatments and interrow types at 36 months in Experiment 2

Interrow type	Subsoiling using 3 tines	Subsoiling using 1 tine	No subsoiling
		(m^3 ha^{-1} yr^{-1})	
Haulage interrow	14.72 a	14.04 a	13.97 a
Log interrow	15.34 a	15.13 a	14.55 a
Slash interrow	17.54 a	16.92 a	15.56 b

Letters a and b indicate significant differences between treatments according to Bonferroni test (threshold: 5%).

Table 7. Growth of trees in treatment combinations at age 36 months in Experiment 2

D/NS	C/3T	D/3T	D/1T	C/1T	C/NS	B/3T	B/1T	B/NS
				m^3 ha^{-1} yr^{-1}				
16.5 a	16.1 a	16.1 ab	15.7 ab	15.2 ab	14.9 ab	14.7 ab	14.1 bc	13.8 c

Letter a, b, c indicate significant differences between treatments according to Bonferroni test (threshold: 5%).

Combined treatments
At 11 and 21 months the best growth was when litter burning was combined with subsoiling with three tines. But at 36 months the best growth was in plots where the litter had been buried or conserved while plots which included controlled burning of the litter had weaker growth (Table 7).

Discussion

Experiment 1

Tree growth and biomass

Removing all slash including litter (BL_0) depressed crown development and tree growth. The opposite effect was observed when high amounts of slash are retained. Decomposition of the leaves of harvested trees has already had a positive impact on growth (BL_2 is slightly better than BL_1). A similar conclusion can be made for bark decomposition (BL_4 vs BL_2). The initial impact of slash burning is still evident at 18 months. This result is consistent with previous observations on Experiment 2 (Nzila *et al.* 1998). It will be important to quantify the real impact of this site preparation in the coming years.

Understorey development

Regardless of the treatment, there was abundant growth of weeds, with the index and cover increasing from 5% before harvesting to more than 40% eight months after planting. However, this weed development is greatly reduced if a large amount of slash is retained, as in BL_3 and BL_4. Weed development is not particularly strong where there was controlled burning of slash residues. This result is consistent with previous observations in Experiment 2 (UR2PI 1999).

Nitrogen mineralisation

Gonçalves *et al.* (1999a) found high rates of N mineralisation when high amounts of residues were maintained at the soil surface in *Eucalyptus grandis* plantations located on oxisols in Brazil. The authors point out the better conditions for mineralisation (cooler temperature and more substrate for the soil microorganisms to process) in comparison with BL_0. Such results were also observed in Australia in *Eucalyptus globulus* plantations located on grey sand sites (O'Connell and Grove 1999; O'Connell *et al.* 1999). However, in our study, N mineralisation in BL_0 was not less than in a single slash treatment, such as BL_4. It will be important to observe if N mineralisation in BL_4 treatment increases in the near future above the level of the BL_0 plots, as observed in Australia from the second year after stand establishment in *Pinus* plantations growing on sandy podzols (Smethurst and Nambiar 1990) or from the third year after planting in *Eucalyptus* stands established on red earth sites (O'Connell *et al.* 1999).

In this study the nitrification is higher than ammonification, contrary to the results obtained in Brazil by Gonçalves *et al.* (1999a) or in Australia by O'Connell *et al.* (1999), but in agreement with the results of Smethurst and Nambiar (1990) from the second year after replanting. Therefore in the Pointe-Noire region there is a risk of marked N leaching in the young stand stage, when the stand uptake is limited by a root system that is not well developed.

The net N mineralisation in the 0-15 cm layer is similar, about 50 kg ha^{-1} for a stand age ranging between 7 and 19 months, for the different treatments. Several other points merit consideration here:

- even though the analyses are still in progress, it can be assumed that the amount of N accumulated by young trees in BL_3 or BL_4 in the first year after replanting must be of the same magnitude (*ca* 50 kg ha^{-1});
- a large part of NO_3-N mineralised may have been leached in the first year after replanting;
- the starter fertilisation provided only 16 kg ha^{-1} of N, a part of which would have been lost by leaching;
- the atmospheric inputs were low (*ca* 5 kg N ha^{-1} yr^{-1});
- the pool of mineral-N in the soil is low (Fig 2).

It appears that trees must take up a large part of the N required from the decomposing forest floor, removed in BL_0. This interpretation is consistent with the marked response to N fertilisation observed on the replanted sites (Safou-Matondo and Bouillet 1999).

Even though the rate of N mineralisation is of the same order of magnitude as in Brazil (Gonçalves *et al.* 1999a) and in Australia (Smethurst and Nambiar 1990), a methodological problem seems to occur at our site. During the rainy season a higher water content is observed inside the incubated cylinders, up to double the field capacity (Fig. 3). This may be due to soil compaction when setting the cores (Jussy 1998). This water accumulation could be also explained by the discontinuity existing between the incubated soil and the actual soil, due to the resin layer put at the bottom of the cores. Similar observations were made with plate lysimeters in a nearby stand.

Figure 2. Changes in mineral-N pool, in field-incubated soils (means of BL_0, BL_3 and BL_4 treatments), during two weeks in 0-15 cm soil layer in Experiment 1

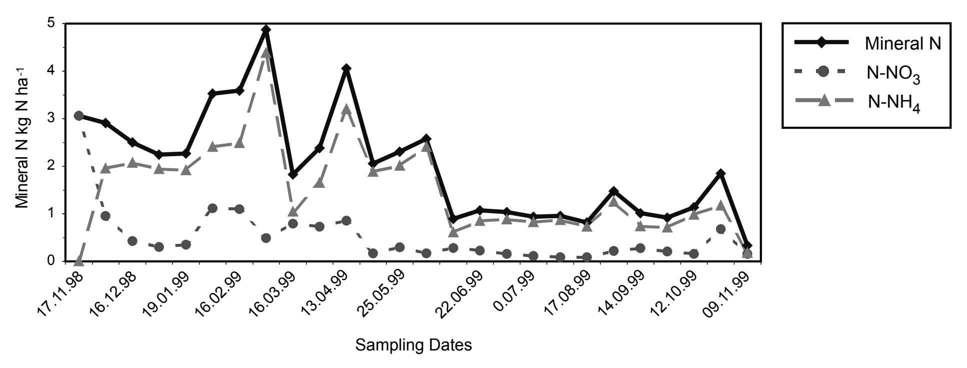

Figure 3. Soil water content in incubated soils and control soils (means of BL_0, BL_3 and BL_4 treatments)

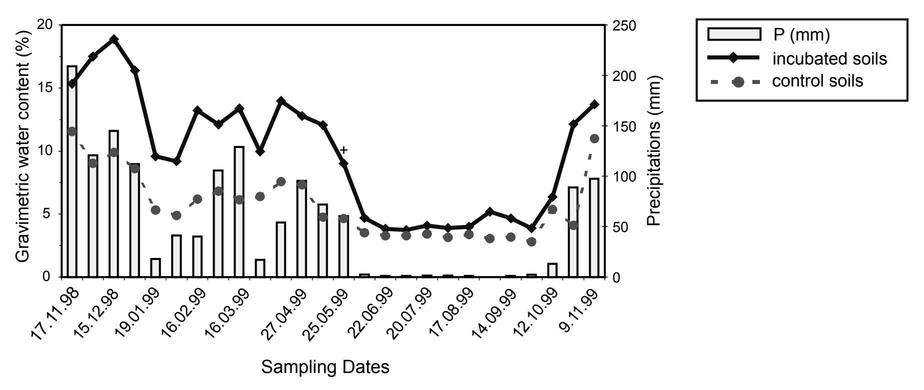

Table 8. Changes in soil water content in incubated soils according to three types of cores and in control soils for treatments BL_0 and BL_3 of Experiment 1

	Control soil	Control soil	Covered cores	Open cores	Open cores + resins
	(1)	(2)			
		Soil water content %			
BL_0	4.4	8.3	9.2	10.2	12.3
BL_3	4.3	8.7	7.7	9.9	14.9
Mean	4.4	8.5	8.5	10.1	13.6

Period: 26 October; (1) - 9 November 1999; (2). Precipitation: 122 mm.

The high soil water content could decrease N mineralisation by reducing aerobic microorganism activity (Sanchez 1976). Losses of N by denitrification could also occur (Jussy 1998). Tests were performed to adapt this methodology to the local site conditions. A methodology (Raison *et al.* 1987, Smethurst and Nambiar 1990, Weston and Attiwill 1996) using open and covered cores without resins at the bottom of the cylinders was tested. After two weeks with 122 mm of rain the water content was the same in the control soil and in the covered cores, but a higher moisture content was observed in the open cores especially when resin was present at the base of the core (Table 8).

Other experiments lead to consistent results (Table 9) with a higher soil water content in the cylinders containing resins. However the comparison of both methods indicates that greater values of net N mineralisation are observed with open cores and resins. This difference may be partly a consequence of the leaching by rainfall of N mineralised in the litter. We conclude that the methods using open cores with resins at the bottom shows rates of mineralisation consistent with the accumulation of N in the stands and so is appropriate to assess N mineralisation in soils at Pointe Noire.

Litter decomposition

A large proportion of organic matter (68-88%) disappeared in 15 months, corresponding to an annual decomposition coefficient (k) of 0.54 to 0.70. If we assume that the decomposed parts were mainly leaves, bark and twigs but not large branches, these results are consistent with previous studies. In the Congo, Bernhard-Reversat (1993) found k values of 0.61 for leaves and 0.24 for total litter for a 10-year-old stand of *E. tereticornis* x *E. grandis*. In Australia, Attiwill *et al.* (1995) reported k values of 0.2 to 0.4 for litter in eucalypt forests.

The rate of decomposition of the litter was particularly high during the first six months after harvesting: 38% (BL_1) to 65% (BL_3) of the slash disappeared during this period. A similar observation was made in Brazil (Gonçalves *et al.* 1999b) where 34% of the litter decomposed during the first six months following the clearcut of a 7-year-old *E. grandis* stand, where the slash had been removed. Thus, the risk of nutrient leaching is high, especially if there is a long interval between clearfelling and planting.

Experiment 2

Initially, treatments with burnt slash residues had a higher production. This starter effect can be explained by the rapid release of nutrients by litter combustion. Soil analyses at one year confirm the increase of base

Table 9. Soil water content and net N mineralisation in incubated 0-15cm soil layer in treatment BL_4 of Experiment 1

Period	Covered cores		Open cores + resins	
	Water content (%)	Net mineralisation (kg ha^{-1})	Water content (%)	Net mineralisation (kg ha^{-1})
04/01/00 - 18/01/00	5.1	-3.56	9.7	-1.92
18/01/00 - 01/02/00	10.8	2.49	19.1	4.20
01/02/00 - 15/02/00	6.5	5.32	11.3	6.08

cation availability in the topsoil of the burnt treatments (Bouillet *et al.* 1999), but burning also leads to a loss of significant quantities of nutrients by volatilisation or leaching since after three years the trees are less vigorous. Conversely, if the litter is incorporated or left undisturbed there is a slow and continuous mineralisation of organic matter.

Subsoiling using three tines had a significant positive effect during the first year. This may be explained by a quicker organic matter mineralisation but not by the decompaction of the interrow as this impact is marked only on slash interrows. We note that a N mineralisation increase due to litter incorporation was also observed in a young *Pinus radiata* plantation (Smethurst and Nambiar 1990). After three years, the planting hole technique resulted in stand growth similar to subsoiling.

Conclusions

These initial results show that management of organic matter of sandy and poor soils is of paramount importance to ensure ecosystem sustainability. Tree growth, but more generally soil quality, is strongly linked to the soil organic matter content mainly through mineral-N production. These results show that site management is able to quickly change the soil organic matter status.

From a practical point of view it is recommended that the maximum quantity of slash be retained on the site i.e. debarking and retention of the upper stem and crown on site. Slash must not be burnt but incorporated in the soil with a disc harrow or left undisturbed. The first option is preferred, especially if uncontrolled fire is a possibility, but the ground slope must be gentle (< 2-3 %) because of high erosion risks on these soils. Subsoiling is likely to be of little benefit.

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4

Effects of Site Management in *Eucalyptus grandis* Plantations in South Africa

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Abstract

This project investigates the effects of early, intensive management operations on stand productivity and long-term nutritional sustainability in *Eucalyptus grandis* plantations. The design, layout and objectives (including crop rotation treatment with *Acacia mearnsii*) are discussed. Before clear felling the previous eucalypt crop, the stand characteristics and biomass in the various ecosystem components were assessed. The standing volume was 147 m^3 ha^{-1}. Biomass of stem wood, harvest residue, forest floor, stumps and roots amounted to 124, 40, 70, 20 and 63 t ha^{-1}, respectively. Treatment implementation (harvesting operations, slash management and re-establishment) are described. Changes in the mass of the forest floor plus harvesting residue over time are illustrated. At the time of planting the residue in the double slash, single slash and burnt treatments amounted to 169, 117 and 31 t ha^{-1}, respectively. Initial indications are that nutrient availability in the fertilised, slash burnt and slash disturbed treatments is responsible for the superior growth responses recorded.

Introduction

Research conducted in hardwood plantations in South Africa over the past 50 years has demonstrated the benefits of early, intensive silviculture. Substantial improvements in productivity have resulted from site preparation (Smith 1998), fertilisation at time of planting (Herbert and Schönau 1990, Herbert 1996, Du Toit 1998) and management of competing vegetation (Little 1998). Site preparation options investigated vary from soil tillage operations where virgin land was afforested to the management of harvesting residue in replanted areas. Research on harvesting impacts showed current levels of soil compaction are unlikely to have an adverse effect on productivity on the most common soil types used for forestry in South Africa (Smith 1998). Soil disturbance and mixing caused by mechanised harvesting operations may significantly affect nutrient availability (Smith and Du Toit 1998), however, the processes governing the magnitude of this effect have not been quantified. There has been research on potential effects of harvesting on the nutrient capital in various biomass pools of hardwood stands (Herbert and Robertson 1991), but the dynamic processes of nutrient movement between pools have not been studied in detail.

The impact of specific operations (harvesting or early silviculture) on the nutrient capital and nutrient dynamics of the site needs to be quantified. Also, since nutrient dynamics are strongly influenced by soil water, the interplay between water dynamics and nutrient dynamics needs examination. These aspects form the basis of this project.

Objectives

Short term objectives are to understand and quantify the processes governing nutrient accretion across a range of silvicultural management options in young tree stands, specifically: (1) rate of macronutrient release from harvesting residue, (2) N and P supplying capacity of the soil, (3) rate of macronutrient uptake by trees, (4) nutrient content and quantity of litter fall as affected by treatments, and (5) carbon cycling and its effect on nutrient dynamics. Also to evaluate the effects of soil water availability and the microclimate on these processes.

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Medium to long-term objectives are to: (1) quantify changes in nutrient capital of the site due to silvicultural and harvesting treatments, (2) quantify changes in soil physical properties induced through compaction and site preparation, and (3) place the variations in nutrient and water dynamics in the broader context, through additional measurements in a mature eucalypt stand, a developing acacia stand and virgin grassland.

Location and Site Description

The Karkloof experiment is located near Howick in the Midlands of KwaZulu-Natal (KZN) province, South Africa. Site location and climatic data are presented in Table 1 (interpolated from various sources) and for the Cedara Agricultural College (a weather station with long-term historical data, situated approximately 17 km from the site).

Estimates of mean monthly rainfall and reference potential evaporation from an open water surface (E_r) have been calculated for the site, using the ACRU Model (Schulze *et al.* 1995). These values are presented in Fig. 1 with the monthly value ($0.3*E_r$) to demonstrate the approximate duration of the water deficit period and the ‘moisture growing season’ on the site, according to the FAO method cited by Schulze *et al.* (1995). The start of the moisture growing season is on day 244 (Julian calendar, i.e. 1 September) and the end is on day 105 (i.e. 15 April). The average duration is 226 days. A pronounced period of water deficit prevails in the winter months of May to August (Fig. 1). Mean monthly minimum and maximum temperatures are shown in Fig. 2. Light frost events occur sporadically

Table 1. Site location and weather data

Site	Karkloof Project	Cedara Agricultural College
Latitude	29° 24' S	29° 32' S
Longitude	30° 12' E	30° 17' E
Altitude	1260 m	1067 m
Mean annual rainfall	*ca.* 950 mm[1]	877 mm
Rainfall concentration index	51%[2]	-
Mean annual temperature	*ca.* 15.2°C[3]	16.2°C
Radiation (monthly min-max) ($MJ.m^{-2}.day^{-1}$)	-	15.9 - 27.8

[1] Mean value of seven stations recording only rainfall, located within a 5 km radius from the site with a mean recording period of 28.7 years;

[2] Based on the methodology of Markham (1970) as cited in Schulze (1997);

[3] Value estimated from adiabatic lapse rate for KZN (5°C per 1000 m increase in altitude).

Figure 1. Mean monthly values for evaporation (E_r), rainfall (P) and the value $0.3*E_r$ (dark line) at the site (the moisture growing season occurs where P> 0.3 E_r, i.e. Sept.-April)

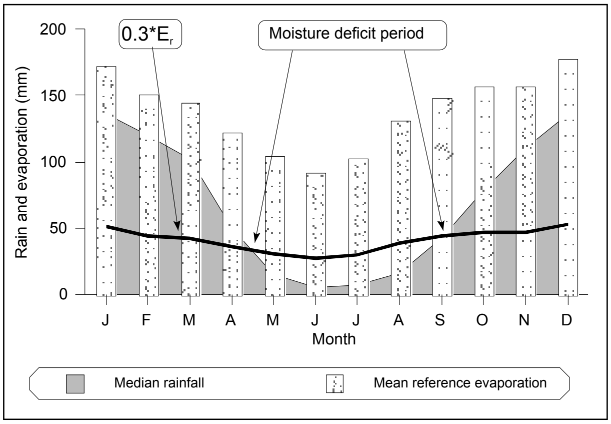
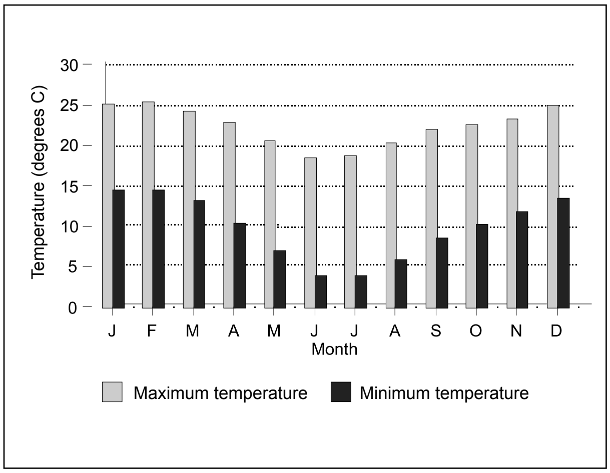


Figure 2. Mean monthly minimum and maximum temperatures at the site



during most winters and episodic snowfalls occur in the region on sites with altitudes over 1150 m (Gardner and Swain 1996). Recording of climatic data at the site started August 1998, about 6 months prior to trial establishment.

The soils suitable for forestry are dominated by highly weathered soils derived principally from sedimentary rocks (shale, sandstone and mudstone), with igneous (dolerite) intrusions. The gently undulating terrain at the site is derived from a mixture of dolerite and shale of the Ecca group. An area with a relatively uniform soil profile and stand characteristics (based on stocking and tree size distribution) was selected for the trial. A representative soil profile is described in Table 2. The soil is classified as a Kranskop 1100 (FAO classification = ferralsols). Soils in this group do not have a well-defined macrostructure since the clay minerals are dominated by 1:1 clays and sesquioxides. A well-developed microstructure ensures that the soils are stable, porous and well-drained. The potential for P fixation is high.

Table 2. Soil characteristics at the trial site

Horizon	Depth of horizon (cm)	Texture class	Particle size analysis Clay (%)	Silt (%)	Sand (%)	pH (KCl)	Organic carbon (%)
A	20	Clay	68	19	13	3.98	6.97
B_1	40	Clay	68	14	18	4.09	3.27
B_2	80	Clay	68	8	24	4.62	1.53
C	95	Silty clay	50	24	25	4.21	0.48

Stand Description

A stand of *Eucalyptus grandis* was established on virgin grassland in 1964. After the initial harvest, the stumps were allowed to coppice and were harvested three times (1973, 1982 and 1991). The fourth and final crop from the stumps was clear felled during the last quarter of 1998. It is common practice in the region to allow for one or two coppice crops. It is less common to allow a third coppice crop to grow to maturity, as was the case on this site.

Following the standard recommendations, coppice shoots are reduced to two or three stems per stump when mean shoot height is 4 m and are then reduced to one or two stems per stump (depending on stump mortality) when mean shoot height is 8 m (Stubbings and Schönau 1980). A spacing of 2.44 x 2.44 m was used in the original stand giving an initial stand density of 1680 stems ha^{-1}.

Experimental Design and Methods

The experimental design has been changed slightly from the plan proposed by Du Toit *et al.* (1999). The vegetation management treatments have been grouped together in a separate trial that will be implemented in 2000. The project is a set of experiments, consisting of a large, replicated trial, two satellite trials using smaller plots (for compaction and vegetation management treatments) as well as several additional plots (grassland, mature eucalypt stand, crop rotation treatments, and short rotation plots). The main *E. grandis* experiment is made up of four replications of three core treatments and the five optional treatments.

The core treatments are:

$\mathbf{BL_0}$	Slash removed: all harvesting residue (including bark, branches and foliage) and litter layer manually removed from the plot.
$\mathbf{BL_2}$	Regular slash load: harvesting residue retained and broadcast on the plot.
$\mathbf{BL_3}$	Double slash: material from the ‘slash removed’ plot deposited on top of existing slash.

The optional treatments are:

BS	Slash burnt: harvesting residue burnt in a medium intensity fire.
SD	Topsoil disturbed: slash disturbed and mixed with soil through mechanical loading and stacking of timber with a three-wheeled loader.
SF	Fertilised: regular slash load, followed by the application of an NP (+Zn) mixture.
SC	Base cation replacement: regular slash load plus gypsum and lime treatment to be implemented in future rotations.
SX	For future use: regular slash load. No follow-up treatment selected for this rotation to allow some flexibility in future.

Additional treatments with the *E. grandis* trial that are used to place nutrient dynamics in a broader context include the following:

G	Virgin grassland: a plot of virgin grassland.
M	Mature crop: mature *E. grandis* coppice crop.
R	Crop rotation: group of plots where *Acacia mearnsii* will be rotated with eucalypts.
C	Compaction: plots compacted by forwarders during timber extraction.
W	Vegetation management: stand-alone trial with various vegetation management treatments (to be implemented in 2000).
E	Stand density: plots with higher stand densities on a shorter rotation span (to be implemented in 2000).

Biomass and Nutrient Pools in the Pre-harvest Stand

The standing crop was surveyed before clear felling. The estimated site index was 18 m (SI_5 - i.e. mean height of the 20% of trees with the largest diameter at the reference age = 5 years). During September 1998, the areas representing future measurement plots were located. The stem number per plot and the diameter at breast height (dbh) of all trees in the plot were measured. The data was used to stratify standing trees into 18 diameter classes weighted by frequency per hectare. Sample trees were selected from the midpoint for each class, felled, debranched and crosscut into 2.5 m sections. A wood and bark disc was taken from each section to determine moisture content and to develop a taper equation for the stems. Bark was removed from the stem sections with thin end diameter > 7 cm over bark. Leaves and fruits (capsules) were removed from the branches. Tree biomass was divided into the following components: stem wood (debarked) for each 2.5 m section, stem top with bark (i.e. the section of the main leader < 7 cm diameter over bark), dead branches, live branches > 3 cm diameter, branches < 3 cm diameter, bark from logs > 7 cm diameter, leaves and capsules of the current growing season, leaves and capsules older than the current season. This separation was made easy by the fact that old capsules had opened and young capsules not. All samples were weighed fresh in the field, and representative subsamples collected for moisture and nutrient content determinations. Leaf areas of subsamples with known mass were determined by scanning with a LiCor(tm) Model LI 3100 Area Meter.

Three stumps with their root systems were excavated to estimate root and stump mass and to obtain samples for nutrient content determination. An area representing the spacing (2.44 x 2.44 m) was marked around each of the stumps. Soil was excavated at: 0-20, 20-60,and 60-100 cm (the bottom end of the deepest layer graded into weathered rock). Four core samples were taken per layer to determine root (< 10 mm diameter mass. The stump and all roots greater than 10 mm diameter were sampled per layer, split into coarse and medium fractions (greater and smaller than 10 cm diameter, respectively), airdried and weighed. Subsamples were taken for moisture and nutrient content determinations.

Pre-harvesting Preparations (November 1998)

Samples of forest floor were taken with a ring sampler of 30 cm diameter. They were separated into coarse (> 10 mm) medium (2-10 mm) and fine (< 2 mm) fractions, and weighed. The fine and medium fractions contained some soil and hence, the ash-free dry mass of each sample has been reported. In the BL_0 (slash removed) treatments, the bulk of the freshly fallen (L) layer was manually raked up into piles and transferred to the BL_3 (double slash) treatments. Old tree stumps were treated with herbicide (glyphosate/triclopyr mix) between one and 14 days before clear felling (the ‘basal frill treatment’ described by Little *et al.* (2000)). Coppice regrowth was not desirable as it would have necessitated several coppice control operations and would have altered the nutrient dynamics on site.

Harvesting and Slash Management Treatments

Experimental treatments were laid out in December 1998. Plots were demarcated and all trees felled by chainsaw and debarked manually. Logs were stacked in rows outside the plots. In the SD treatments, a three-wheeled loader with grapple was used to pick up all logs. This operation mimicked a loading operation since the loader travelled in a zigzag fashion across virtually the entire plot (only the borders of the outer plots were not impacted). The forwarder (25 t) was only allowed to travel in a predetermined path on the outside of the two lines of stacked timber. No vehicular traffic was allowed in the plots, except for the topsoil disturbed treatments. In the slash removed treatments the harvesting residue was raked up and transferred to the double slash treatments. Internal firebreaks were cleaned between replications as well as around the plots where the slash was burnt. The slash was burnt in one medium intensity fire.

Re-establishment, Fertilisation and Weed Control

Improved seeds of *E. grandis* were collected from trial EB 011K, of Sappi (Pty) and seedlings were raised in the ICFR nursery. The original spacing was maintained when the site was pitted for replanting because optimum economic returns on low productivity sites (such as the trial site) can be obtained with a final stocking of 1400-1500 trees ha^{-1}. *Acacia mearnsii* seedlings from genetically improved stock were used in crop rotation plots. The acacias were planted at a high stocking (2560 stems ha^{-1}) to accommodate for mortality, possible frost damage, browsing by buck, and to permit a light thinning. Eucalypt seedlings were planted on 3-4 February 1999, following substantial rains (45 mm during 1-3 February). A drench, consisting of 0.5 ml of Deltamethrin (5% suspension concentrate) in one litre of water, was applied to seedlings at planting to prevent problems with insect pests. Acacia seedlings were planted on 9 February 1999. Eucalypt mortality rate was assessed at 20 and 43 days after planting and dead trees replaced (blanked). Blanking amounted to 2.5% overall. Eucalypts were fertilised with 90 g of mono-ammonium phosphate (MAP + Zn) per tree (16.6 kg N + 33.2 kg P and 1.1 kg Zn ha^{-1}). The acacias were fertilised with 76 g concentrated superphosphate per tree (39.2 kg P ha^{-1}). The fertiliser was applied as a spot treatment 15 cm from the seedling. Fertiliser application rates were based on recommendations by Du Toit (1995, 1999).The few coppice sprouts were removed manually. Weeds were controlled once in the first nine months after planting by spot-spraying with glyphosate.

Slash Decomposition and Nutrient Availability

Two sets (each consisting of three bulked samples) of harvesting residue plus forest floor (hereafter called slash) were collected at three-monthly intervals from each plot in the burnt, double slash and single slash treatments (eight bulked samples per treatment per sampling). To allow for differences in nutrient content due to differences in degree of decomposition, the samples were separated into fine, medium and coarse fractions. After sieving, each fraction was oven-dried, weighed and analysed for macronutrient content.

The nitrogen mineralisation rate was determined quarterly (Raison *et al.* 1997) incorporating some modifications suggested by A.M. O'Connell, CSIRO, Australia (personal communication). The principal modification was that the uncapped core used to estimate leaching losses was omitted. Topsoil samples were also collected quarterly (using soil cores) to study the fluctuations in soil organic C and plant-available P.

Tree Growth, Leaf Area Development and Nutrient Uptake

Height of all trees in the measurement plots was measured every three months.. The following measurements are taken each six weeks from 16 trees per plot: height (Ht), crown diameter (CD), live crown length (CL), and ground level diameter (GLD). Biomass index (BI) of individual trees were calculated as a non-destructive measure of tree performance (Eccles *et al.* 1997) using the formula:

BI = mean Ht x $(GLD_q)^2$ x stocking (where GLD_q is the quadratic mean diameter).

Leaf surface index (LSI) (modified from the method of Shiver and Knowe 1990) was calculated as CD x CL.

Four trees per treatment were selected for destructive sampling at quarterly intervals. These samples were divided into foliar and woody components and weighed. Subsamples were taken for nutrient and moisture content and leaf area determinations.

Climatic Variables and Soil Water Contents

An automatic weather station (AWS), installed in July 1998 on a farm 2 km north of the trial, records the air temperature, relative humidity, solar radiation, rainfall, wind speed and direction. The data logger attached to the AWS has been programmed to calculate reference evaporation from a short grass surface, using the Penman-Monteith equation (Monteith 1965). Through the use of suitable crop coefficients, E_r can be transformed to an equivalent E_r for *E. grandis*. An additional rain gauge has been installed in the grassland plot on the trial site for purposes of comparison with the AWS.

The water retention characteristics data are being determined using undisturbed soil cores. Variations in soil water content (SWC) are monitored through a network of loggers and sensors. Instrumentation using frequency domain reflectometry (FDR) technology was installed during February and May 1999 and comprises two CR10 loggers and 15 CS615 soil water sensors. These sensors have been placed within the BL_2, BL_3, SB and SD treatments, in two of the four replications, and measure the SWCs at a depth of 0.15 m. Variations in soil water content in the deeper layers are currently monitored on weekly intervals with a neutron moisture meter.

Results

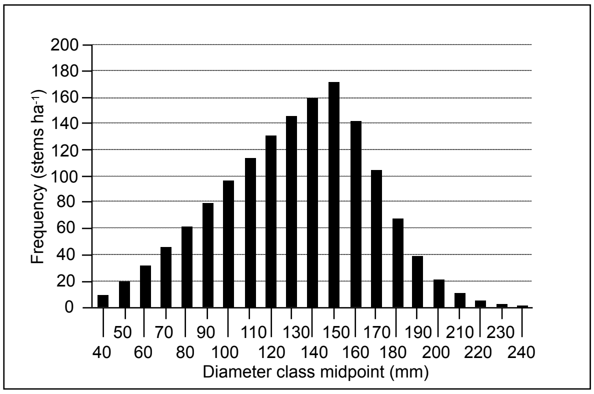
Characteristics and Biomass of the Stand before Harvest

The mean stocking at harvest was 1461 stems ha^{-1} from 1306 stumps ha^{-1}, an average of 1.1 stems $stump^{-1}$. Sample tree height was regressed against dbh as:

$Ht = 24.25 - 27.75 \text{ x } 0.8860^{(dbh)}$ ($n = 18$; s.e. = 0.72; variance accounted for = 92.5%)

The mean dbh of the stand was 134 mm in the seven year-old stand (Figure 3) and the estimated top height 21.1 m (mean height of the 20% of trees with greatest dbh). Basal area was 23.3 m^2 ha^{-1} and the utilisable timber volume 147 m^3 ha^{-1}. The stand had a leaf area index of 3.2.

Figure 3. Diameter class distribution of the stand before harvest



The biomass of components is shown in Table 3. Nutrient content analyses of the biomass components have not been completed. The mass of aboveground components was slightly lower than that of another *E. grandis* crop of similar age grown on a comparable site (Herbert and Robertson 1991). This was probably because the stand in this study is fourth coppice compared to the stand used by Herbert and Robertson (1991) which was based on trees grown from seedlings. The litter accumulation under the stand was large (70 t ha^{-1}) and this is assumed to be primarily due to the cool climate of the site and associated slow decomposition rate. The amount found in this study is high compared to tropical plantations (O'Connell and Sankaran 1997).

Table 3. Mass and distribution of biomass of the standing crop

	Components	Dry mass (t ha^{-1})
Standing crop	Bark	9.0
	Branches	23.7
	Capsules	2.8
	Leaves	4.7
	Total potential residue	**40.1**
	Stem wood	83.2
	Total standing crop	**123.3**
Forest floor	Coarse fraction (> 10 mm)	26.2
	Medium fraction (2-10 mm)	18.9
	Fine fraction (< 2 mm)	25.2
	Total forest floor	**70.3**
Stumps	Old stumps (above ground)	19.5
Roots	Coarse roots (> 100 mm ø)	41.7
	Medium roots (10-100 mm ø)	21.5
	Total roots > 10 mm	**63.2**
Total biomass	Standing crop + roots + stumps	206.0
	Standing + roots + stumps + litter	276.3

The root biomass was 30% of the total biomass, which exceeds the range of 4-11% for tropical plantation species given by Vogt *et al.* (1997) by a large margin. Two factors may have contributed to this: (1) the age of the root system is 34 years and that of the pre-harvest coppice crop is 7 years, and (2) the bulk of the entire root system that has roots > 10 mm diameter has been excavated at each sampling since the excavation extended into the weathered rock in each case. This differs from most studies where the soil depth is much deeper than the zone of root sampling.

Early Growth of Replanted Trees

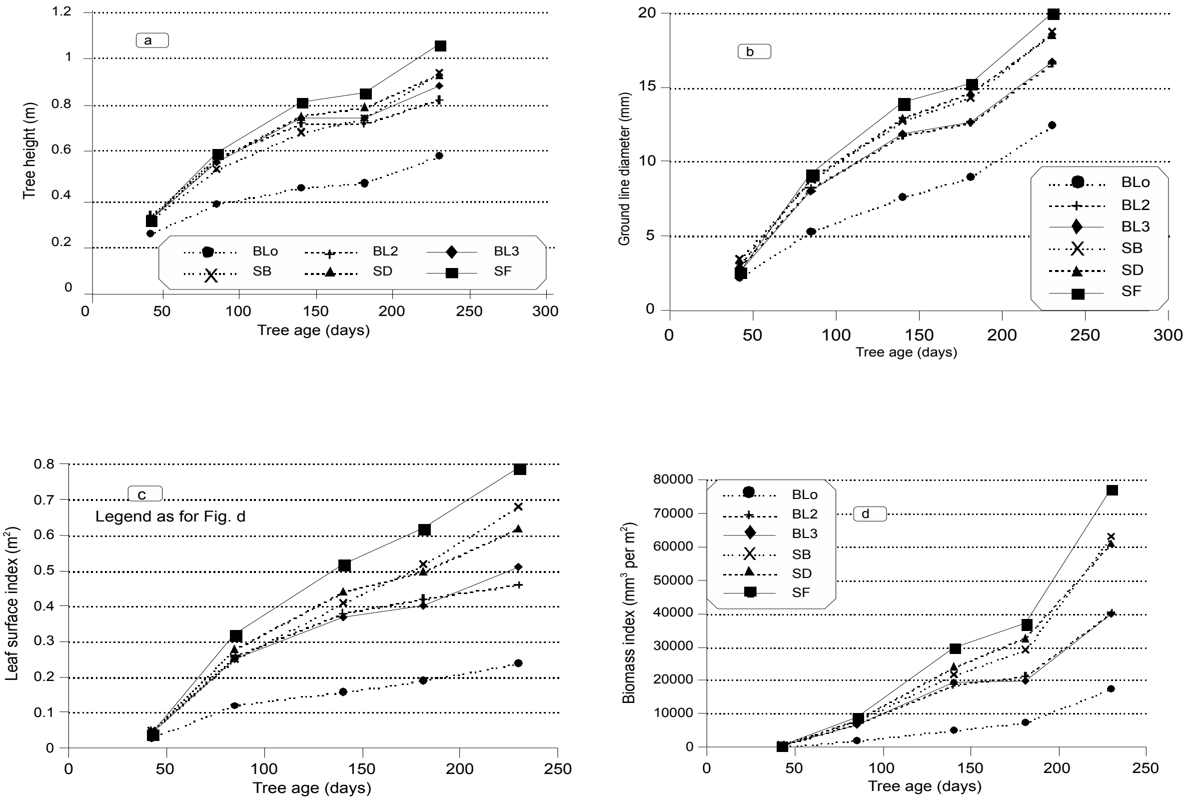
The development of tree height, ground level diameter, leaf area index and biomass index is shown graphically in Fig. 4 (a,b,c,d). Based on biomass index, leaf area index and ground level diameter measurements treatment effects can be ranked in the following (increasing) order:

1. Slash removed
2. Regular slash and double slash
3. Slash disturbed and slash burnt
4. Fertilised

It is difficult to interpret these results at this stage as the results of N mineralisation rate and plant-available nutrients are still being processed. The growth in the slash-removed treatment (BL_0) was very poor, all parameters growth had decreased from the other treatments as early as 40 days after planting (Fig. 4 a,b,c,d). This growth reduction does not appear to be due to lack of soil water for the following reasons: the topsoil in both slash-removed treatment and burnt plots was exposed after treatment. During the water deficit months (Fig. 1) the volumetric soil water content at a depth of 15 cm in these two treatments was similar (data not shown), but the growth responses were very different. The main reason for the poor growth in the BL_0 treatment is likely to be due to low nutrient availability. Despite the exposed surface, there was hardly any weed growth in slash-removed plots, in contrast to the burnt treatments where weeds re-established well.

The single and double slash treatments had similar growth rates. Any positive effects of the double slash treatment (in terms of increases in the nutrient capital) are likely to show only over the longer term. However, in the short term it has become apparent that the temperatures in the planting pits that were made in the double slash treatment are more extreme than that in other treatments (data not presented). Similar observations were recorded in heavy slash in pine stands in South Africa (Allan 1999). The double slash

Figure 4. Development of (a) tree height, (b) ground level diameter, (c) leaf area index, (d) biomass index

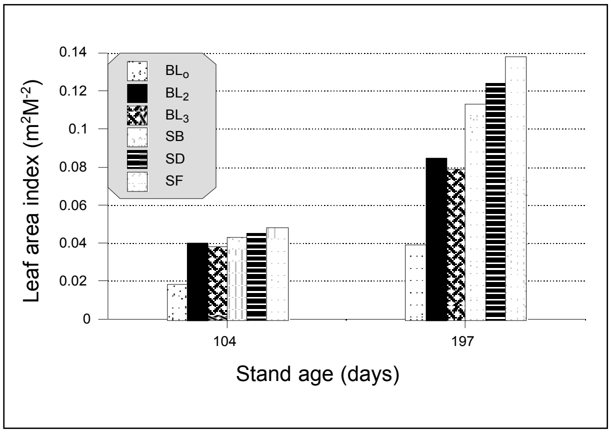


treatment had the highest level of mortality in the trial, possibly due to the formation of localised frost pockets.

The tree growth responses in the disturbed, burnt and fertilised treatments were higher than average. The increased growth on the fertilised treatment started to diverge from treatments BL_2 and BL_3 at 80 days after planting (Fig. 4 b,c,d), while the burnt and disturbed treatments started to diverge at 140 days after planting (Fig. 4 b,c,d).

The development of leaf area is illustrated in Fig. 5. Leaf Area Index (LAI) values are very low since trees are still small and canopy closure is expected to occur only during the second year. LAI development in the slash-removed treatment already lagged behind by day 104, while all other treatments had similar values. However, large treatment differences in LAI developed by day 197, with the disturbed, burnt and fertilised treatments having the highest LAIs.

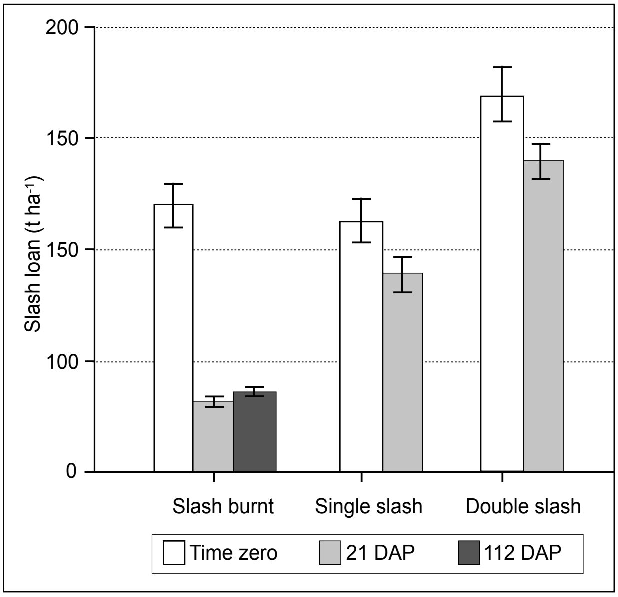
Figure 5. Effects of treatments on leaf area index



Changes in the Forest Floor and Slash

After harvest, the mass of slash was about 40 t ha^{-1} and the forest floor about 70 t ha^{-1} (Table 3). About 50-70% of the forest floor was removed during the litter raking. The difference in litter/slash quantity between single and double slash treatments should be approximately 40 t ha^{-1} (harvesting residue) plus 40 t ha^{-1} (coarse fraction of the forest floor that was transferred). The differences between double and single slash approximately 100 days after clear felling (i.e. 21 days after planting in Fig. 6) amounts to 52 t ha^{-1}. The difference in mass can be ascribed to two factors: (1) it was not always possible to broadcast slash evenly during clear felling, and (2) some collection of firewood by local people. It appears that the rate of decomposition is similar in the single slash and double slash plots. The mass of forest floor plus harvesting residue lost due to burning was about 90 t ha^{-1}.

Figure 6. Changes in slash load in selected treatments 0, 21 and 112 days after planting (DAP)



Climate and Soil Water Content

Monthly recorded reference evaporation (E_r) ranged between 145 mm in January 1999 to 76 mm in July 1999 (data not shown). Approximately 76% of the annual rainfall, for the period of 1998 and 1999, occurred between October and May. Between January 1999 and September 1999, there was 285 mm of rainfall compared to a long-term average of 579 mm. The driest period in 1999, which was longer than usual, occurred from April to September 1999 when there was only 42 mm of rainfall.

Figure 7 shows the rainfall and soil water data from March to November 1999. These preliminary results show that the soil water content in the slash treatment retained more soil water during winter and wetted up at a slower rate during the spring months, compared to the other treatments.

Water retention characteristics of two treatment plots in one replication have been determined and are shown in Table 4. The interplay between rainfall, treatments and soil water dynamics will be explored further as more results become available.

Figure 7. Rainfall and variations in volumetric soil water contents between treatments BL_2, BL_3, SD and SB from March to November 1999

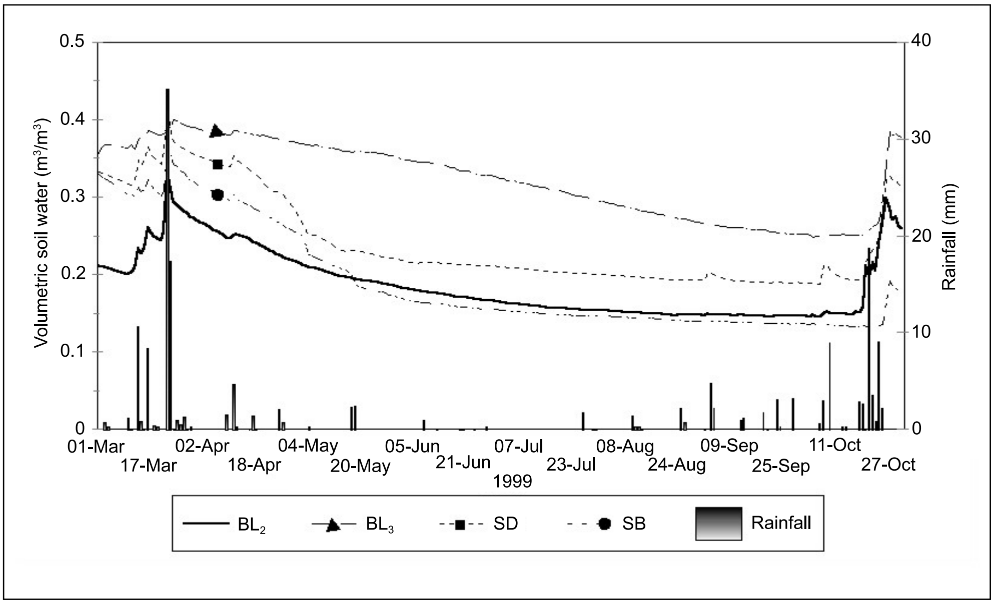


Table 4. Soil water parameters determined from the water retention characteristic

Treatment (Replication 3)	Bulk density ($Mg\ m^{-3}$)	Porosity	Field capacity	Wilting point	Plant available water
				($m^3\ m^{-3}$)	
Double slash (BL_2)	0.90	0.67	0.33	0.14	0.19
Slash disturbed (SD)	0.89	0.66	0.41	0.19	0.22

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5

Effects of Site Management in *Eucalyptus urophylla* Plantations in Guangdong Province, China

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Abstract

Effects of harvest residue management, intercropping with N-fixing trees, fertilisation and regeneration by coppice and replanting on tree growth, soil properties and soil nutrient availability are discussed in this paper. A 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 after tree planting. Tree growth in the treatment where all organic matter was removed and weeds were periodically controlled was better than in the whole tree harvest plots because of reduced weed competition. Intercropping with N-fixing trees enhanced tree growth two years after planting. Application of N, P and K fertiliser increased tree growth substantially. Growth increment was much higher than that obtained by harvest residue management on this poor degraded soil. Coppice trees grew better than replanted trees. The difference between coppice and replanted trees was reduced by fertilisation. Harvest residue retention, adequate fertilisation and coppice regeneration are therefore recommended as operational practices for eucalypt plantations in south China.

Introduction

There are more than one million hectares of eucalypt plantations in southern China and most have been established recently (Xu *et al.* 2000). Former land practices have led to site degradation and soils on sites available for eucalypt plantations are poor. Productivity is very low (average 5-10 m^3 ha^{-1} yr^{-1}) and variable (3-40 m^3 ha^{-1} yr^{-1}) compared with eucalypt plantations in other countries (Brown *et al.* 1997, Xu *et al.* 1999a). Chinese eucalypt plantations commonly have trees with very small crowns and grow slowly when more than 4 years old (Xu 1997), so trees are harvested after a short rotation period (3-6 years). Even though productivity is already low, it appears to be declining with successive rotations in some areas. Some reports relate the low productivity to low soil fertility (Dell and Malajczuk 1994; Xu and Dell, 1997) and low available soil P (Wang and Zhou 1996). Serious soil erosion (>13 t ha^{-1} yr^{-1}) after plantation establishment and associated nutrient loss (Xu *et al.* 1997) and organic material harvesting (Xu 1996) may be contributing factors. Fertilisation in the first year or first two years is a common practice (Wang and Zhou 1996; Zhong *et al.* 1998). Therefore, improving or maintaining soil fertility is essential to prevent tree growth stagnation in mid-rotation (3-4 years) and to increase or sustain productivity of eucalypt plantations.

The goal of this collaborative project is to develop alternative options for site management that will sustain or improve productivity of eucalypt plantations over succession rotations in southern China. More specifically the objectives are to understand the relationship between site management practice and productivity over successive rotations by studying:

1. impacts of different harvest levels and intercropping on soil physical and chemical properties, tree growth, biomass accumulation and nutrient cycling;

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2. impacts of regeneration options and fertilisation on soil physical and chemical properties, tree growth, biomass accumulation and nutrient cycling;
3. impacts of site management options on the process of soil fertility; and
4. long-term change in productivity over successive rotations.

Materials and Methods

Site description

The experimental site is located in Yangxi county, 5 km from Zhilong town ($21^0$43'N, $111^0$35'E), Guangdong province. The site is 20-50 m asl on a small hill with a slope of about 5 degrees.

The main features of the climate are: average annual rainfall 2178 mm, maximum rainfall in a day 242 mm, annual mean temperature 22.0^0C, maximum temperature 37.0^0C, minimum temperature 2.1^0C, mean temperature in the coldest month 15.0^0C, mean temperature in the hottest month 28.0^0C, and annual mean humidity 81%. More detailed climatic information was reported by Xu *et al.* (1999b).

The soil is lateritic red soil (Ultisol) over granite. The soil profile is more than 2 m deep with less than 20 cm A horizon. Soil bulk density is quite high and about 60% of the topsoil (0-40 cm) is white granitic sand (Xu *et al.* 1999b). As the soil was tilled for the first rotation eucalypt plantation, the bulk density of the 0-10 cm soil layer (1.46 g cm^{-3}) is compared to 1.43 g cm^{-3} in the 10-20 cm layer. Because it is degraded land and soil erosion was quite serious after cultivation for the first rotation, the fraction of white sand in the topsoil is higher than in the subsoil. Organic C in the topsoil is very low compared with other soils in south China. However, the relatively higher organic C in the 0-10 cm layer compared to the 10-20 cm layer indicates that litter from the first-rotation plantation contributed some organic C to the topsoil. Both total and available nutrient concentrations in the soil are low compared with undisturbed forest soils in south China (Xu *et al.* 2000). More information on soil was reported by Xu *et al.* (1999b).

This site is typical for eucalypt plantations planted on degraded soils in southern China. As a result, nutrient and water availability is limited in the topsoil during the dry season, and *Eucalyptus urophylla* S.T. Blake cannot grow well without soil cultivation and fertilisation. Soil erosion on the site was very serious after site preparation and tree planting (*ca* 13 t ha^{-1} yr^{-1}). In the dry season (October to March), water stress limits tree growth because of the shallow root system of *E. urophylla*.

In 1991, the original vegetation of mixed shrubs with scattered trees of *Pinus massoniana* Lamb. was cleared and the site cultivated to establish a plantation of *E. urophylla*. Spacing for the plantation was 2 x 3 m. At planting, 100 g NPK fertiliser (10.0% N; 4.4% P; 8.3% K) was applied per tree as basal fertiliser. In 1992, the fertilisation was repeated.

Soil and plant analysis

Soil samples for chemical analyses were made after plots were established but before any treatments were applied. More soil samples were collected two years after planting. Five points in each plot were sampled in Experiment 1 and three points in each plot in Experiment 2, and the soil separated into three layers (0-10, 10-20 and 20-40 cm). Soil samples (0-20 cm layer) for NO_3-N, NH_4-N, available P and exchangeable K determinations were collected at 2-month intervals in the rainy season and 3-month intervals in the dry season. Methods for soil analysis were:

- total N, by H_2SO_4 digestion (with K_2SO_4, $CuSO_4$ and Se) and H_3BO_3 absorption;
- available N (hydrolysable N), 1 mol L^{-1} NaOH hydrolysis and H_3BO_3 absorption (Cornfield 1960);
- total P, by ignition followed by colorimetric molybdate blue (Murphy and Riley 1962);
- available P, by Mehlich-1 extractant (0.05 mol L^{-1} HCl and 0.025 mol L^{-1} H_2SO_4 extractable P);
- total K, by ignition method (same as total P) and determined by flame photometer;
- exchangeable K, by 1 mol L^{-1} NH_4OAc extraction and determined by flame photometer;
- exchangeable Ca and Mg, by NH_4OAc extraction and determined by atomic absorption;
- pH, 1:2.5 water solution;
- organic C, by Tyurin method (Tyurin 1931).
- NO_3-N, by $CaSO_4$ extraction and C_6H_5OH and H_2SO_4 colorimetry (Bremner 1965). and
- NH_4-N, by MgO and H_3BO_3 absorption (Bremner 1965).

Methods for plant analysis were:

- N by: H_2SO_4 ($ZnSO_4$, $FeSO_4$) digestion and Kjeldahl;
- P by HNO_3 and HClO4 digestion and colorimetry;
- K by HNO_3 and $HClO_4$ digestion and flame photometer; and
- Ca and Mg, by HNO_3 and $HClO_4$ digestion and atomic absorption.

Experimental Design and Layout

The subproject consists of two adjacent experiments having separate but complementary objectives and experimental designs.

Experiment 1: Impacts of different harvest intensities and intercropping with acacia

The impacts of different harvest intensities and intercropping are measured when a first-rotation *E. urophylla* plantation is harvested and a second crop established. The experimental design is a randomised complete block with five treatments and four blocks. The treatments are:

BL_0 All aboveground organic residue is removed from the plot (tree components, understorey and litter).

BL_1 Whole tree harvest (aboveground tree components excluding stem wood removed from plot and distributed on BL_3).

BL_2 Stem and bark harvest (remaining branches and foliage distributed evenly on the plot).

BL_3 Double slash (foliage and branches from trees harvested from plot plus the slash from BL_1 are distributed evenly over the plot).

BL_4 Stem and bark harvest plus intercropping with *Acacia holosericea* A. Cunn. ex G. Don.

Each of the 20 plots is 360 m^2 in area with 60 trees (6 x 10) spaced at 2 x 3 m. They were laid out in a complete block design. The designated harvest level was applied to each plot as it was harvested in March 1997. Planting holes (40 x 40 x 30 cm) were prepared at the same spacing as the former plantation (2 x 3 m). Fertilisers used were: urea (46% N), potassium chloride -KCl (40% K) and superphosphate (6.4% P) were placed in each hole. On 8 April 1997, seedlings grown from seeds collected in the plantation were planted and coppice from the first rotation stumps was removed every 2-3 months. In the BL_4 treatment, seedlings of *A. holosericea* were planted between rows of planted eucalypt seedlings without any fertiliser.

Experiment 2: Impacts of different regeneration methods and fertilisation

The experimental design is split plot with three treatments (fertilisation level), two subtreatments (regeneration method) and four blocks. The main treatments are:

F_0 no additional fertilisation;

F_1 low level fertilisation: N 76.7 kg ha^{-1}, P 16.0 kg ha^{-1} and K 53.4 kg ha^{-1};

F_2 high level fertilisation: N 153.3 kg ha^{-1}, P 32 kg ha^{-1} and K 106.7 kg ha^{-1}.

The two subtreatments are:

MT_0 coppice;

MT_1 seedling planting.

Seedlings were planted on April 8, 1997. The coppice subtreatment was thinned to two coppice stems per tree on 15 July 1997. The harvesting level on all of these plots was BL_1. An additional two subplots were added in each block to compare the effects of different harvest levels when no fertiliser is added. They were BL_0 (all aboveground organic residue removed from the plot) and BL_3 (double slash). There are 72 trees in each plot (6 x 12) and 36 trees in each subplot. The spacing is 2 x 3 m. The area of each plot is 432 m^2. As in Experiment 1, the designated harvest level was applied to each plot in March 1997. Trees were harvested in March 1997 and the experiment was laid out. Planting holes (40 x 40 x 30cm) were prepared on the planted subplots while the coppice plots were left undisturbed.

The F_1 treatments received 25 g urea, 40 g KCl and 150 g superphosphate as base fertiliser for each tree before planting and 25 g urea was applied 3 months after planting. In coppice subplots, the entire 50 g urea, 40 g KCl and 150 g superphosphate were applied 3 months after cutting. Both the planted and coppice plots received 50 g urea and 40 g KCl one year after planting. The F_2 fertiliser treatments were the same as in F_1 except the seedling subplots received 50 g urea, 40 g KCl and 150 g superphosphate as base fertiliser and another 50 g urea and 40 g KCl were applied 3 months after planting. The F_2 coppice plots received 100 g urea, 80 g KCl and 150 g superphosphate 3 months after cutting. On both planted and coppice subplots, an additional 100 g urea, 80 g KCl and 150 g superphosphate were applied one year after planting.

Results

Experiment 1: Impacts of different harvest intensities and intercropping with acacia

Tree height was significantly different among the 5 treatments (p<0.01) 8 months after planting and this difference increased with time (Fig. 1). Until 8 months old, trees in BL_3 and BL_0 were taller than trees in the other three treatments (Fig. 2). After 31 months the tallest trees were in BL_3 and BL_4 and the poorest growth was BL_1. Treatments BL_0 and BL_2 were intermediate (Fig. 2). Tree height growth of BL_0, BL_1, BL_2, BL_3 and BL_4 from 8-20 months was 1.7, 1.6, 1.9, 2.2 and 2.0 m respectively. Compared to BL_2 and BL_3, the rate of height growth in BL_0 and BL_1 declined in the period. Height growth of BL_0 BL_1, BL_2, BL_3 and BL_4 from 20 to 31 months was 1.8, 1.6, 1.7, 1.9 and 2.1 m respectively. The rate of tree height growth in BL_4 increased after age 20 months compared to all of the other treatments.

Figure 1. Tree height of different harvest residue treatments

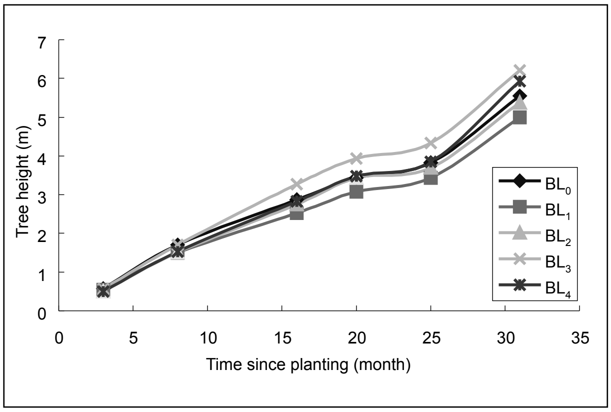
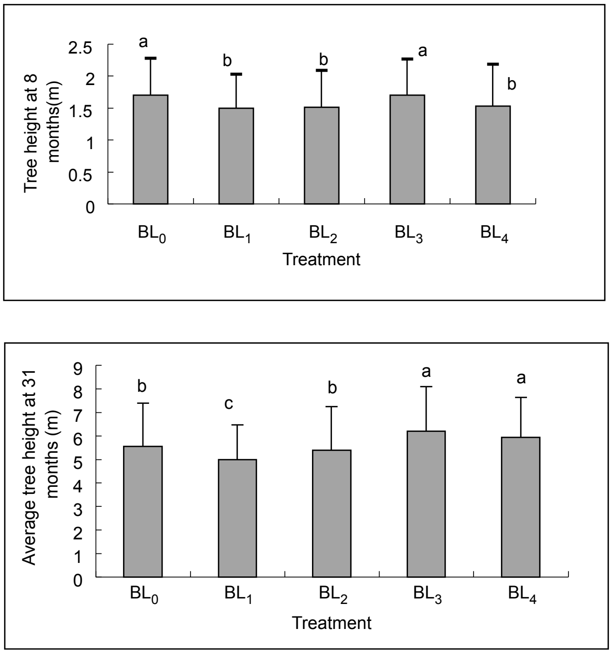


Figure 2. Tree height at 8 and 31 months after planting. Means of the treatment with same letter are not significantly different at the level of P=0.05 using Newman-Keuls critical range test. Bars = standard deviation



Tree diameter was significantly different in the five treatments (p<0.001). At 8 months, the best two treatments for diameter were BL_0 and BL_3 (Table 1). At 16 months, the best treatment was BL_3 and BL_3 poorest was BL_1. At 31 months, the best treatment in tree diameter was still BL3 and the next was BL_4. The poorest was still BL_1 (Table 1).

Table 1. Tree diameter between 3 and 31 months from planting (the first two measurements were at 10 cm height and the others at 1.3 m)

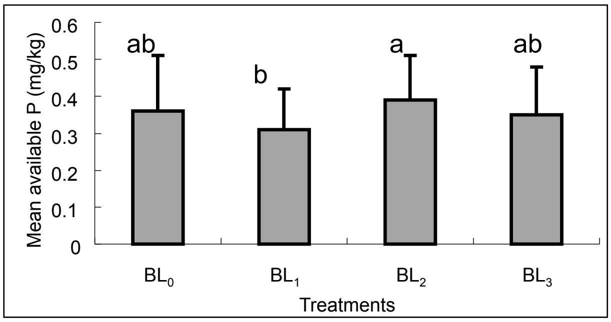
Treatment	Age (months)					
	3	8	16	20	25	31
				cm		
BL_0	0.9	3.1 a	2.4 b	3.0	3.7	4.5 b
BL_1	0.8	2.5 b	2.0 c	2.5	3.0	3.9 c
BL_2	0.7	2.5 b	2.3 b	2.8	3.4	4.3 b
BL_3	0.9	2.9 a	2.8 a	3.2	4.0	4.9 a
BL_4	0.7	2.5 b	2.4 b	2.8	3.5	4.5 ab

Means of the treatment with same letter are not significantly different at the level of P=0.05 using Newman-Keuls critical range test.

Available nutrients in topsoil

BL$_3$ had the highest mean available P in 0-20 cm topsoil over 10 collection times and BL$_1$ the lowest ($p<0.005$). BL$_0$ and BL$_2$ were similar (Fig. 3).

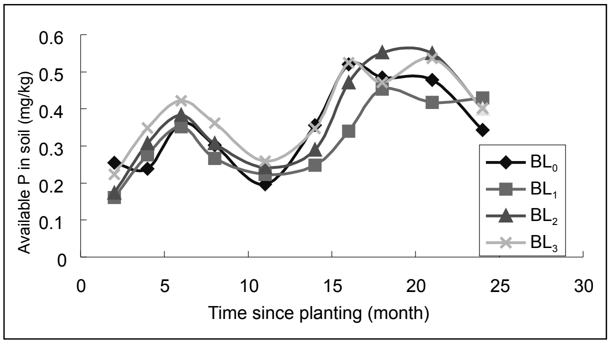
Figure 3. Mean available P in topsoil of different harvest treatments over 10 collection times



Means of the treatment with same letter are not significantly different at the level of P=0.05 using Newman-Keuls critical range test. Bars = standard deviation.

There was also a significant difference ($P<0.001$) of available P among 10 sampling times. Available P in the topsoil in the second year was higher than that in first year after planting (Fig. 4). During the 2 years (3-8 and 15-20 months after planting), available P in the topsoil was higher in the wet season than that in the dry season.

Figure 4. Change in concentrations of available P in the topsoil



Available P in the harvest residue treatments varied with sampling time. Generally it was highest in BL$_3$ and lowest in BL$_1$. Two months after planting, available P in BL$_0$ was the highest but by 4 months it was the lowest and remained lower than BL$_3$ and BL$_2$ until 13 months after planting (May, the end of dry season) when it increased temporarily (May-July).

There was a significant difference ($p<0.01$) of exchangeable K in topsoil between 10 sampling times (Fig. 5) but there was no seasonal pattern. There was no significant difference ($p>0.05$) among the harvest residue treatments. There was a significant difference ($p<0.01$) of NH$_4$-N in topsoil over the sampling times. The NH$_4$-N was higher in the first year after planting than that in the second year (Fig. 6). There was also some difference ($p=0.065$) of NH$_4$-N in the four harvest residue treatments. NH$_4$-N in BL$_3$ was higher than that in other three treatments in the first year, but not in the second year after planting.

Figure 5. Change in concentration of exchangeable K in the top soil

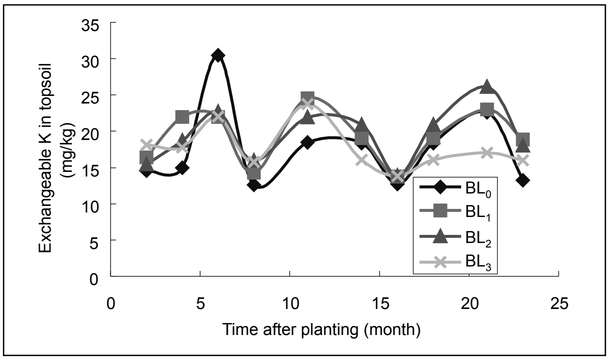
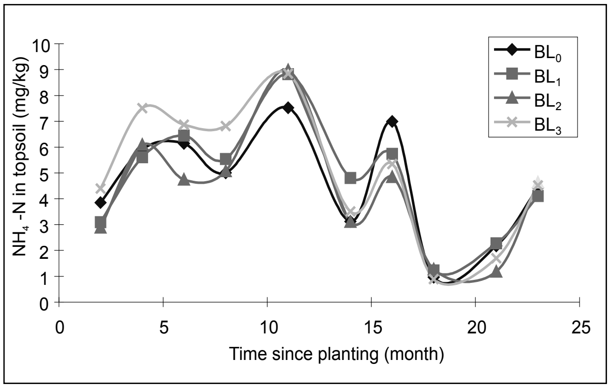
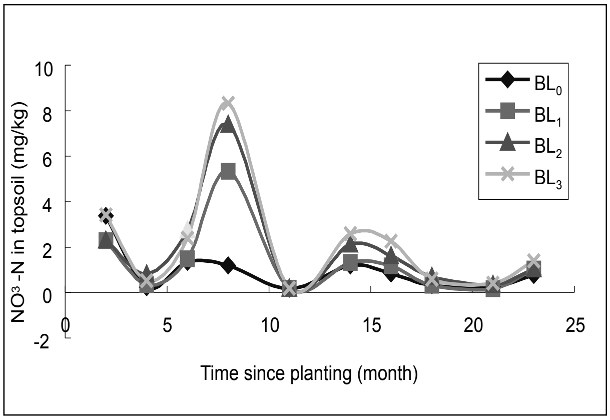


Figure 6. Change in concentration of NH$_4$-N in the topsoil



There was a significant difference ($p<0.01$) of NO$_3$-N in topsoil over the sampling times. Nitrate-N in topsoil in the first year was higher that that in the second year after planting. It was more variable in different sampling times than available P, exchangeable K and NH$_4$-N. However there was no significant difference ($p>0.05$) among the harvest residue treatments. NO_3-N in BL_3 and BL_2 was only higher than the no harvest residue treatments (BL_0 and BL_1) at four sampling times (Fig. 7).

Figure 7. Change in concentration of NO_3-N in the topsoil



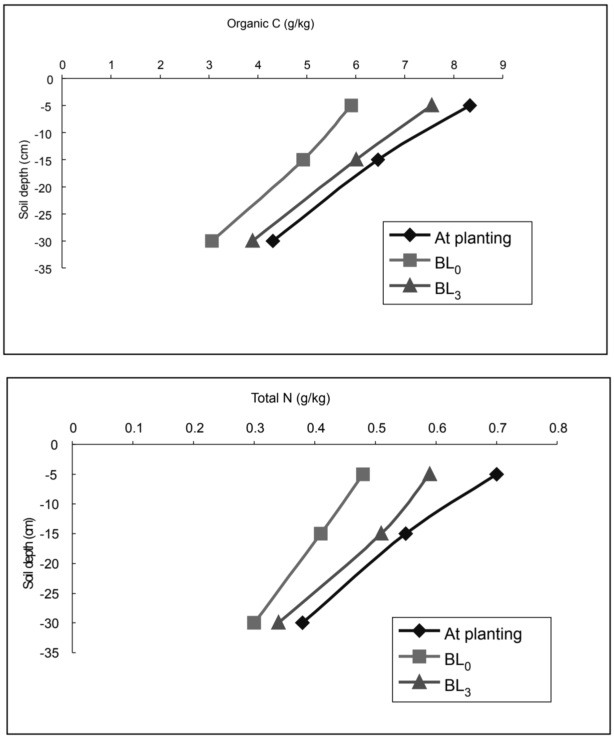
Changes in soil properties two years after tree planting

In the 2 years after planting, soil organic C decreased across all treatments but the retention of harvest residue reduced the decline (Fig. 8). In BL_0 (removal of all organic materials), C in the 0-10 cm layer declined by 2.4 g kg^{-1} whereas in BL_3 (double harvest residue) it fell by less than 1.0 g kg^{-1}. In the 10-20 cm soil horizon, organic C fell by 1.5 g kg^{-1} but the decrease in BL_3 was much lower than other treatments. In the 20-30 cm soil layer the declines were less than in the topsoil, nevertheless, even at this depth C declined by 1.3 g kg^{-1} in BL_0. The decline was caused by decomposition of organic C present in the soil prior to replanting. It is concluded that replacement of this organic C by slash was helpful in slowing the loss of organic C. Removal of all organic materials in BL_0 is likely to have increased soil temperature resulting in faster decomposition.

Total soil N also declined after planting. The trends in the three soil layers were similar to those for organic C. The largest decline occurred in BL_0 and BL_1. There was no obvious change of total P and total K in different treatments.

Available N and P, and exchangeable K, Ca and Mg increased in the 2 years after tree planting (Fig. 9). Available N in BL_0 was lower than that in the other treatments but in the surface horizon of BL_0 it increased, possibly due to decomposition of organic matter in the topsoil. Available P was highest in BL_3 and lowest in BL_0 indicating the importance of harvest residue as a source of P to the soil. Exchangeable Ca in topsoil was also increased by harvest residue intensity. There was also a positive effect of harvest residue on exchangeable K and Mg.

Figure 8. Soil organic C and total N in different harvest residue treatments at planting and 2 years later



Considering total nutrient content in 0-40 cm topsoil, it was found that organic C and total N decreased but less so with high slash retention (Table 2). Total P was not changed and total K was slightly increased. Available N and exchangeable Mg significantly ($p<0.05$) increased in the 2 years, as did available P and exchangeable Ca and K ($p<0.01$), all assisted by higher slash retention.

Experiment 2: Impacts of regeneration methods and fertilisation

The effect of fertilisation on tree growth was very significant ($p<0.001$). It dramatically increased tree height and diameter growth at all measurement times (Fig. 10).

Figure 9. Available nutrient changes in different harvest residue treatments 2 years after planting

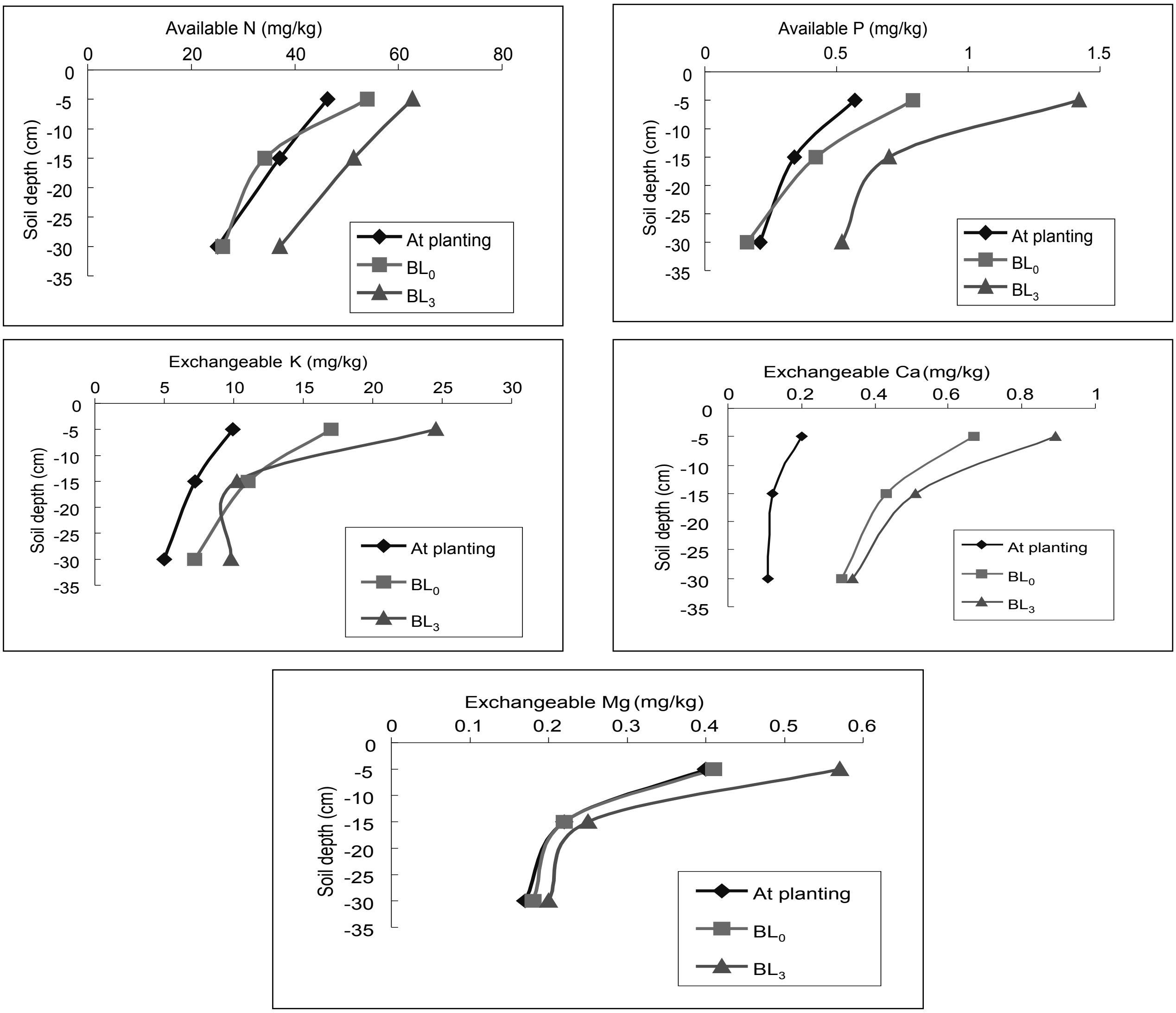


Table 2. Organic C and nutrients in the top 40 cm of soil before harvest and 2 years after planting

Properties	Before harvest	Two years after planting				
		BL_0	BL_1	BL_2	BL_3	BL_4
Organic C (t ha^{-1})	34.4	25.3	26.6	26.9	31.3	32.2
Total N (t ha^{-1})	2.9	2.2	2.4	2.4	2.6	2.6
Total P (t ha^{-1})	0.6	0.7	0.7	0.7	0.7	0.7
Total K (t ha^{-1})	18.4	21.1	21.3	19.1	21.3	22.6
Available N (kg ha^{-1})	192.9	209.8	225.7	228.7	276.8	270.2
Available P (kg ha^{-1})	2.3	2.3	2.46	3.2	4.7	3.7
Exchangeable K (kg ha^{-1})	40.0	63.5	75.9	72.3	70.0	90.4
Exchangeable Ca (kg ha^{-1})	0.8	2.3	2.4	3.2	4.7	3.7
Exchangeable Mg (kg ha^{-1})	1.4	1.5	1.8	2.1	1.8	1.7

Figure 10. The effect of fertilisation on height growth of planted trees and coppice

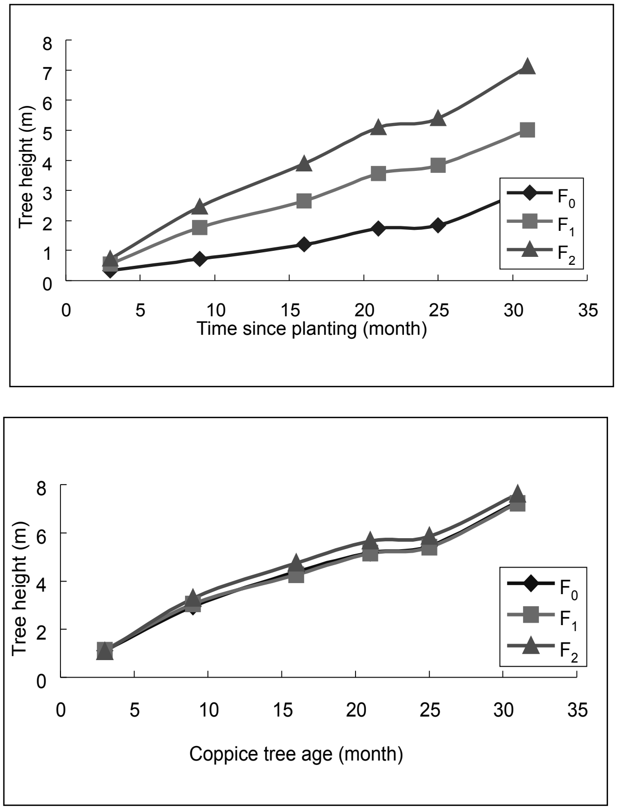
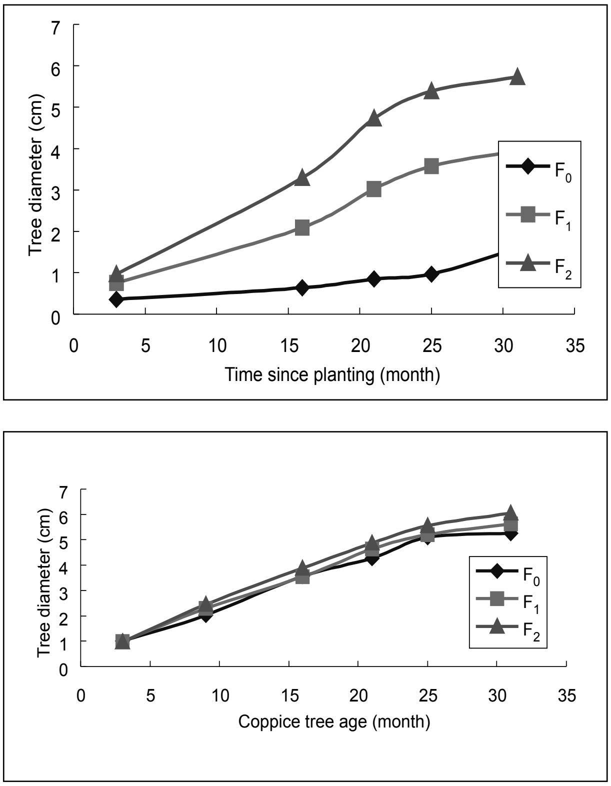


Figure 11. The effect of fertilisation on stem diameter of planted trees and coppice (First diameter measurement was at 0.1 m height, later measurements were at 1.3 m)



In the coppice, there was little effect of fertiliser on growth. Tree height in F_2 was higher than in F_0 and F_1. Tree diameter was in the order $F_2>F_1>F_0$ (Fig. 11).

Up to 25 months old the coppice was larger than the replanted trees and there was an interaction between fertilisation level and regeneration method (Fig. 12). In both tree height and diameter, the difference between coppice and planted trees was greatest in F_0 (*ca* 4.3 m in height and 3.7 cm in diameter) but the effect declined with fertiliser application.

Without fertilisation, trees in BL_0 grew faster than trees in BL_3 (Fig. 13). This is because in BL_0 were regularly controlled but not in BL_3. Weed competition in Experiment 2 was more serious and affected tree growth more severely than that in Experiment 1, explaining the difference in results (BL_0 *vs* BL_3) between the two experiments.

Available nutrient supply in BL_3F_0 was much better than that in BL_0F_0 (Table 2). Available N and P and exchangeable K, Ca and Mg in 0-40 cm topsoil of BL_3F_0 were significantly ($p<0.05$) higher that those in BL_0F_0. Organic C and total N in BL_3F_0 were also significantly higher. Although estimates of total P, total K and organic P in BL_3F_0 were marginally higher than in BL_0F_0, they were not statistically significant. The results suggest that retention of harvest residue and litter on soil surface can increase soil organic matter and total N content and improve soil nutrient supply. It was shown that weeds greatly reduce tree growth if no fertiliser is applied.

Figure 12. Interaction between regeneration methods and fertilisation levels on tree growth

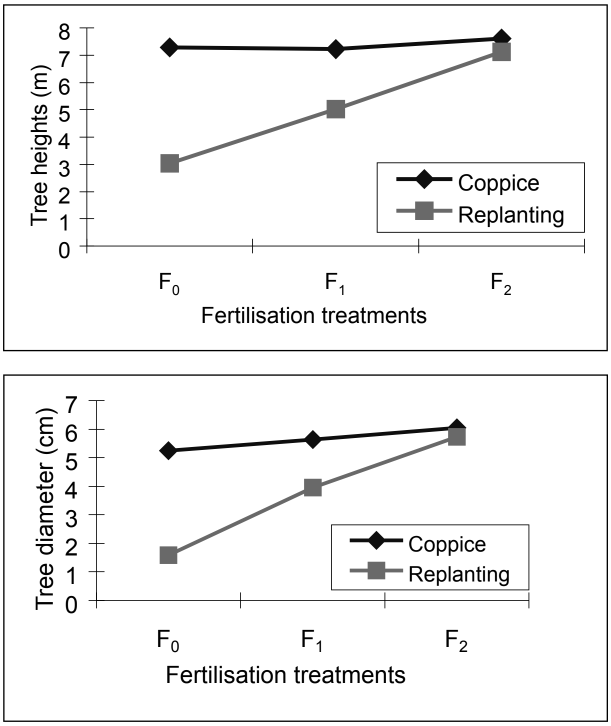


Figure 13. Average tree diameter (D) and height (H) in BL_0 and BL_3 without fertilisation

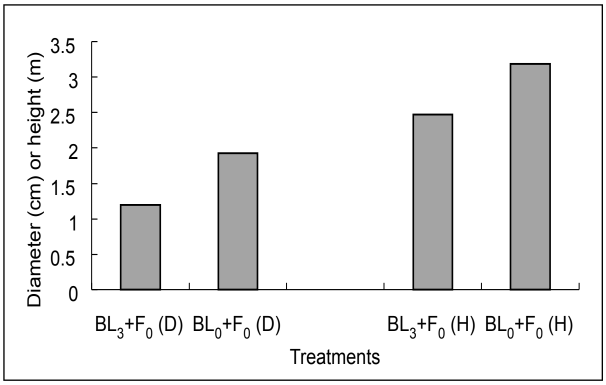


Table 2. Main chemical properties of 0-40 cm topsoil in two residue treatments

Properties	Residue/fertiliser/treatment	
	BL_0F_0	BL_3F_0
Organic C (g kg^{-1})	5.38 b	7.43 a
Total N (g kg^{-1})	0.46 b	0.56 a
Total P (g kg^{-1})	0.11	0.12
Total K (g kg^{-1})	3.82	3.52
Organic P (g kg^{-1})	29.89	33.86
Available N (mg kg^{-1})	44.28 b	62.49 a
Available P (mg kg^{-1})	0.59 b	1.18 a
Exchangeable K (mg kg^{-1})	13.25 b	18.78 a
Exchangeable Ca (mg kg-^{1})	0.46 b	0.59 a
Exchangeable Mg (mg kg^{-1})	0.36 b	0.49 a

Values designated a and b for each property are significantly different ($P<0.05$) from each other.

Discussion and Conclusions

Harvest residue management had significant impact on tree growth in the early stage of the second rotation of an *E. urophylla* plantation because harvest residue increased the available nutrient supply and lessened the reduction of organic C and total N in the topsoil during the inter-rotational period. At the same time, retention of harvest residue also reduced soil loss and water runoff during plantation establishment. Before the 1980s almost all harvest residues, understorey and litter on the soil surface in eucalypt plantations in southern China were collected as firewood. Even today, all harvest residues (including leaves, branches and main roots) are collected from sites, mainly for firewood. This, along with serious soil and nutrient runoff, due to inappropriate site cultivation, partly explains why soil degradation and productivity decline of eucalypt plantations have been so common in southern China. Study is needed to determine the impact of harvest residues on soil and water runoff in eucalypt plantations. Weed control was another important factor significantly affecting productivity. As noted earlier, BL_0 alone was weeded regularly in the early stages of plantation establishment and this resulted in the trees in BL_0 growing at a rate similar to those in BL_2 and faster than in BL_1. Without fertilisation, weed control obscured the effects of slash management so that trees inBL_3F_0 were smaller than trees in BL_0F_0 although nutrient supply in BL_3F_0 was better than that in BL_0F_0. Weed control has not been an important problem in eucalypt plantations in southern China in the past because of total soil tillage and understorey harvesting. If new site preparation methods are adopted for soil fertility conservation and there is less and less understorey collection, weed control should be practised. More study is needed to develop weed control options for forest farmers.

Coppice was better than planting for the second rotation up to 31 months old. There was interaction between the regeneration method and fertilisation level. Response of coppice trees to fertilisation was much lower than planted trees. It suggests that well-developed root systems helped the coppice to uptake soil nutrients better than the smaller root systems of the planted trees. The coppice probably used more nutrients from the soil than from fertiliser. It is recommended that coppice should be adopted for second rotation eucalypt plantations unless better genetic material is available for planting.

Acknowledgements

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6

Effects of Site Management in *Acacia mangium* Plantations at PT. Musi Hutan Persada, South Sumatra, Indonesia

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Abstract

Acacia mangium plantations managed by PT. Musi Hutan Persada are located mostly on red yellow podsolic soils having poor nutrient reserves. This study on the effects of inter-rotation management on site productivity addresses the growing concern about the long-term productivity of the plantations. Preliminary results indicate total standing biomass at 9 years of age was 18.95 t ha^{-1} and litter production 16.80 t ha^{-1}. Nitrogen, Ca and K are in high demand by *A. mangium*, while P and Mg are taken up in smaller amounts. Harvesting merchantable stems with minimum diameter of 10 cm will remove from one hectare 375 kg N, 9.3 kg P, 73 kg K, 267 kg Ca and 18 kg Mg.

Introduction

PT. Musi Hutan Persada has managed a plantation forest of 193 500 ha in South Sumatra, Indonesia since 1990. *Acacia mangium* Willd. is the principal species used and comprises over 90% of the plantation area. A species trial conducted on the site in the early 1980s confirmed the superiority of *A. mangium* over other species. Silviculturally *A. mangium* is easy to manage in the nursery and in the field, relatively free from serious pests and diseases, and fast-growing. Its wood is suitable for pulp and papermaking (Logan 1987). Since 1999 the company has harvested its plantations for a pulp mill with capacity of 450 000 t of bleached kraft pulp annually. Only merchantable wood with diameter more than 10 cm, including bark, is currently harvested, while the remainder of the tree is left on site. The logged-over areas are replanted with *A. mangium*.

Tree harvesting and establishment of second rotation plantations are new activities for PT. Musi Hutan Persada and experience is limited. On the other hand, the company is very concerned with the long-term sustainability of its plantations as it has a long-term commitment to supply wood to the pulp mill. Inter-rotation site management has been identified as one of the critical factors contributing to the productivity (Nambiar and Brown 1997). This paper reports progress in the inter-rotation site productivity and management research in an *A. mangium* plantation.

Location and Site Description

The overall concession area is geographically located at 103^0 10'-104^0 25'E longitude and 3^0 05'-5^0 28'S latitude. The plantations are established on alang-alang (*Imperata cylindrica*) grassland, scrublands and logged-over secondary forest areas. Both the grassland and shrublands were the result of long-term shifting cultivation using fire for site preparation. The altitude ranges from 60 to 200 m above sea level. The terrain is flat to undulating (0-8%) although some areas are quite rolling (8-15%). The experimental site is flat with slope of 0-3%.

The area has a lowland humid environment with the average daily temperature *ca* 29^{0}C (range 22-33^{0}C).

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The annual rainfall in the last eight years has been in the range 1890-3330 mm, mostly between January to May with a dry spell between October and December. However, during the dry spell there may be some light rain. The average relative humidity varies from 56% in the dry season to 81% in the rainy season. In 1991, 1994 and 1997 prolonged dry seasons increased fire incidence.

The soil is a red-yellow podsolic or typic kandiudult (Soil Survey Staff 1992). It has an Ap horizon of dark grey clay (0-25 cm) overlying a brownish red clay B horizon of 25-80 cm depth over a well-defined yellowish red clay BC horizon (80-150 cm). The soil is mainly derived from sedimentary rocks of tuff, sandy tuff, sandstone and claystone with a very small portion from volcanic materials. The majority of the soils are red-yellow podsolics (ultisol and oxisol). This soil is inherently poor in nutrient reserves, and has low pH and low base saturation. Data on soil chemical properties under stands of *A. mangium* of different ages in the area reported by Setiawan (1993) are given in Siregar *et al.* (1999). Organic C ranged from low to high, Ca and Mg were low, N and K were low to medium, and P ranged from medium to high.

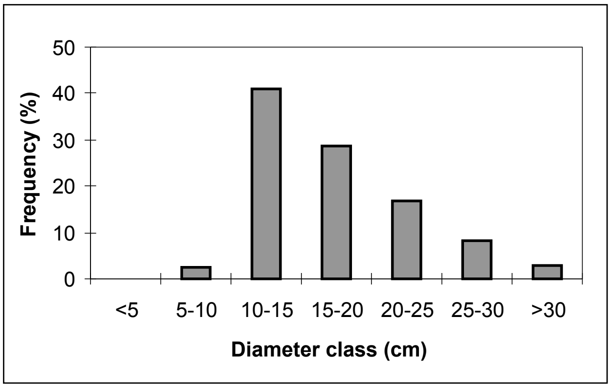
Stand Description

The first rotation plantations of *A. mangium* were established using unimproved genetic materials from a local land race (Subanjeriji). This seed source was derived from provenances from the Cairns region of Queensland, Australia. Plantations grown from this seed source had suboptimal growth on the plantation site (Hardiyanto *et al.* 1997, Siregar *et al.* 1999). The land preparation methods for grasslands included mechanical preparation (clearing and ploughing) on flat land or herbicides on sloping areas. Before 1995 the debris was burnt. Trees were planted manually and fertilised one month after planting. Weeds were controlled, particularly in the first two years, by manual slashing or the application of herbicide as required.

The majority of trees in first rotation plantations are multistemmed since singling (reducing multiple leaders to one leader) was not applied. Singling is now the normal silvicultural practice. Consequently, the stem density sometimes exceeds 2000 stems ha^{-1}. At six years of age the stand usually begins to self-thin and some trees die. Currently 150-300 m^3 ha^{-1} of marketable wood with a minimum stem diameter over bark of 10 cm can be harvested with overall average production *ca* 175 m^3 ha^{-1}.

The first rotation stand in which this study is being conducted was established in January 1990 on alang-alang grassland. A spacing of 3 x 3 m was used. Fertiliser at a rate of 10 g urea (4.6 g N), 10 g triple superphosphate (2.0 g P) and 10 g KCl (5.0 g K) was applied to each seedling one month after planting. There was no singling and the majority of trees were multistemmed. The average density of the stand was 1382 stems ha^{-1}, 19 % of stems in the stand were dead. At clear felling the predominant height was *ca* 22 m and basal area 30.4 m^2 ha^{-1}. The diameter range was 5-38 cm and the average diameter was 17.7 cm. More than 40% of living stems were in diameter class 10-15 cm, and 28% in diameter class 20-25 cm (Fig. 1). The marketable wood was 228 m^3 ha^{-1}.

Figure 1. The diameter class distribution of live standing trees



Experimental Details

Core Experiment

The experiment was arranged in a randomised complete block design, with five core treatments and four replications. The plot size is 40 x 36 m. There are 180 trees (4 x 2 m) in total or 128 measured trees within each plot.

The treatments in the core experiment are:

BL$_0$	No slash. All above ground biomass, litter and understorey removed.
BL$_1$	Single slash, whole-tree harvest. All trees including non-commercial parts removed. Understorey and litter are retained.

$BL_{2(1)}$ Single slash, merchantable tree harvest. Only stems of commercial size (diameter >10 cm including bark) removed. Non-commercial wood components, foliage, litter and understorey distributed evenly.

$BL_{2(2)}$ Similar to $BL_{2(1)}$ to be used for destructive sampling for biomass and nutrient accumulation data.

BL_3 Double slash, merchantable tree harvest. The same as BL_2 but non-commercial residues from plot BL_1 are brought in and distributed evenly, adding to the slash already present.

SC Standing crop. An area of *ca* 2 ha close to and representative of the harvested stand left as a control for comparison and for measuring changes in soil and other site properties.

Before starting the inventory of trees in each plot, standing dead trees were pushed by hand; those which fell were categorised as litter. All trees within each plot were measured for diameter at breast height. Sample trees representing the whole range of diameter were taken to determine the dry mass of all aboveground biomass components. Allometric relationships between diameter and biomass components were developed using the model: $Y = a + bX$ where Y is the dry biomass component in kg and X is diameter. Biomass and nutrient quantities within each plot were then estimated from the inventory tree data using the developed regression equations.

The dry mass of dead standing trees was calculated separately based on measured dbh, height and sample dry mass. Litter (woody materials, leaves (phyllodes) and reproductive parts) and understorey were sampled before tree felling. Four square plots, 1 m^2 in area, were distributed randomly, the litter sampled, and the dry weight of litter components and understorey were then determined.

The biomass and litter components as well as understorey were subsampled and oven-dried at 76^0C to a constant weight. Half of the subsamples were sent the laboratory for chemical analysis, while the remaining subsamples were kept for future use.

Soil cores were taken from five points within each plot at soil depths: 0-10, 10-20 and 20-40 cm. Bulk density was measured from three points in each plot in every block and also separated into soil depths similar to those for chemical analyses. The soil core samples were air dried and sieved through a 2 mm screen. The samples were subsampled; some of the subsamples were sent to the laboratory for soil analysis and the remaining subsamples were kept for further use.

Plant and soil analyses were carried out at the Laboratory of the Center for Soil and Agroclimate Research, Bogor. Methods of biomass and litter analysis were (Sudjadi *et al.* 1971, Staf Laboratorium Kimia 1998):

- total N, by H_2SO_4 digestion and Kjeldahl;
- total P, by HNO_3 and $HClO_4$ digestion followed by spectrophotometer;
- total K, by HNO_3 and $HClO_4$ digestion and measured by flame photometer; and
- total Ca and Mg, by HNO_3 and $HClO_4$ digestion and determined by atomic absorption spectrophotometer (AAS).

Methods for soil analysis were:

- organic C, by K_2CrO_7 and H_2SO_4 digestion and measured by spectrophotometer;
- total N, by H_2SO_4 digestion and Kjeldahl;
- available P, by the Bray # 1 extraction;
- exchangeable K, Ca and Mg, by NH_4Ac extraction and measured by AAS; and
- pH, in 1:2.5 water solution.

Tree felling and wood extraction from plots were carried out manually from 31 August to 5 October 1999. This was followed by treatment application. Planting was done in December 1999 with a spacing of 4 x 2 m. The best available genetic source (Wipim, Papua New Guinea, provenance seed stand) was used. Fertiliser was applied at following rates per tree: 30 g urea (13.8 g N) and 87.5 g SP_{36} (superphosphate containing 36 % P_2O_5 (14.0 g P) given at planting time. Singling will be done three months after planting.

The experiment will be measured for growth (diameter and height) every six months for the first-two years and every year thereafter up to the end of rotation (8 years). Biomass and foliar sampling for nutrient will be undertaken from $BL_{2\,(2)}$ plots.

In addition to growth measurements and chemical analyses, information on litter decomposition will also be obtained. Freshly fallen leaves were collected from the stand in the study site before the stand was harvested, while branches (diameter of <1 cm and 1-5 cm) were collected from newly felled trees. Leaves and branches were oven-dried at 35^0C to a constant moisture content. The oven-dried leaves and branches will be put in into 20 x 20 cm nylon mesh bag of 2 mm, 25 g for each bag. Nylon bags containing litter components will be spread randomly over the soil surface on BL_2 after seedlings have been planted in the field. A similar study will be repeated under the designated standing crop. A plot 40 x 36 m will be located away from the stand boundary. The plot will be divided into three subplots with a size of 40 x 12 m for each subplot. The previously prepared litter samples will be randomly distributed in each subplot. Weight loss will be determined every month for the first three months, followed by two monthly intervals up to the 13 months and then every three months to the end of the trial (2 years).

Optional Treatments

Two optional treatments, Nutrition studies A and B, will be applied. Nutrition study A is a 3 x 3 factorial experiment involving different rates of N and P application. The following rates of N will be used (g N tree^{-1}): 0, 13.8 (30 g urea) and 27.6 (60 g urea), while those of P are (g P tree^{-1}): 0, 14.0 (87.5 g SP_{36}), and 28.0 (175 g SP_{36}).

Nutrition study B is a missing element trial involving K and Ca. In total there will be four treatments: control, Ca, K and K+Ca. The rate of K is 0 g and 75 g (150 g KCl) tree^{-1}, while that of Ca is 0 kg ha^{-1} and 275 kg ha^{-1} or 730 kg ha^{-1} hydrated lime [$Ca(OH)_2$]. All fertilisers will be applied at planting time. Each combination of treatments will also receive the fertilisers currently applied: 30 g urea and 87.5 g SP_{36}. Phosphorus fertiliser will be put in the planting hole, while N and K fertilisers will be placed in a furrow about 10 cm from the seedling. Lime will be broadcasted.

The experiment is also laid out as a randomised complete block design replicated four times. The nutrient studies are set up at the same site as the core experiment and the block positions are adjacent to the corresponding block of the core experiment. The plot size is 24 x 36 m with a spacing of 4 m between rows and 2 m within rows (108 trees in total or 64 measured trees.

Ten soil cores per replication were taken across the two nutrient studies for chemical analyses. Soil was separated into three soil depths: 0-10, 10-20 and 20-40 cm.

Results

Soil Properties

Soil physical and chemical properties of the experimental site are given in Table 1, and nutrient storage status of the experimental site is shown in Table 2. The soil in the experimental site has a high clay content and medium bulk density. As is the case with most soils in Sumatra, it is very acidic and the pH gradually increases with soil depth.

Table 1. Soil physical and chemical properties of the experimental site

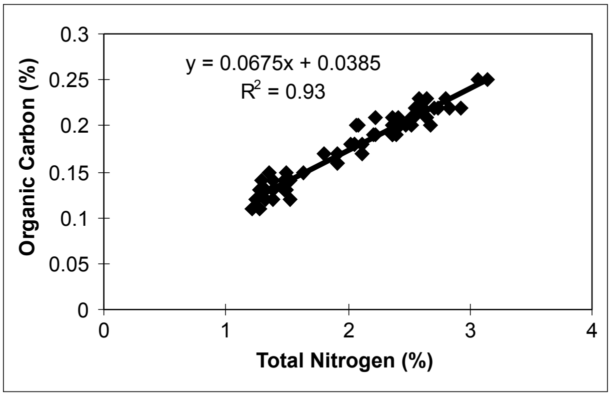
Properties	Soil depth (cm)		
	0-10	10-20	20-40
Bulk density (g cm^{-3})	1.22	1.24	1.24
Sand (%)	23.5	27.0	24.5
Silt (%)	12.25	11.0	9.25
Clay (%)	64.0	62.0	66.5
pH (H_20)	4.29	4.34	4.40
pH (KCl)	3.84	3.85	3.89
Organic C (%)	2.64	2.19	1.39
N total (%)	0.23	0.19	0.13
C/N	12.1	11.6	10.7
P total (mg kg^{-1})	172.1	161.4	134.9
Available P (mg kg^{-1})	5.77	4.95	3.35
Exchangeable K (mg kg^{-1})	33.74	32.57	27.89
Exchangeable Ca (mg kg^{-1})	148.6	110.7	74.4
Exchangeable Mg (mg kg^{-1})	62.52	55.20	43.02

Table 2. Organic C and nutrient content of soil in the experimental site

Soil depth	Nutrient content (kg ha^{-1})					
cm	OC	N	P	K	Ca	Mg
0-10	32 270	2660	7.1	41.3	182	76.5
10-20	27 110	2317	6.1	40.3	137	68.2
20-40	17 280	1623	4.2	34.5	92	53.3
Total	76 660	6600	17.4	116.1	411	198.0

The N concentration in the surface layer is medium-low and decreases with soil depth. The level of organic C in the top layer is medium, decreasing to low at 20-40 cm. The C/N ratios are relatively low which favours N mineralisation. Concentrations of other elements such as P and Ca are very low. Nitrogen level is highly correlated with soil organic C (R^2=0.93) (Fig. 2). Correlation between the organic C content and P concentration (available P or total P) is very low, indicating that the soil organic C has no direct effect on the available P in this acidic soil with high P fixation.

Figure 2. Regression between total N and organic C in the soil

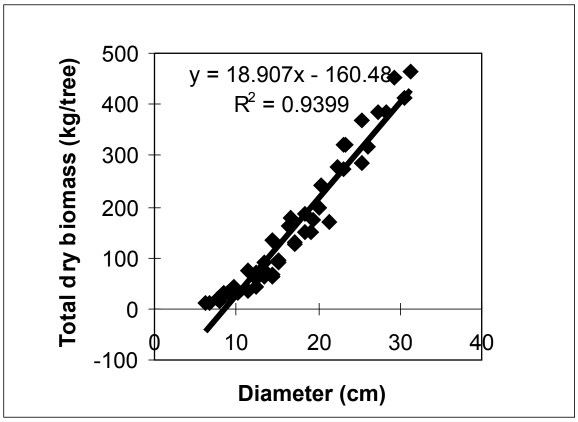


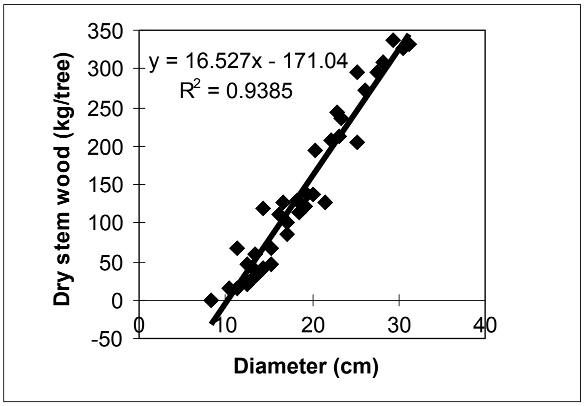
Biomass

Regression analysis

The regression analysis involving stem diameter with dry weight of biomass components generally gave good precision, except for branches which showed less precision (R^2 = 0.71). This is probably due to forking in some sample trees. For illustration, Fig. 3a. shows the relationship between diameter and dry weight of total standing biomass, and Figure 3b the relationship between diameter and dry weight of stem wood.

Figure 3 a. Regression between diameter and dry weight of total standing biomass
b. Regression between diameter and dry weight of stem wood





Biomass distribution and nutrient content

The dry mass of tree components between plots varied little. The average biomass per plot was: stem wood (17.95 t), bark (2.05 t), branches, including stem less than 10 cm diameter, (6.71 t) and leaves (0.59 t). Dry mass of standing dead wood varied between plots, from 0.66 to 1.16 t with the average 0.84 t. Litter biomass

Table 3. Biomass and nutrient content of *Acacia mangium* stand at 9 years of age

Component	Biomass	Nutrient (kg ha^{-1})				
	(t ha^{-1})	N	P	K	Ca	Mg
Leaves	4.1	113	3.5	58.3	20.5	6.4
Branches and stem (<10 cm)	46.6	173	1.5	59.9	128.1	17.5
Stem wood (>10 cm)	124.7	236	7.8	37.4	103.5	12.5
Bark	14.2	1390	1.5	35.6	163.7	5.5
Total living standing biomass	189.5	661	14.3	191.2	415.8	41.9
Standing dead wood	5.8	15.8	0.3	2.7	10.1	0.9
Litter	16.8	271	2.5	29.5	123.3	21.9
Understorey	1.9	35.5	1.2	33.9	7.3	4.5

ranged from 2.2 to 2.81 t plot^{-1}, while that of understorey varied from 0.15 - 0.47 t plot^{-1}.

The dry weights for biomass of the stand in the slash study are given in Table 3. The total weight of standing biomass was 189.5 t ha^{-1}. More than 73% of the total dry biomass was merchantable stem, of which 66% was wood and 7.5% bark. Leaves (2.2%) and branches/upper stem (24.6%) made up the remaining biomass. Fruits and flowers made up only a small portion and their presence depends on the season. Litter production in this stand was 16.8 t ha^{-1} and understorey was 1.9 t ha^{-1}.

Nitrogen, Ca and K appear to be in the highest demand as shown by nutrient content in the biomass. In comparison Mg and P were a smaller quantities. In general the highest concentrations of nutrients were found in leaves, flowers and fruit. These were followed by stem bark, branches and stem wood in that order (Table 4).

The nutrient content in the litter indicates that N is found in the largest quantity followed by Ca, K, Mg in that order. Phosphorus is found in the smallest quantity at 2.5 kg ha^{-1}. For nutrient content in the understorey N was found in the greatest quantity at 33.9 kg ha^{-1} followed by K, Ca, and Mg. Again, P was found in the smallest quantity.

Distribution of Harvest Residues, Litter and Understorey

Following treatment application, the average biomass in BL$_1$, BL$_2$ and BL$_3$ plots are shown in Table 5. The results are estimates based on biomass regressions described earlier (Fig. 3, Table 3).

Table 4. Nutrient concentration of biomass components

Biomass component	Nutrient (%)				
	N	P	K	Ca	Mg
Stem wood	0.19	0.01	0.03	0.08	0.01
Stem bark	0.98	0.01	0.25	1.15	0.04
Live branches (<1 cm)	1.00	0.03	0.82	0.56	0.22
Live branches (1-5 cm)	0.36	0.01	0.13	0.26	0.03
Live branches (5.1-10 cm)	0.26	0.00	0.06	0.22	0.02
Dead branches (< 1 cm)	0.67	0.01	0.11	0.62	0.09
Dead branches (1-5 cm)	0.63	0.00	0.07	0.58	0.05
Dead branches (5.1-10 cm)	0.45	0.00	0.09	0.42	0.03
Leaves	2.76	0.09	1.42	0.50	0.16
Flowers	2.16	0.12	1.74	0.37	0.18
Pods	1.76	0.08	1.46	0.20	0.11

Table 5. The average biomass residues and nutrient content for different plots

Plot	Biomass residues (t ha^{-1})	Nutrient (kg ha^{-1})				
		N	P	K	Ca	Mg
BL_1	17.49	303.9	5.8	70.7	133.3	28.5
BL_2	62.66	627.2	75.1	254.1	295.6	58.8
BL_3	99.54	1000.3	139.0	419.7	471.6	91.8

It is clear that the increasing amount of harvest residues in BL_3 plot (double slash) will also improve the nutrient status in the plot. The nutrient content in BL_1 plot will only come from litter and understorey. Treatment BL_0 would have only negligible amounts of residue and nutrients associated with slash and litter.

Discussion

The productivity of *A. mangium* at this site is high (189.5 t ha^{-1} aboveground biomass). It is much higher than reported by Ihwanudin (1994) for an *A. mangium* stand in the same region (Subanjeriji) at the same age. It is also much greater than reported by Helenda (1988) from a biomass study in Sarawak where at six years of age total dry weight living biomass of the plantation was estimated at 123.2 t ha^{-1}. Total biomass of *A. mangium* in this study is slightly lower than *Eucalyptus grandis* planted in Brazil (Table 6).

Litter production of the stand was also reasonably high (16.8 t ha^{-1}). Rachmawaty (1993) reported that litter accumulation under an 8-year-old *A. mangium* stand in Subanjeriji was 13.0 t ha^{-1}. The rate of litter decomposition and mineralisation of *A. mangium* is likely to be relatively rapid as suggested by low C/N ratios in the soil (Table 1). The litter decomposition study which is being conducted will investigate this. A study by Setiawan (1993) indicated that under an 8-year-old stand the remaining weight of litter after 12 months was 26.8% for leaves, 31.1% for reproductive parts and 35.5% for twigs. As expected the N content in the litter is high because of the N-fixing ability of *A. mangium*.

Litter has an important role in the *A. mangium* stand, making up about 8.9% of the total living biomass, while understorey plays a minor role as it comprises only 1.03% of the total living biomass.

Table 6. Biomass comparison of *Acacia mangium* with other tree species

Species	Site	Age (yr.)	Biomass (t ha^{-1})	MAI Biomass (t ha^{-1} yr^{-1})	Reference
Acacia mangium	Subanjeriji, South Sumatra	9	189.5	21.1	This study
A. mangium	Subanjeriji, South Sumatra	9	146.4	16.3	Ihwanudin (1994)
A. mangium	Sarawak, Malaysia	4.5	82.1	18.2	Tsai (1986)
A. mangium	Sarawak, Malaysia	6	123.2	20.5	Helenda (1988)
Eucalyptus grandis	Sao Paulo, Brazil	7	160.9	23.0	Goncalves *et al.* (1999)
Paraserianthes falcataria	Philippines	5	76.6	15.1	Kawahara *et al.* (1981)

The dead standing trees in the stand are more than 5.8 t ha^{-1} which is high. As mentioned in the preceding section, the stand had high stocking density which is very typical in *A. mangium* stands with multiple stems and grown at close spacing.

Soil nutrient depletion in plantations grown on intensive short rotations (6-7 years) will be very rapid if they are improperly managed. If harvesting removes stem wood of merchantable size and bark, the loss of nutrients per hectare will be: N 375 kg, P 9.3 kg, K 73 kg, Ca 267 kg and Mg 18 kg. This represents a 5.7% loss of total N; loss of exchangeable cations will be 63.4% K, 65.0% Ca and 9.1% Mg of the total nutrient pool and that of extractable P in the soil 53.8% (based on a soil depth of 40 cm). The magnitude of the loss of these nutrients, particularly P, K and Ca is cause for concern about the long-term site productivity since, apart from N, nutrient reserves in the soil are very low (Tables 1 and 2). Reduction of nutrient removal by leaving all harvest residues on the site and returning nutrients to the site in the form of fertiliser seems essential. The nutrition study currently being conducted will examine this further.

Conclusions

Total standing biomass of *A. mangium* on the study site is high (189.5 t ha^{-1}) at 9 years old. Among the nutrients taken up by *A. mangium* stand, N, Ca and K are in the highest demand. The net amount of P in biomass, although it appears small, represents a large portion of extractable P. Harvesting of merchantable stems, including bark, will remove large quantities of nutrients. The level of nutrient removal and the means of reducing nutrient loss are among the many factors that need to be taken into account in managing long-term site productivity of *A. mangium* plantations, since the nutrient reserves in the soil are low.

Acknowledgements

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7

Effects of Site Management on *Eucalyptus* Plantations in the Monsoonal Tropics - Kerala, India

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Abstract

The research is being conducted at four different locations in Kerala and is based on the two main eucalypts (*Eucalyptus tereticornis* and *E. grandis*) used in industrial plantations in the region. At each location, a series of six designed experiments has been initiated to investigate aspects of harvest residue management, nutrient application, ground vegetation control, use of legume undercrops to increase soil fertility and practical methods of water and soil conservation. Within the general experimental framework established, research is focused on four inter-linked subprojects, investigating the impact of silvicultural options on - (1) nutrient status and nutrient cycling, (2) plant physiology and water relations (3) tree growth and nutrient uptake, and (4) soil process and tree growth modelling. In this paper we give details of the research programmes and describe initial results on site inventory, turnover of nutrients in harvest residues and plant physiological and tree growth responses to applied treatments.

Introduction

Nutrient cycles in undisturbed natural forests are in a state of dynamic equilibrium where inputs and outputs of nutrients are in balance and plant demand for nutrients is met by efficient recycling systems - the so-called 'closed nutrient cycle' (Zech and Drechsel 1995). Where short-rotation plantations replace natural forests, changes in nutrient storage and cycling processes occur. These changes are due to factors such as harvest exports, changed distribution and quality of organic matter, altered patterns of nutrient inputs and outputs (fertilisation, erosion, leaching, volatile losses etc.) and modified patterns of organic matter turnover. All of these factors can impact on storage and supply of soil nutrients for plant growth and consequently the sustainability of plantation systems.

India is the world's largest grower of eucalypt plantations. They occupy 4.8 million ha (Davidson 1995) and represent about 25% of the country's plantation estate. Because natural forests cannot be harvested in India, plantations of various tree species are becoming increasingly important for supply of forest products such as industrial wood and domestic firewood. However, earlier studies have suggested that short rotations of some species in plantations will not be sustainable in the long-term (e.g., Bargali and Singh 1991). Nevertheless, there is clear evidence from research in other parts of the world that prudent management, especially that directed at conservation and enhancement of soil organic matter and soil nutrient status, can result in sustainable ecosystems. Furthermore, it has been demonstrated that site quality and wood production can be improved over successive crop rotations (Nambiar 1996). The need to apply these principles in India in order to maximise sustainable production from plantations is given additional impetus because of the limited land-base available and the constraints to increasing the area under plantations.

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Thus, enhancing productivity from existing eucalypt forests and sustaining productivity in subsequent rotations is a priority for research.

Kerala has about 40 000 hectares of eucalypt plantations distributed across two broad elevational regions. At lower elevations on the undulating coastal plains *E. tereticornis* dominates and accounts for about 60% of the State's eucalypt resource. Here, soils are derived from erosional material deposited as colluvium and from *in situ* weathering of granitoid rock. Laterite also occurs frequently. At higher elevations, in the Western Ghats, *E. grandis* is the principal plantation species. The research is focussed on these two species. A brief account of the productivity of eucalypt plantations in Kerala and aims of this research are given in Sankaran (1999). In summary, the aim is to provide the scientific data for developing silvicultural regimes to optimise conservation and use of site resources. It is hypothesised that these principles will form the basis for developing sustainable management systems for eucalypt plantations in India in general.

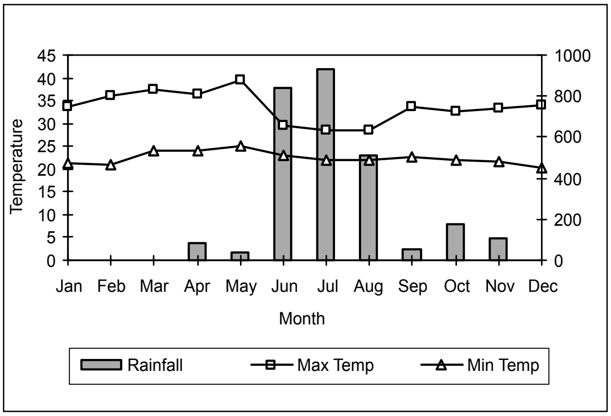
In this paper we describe research directed at identifying and developing practices for manipulating soil organic matter, and soil and tree nutrient and water status. We focus on results from the harvest residue manipulation experiments but also include data from other experiments, especially the nutrient rate trials, for comparative purposes.

Location and Site Description

Kerala State, located between latitudes 8-13^{0}N, is situated in southwest India between the Arabian Sea and the Western Ghats mountain ranges. There are two low altitude experimental sites based on *E. tereticornis* at Kayampoovan (10^{0}41'N, 76^{0}23'E, 120 m) and Punnala (9^{0}06'N, 76^{0}54'E, 150 m) located on foothills adjacent to the undulating coastal plain. respectively. In the Western Ghats there are two sites with *E. grandis* at Surianelli (10^{0}02'N, 77^{0}10'E, 1280 m) and Vattavada (10^{0}08'N, 77^{0}15'E, 1800 m)

For a detailed description of the environment of Kerala and the experimental sites see Sankaran (1999). The climate is tropical warm humid monsoonal. There are two main monsoons. The southwest monsoon, corresponding with the principal rainy season, starts in early June and extends to October. At the main KFRI research centre at Peechi annual rainfall is 2500 mm, most falling in June, July and August (Fig. 1). This is also the coolest period of the year. The northeast monsoon is relatively dry with only occasional rains during December to February. The summer season is March to May. Average rainfall for Kerala is 3000 mm (range 2200-3600 mm) in about 120 rain days. Mean temperature is 27^{0}C (range 20-42^{0}C) and relative humidity ranges between 64% (Feb-March) and 93% (June-July).

Figure 1 Climatic data for Peechi



At all four experimental sites the soil parent materials were saprolite or predominantly saprolitic colluvium derived from Precambrian granites and gneiss. These igneous and metamorphic rocks and in particular the charnockites may contain abundant ferro-magnesian minerals that contribute to the chemical fertility of sites where rocks are present at shallow depth or in outcrop. At all sites the local relief and depth to bedrock or saprolite is highly variable and may be reflected in the heterogeneity of stand performance.

Most soil profiles contained a ferralic B horizon (FAO 1988) although the persistence of rock structure as remnant geneissic saprolite fragments sometimes exceeded 5 volume percent which is the upper limit for the horizon and may require assignment to an argic B horizon. Until complete analytical data are available, the soils have been broadly classified as ferralsols. The very low contents of exchangeable cations present in the B horizon of some profiles may lead to their assignment as geric ferralsols.

Because of the complex interactions of erosion of saprolite and deposition of colluvium, there is a considerable variation in profile depth and morphology at each site. This variation is reflected in the very variable extent of root proliferation in subsoil horizons. It is probable that the capacity of the soil column to retain water is strongly dependent on the depth of soil over bedrock or saprolite.

Experimental Design

The project incorporates experiments within two basic frameworks: (1) experiments at the inter-rotation period when plantations are harvested and re-established (inter-rotation phase), and (2) a smaller experiment where comparisons of nutrient status and nutrient cycling are being made between an established eucalypt plantation and adjacent areas of native vegetation. The inter-rotation experiments are the core of our research and have been established in plantations at four locations.

Five experiments were established at each location during 1998. The design of each is a randomised block with 4 replicates. Plot size is 20 x 20 m, tree spacing 2 x 2 m, with 100 seedlings per plot (36 measurement trees after allocating buffer rows - except at Kayampoovam where 18 x 18 m plots were used due to restricted area available). Following harvesting of stands at each site, experiments were established to investigate impacts of (1) manipulation of harvest residue slash, with six treatments, including burning, slash removal, slash retention and slash addition; (2) use of inter-row legumes as cover crops, with three legumes plus a non-legume control at each site; (3) conservation of soil and water using soil trenching to minimise overland flow during heavy monsoonal rainfall events; (4) ground vegetation management using three different strategies for control of weed growth; and (5) nutrient additions, primarily focussing on application of N and P fertilisers with basal additions of other major and minor nutrients.

The harvest residue management study incorporated 6 treatments. The first five treatments included the addition of a spot application of fertiliser (100g N:P:K 17:7:17) applied in two doses at planting and 3 months later to assist seedling establishment. Harvest residue management treatments were:

BL$_0$	No slash - all litter and, slash material removed.
BL$_1$	Single slash - uniformly redistributed.
BL$_3$	Double slash - addition of slash from the ‘no slash’ (BL$_0$) treatment.
L	Leaf residue only retained; all wood removed.
BS	Burn - (BL$_1$ - slash burnt).
B	Burn without added starter fertiliser.

Experimental Details

In each experimental area soils were characterised in two to three soil pits excavated to depths exceeding 1 m. Soil samples were collected for chemical and mineralogical analysis. Pre-harvest inventories of plant and litter biomass and their nutrient stores were obtained for each site. Aboveground biomass and nutrient stores in trees were determined by measuring tree diameter on each plot and applying allometric functions derived from destructive tree harvesting. Biomass and nutrient content of shrubs and litter were determined from harvested quadrats. Surface soils (0-10 and 10-20 cm) were sampled within each experimental plot in May 1998 to provide base-line soil chemical characteristics for each of the applied organic matter treatments (nine soil cores, 42 mm diameter, bulked within each plot). Annual sampling of soil from selected treatments is being conducted in July-September each year to evaluate impacts of applied treatments on critical soil characteristics and processes. The focus is on changes in C and P status of soils and their N supplying capacity. Organic matter turnover and nutrient release from decomposing harvest residues is being evaluated by sequential harvest of bulk residue quadrats in the field and by the litter bag technique using specific harvest residue fractions in each bag. Plant physiological responses are being evaluated on selected treatments at two sites through measurements of leaf area index, leaf water potential, stomatal conductance and photosynthesis. Tree growth is being monitored at regular intervals through measurements of stem diameter and height.

Results

Stand Description

Biomass of the original stands varied four-fold between the different sites, partly as a result of differences in stocking rates of the coppiced regrowth

Table 1. Vegetation characteristics prior to harvesting the existing stands

Site	Species	Density (stems ha^{-1})	Tree biomass (t ha^{-1})	Shrub biomass (t ha^{-1})	Litter biomass (t ha^{-1})
Kayampoovam	*E. tereticornis*	1356	63.0	6.7	12.1
Punnala	*E. tereticornis*	965	33.7	4.5	10.5
Vattavada	*E. grandis*	3898	141.9	2.4	10.6
Surianelli	*E. grandis*	1056	43.5	9.0	14.4

and partly due to differences in soil fertility and competition from weeds between the experimental areas. At each site the majority of tree biomass was in stem wood (70-80%) while bark contributed 9-14% of total tree weight (Fig. 2). Leaves were a minor contributor, representing 3% of the mass.

Differences in nutrient distribution between stands (Table 2) reflected in part the different amounts of total biomass accumulated at the various sites (Fig. 2) and the amounts of nutrient-rich materials such as leaves and small twigs present in each. The Punnala site was notable in this respect. Trees at this site produced the smallest amounts of total aboveground biomass and the smallest amounts of leaves and twigs. Across all sites about half the P in the tree biomass was associated with bole wood. Aboveground biomass at Punnala was particularly low in P, possibly because of the low natural plant-available P status of soil at this site as indicated by the response in tree growth to added fertilisers (see Fig. 7 below).

Aboveground storage of N was dominated by leaf and wood fractions. All the P and N in boles would have been removed by harvesting the wood. Nitrogen stored in leaves and deposited in harvest residues would have been either volatilised during site preparation burning or recycled through decomposition and N mineralisation where residues were retained.

Figure 2. Distribution in biomass of tree components at the four experimental sites

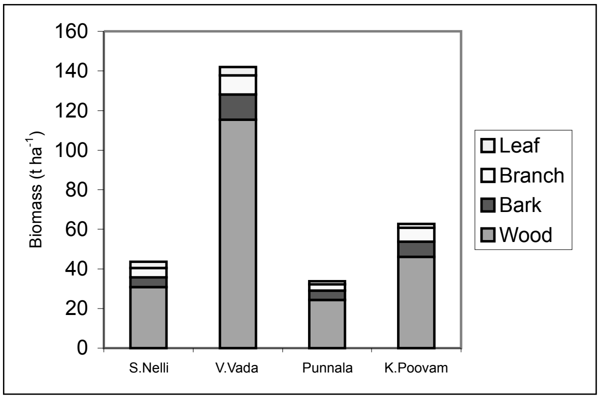


Table 2. Nutrient distribution in tree components

Site/species	Nutrient	Nutrients stores (kg ha^{-1})				
		Leaves	Branches	Bark	Wood	Total
Kayampoovam	N	38.9	32.0	32.5	74.6	178
(E. tereticornis)	P	2.4	8.2	11.0	20.5	42.1
	K	23.0	45.6	70.8	90.3	230
Punnala	N	20.7	8.1	20.2	42.7	92
(E. tereticornis)	P	1.3	1.5	2.6	2.9	8.3
	K	14.5	12.3	24.3	33.3	85
Surianelli	N	58.1	15.3	9.0	23.5	106
(E. grandis)	P	4.2	2.5	3.7	11.9	22.3
	K	16.9	16.1	16.5	39.9	89
Vattavada	N	82.0	36.7	34.9	78.8	232
(E. grandis)	P	5.4	4.7	5.2	12.8	28.1
	K	42.0	52.7	67.1	109.1	271

Site Inventory of Nutrient Stores

Aboveground nutrient stores for each site are shown in Table 3. These pools are small compared with the total stores in the soil within the tree rooting zone (data not shown). However, they do represent the biologically active pool of nutrients at each site. The aboveground component is also that part of the ecosystem most likely to be affected by stand harvesting and subsequent management of harvest residues during site preparation for the next tree crop.

Harvest Residue Biomass and Nutrient Content

The amounts of harvest residues (treatment BL_1 - Table 4) partly reflected differences in site productivity and accumulated biomass at each site. Smallest amounts of residues were at Punnala and Surianelli and greatest amounts at Kayampoovam and Vattavada. The amount of harvest residues at Vattavada was lower than expected and may reflect greater efficiency of wood extraction following logging. Total amounts of harvest residue, the proportion of the various slash fractions and differences between species in tissue nutrient concentrations determined the quantities of nutrients deposited on the soil during logging operations. The amounts of nutrients in slash at Punnala were markedly lower than at the other three sites and resulted from both the small weight of harvest residues and the low proportion of leaf material in the slash.

Figure 3. Weight loss from mesh bags during decomposition of harvest residue fractions for 1 year at Punnala (*E. tereticornis*) and Vattavada (*E. grandis*)

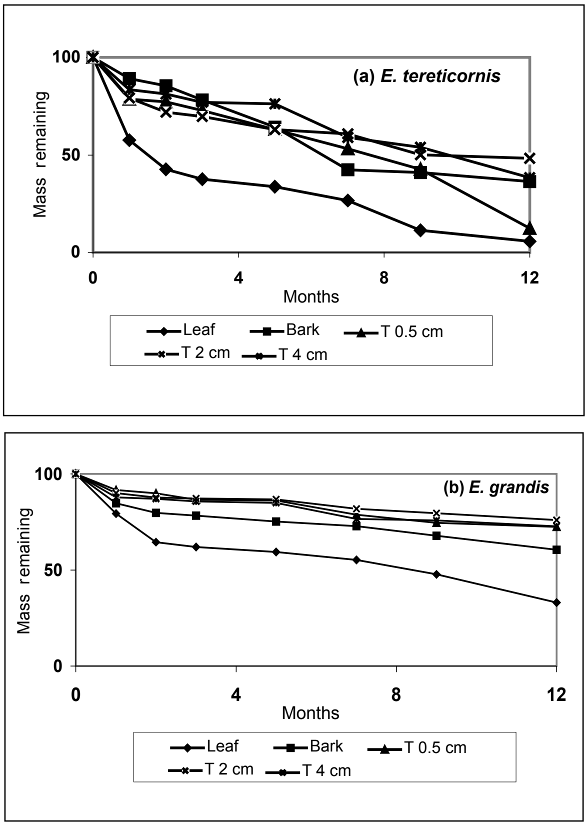


Table 3. Nutrients in trees, shrubs and litter for each site prior to harvesting

	Kayampoovam			Punnala			Surianelli			Vattavada		
	N	P	Ca	N	P	Ca	N	P	Ca	N	P	Ca
	(kg ha^{-1})											
Trees	178	42.1	405	92	8.2	194	106	22.3	405	236	28.1	724
Shrubs	66	5.6	55	41	3.5	44	87	6.5	51	48	6.2	29
Litter	117	8.1	175	96	7.1	121	110	6.6	207	66	5.0	145

Table 4. Harvest residue biomass and nutrient content at each site (treatment BL_1)

	Kayampoovam			Punnala			Surianelli			Vattavada		
	Mass	N	P	Mass	N	P	Mass	N	P	Mass	N	P
	t ha^{-1}	kg ha^{-1}		t ha^{-1}	kg ha^{-1}		t ha^{-1}	kg ha^{-1}		t ha^{-1}	kg ha^{-1}	
Leaf	2.9	52	2.7	0.5	8	0.4	5.5	96	5.1	2.3	49	2.9
Bark	5.3	20	5.0	3.3	12	3.1	1.4	8	0.5	4.7	18	2.2
Wood	11.2	56	10.3	2.6	13	2.4	4.9	27	2.2	11.9	62	6.6
Total	19.4	128	18.1	6.4	33	5.9	11.8	131	7.9	18.9	128	11.7

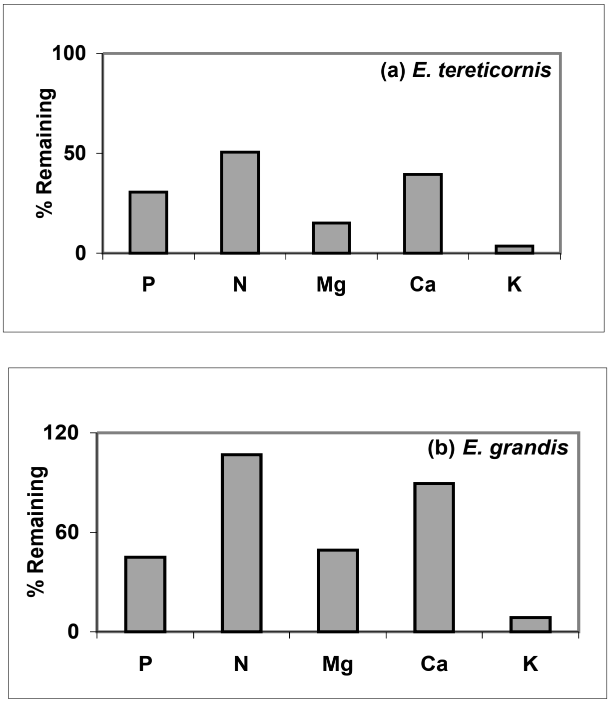
Organic Matter Turnover

Decomposition of harvest residues and return of nutrients to the soil is being evaluated by two methods. Firstly, pre-selected randomly located quadrats within the harvest residue experiment are being sampled periodically to determine changes in weight and nutrient content. Secondly, a conventional mesh bag study is being used to determine decomposition rates of five fractions from the harvest residues at each site. Here we report data from the mesh bag study for one each of the *E. tereticornis* and *E. grandis* sites (Fig. 3, Table 5).

Weight loss differed markedly between residue fractions and species. Among the various slash residues, leaves decomposed fastest at all sites compared to other fractions. Decay rate of bark was similar to (*E. tereticornis*) or greater than (*E. grandis*) that of twigs. Decay rates of slash residues at *E. tereticornis* sites were higher than those at the high elevation *E. grandis* sites. For example, more than 90% of leaves decomposed in the first year after harvest at the *E. tereticornis* sites while about one third of leaf residues remained at the *E. grandis* sites after the same period. Likewise, while about two thirds of the bark weight was lost in 12 months at *E. tereticornis* sites, more than 60% remained at the *E. grandis sites*. Decomposition rate constants and residue half lives (Table 5) determined from fitted first order decay functions (Olson 1963) reflected these differences between the sites and species. In general, half-lives were two to four-fold greater for *E. grandis* than for *E. tereticornis* residues.

Release of nutrients from decomposing harvest residues also differed markedly between the species and the fractions examined (Fig. 4).

Figure 4. Nutrients remaining in decomposing leaf material after 5 months at (a) Punnala (*E. tereticornis*) and (b) Vattavada (*E. grandis*)

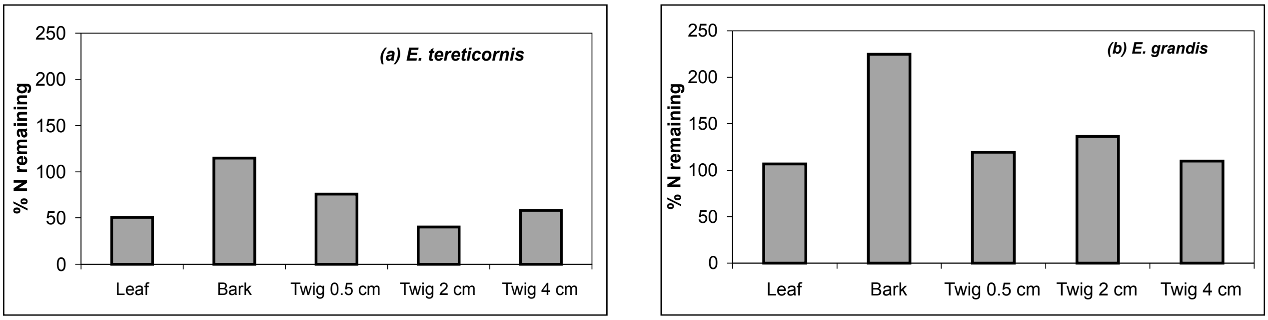


For both species, release of K during decomposition was rapid with the majority of K lost from all residues in the first month of exposure in the field. Release of other nutrients was slower with rates following the trend Mg and P most rapid, Ca intermediate and N slowest for most residue fractions. Release of all nutrients was generally most rapid from leaf residues, reflecting the rapid decomposition rate of this fraction relative to the other residues (Fig. 4, Table 5).

Table 5. Decomposition rate constants and half lives for various harvest residue fractions of *E. tereticornis* and *E. grandis* and goodness of fit of the first order decay function (Olson 1963)

Residue type	Punnala (*E.tereticornis*)			Vattavada (*E. grandis*)		
	K (yr^{-1})	Half life (yr)	R^2	K (yr^{-1})	Half life (yr)	R^2
Leaf	2.83	0.24	0.92	1.12	0.62	0.82
Bark	1.13	0.60	0.95	0.56	1.25	0.68
Twig 0.5 cm	1.58	0.4	0.83	0.37	1.88	0.87
Twig 2 cm	0.87	0.8	0.72	0.31	2.21	0.64
Twig 4 cm	0.90	0.77	0.95	0.38	1.83	0.66

Figure 5. Amounts of N remaining in various decomposing harvest residue materials after 5 months at Punnala (*E. tereticornis*) and Vattavada (*E. grandis*).



Differences between the species in release rates of nutrients generally mirrored the difference in decay rates, with more rapid release of nutrients from *E. tereticornis* than *E. grandis* residues. In particular N dynamics differed markedly between the two species (Fig. 5). For *E. grandis* there was no net mineralisation of N from decomposing residues after 5 months, with all fractions showing immobilisation of N. For the more rapidly decaying *E. tereticornis* residues net N mineralisation occurred in all fractions except bark during this period.

Plant Physiological Responses to Applied Treatments

At this stage, plant physiological data (pre-dawn leaf water potential, stomatal conductance photosynthesis and leaf area index) are available only during the first year of tree growth. No clear trends due to treatment effects are evident in the data. However, these may develop over time as the trees grow and completely occupy the sites. Measurements to date indicate low levels of water stress in both *E. tereticornis* and *E. grandis* with pre-dawn leaf water potentials in the range 0.4 to 0.8 MPa at both sites during the hottest period of the year in February-March 1999. Decline in pre-dawn leaf water potential in March corresponded with periods of increased air temperatures and to a reduction in soil water content at both sites. From April onwards pre-dawn water potentials gradually increased in both species.

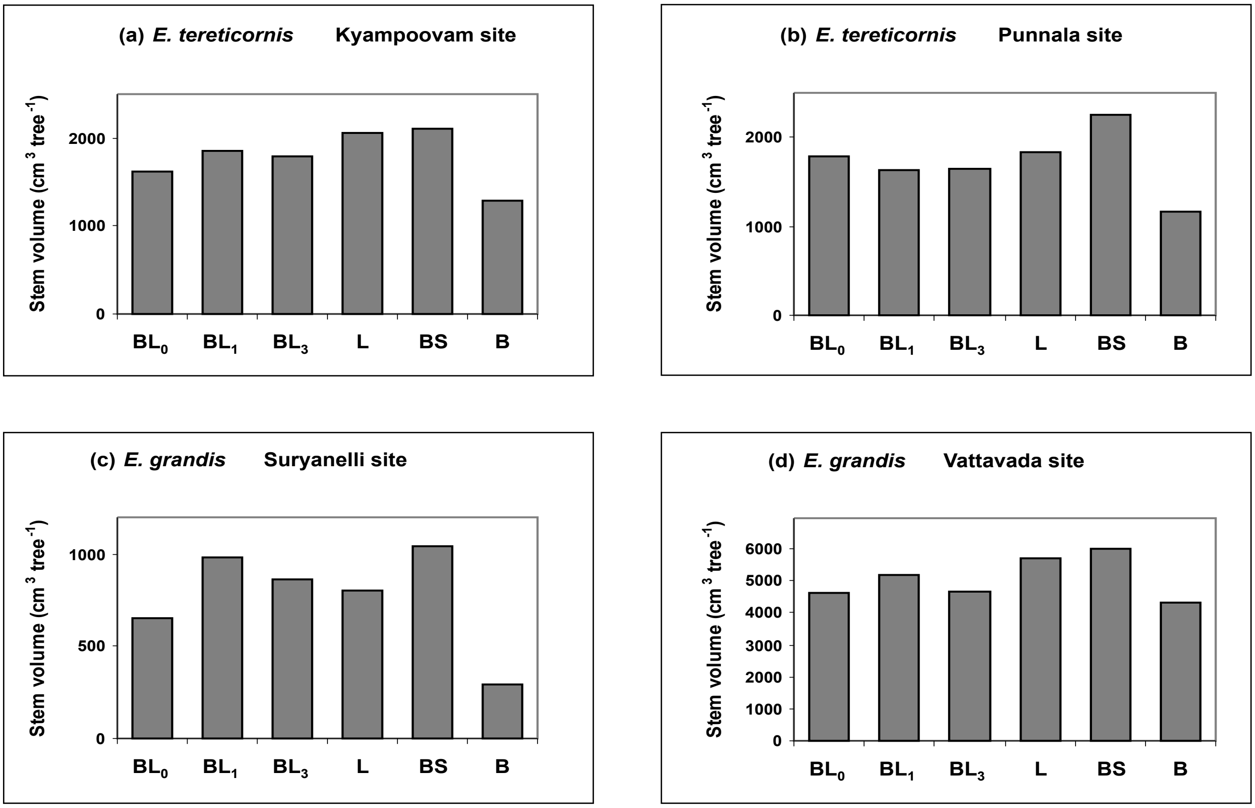
Measurements of stomatal conductance (gs) in November and March in *E. tereticornis* showed no clear treatment effects and no decline over the measurement period. In contrast, in *E. grandis*, there was a marked decline in gs between November and March on all treatments, suggesting greater adjustment in this species in response to environmental constraints. Further measurements are in progress to follow these trends as the stands age.

Leaf area index (LAI) of each species increased in the period December to March as the trees established and crown expansion occurred. However LAI values by March were still mainly in the range 0.3 to 1.0 at the *E. tereticornis* site and 0.2 to 0.5 at the *E. grandis* site, reflecting the early stage of tree growth. Estimates of LAI within each of the harvest residue management experiments showed no clear treatment effects at this stage of tree development.

Tree Growth in Response to Organic Residue Treatments

Seedling growth at the four experimental sites paralleled the productivity of the previous stands (Figs. 2 and 6) with Surianelli being the least productive and Vattavada the most productive sites. However, in the newly established stands there was only limited response to applied harvest residue management treatments (Fig. 6). Of the six treatments, the burn without added starter fertiliser showed systematically less growth than the other residue treatments. At Punnala and Surianelli these differences were statistically significant. However, these effects were due to differences in applied nutrients (addition or not of a spot application of starter fertiliser) rather than the harvest residue management treatments applied. There were no significant differences in growth between the other harvest residue treatments at any of the four experimental sites. However, the BS treatment showed greatest growth across all sites, suggesting an early positive effect to burning on growth. This is consistent with an increase in available nutrients in surface soils due to ash additions following burning as indicated by the surface soil chemistry (data not shown).

Figure 6. Growth responses after one year to alternative harvest residue management treatments at the four experimental sites



Discussion

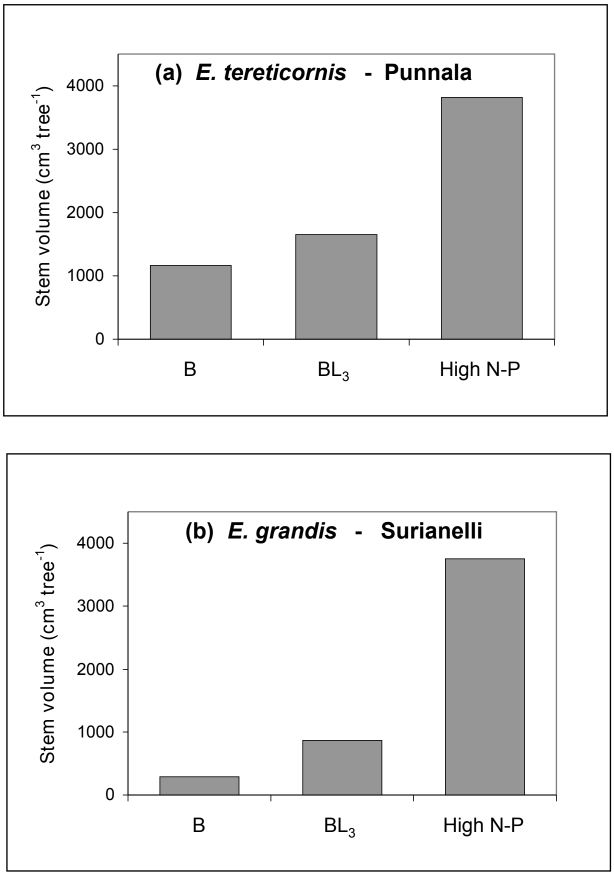
The amounts of nutrients in harvest residues (Table 4) correspond to a relatively small proportion of the total store of site nutrients to 1 m depth of soil. Nevertheless, the pool of nutrients in harvest residues does represent a significant part of the biologically active component of site nutrients. Consequently, any management practice adversely affecting this pool is likely to impact on site productivity in the longer term. Current plantation management in Kerala involves several rotations of coppice regeneration following successive harvests. When plantations are re-established with seedlings, sites are prepared by burning accumulated harvest debris and understorey vegetation and litter. This practice will result in immediate volatile loss of some nutrients and increase the run-off and erosion with associated nutrient loss during the monsoon season. We estimate that at our experimental sites, between 30 and 130 kg N ha^{-1} would have been volatilised from harvest residues during site preparation burning operations. Burning of litter and understorey vegetation (Table 3) would contribute further to this loss, while additional N in near-surface soils could also be also be volatilised, especially if high intensity fires were used in preparing the sites. These losses represent a direct depletion of site nutrient capital, which can only be replaced by fertiliser additions or through the biological N fixation systems.

Although burning does assist in clearing the site, our data show that harvest residues decay rapidly (Fig. 3) and are unlikely to be a serious impediment to site preparation and planting operations, especially on the low elevation *E. tereticornis* sites. Furthermore, in general the amount of slash left after log removal is small because of the low productivity. For example, within 7 months of harvest, 70-80% of leaf residues had decomposed and after 1 year little leaf material remained. Additionally, by the end of the first year following harvest, more than half of most of the wood residues had disappeared from the *E. tereticornis* sites. These decomposition rates are much more rapid than has been reported generally for eucalypt residues in the tropics (O'Connell and Sankaran 1997) and for decay of eucalypt litter in the same geographic region (Sankaran

1993). This difference probably reflects differences in chemical composition between harvest residues, which originate from green tissues, and normal leaf litterfall, which is largely composed of senescent tissues. Similar differences have been reported in temperate eucalypt forests (O'Connell 1997). In addition to the fast turnover of harvest residues, release of nutrients from these materials is also rapid (Figs. 4 and 5). Thus where residues are retained on these lowland sites, much of the nutrient capital stored in them is quickly returned to the soil for re-use by the newly planted tree crop. Decomposition of residues was much slower at the *E. grandis* sites, reflecting the generally lower temperatures and less favourable conditions for decomposers in these higher elevation regions. Nevertheless, retention of harvest residues on these sites probably acts as an important buffer against nutrient loss through leaching during the wet season. This may be particularly important for retention of site nitrogen stores, which appear to be readily immobilised in the decomposing harvest residues (Fig. 5).

There were few growth responses during the first year after planting attributable to the different options for managing harvest residues. Lower growth rates on the burn (B) plots compared with the other five treatments (Fig. 6) is due to the absence of starter fertiliser on the B areas. In contrast to the harvest residue management experiments, there were large growth responses in adjacent trials where effects of added nutrients (N and P) were being investigated. Figure 7 compares tree growth on the harvest residue management experiment for the B and BL_3 treatments with the best responses obtained in the N and P rate trials at two sites. Twelve months after planting, application of optimum rates of N and P resulted in up to a four-fold increase in growth over residue treatments with added starter fertiliser, and a 13-fold increase where no starter fertiliser was used. Consequently, at these sites there are good prospects for significant increases in productivity with appropriate nutrient management strategies. Where these regimes are combined with conservative site management practices, such as retention of harvest residues rather than burning, the nutrient capital of the site will be better protected. This will enhance the prospect of increased and sustainable plantation production in the long-term.

Figure 7. Growth response comparing the B and BL_3 treatments from the harvest residue management experiment with treatments from the N and P rate experiments showing optimum growth. Data for experiments at Punnala (*E. tereticornis*) and Surianelli (*E. grandis*)



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8

Effects of Site Management in Eucalypt Plantations in Southwestern Australia

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Abstract

The impact of alternative strategies for managing harvest residues in second rotation *Eucalyptus globulus* plantations is being examined at two sites of contrasting soil fertility status in southwestern Australia. Treatments being examined in a randomised block experiment are complete residue removal, residue retention, increased residue and residue burning. Large changes in soil properties due to burning residues (increases in pH, cation concentrations and labile P) were relatively short-lived with these properties returning to near pre-burn levels within 1 to 2 years after treatment. High rates of residue application significantly increased cation concentrations in near surface soil (0-5 cm). There were very few significant effects below this depth. Effects of residue manipulation on soil organic C levels were limited even at rates of application up to 160 t ha^{-1}. Variation in some soil properties (labile C and exchangeable K) was related to time since harvest rather than residue treatment effects. Mineral N dynamics were significantly affected by residue treatments with higher rates of mineralisation and greatest concentrations of potentially available N being associated with high residue treatments. Tree growth responses to treatments were small at the two sites. At the more fertile site there were no impacts of harvest residue management on growth 4 years after planting. At the less fertile site, highest levels of retained residues were associated with trends of increased growth, but differences in growth rates between treatments were significant at only a limited number of measurement periods.

Introduction

Eucalypt plantations in southwestern Australia currently cover about 150 000 ha. The planted area is expanding at more than 30 000 ha yr^{-1} with most existing plantations having been established within the last 10 years. In this region, eucalypt plantations are predominantly developed by industry with wood processing interests or by investor groups and individual landholders that supply wood for these industries. Trees are also being planted increasingly by farmers for multipurpose values, including the amelioration of environmental problems resulting from wind erosion, salinisation and waterlogging. However, the main impetus for plantation establishment has been the development of a hardwood plantation industry. The dominant species is *Eucalyptus globulus* Labill. grown on 10-year rotations to provide wood for the pulp and paper industries.

Plantations are mostly established on cleared land that has been utilised for agriculture. Much of this land has a low level of soil fertility due to long periods of weathering and the absence of soil rejuvenation processes. However, management practices employed by farmers, primarily annual applications of phosphate-based fertilisers and the introduction of leguminous pasture species, have markedly improved the fertility

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status of these soils. Consequently, the growth rate of plantations established on farms is usually three to four times greater than is obtained where trees are grown on sites recently cleared of natural vegetation. The extent to which soil fertility and plantation productivity on farmland will be maintained in the long-term is uncertain and is the focus of our research programme.

Our overall research objectives are to (1) quantify longer-term changes in the nutrient-supplying capacity of soils in eucalypt plantations growing on agricultural land, (2) determine nutritional requirements for growth of trees in second-rotation plantations, and (3) develop methodologies to manage soil fertility to maintain high productivity. An outline of the experimental approach is given in O'Connell and Grove (1999). In this paper we report on aspects of the inter-rotation site management experiments which relate to the CIFOR Network Project. Our focus is on management of harvest residues and its impact on soil organic matter, soil nutrient status, nutrient flux rates and tree growth in the four years following harvest of the first rotation of *E. globulus* plantations.

Location and Site Description

The southwest region of Australia has a Mediterranean type climate (Table 1) with cool wet winters and warm dry summers. Mean monthly temperatures increase from south to north and summer evaporation increases two-fold from the southern coast to the northern extent of jarrah forest near Perth. Rainfall is highest on the south coast and to the west along the Darling escarpment just south of Perth and declines from southwest to northeast from the southern coast and from west to east along the western coast.

The majority of eucalypt plantations are established within the southwest region where annual rainfall exceeds 700 mm. Here, the pattern of rainfall is markedly seasonal, with the majority of precipitation in the cool winter period (June, July and August). As a consequence, growth and survival of plantations during the dry season is dependent on access to water stored in deep soil profiles. Where soil water storage is insufficient to meet tree demands during the summer period, plantations are subject to water stress. On sites with shallow soils having insufficient moisture storage capacity, tree death can occur as plantations develop maximum leaf area from age four years onwards.

Soils of this southwestern region are derived from the erosion of an ancient plateau developed on the Archaean crystalline rocks, comprised primarily of granites and granitic gneisses. Much of this plateau has been subject to extended periods of weathering and is covered by deep profiles mantled by laterite (McArthur 1991). Various elements of the lateritic profile form the source materials for many of the soils of the region. As a consequence, the soils are often inherently low in nutrients and organic matter, and generally contain high levels of Fe and Al oxides that are strongly reactive with applied P (Turton *et al.* 1962).

Stand Description

Our research was conducted at two second-rotation *E. globulus* plantation sites in southwestern Australia (O'Connell and Grove 1999). They were established on farmland. The two sites, near Busselton (latitude 33°45'S, longitude 115°07'E) and Manjimup (latitude 34°20'S, longitude 116°00'E), fall within the main climatic range where the majority of eucalypt plantations are established (Table 1). The site near Manjimup is on relatively fertile karri forest soil (red earth - Ferralsol). The site near Busselton is on a low-fertility soil (grey sand over laterite - Podzol). General chemical properties of surface soils at each site are listed in Table 2.

Table 1. Climatic data at Manjimup and Busselton

Location	Annual (mm) rainfall	Mean daily max. temperature (°C)		Mean daily min. temperature (°C)		Cloudy days	Clear days	Mean annual RH (9 am) (%)
		Jan.	July	Jan.	July	(yr^{-1})		
Manjimup	1023	27.1	14.2	13.0	6.4	145	64	56
Busselton	825	28.5	16.3	13.8	7.5	101	97	72

Table 2. Soil chemical properties at the two experimental sites at time of application of harvest residue treatments

Site/ depth(cm)	pH	Organic C (g kg^{-1})	Labile C (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})	Bray P (mg kg^{-1})	Cations (cmol kg^{-1}) Ca	Mg	K
Red earth									
0-5	5.81	55.3	17.1	2.5	0.45	104	2.50	0.54	0.42
5-10	5.60	43.5	12.1	1.9	0.35	90	1.32	0.24	0.23
10-20	6.02	30.5	8.3	1.1	0.20	35	2.05	0.24	0.15
Grey sand									
0-5	5.13	45.6	14.3	1.8	0.10	3.5	1.99	0.59	0.18
5-10	4.77	33.8	12.1	1.2	0.06	1.8	1.18	0.33	0.12
10-20	4.76	22.4	7.2	0.6	0.04	1.8	0.77	0.17	0.06

The first rotation stand of *E. globulus* at the Manjimup site was established in 1986 at a spacing of 4 x 2 m. At the time of harvest in August 1994, aboveground biomass of the stand totalled 275 t ha^{-1}, with 170 and 24 t ha^{-1} removed in harvested bole wood and associated stem bark, respectively. At Busselton, the first rotation of *E. globulus* was established in 1987 and harvested in May 1995. Productivity at this site was lower than at the Manjimup site with total aboveground biomass accumulation of the stand being approximately 98 t ha^{-1} at the time of harvest. About 59 t ha^{-1} was removed from the site in harvested bole wood and 8 t ha^{-1} in bark.

Both sites were replanted with seedlings during winter in July-August 1995 at a density of 1250 stems ha^{-1}. There was no prior cultivation of the soil. A single spot application of 130 g of a compound fertiliser containing 23 g N, 10 g P, 22 g S was applied adjacent to each seedling. Weeds were controlled by hand cultivation and by glyphosate herbicide in the first two years after planting.

Experimental Design and Methods

At each site, four experiments were established to investigate impact of organic matter amendment (harvest residue management), inter-row cover crops (five agricultural legumes), and the responses to added N and P fertilisers at different rates. Only the harvest residue management studies are discussed in detail in this paper.

A randomised block design was used, with six treatments randomised within each of four replicate blocks. Treatment plots were 18 m x 18 m, with 40 trees per plot. Harvest residue management treatments were:

BL0 No slash - all litter and, slash material removed.
BL2 Single slash - uniformly redistributed.
BL3 Double slash - addition of slash from the 'no slash' (BL_0) treatment.
B Burn - (BL_2 with retained slash burnt).
BL2 + fertiliser - broadcast (50 kg P ha^{-1} as triple superphosphate and 45 kg K ha^{-1} as K_2SO_4).
BL2 + fertiliser + legume - broadcast P and K fertiliser with cover crop of vetch (*Vicia sativa*).

Results from the first four treatments are discussed here.

Soils were sampled annually in December each year to assess the impact of treatments on soil chemical properties over time, with the exception that at Busselton the first sampling was made in June 1995. Additionally, samples were collected on the burn plots (B) at each site immediately after the residues had been burnt to assess the direct effects of fire. At each sampling time, nine steel tubes, 44 mm diameter, were driven into the soil to a depth of 20 cm at randomised locations within each plot. Soils were separated into three depths (0-5, 5-10, 10-20 cm) and the nine cores within each plot were bulked, air dried and sieved through 2 mm. Soils were analysed for pH (1:5 water extracts), organic C (Walkley Black method), cations (NH_4Cl extracts) and Bray-extractable P according to procedures outlined by Hingston *et al.* (1979). Labile organic C was determined by partial oxidation with 333 mM permanganate as outlined by Blair *et al.* (1995).

Labile N status and rate of N mineralisation were assessed by the *in situ* coring technique (Raison *et al.* 1987). Field incubations were conducted every 4 weeks. At the commencement of each sampling period, 18 steel tubes (44 mm diameter) were driven into the soil to 20 cm at each plot. Nine of the soil cores were withdrawn immediately and returned to the laboratory for analysis and the remainder were covered with plastic caps and allowed to incubate for 4 weeks under field conditions and then returned to the laboratory for analysis. Immediately following sampling, soil cores were placed in cooled insulated containers, transported to the laboratory and stored at 4^0C before preparation and analysis. Soil cores were divided into two depths (0-10 and 10-20 cm), sieved through a 5 mm screen to remove large roots and gravel and the nine cores of each type within each plot were bulked for analysis of ammonium and nitrate. Net N mineralisation rates were calculated each month from the difference in mineral N content of incubated and unincubated soil core samples. Potentially mineralisable N was determined on all unincubated soil samples by the anaerobic incubation method of Keeney and Bremner (1966).

Tree growth was assessed periodically by measuring tree diameter and height within a central measuring plot containing 18 trees. Biomass was determined by relating tree volume to weight using allometric relationships derived from harvested sample trees. These sample trees were also used to determine allocation of biomass between various tree components. LAI was determined from allometric functions relating leaf area to stem basal area at the crown base.

Results

Amounts and Nutrient Content of Harvest Residues

Markedly lower concentrations of total and labile P as well as exchangeable K in the coarse textured grey sand compared to the soil from the red earth site were the main features differentiating soil nutrient status of the two sites (Table 2). This in turn was one of the factors that affected the relative tree growth at each site and consequently the amounts of harvest residues (Table 3). At the red earth site, which represents the upper range of plantation production in Western Australia, more than 50 t ha^{-1} of residues with end diameter < 3 cm were deposited on the forest floor during harvesting. At the less fertile grey

Table 3. Biomass dry weight and nutrients in harvest residues at the two experimental sites

	Biomass	Nutrients (kg ha^{-1})				
	(t ha^{-1})	N	P	Ca	Mg	K
Red earth						
Leaves	21.5	259	15	315	30	96
Wood, bark and miscellaneous[(a)]	29.6	88	8	282	29	86
Total	51.1	347	23	597	59	182
Grey sand						
Leaves	13.0	138	9	188	18	56
Wood, bark and miscellaneous[(a)]	18.3	81	7	200	18	55
Total	31.3	219	16	388	36	111

[(a)] Wood residues < 3 cm diameter. At the red earth a further 30 t ha^{-1} of larger wood residues (> 3 cm diameter) was present on the soil surface following harvesting. This is a greater amount of wood residues than left under current harvest practice and it has not been included in calculating the nutrient stores in Table 3.

sand site 31 t ha^{-1} of residues remained following harvesting. There was a corresponding difference in the nutrient loads added in harvest residues (Table 3).

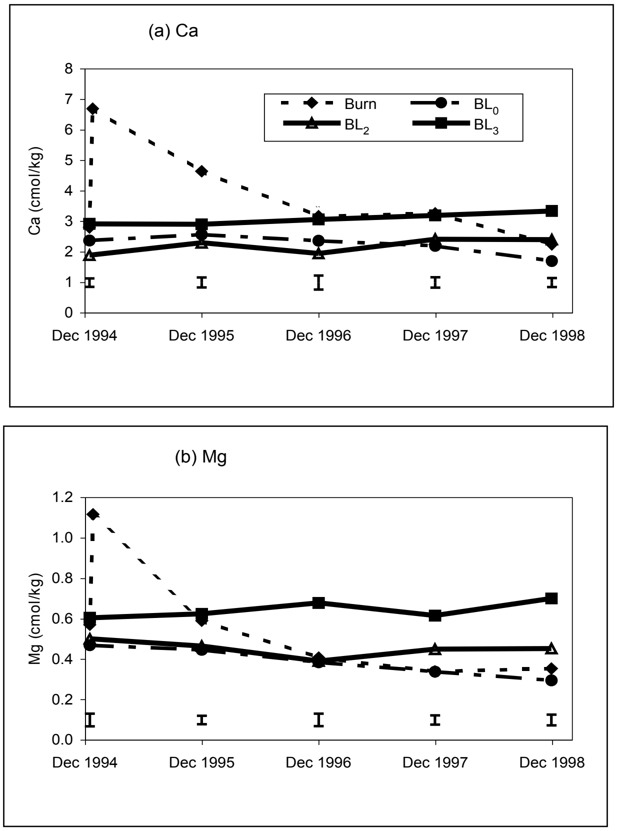
Impact of Harvest Residue Management on Soil Stores of Nutrients

Changes in soil chemical properties have been monitored annually since December 1994 (red earth site) and June 1995 (grey sand site), with the most recent results available for December 1998 at both sites. Changes in soil nutrient status appear to result from three processes, namely (i) immediate effects of fire in the burn treatment, (ii) longer term impacts due to addition of harvest residues to the soil surface, and (iii) longer term changes in soil which appear to be largely independent of applied treatments.

Burning harvest residues significantly increased soil pH, cation concentrations and labile P (grey sand site only) in surface (0-5 cm) soil due to the addition of ash. There was little impact of fire on lower soil horizons. Many of the observed changes were large with increases of up to more than 1 unit in pH, more than 100% in some exchangeable cation concentrations (Figs. 1, 2), and greater proportional change in labile P. However, all these effects were relatively short lived, with soil properties returning to near pre-burn levels within one to two years after treatment.

The main long-term impacts on soil nutrient status of harvest residue management relate largely to effects on soil cation concentrations and are primarily associated with the highest levels of added residues (BL_3). At each of the sites this treatment resulted in significantly increased surface soil concentrations of exchangeable Ca and Mg (Fig. 1) and at the red earth site significantly increased exchangeable K (Fig. 2). Again, these effects were largely confined to the upper 5 cm of the soil profile. Despite the large amounts of residues added, there appears to have been limited impact on soil C status. At the grey sand site there was no significant effect of harvest residue management on soil organic C concentrations for any of the treatments at any soil depth. In surface soil (0-5 cm) at the red earth site there were significant treatment effects ($P<0.05$) on soil organic C levels during the last two of the five sampling periods (3.5 and 4.5 years after stand harvest). At these times the BL_3 treatment, which had received about 160 t ha^{-1} added residues, contained organic C levels in 0-5 cm soil which were 20-25% greater than in the other three treatments. There were no significant treatment effects at other depths.

Figure 1. Variation in (a) exchangeable Ca and (b) exchangeable Mg concentration in surface (0-5 cm) soil at the red earth site in relation to harvest residue management treatments and time since harvest. Standard error of the treatment means shown at each sampling time



Changes in soil chemical status appear to be related more to time since stand harvest than to the treatments applied. This was evident for several elements. In particular, soil exchangeable K concentrations declined in all treatments during successive sampling periods (Fig. 2) at both sites. The decrease in K concentrations was greatest in surface soil (2.1 to 2.8 fold), intermediate in 5-10 cm soil (1.8 to 2.1 fold) and least in 10-20 cm soil (1.2 to 1.6 fold) over the period of the experiment. Likewise, labile C concentrations were not affected by harvest residue treatments but they did vary significantly with time since stand harvest at both sites (Fig. 3). In the first one to two years after harvest, labile C concentrations decreased and in subsequent years gradually increased again to approach levels similar to those in immediate post-harvest soil samples.

Figure 2. Variation in exchangeable K at (a) the red earth and (b) the grey sand site in surface soil (0-5 cm) in relation to harvest residue treatments and time since harvest. Standard error of the treatment means shown at each sampling time

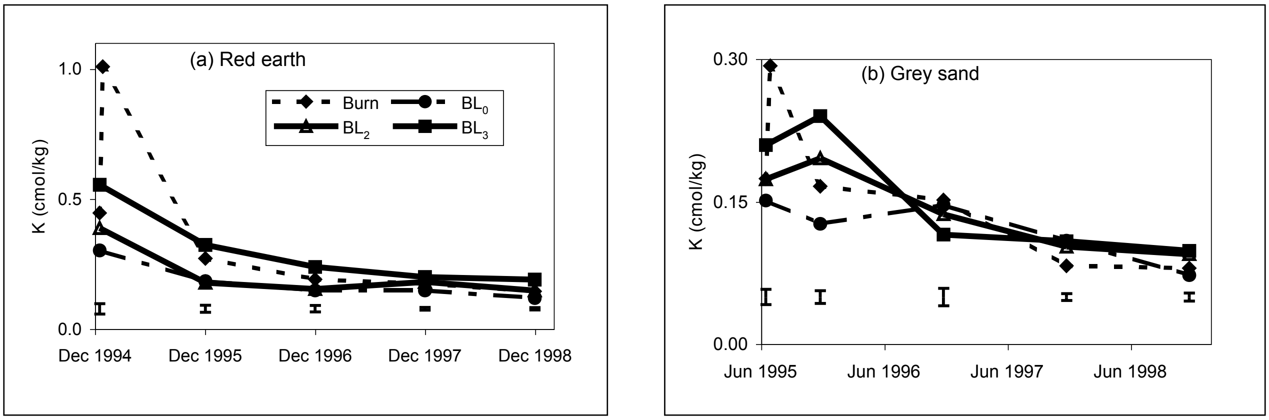
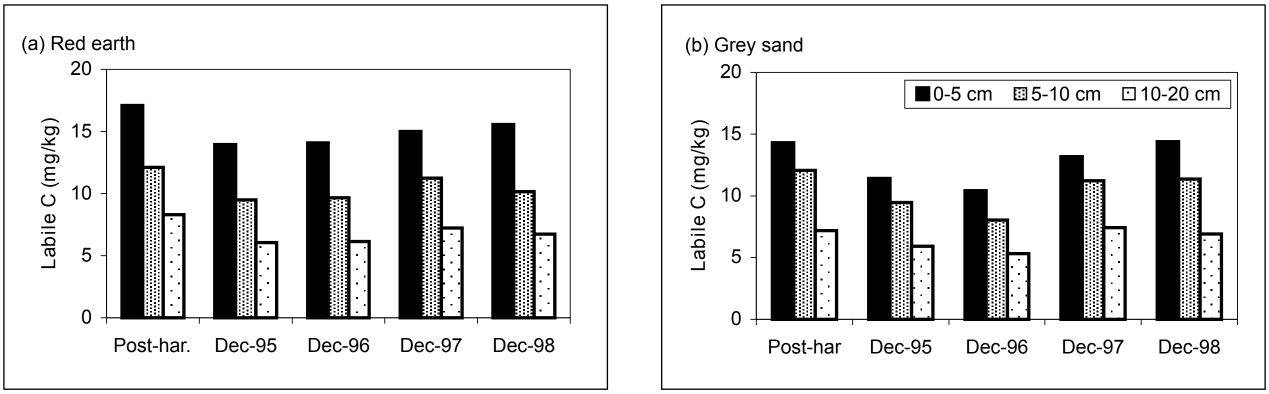


Figure 3. Variation in concentrations of labile soil C with time since stand harvest (July 1994 at the red earth site and April 1995 at the grey sand site)



Impact of Slash Treatments on Mineral Nitrogen Flux Rates

Harvest residue management had a significant impact on the dynamics of soil mineral N. High concentrations of mineral N were present in soil immediately following harvest (Fig. 4). These pools declined in subsequent years, probably largely through leaching of nitrate below the root zone. At the more highly textured red earth site, mineral N pools were significantly higher where residues had been removed (BL_0 and B treatments). At the sandy site the opposite was the case - highest mineral N concentrations in soil after harvest were associated with the highest level of residue retention (BL_3 treatment).

Both the measured rates (Fig. 5) and potential (Fig. 6) for N mineralisation in surface soil (0-10 cm) were significantly affected by harvest residue treatments. At both sites cumulative annual rates of N mineralisation were significantly higher on high residue (BL_3) treatments compared to low residue treatments in the third and fourth years of measurement. At the red earth site treatment BL_2 followed similar trends. For these treatments the cumulative annual rates of N mineralisation also appear to be increasing over time. Annual rates of mineralisation per unit weight of soil were generally higher in the more highly textured and fertile red earth soil than in the grey sand.

Figure 4. Impact of harvest residue treatments on annual average concentrations of mineral N in surface (0-10 cm) soil at (a) red earth and (b) grey sand sites. Standard error of the treatment means shown for each year

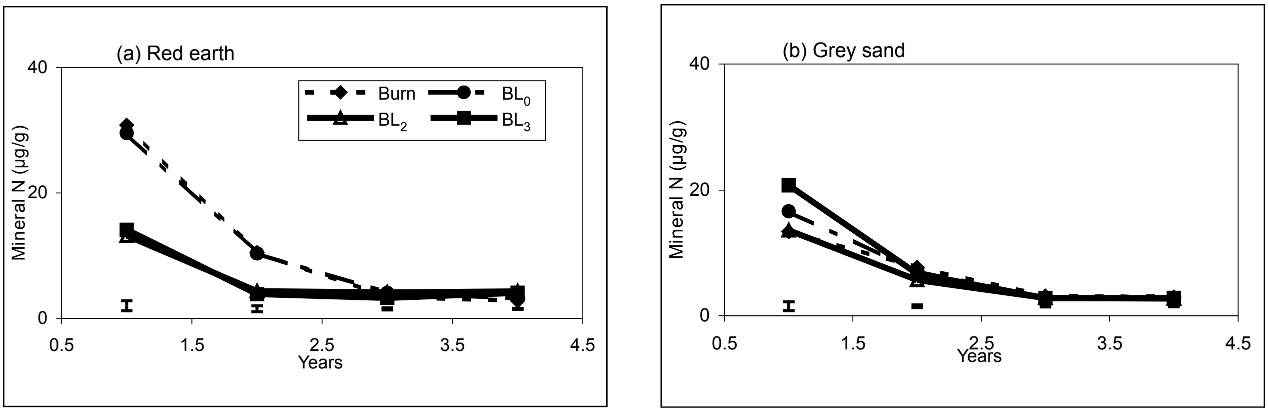


Figure 5. Impact of harvest residue treatments on cumulative annual N mineralisation rates in surface (0-10 cm) soil at (a) red earth and (b) grey sand sites. Standard error of the treatment means shown for each year

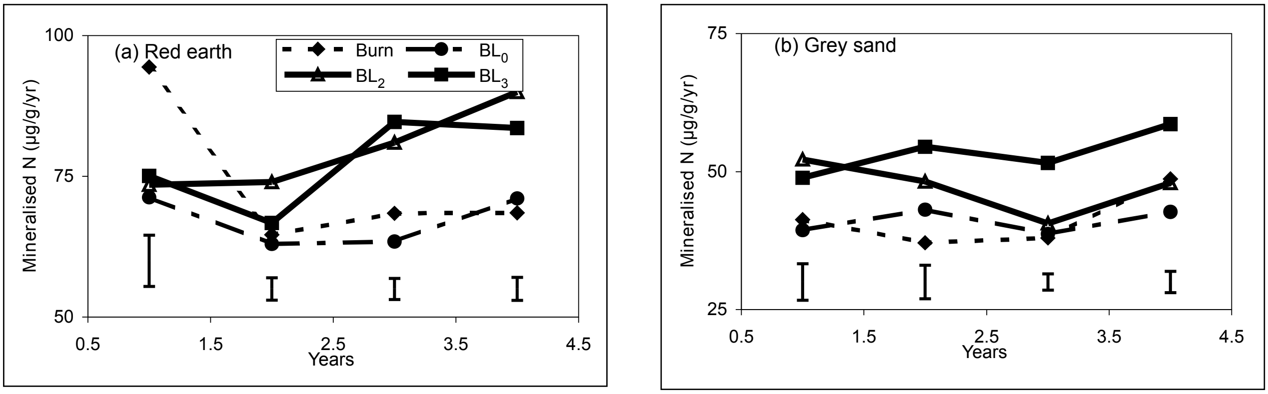
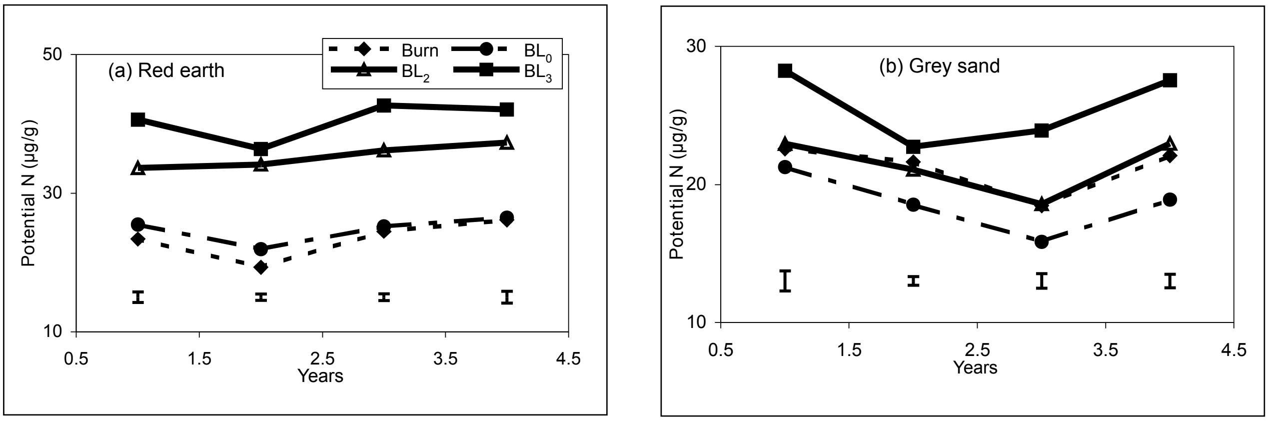


Figure 6. Impact of harvest residue treatments on mean annual potential rates of N mineralisation in surface (0-10 cm) soil at (a) red earth and (b) grey sand sites. Potential for N mineralisation is estimated as the ammonium produced after anaerobic incubation at 40^{0}C for 7 days. Standard error of the treatment means shown for each year



Annual average potential rates for N mineralisation in soil showed similar treatment effects to the measured rates of mineralisation. High residue treatments resulted in significantly higher concentrations of potentially mineralisable N at both sites during each measurement period. As with mineralisation rates, potential for N mineralisation was systematically higher in the red earth soil compared to the grey sand.

Impact of Harvest Residue Management on Tree Growth

There were little or no responses in tree growth to harvest residue treatments at the two sites (Fig. 7). At the red earth site, growth rates during the first year after planting were significantly greater ($P<0.05$) on the highest residue plots (BL_3) compared with other treatments. However in subsequent years growth on treatments BL_0 and BL_2 increased relative to BL_3 (Fig. 8a) and the significance of growth differences between residue treatments declined. In years 2, 3 and 4 after planting there were no significant differences in growth amongst the applied treatments.

At the grey sand site there was a significant difference in tree growth between residue treatments during the first year after planting with highest growth where residues had been removed. This trend was reversed by the end of the first year (Fig. 8b) with greater relative growth rates for treatments with highest amounts of retained harvest residues. However, although growth on the high residue treatment BL_3 was greater than on other treatments during the last three years of measurement, these differences were generally not statistically significant.

Figure 7. Impact of harvest residue treatments on mean tree conical volume at the (a) red earth and (b) grey sand sites

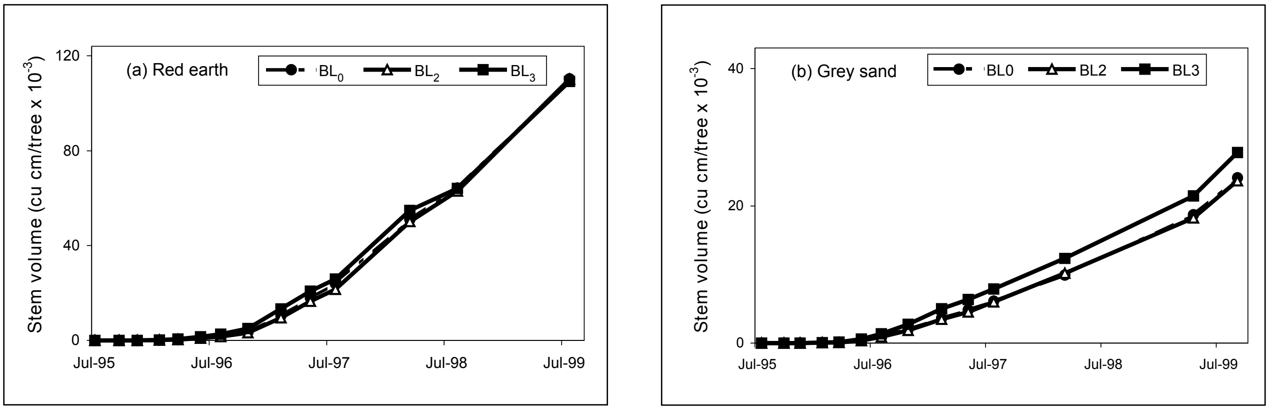
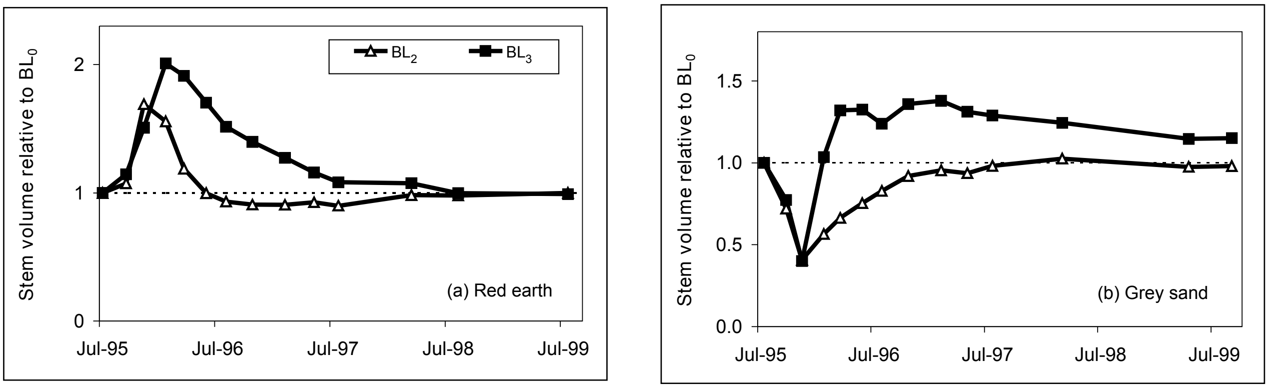


Figure 8. Growth on BL_2 and BL_3 treatments relative to BL_0 over the 4-year measurement period since planting at (a) red earth and (b) grey sand sites



Leaf area index (LAI) differed markedly between sites, reflecting differences in soil nutrient status, water availability and tree growth rates. At each site leaf area increased rapidly in the second year of growth, reaching a plateau between 3.5 to 3.7 at the red earth site and 1.2 to 1.4 at the grey sand site. Over most of the growth period there was no significant systematic difference in LAI between the applied harvest residue treatments.

Discussion

The amounts of added residues and their nutrient contents were significant in relation to the stores in surface soils at both sites. For the BL_2 treatment, total C additions (assuming approximately 50% C content in residues) amounted to more than two thirds and one third of the soil-stored C in surface soil (0-10 cm) at the red earth and grey sand sites, respectively. When larger woody residues (> 3 cm) are considered, the amount of C in harvest residue additions to the red earth site exceeded that present in surface soil. Much of this material had decomposed by December 1998 (4.5 and 3.5 years after harvest of the red earth and grey sand sites, respectively). Surprisingly, the addition of these residues has resulted in very little change in soil-stored C over the period of the experiment. Treatment BL_3, which received double the residue additions applied to BL_2, also showed limited change in the pool of C in surface soil. At the red earth site, C stored in 0-10 cm soil increased during the 4-year measurement period by only about 2% from values found at the initial sampling 6 months after harvest. There was a small decline in C storage in 0-10 cm soil at the grey sand site during the same period. Several studies in the tropics have suggested that decay of eucalypt residues results in smaller contributions to soil organic matter than does turnover of residues from other species (Bernhard-Reversat 1987, 1993; Wang *et al.* 1991; Bargali *et al.* 1993). The extent to which these conclusions apply to temperate forests is uncertain. Monitoring of soils in the current study will continue annually throughout the rotation and should provide insights into dynamics of soil C.

Burning of the harvest residues impacts markedly on soil pH and the storage and availability of many of the nutrients. Increases in plant availability of the cations and P after fire is one of the most common responses found (Grove *et al.* 1986). In our study, these effects tended to be relatively short lived, with most soil properties returning to their pre-fire levels within the first or second year after fire. Possibly of more importance is the long-term impact of residue burning on site N status (Raison *et al.* 1993), especially if fire is used repeatedly after harvesting short rotation plantation forests. We estimate that at the red earth site, N volatilisation losses from burning harvest residues and associated surface soil organic matter, together with removal of N in harvested logs, probably exceeded 500 kg N ha^{-1}. Replacement of these amounts of N would not normally be possible within the time scale of one 10-year rotation.

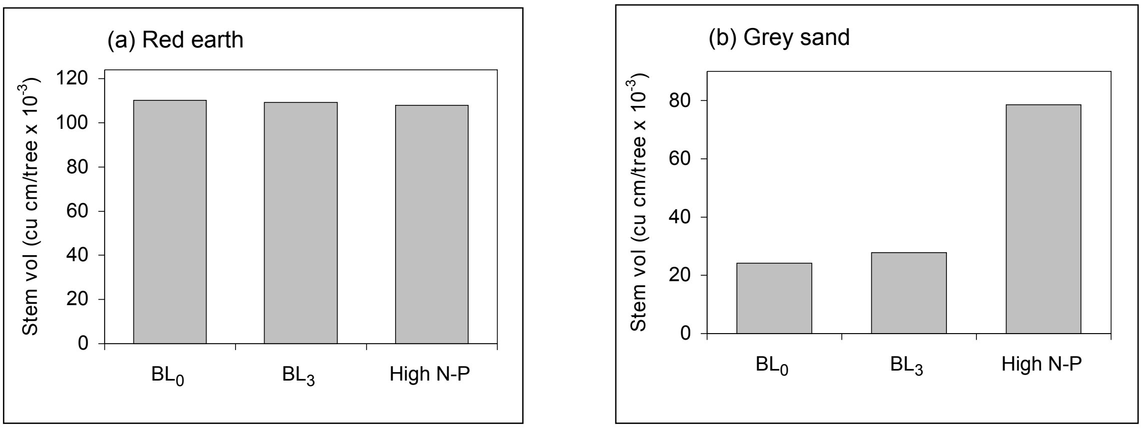
Retention of harvest residues may also play an important role in moderating the fluxes of mineral N in the early stage of tree growth following harvest and re-establishment of the new plantation. In a laboratory study, Aggangan *et al.* (1999) found eucalypt litter to be an effective agent for immobilisation of mineral N and hypothesised that eucalypt residues may act as an important buffer against N loss through leaching or other processes during periods of disturbance. At our sites there were large accumulations of mineral N in soil following harvest, probably because of the maintenance of conditions conducive to N mineralisation and the limited uptake by a newly developing root system. At the red earth site much of this labile N was present as nitrate and would have been subject to leaching loss with the onset of winter rains. Accumulations of nitrate were lower where residues had been retained, probably as a result of N immobilisation as suggested by Aggangan *et al.* (1999), with the concomitant reduced prospect of N loss through leaching. In the third and fourth years after seedling establishment N mineralisation on BL_2 and BL_3 treatments increased above BL_0 plots but at this time most of the mineralised N would have been taken up by the well-established root systems. At the less fertile grey sand site, N mineralisation tended to be higher where residues had been retained at all stages of stand development. The standing pool of mineral N was initially highest at the greatest level of residue retention (BL_3), but in this case labile N was predominantly in the ammonium form and would have been less likely to be leached below the rooting zone.

Two soil changes which are unrelated to residue treatment, but which are of importance in relation to C storage and plantation nutrition are (1) the patterns of labile C variation (Fig. 3) and (2) the decline in soil K status at both sites following stand harvest (Fig. 2). Worldwide, there is currently great interest in sequestration and storage of atmospheric CO_2 by alternative land use systems. The data presented here illustrate the difficulty in measuring changes in total soil C levels in response to land management, despite the large amounts of added residues and the robust experimental designs. Alternative measures of soil C status, such as the fraction of C oxidised by weak permanganate solution, may provide a more sensitive option for tracking changes in soil C in response to different land management options.

The decline over time in exchangeable soil K at both sites to about half the levels present in the first soil sampling following harvest is of interest. The extent to which this represents a general pattern across a wide range of plantation sites is uncertain but warrants further examination. If such a trend exists more generally then greater attention to managing K nutrition in *E. globulus* plantations in second and subsequent rotations may be required in the future.

At the red earth site there was no impact of residue management on tree growth 4 years after planting. This site is at the upper end of soil fertility of the land utilised for plantations in southwestern Australia. Growth rates on BL_0 and BL_3 treatments were similar to those where high rates of N and P had been used in nutrient application rate experiments at this site (Fig. 9a) indicating that nutrient limitations were not restricting growth on the harvest residue management experiments. Consequently, in the short term, harvest residue management is unlikely to impact on plantation growth on such sites. However, in the longer term, over a number of rotations, any management practice which affects nutrient status of the site, such as N loss associated with burning, may adversely impact on site productivity. At the grey sand site, which has a low natural fertility, there was a trend towards higher growth associated with greatest application rates of harvest residues. However during the majority of measurement periods these differences were not statistically significant. At this site, there were also large responses to added nutrients (Fig. 9b). Greater retention of harvest residues is associated with significantly increased rates of soil N mineralisation and this may partly explain the relative patterns of tree growth found at the grey sand site. Growth trends will be monitored throughout the rotation to assess whether slash residue management impacts significantly on productivity of the second rotation harvest. Our current results indicate that demonstrating statistically significant growth differences between the alternative options for managing slash materials may be difficult in some circumstances. Nevertheless, conservative harvest residue management will assist in maintenance of site nutrient capital and this, coupled with appropriate fertiliser regimes, will favour sustained plantation productivity in the long-term.

Figure 9. Comparison of growth of 4-year old trees on harvest residue management treatments and treatments with high rates of applied N and P fertilisers over BL_2 treatment at (a) red earth and (b) grey sand sites



Acknowledgments

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9

Effects of Site Management in Pine Plantations on the Coastal Lowlands of Subtropical Queensland, Australia

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Abstract

Biomass and nutrient distribution in a 30-year-old slash pine (*P. elliottii*) plantation were estimated at clear fall to provide a basis for interpreting changes in the nutrient pools and tree responses to harvest residue management practices applied at the establishment of the second rotation. Total biomass at clearfall of a typical slash pine stand is 316 t ha^{-1}, of which 206 t ha^{-1} is removed in logs. Nitrogen and P removed in logs account for 7.6% and 3.4% of total N and P in the ecosystem. Residues remaining after logging contain 12% of the total N and 5.2% of the total P. Proper management of these residues is therefore critical for sustaining site productivity. Following clear falling, a long-term experiment was established to assess the impacts of harvesting residues and litter management regimes on soil fertility and productivity of the second crop F_1 hybrid between slash pine and Honduras Caribbean pine (*P. caribaea* var. *hondurensis*). The early results from this experiment show tree stem volume and above ground biomass production have been increased by 31% and 29% respectively at age 39 months by retaining litter and logging residues, compared with the treatment in which logging residues and litter were removed. Further improvements in tree growth have been achieved by doubling the quantity of residues retained and by controlling weed competition. Foliar nutrient concentrations indicated that N may play an important role in the maintenance of long term site productivity. Differences exist in the growth and foliar nutrient concentrations between the different hybrid families tested but all families responded similarly to the residue treatments. The presence of the residues increased soil moisture levels in the surface soil during a dry season. There was a marked reduction in the quantity of residue, especially the finer fraction, after 39 months. This study has contributed to an improved understanding of the soil and plant factors controlling productivity and provided a basis for more detailed studies on processes underpinning plantation sustainability.

Introduction

In Queensland, the exotic pine estate (129 497 ha) is comprised of 37% slash pine (*Pinus elliottii* Engelm.), 42% Honduras Caribbean pine (*P. caribaea* var. *hondurensis* Barr. et Golf.) and 18% the hybrid between these two taxa. Since 1991 most plantings have been with hybrids. In 1997/98, 90% of the pine plantings were with the hybrid and 97% of sites planted were second rotation areas. Typical rotation length is 30 years. Maintenance and improvement of long-term site productivity of plantations is an important goal of management.

Tiarks *et al.* (1998) have described the needs, objectives and basis of long-term experimentation for this international network, coordinated by the Center for International Forestry Research (CIFOR). Currently this is the only trial using a *Pinus* species. Two trials with eucalypts in Western Australia (O'Connell *et al.* 1999) are relevant to the work being undertaken in Queensland and will provide a useful contrast at a national level. Simpson *et al.* (1999) described the experimental site in

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southeast Queensland and reported the early results of the work which formed a part of the international network. Biomass and nutrient distribution in a typical rotation aged slash pine stand were also reported. The early responses of F_1 hybrid pine established in the second rotation under a range of logging residue management treatments showed that retention of logging residues did not affect survival but improved height growth by 11-24% at age 17 months. This paper provides further details on the experimental methods and recent results.

Site and Stand Description

Details of the experimental site were described by Simpson *et al.* (1999). The study was carried out at Toolara in Queensland, Australia (26°00'S latitude, 152°49'E longitude and 61 m altitude). The area has a humid subtropical climate, with a mean annual rainfall of 1354 mm. The site originally carried dry sclerophyll native forest which was cleared in 1959 for plantation establishment. Soils at the site are derived from Mesozoic sandstones, and are acidic, deep and sandy, and classified as Grey Kandosols (Isbell 1996) or Gleyic Acrisols (FAO 1974). Inherent soil fertility is low and large responses of the first rotation stand to the additions of P fertiliser were obtained (Simpson and Grant 1991, Simpson 1995). The soils are well-drained in the upper horizons but can become waterlogged for short periods during the wet season when the watertable rises within 50 cm of the soil surface.

The first rotation slash pine stand was planted in July 1966 at 1234 stems ha^{-1}. Fertiliser, 310 kg ha^{-1} Nauru rock phosphate (50 kg P ha^{-1}) was broadcast in 1966 and a further application of triple superphosphate (44 kg P ha^{-1}) was applied aerially in 1980. The stand was thinned at age 15.6 years to a stocking of 679 stems ha^{-1}, and clearfelled in November 1995, at age 29.4 years. The site index [average height (m) of the 50 tallest stems ha^{-1} at age 25 yr] of the area was 23.7, compared with a district average of 23.4 for the species. At clearfelling, the stand had a predominant height of 25.2 m, standing basal area of 39.6 m^2 ha^{-1} and standing volume to a 7 cm top end diameter of 325.4 m^3 ha^{-1}.

Allometric relationships were established from sample trees harvested from a 29.4-year-old first rotation slash pine stand and biomass nutrient pools estimated. Litter, underground biomass and soil nutrient pools were also estimated.

Experimental Design and Methods

The residue management trial consists of six treatments laid out as a randomised complete block experiment replicated four times. Gross plots are 12 rows by 12 trees at 3m x 3m spacing (0.13 ha) with a 6 m border and net plots of 0.058 ha. The treatments were:

BL0	Removed both litter and logging debris + 50 kg P ha^{-1}.
BL2	Retained both litter and logging debris + 50 kg P ha^{-1}.
BL3	Applied double quantities of litter and logging debris + 50 kg P ha^{-1}.
BL2 + Legumes	BL_2 + leguminous cover crops.
BL2 - Weeds	BL_2 + complete weed control.
BL2 - P	BL_2 without P fertiliser.

It was not possible with the equipment used to remove the small amount of litter/logging residue (< 10 t ha^{-1}) remaining in the BL_0 without excessive site disturbance. The normal residue treatments (BL_2) carried 60 t DM ha^{-1} (50.8 to 73.8 t ha^{-1}) of which approximately 40% was in the forest floor litter. Double residue (BL_3) treatment (140 t ha^{-1}) was not intended as an operational alternative, but to widen the treatment effects on tree growth and soil processes.

The slash management treatments were applied in February 1996, 3 months after clearfalling, and surface biomass estimated for individual plots. Planting spots were prepared using an excavator-mounted rotary cultivation head. Pre- and post-planting herbicides were applied in the first year along the planting rows. The plots were planted in May 1996 at 3 x 3 m spacing (1111 stems ha^{-1}) with container-grown F_1 hybrid seedlings raised from seed collected from six separate orchards. Each orchard was comprised of a single family of slash pine which was mass-pollinated following emasculation. The same families were represented in two old and two young orchards and the same pollen used in mass pollination but a degree of self pollination occurred in the older orchard as a result of difficulty in achieving complete emasculation. Seed source identity was retained. Triple superphosphate was applied to supply 45g P $seedling^{-1}$ in all treatments except for BL$_2$-P. A mixture of legume seeds containing lotononis (*Lotononis bainesii*), Wyns cassia (*Cassia rotundifolia*) and Maku lotus (*Lotus pedunculatus* cv Maku) was sown on three occasions in the BL$_2$ + Legumes treatment. The legumes were slow to develop and in 1999 covered < 50% of the area.

Tree height and diameter were measured annually. Foliar samples of the most recent fully formed fascicles from the basal spring whorl developed in the season prior to sampling were collected in August 1998 and August 1999. Fifty fascicles from each of four trees were combined to give a composite sample for each sample. Biomass and nutrient pools in the above ground tree fractions were estimated immediately before non-merchantable thinning of the stand at age 39 months. following the same principles used for the biomass sampling of the first rotation stand. Sample trees, representing the diameter distribution of the stand, were harvested. Weights and nutrient concentrations of the tree components were determined. Allometric relationships were established and biomass and nutrient contents estimated. Slash residues were sampled at age 0 and 30 months by taking five one-metre square samples per plot, and at 39 months with two similar samples per plot. After collection, the material was sorted into size classes, oven dried and sampled for chemical analysis. Nutrient analysis of plant and soil samples was carried out by the Queensland Forestry Research Institute’s chemistry laboratory (Collins 2000a, b). Gravimetric moisture content of the surface soil (0-10 and 10-20 cm) at the time of residue sampling (30 and 39 months) was recorded.

Results

Impacts of Harvesting and Site Preparation on Biomass/Slash and Nutrients

In this study, 80% of the biomass on the site was aboveground and contained between 72 and 78% of macronutrients in the biomass (Table 1). Between 52 and 72% of the macronutrients in the biomass were in the standing trees. The relatively low quantity of K in the litter is of note. Depending on the nutrient, between 16 and 28% of the nutrients in the biomass were in tree roots. Integrated logging removed 65% of the biomass, 39% of N and P, and 54% of K in the biomass. Details of the biomass and nutrient distribution in mature slash pine stands were reported in Simpson *et al.* (1999).

The weight of the aboveground biomass (including litter but excluding logs) was lower (46 t ha^{-1} than that harvested as merchantable timber (wood + bark) (206 t ha^{-1}) but both components contained similar quantities of nutrients, except for K (Table 1). Log harvest removed an estimated 7.6% of the N, 3.4% of the P and 171% of the exchangeable soil K, 16.3% of the exchangeable soil Ca and 5.6% of the exchangeable soil Mg in the ecosystem. While the loss of N and P from the pool through logging is relatively small, this loss is doubled if the logging residues plus litter were removed during site preparation at establishment of a second crop. Any acceleration of nutrient loss from a site would adversely impact on the maintenance of long-term site productivity unless replaced by fertiliser.

Table 1. Biomass and nutrient distribution in a 29.4-year-old slash pine stand at Toolara, Queensland

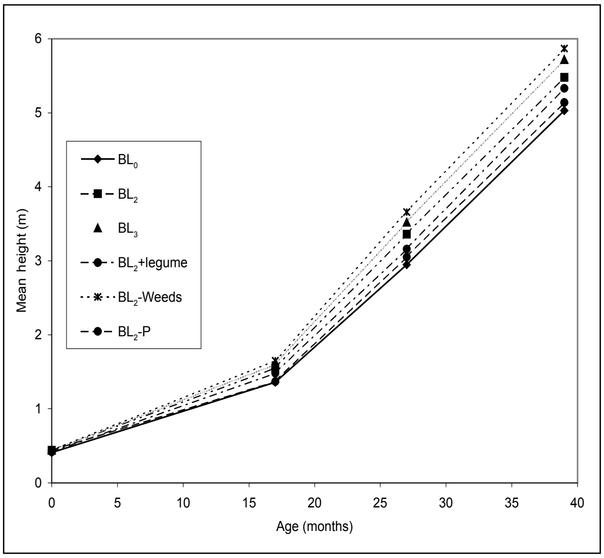
Component	Biomass	N	P	K	Ca	Mg
	(kg ha^{-1})					
Foliage	2 03	16.0	1.3	4.1	7.8	4.0
Branches and stem tip	24 18	48.1	3.7	17.0	68.2	17.5
Stem wood, bark (>7cm diam.)	205 74	189.1	10.8	63.2	170.3	64.6
Litter	19 80	98.2	4.3	4.7	83.4	20.3
Stump	33 00	38.3	2.1	11.1	20.7	10.7
Roots	30 94	95.7	5.1	16.4	71.6	22.2
Total biomass	315 69	485.4	27.3	116.5	422.0	139.3
Soil (to 120 cm)		1991	288	37[a]	1045[a]	1148[a]
Total ecosystem	315 69	2476	315	-	-	-

[a] Exchangeable cations determined in neutral ammonium acetate extract (Collins 2000b).

Survival and Growth

At the end of the first season seedling survival was 99% in all treatments. Trees grew little during the winter and no treatment effects were apparent by spring of the first year. Treatment differences became apparent during the following spring season. At age 17 months there was little difference in development of the trees in the treatments where litter was retained and P fertiliser applied. The legume treatment was ineffective (Fig. 1).

Figure 1. Height growth of hybrid pine to residue management treatments on a second rotation site at Toolara



At age 39 months, residue retention treatments had resulted in improved tree growth (Table 2); height by 8.9%, diameter by 11.6%, basal area by 23.9%, and total volume by 31.4%. Doubling the quantity of residues retained resulted in a further improvement in tree growth. Complete weed control markedly improved tree growth when compared with the single residue retention treatment (mean height increased by 7.1%, diameter by 17.7%, basal area by 38.5% and total volume by 52.1%). The legume treatment had no effect on tree growth. The treatment without P is equivalent to the nil residue plus P treatment. These differences are also reflected in current increments for diameter, basal area and total volume (Table 2).

The residue treatments had a major influence on biomass production, with retention of litter and logging residues improving tree biomass by 29% (Table 3). Double amounts of residues improved biomass by a further 17% and weed control resulted in an improvement of 38% over the single residue treatment. The increased production is accompanied by a corresponding increase in nutrient uptake.

Family Effects

Family variation in tree growth is shown in Table 4. There were significant differences between families but the family by residue interaction is generally non-significant. This suggests that the families responded in a similar fashion to residue management treatments.

Table 2. Effect of slash treatments on the stand growth at age 39 months

Treatment	Mean height	DBH	Basal area	Volume	Increment 27-39 months		
	(m)	(cm)	(m^2 ha^{-1})	(m^3 ha^{-1})	DBH (cm)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
BL$_0$	5.0	8.6	6.7	15.9	4.1	4.8	13.2
BL$_2$	5.5	9.6	8.3	20.9	4.2	5.6	16.8
BL$_3$	5.7	10.4	9.8	26.3	4.6	6.7	21.0
BL$_2$ + Leg.	5.3	9.3	7.8	19.4	4.3	5.5	15.9
BL$_2$ - Weed	5.9	11.3	11.5	31.8	4.6	7.3	24.4
BL$_2$ - P	5.1	8.9	7.1	17.2	4.2	5.1	14.2
LSD p=0.05	0.4	1.0	1.8	5.9	0.23	0.83	3.9

Table 3. Effect of slash treatments on aboveground tree biomass and nutrient pools at age 39 months

Treatment	Biomass	N	P	K	Ca	Mg
		(kg ha^{-1})				
BL_0	13 365	30.3	5.1	21.9	27.7	9.7
BL_2	17 292	39.3	6.4	29.7	36.2	12.2
BL_3	20 292	46.3	7.3	35.7	42.6	14.2
BL_2 + Leg	16 234	36.9	6.0	27.6	33.9	11.5
BL_2 - Weeds	23 920	54.6	8.5	42.8	50.3	16.5
BL_2 - P	14 678	33.3	5.1	24.5	30.6	10.5
LSD p=0.05	3 860	8.9	1.2	7.5	8.2	2.5

Table 4. Growth of six hybrid pine families at age 39 months

Family number	Mean height (m)	DBH (cm)	Basal area (m^2 ha^{-1})	Total volume (m^3 ha^{-1})	Increment 27-39 months.		
					Height (m)	Basal area (m^2 ha^{-1})	Total volume (m^3 ha^{-1})
1	6.1	10.6	10.1	28.3	2.3	6.6	22.1
2	6.1	11.0	10.8	29.6	2.4	7.2	23.5
3[a]	4.5	8.1	5.8	12.0	1.8	4.2	10.0
4[b]	5.7	10.5	9.8	25.8	2.2	6.7	20.7
5[b]	4.6	7.5	5.1	10.8	2.0	3.6	8.9
6[a]	5.7	10.4	9.7	25.1	2.2	6.6	20.2
Mean	5.4	9.7	8.5	21.9	2.2	5.8	17.6
LSD p=0.05	0.2	0.4	0.8	2.7	0.1	0.5	1.9
Interaction[c]	0.013	NS	0.011	0.001	NS	NS	0.001

[a - b] Family numbers with the same superscript have the same nominal parentage but originate from different-aged orchards and have a different degree of self-pollination; [c] Refers to the significance (p levels) of the family by residue interaction; NS = not significant.

Foliar Nutrients

For the initial collection, samples were kept separate for each family. The residue treatments had little effect on foliar concentrations of macronutrients. The K effect was significant with the trees in the nil residue treatment having the lowest foliar K concentrations and trees in the double slash treatment having the highest concentration (Table 5). The converse situation occurs for foliar Na concentrations which were significantly higher in the nil residue treatment than all other treatments. There were significant differences in foliar N, P, Ca, Mg, Na, and Zn concentrations between the families. The residue treatment by family interaction was not significant for any of the nutrients.

Foliar concentrations of P, K, Ca, and Mg were above the critical concentrations for both samplings, indicating that deficiencies of macronutrients were not a factor limiting tree growth (Table 6). Foliar N concentrations declined markedly between ages 27 and 39 months, especially in the nil residue treatment, suggesting that N nutrition over time may play an important role in maintenance of long-term site productivity. The addition of inorganic P fertiliser has not significantly improved foliar P concentrations at this age. Foliar K concentrations, although above critical concentrations, are lowest in the nil residue treatment.

Table 5. Effect of residue management on foliar nutrient concentrations of hybrid pines

Treatment	Foliar nutrient concentrations (%)											
	N		P		K		Ca		Mg		Na	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
BL$_0$	.90	.48	.12	.10	.39	.39	.35	.18	.14	.09	.10	.11
BL$_2$	.87	.57	.12	.09	.48	.46	.34	.18	.15	.09	.08	.07
BL$_3$	.91	.61	.11	.11	.59	.62	.33	.22	.15	.12	.07	.07
BL$_2$+ Leg	.94	.64	.12	.08	.53	.46	.34	.19	.14	.10	.08	.07
BL$_2$ - Weeds	.88	.55	.12	.09	.57	.51	.33	.17	.14	.10	.07	.08
BL$_2$-P	.89	.55	.10	.09	.53	.63	.34	.18	.14	.11	.07	.07
LSD p=0.05	NS	.071	NS	NS	.11	NS	NS	NS	NS	.02	.02	.02

[(a)] August 1998; [(b)] August 1999.

Table 6. Surface biomass at ages 0, 30 and 39 months in residue management treatments

Treatment	Age (months)	Logging residue plus litter (t ha^{-1})		
		< 1mm Fraction	> 1mm Fraction	Total
BL$_0$	0	6.37	2.61	8.98
	30	2.64	1.76	4.40
	39			2.84
BL$_2$	0	25.28	25.47	50.75
	30	11.18	19.43	30.61
	39			13.93
BL$_3$	0	56.98	84.45	141.43
	30	17.56	27.23	44.79
	39			24.89
BL$_2$+ Leg	0	22.73	33.65	56.38
	30	8.57	9.46	18.03
	39			12.32
BL$_2$-Weeds	0	25.33	32.65	57.98
	30	12.38	32.70	45.08
	39			21.18
BL$_2$-P	0	34.88	38.99	73.87
	30	14.85	22.77	37.62
	39			33.96
Mean	0	28.59	36.30	64.89
	30	11.20	18.89	30.09
	39			18.19

Decomposition of Residue

There was a marked reduction in the quantity of litter plus residue on the soil surface during the 39 months since establishment (Table 6). The reduction was most marked in the < 1mm fraction. Weeds contributed only a small proportion to the total surface biomass. Legume establishment has been variable and unsuccessful.

There was a strong positive, linear relationship (r^2 = 0.91) between soil moisture and quantity of residue at 30 months. At the time of sampling the soil was quite dry with gravimetric moisture contents in the range 7-12%. This relationship was poor (r^2 = 0.11) in the 39 month samples which were collected after rainfall and the soil moisture contents in the range 20-

25% (approaching field capacity). The litter plus logging residues apparently reduced evaporation from the soil surface during dry conditions.

The stand was thinned at 39 months to 694 stems ha^{-1} to remove the less vigorous and poorly formed stems with due regard to spacing. Estimates of aboveground biomass and nutrient content for thinned and remaining stems are summarised in Table 7 and for the aboveground tree components in Table 8. The distribution of biomass was as follows: wood 45%, foliage 28% and bark plus branches 26%. The proportion of the nutrient pools in the various tree fractions is vastly different from the biomass proportions. For N, 63% is in the foliage, compared with 10% in the wood (cf biomass figures of 28% and 45% respectively). For P and K approximately 55% is in the foliage and 22% in the wood whereas for Ca, 73% is contained in the foliage and only 11% is in the wood.

While 38% of the stems were thinned they contained only 26% of the aboveground biomass and between 25% and 28% of the nutrients in the biomass. There was no litter fall observed at age 39 months.

Table 7. Estimated above ground biomass and nutrient content of thinnings and remaining trees at age 39 months

Treatment	Stand component	Biomass t ha^{-1}	N	P	K	Ca	Mg
			(kg ha^{-1})				
BL_0	Stand	9.89	22.5	3.7	16.7	20.6	7.1
	Thinnings	3.47	7.8	1.4	5.2	7.1	2.6
	Total	13.36	30.3	5.1	21.9	27.7	9.7
BL_2	Stand	12.79	29.1	4.7	22.4	26.9	8.9
	Thinnings	4.50	10.2	1.7	7.3	9.3	3.3
	Total	17.29	39.3	6.4	29.7	36.2	12.2
BL_3	Stand	14.94	34.1	5.3	26.7	31.4	10.4
	Thinnings	5.36	12.2	2.0	9.0	11.2	3.8
	Total	20.29	46.3	7.3	35.7	42.6	14.2
BL_2+ Leg	Stand	12.09	27.5	4.4	21.0	25.3	8.5
	Thinnings	4.14	9.4	1.6	6.6	8.6	3.0
	Total	16.23	36.9	6.0	27.6	33.9	11.5
BL_2-Weeds	Stand	17.19	39.3	6.1	31.1	36.2	11.8
	Thinnings	6.74	15.3	2.4	11.6	14.1	4.7
	Total	23.92	54.6	8.5	42.7	50.3	16.5
BL_2-P	Stand	10.82	24.6	4.0	18.6	22.7	7.6
	Thinnings	3.86	8.7	1.5	6.0	7.9	2.9
	Total	14.68	33.3	5.5	24.6	30.6	10.5

Table 8. Biomass and nutrient content of above ground tree components at age 39 months (prior to thinning)

Parameter		Tree component				
	Biomass	N	P	K	Ca	Mg
		(kg ha^{-1})				
Wood	7 910	6.7	1.5	6.7	4.2	2.1
Bark	2 750	5.1	0.8	4.5	2.1	1.5
Branch	1 920	3.0	0.5	2.3	3.8	1.3
Foliage	5 050	25.4	3.6	16.8	26.8	7.5
Total	17 630	40.2	6.4	30.3	36.9	12.4

Discussion

With more emphasis on improved productivity and profitability of plantations in Queensland, intensive silvicultural practices are being employed, for example improved genetic material is being deployed and more attention is being placed on implementing optimum site specific silvicultural prescriptions. These measures, which result in increased plantation productivity, are expected to increase nutrient demands on the site. As sustainable forest management is a goal, this study is aimed at helping to provide a scientific basis for identifying desirable inter-rotation management practices. The nutrient input-output budgets provide essential data for identifying potential long-term nutrient problems.

In this study, on an infertile site, retention of harvesting residues has resulted in improved plantation productivity. This result is similar to the 5-year results from a trial in Mississippi, USA where, on a low nutrient status site, litter and logging debris retention improved volume production of loblolly pine (*P. taeda*) by 40% (Tiarks *et al.* 1999). In a comparable trial with *P. taeda* in Louisiana, retention of litter and logging residue on a site high in nutrients and organic matter did not improve tree growth. O’Connell *et al.* (1999) found a similar pattern in young eucalypt plantations in southwestern Australia with no growth response to retained litter and residues on a relatively fertile site but significantly increased growth on a less fertile site.

In the Queensland trial, foliar N concentrations of the hybrid pines declined markedly between ages 2.2 and 3.2 years, especially in the nil residue treatment, suggesting that N may play an important role in the maintenance of long-term site productivity of these infertile sites. Retention of harvesting residues on site has resulted in improved plantation productivity. The mechanisms resulting in this improvement have not been clearly identified and are likely to include enhancement of soil physical, chemical and biological properties. These results indicate that improved moisture conditions under retained residues are a contributing factor, but several other mechanisms are also likely to be involved. Identifying and interpreting the significance and application of these factors to operational forestry present a challenge. Addressing this challenge is necessary if a reliable prognosis for the long-term maintenance of productivity of exotic pine plantations in Queensland is to be achieved.

Conclusions

The major findings of this study are:

The nutrient losses due to harvesting and the removal of litter and logging residue combined were significant and in some cases high in relation to the total and available nutrient pools in the ecosystem.

Survival of F_1 hybrid pines was not affected by the residue management treatments.

At 39 months, tree volume was improved by 31% as a result of retaining litter and logging residues; doubling the quantity of residues retained improved volume growth by a further 30%; complete weed control improved tree volume by 52% over residue retention alone; legumes had no effect and the slash retention without P treatment was the same as nil residue plus P treatment.

The increased tree growth was accompanied by a corresponding increase in nutrient uptake in tree biomass.

Major differences were found in the growth of different families but all families responded in a similar fashion to the residue treatments.

Foliar nutrient concentrations were above critical concentrations and little affected by the residue management treatments. Significant differences existed between families.

Foliar N concentrations declined markedly between ages 2.2 and 3.2 years, especially in the nil residue treatment, indicating that N may play an important role over time in the maintenance of long-term site productivity.

There was a marked reduction in the quantity of residue remaining by age 39 months and this reduction was most marked in the < 1 mm residue fraction.

In dry conditions residue retention increased moisture levels in the surface soil.

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Effects of Site Management in Chinese Fir (*Cunninghamia lanceolata*) Plantations in Fujian Province, China

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Abstract

The effects of leaving different amounts of logging residue on the growth of 2-year-old Chinese fir (*Cunninghamia lanceolata*) planted after harvesting a 29-year-old, first rotation plantation in Fujian province, China, were studied. The best survival and growth of the trees were on the double slash treatment but the next best treatment was complete removal of organic matter residues. The poorest biomass accumulation was 372 g tree^{-1} in the whole tree harvest treatment and increased incrementally as more slash was retained with 576 g tree^{-1} in the double slash treatment. Burning logging slash did not have any significant effect on survival or growth compared to the treatment with the same amounts of slash but not burned.

Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook. is a fast-growing tree species that is used for timber. It plays a very significant role in wood production in southern China. Generations of consecutive planting have led to degradation of land productivity (Sheng 1992, Yu 1996, Yu *et al.* 1996). When good land management is not practised, productivity decline of Chinese fir plantations has been serious. The research group is conducting long-term and fixed-site research on the effects leaving different amounts of logging residue during harvest as a method of preventing loss of productivity.

Site Details

The experimental site is located in Fujian Province, southeastern China (Xiayang state forest farm, Nanping), latitude 26°45'N, longitude 118°10'E and altitude *ca* 250 m. This is in the middle subtropical zone with mean annual precipitation 1817 mm, mean annual temperature 19.4°C, and extreme temperature range from -5.8°C to 41°C.

The soil is an unidentified red soil with a depth more than 1 m. Soil samples were collected from five points in each plot at depths of 0-10, 10-20 and 20-40 cm. The soils are acidic and have high levels of exchangeable Al. The soil chemical and physical properties are summarised in Table 1.

Stand Description

The Chinese fir stand of the previous rotation was 29 years old when felled in the winter of 1996. Before felling, the height and diameter of all trees in the plot were measured. Biomass and nutrient content were determined on selected sample trees before felling. The trees averaged 19.6 m in height and 23.7 cm dbh. The average stocking was 1259 trees ha^{-1}, but ranged from 900 to 1597 trees ha^{-1} in the four blocks. The average volume for the experimental area was 518 m^{3} ha^{-1} and the mean annual volume growth was 17.9 m^{3} ha^{-1} yr^{-1}. The total biomass and nutrient accumulation of the trees, the litter and understorey were also determined (Table 2).

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Table 1. Soil chemical and physical properties of the experimental site

Parameter	Soil depth (cm)		
	0-10	10-20	20-40
pH	5.1	4.9	4.9
Organic matter (%)	5.3	4.3	3.0
Total N (%)	0.113	0.088	0.067
Total P (mg kg^{-1})	367	357	411
Available P (mg kg^{-1})	3.1	2.3	1.1
Exchangeable cations (c mol kg^{-1})	156.5	132.6	126.6
Ca	10.7	6.6	5.8
Mg	5.5	2.8	2.3
K	2.5	1.6	1.2
H	1.5	1.1	1.0
Al	53.6	57.9	51.2
Soil bulk density (g cm^{-3})	0.94	1.00	1.08

Table 2. Biomass and nutrients in the Chinese fir, ground cover (herbs + litter + shrubs) and slash (leaves + branches) of the first-rotation stand

Biomass component	Biomass	Nutrients				
		N	P	K	Ca	Mg
	(t ha^{-1})	(kg ha^{-1})				
Trees	197	195	39.8	241	246	76.7
Ground cover	9.9	82	6.8	126	79	27.9
Slash	26.1	114	15.6	134	147	41.7

Experimental Design and Methods

The experimental design is a completely randomised block with four replications containing five plots. The treatments were arranged into four blocks, with the blocking based on slope position and aspect. The area of each of the 20 plots is 600 m^2 and each has 150 trees planted in it (2500 trees ha^{-1}). The five residue treatments applied after harvest were:

BL$_0$ No slash. All aboveground organic residue including the crop trees, understorey and litter was removed from the plots.

BL$_1$ Whole-tree harvest. All aboveground parts of the trees removed.

BL$_2$ Stem + bark harvest. Only the main bole and attached bark was removed.

BL$_3$ Double slash. Branches, leaves and other non-commercial components of trees from the BL$_1$ treatment were applied to this treatment.

BL$_{2B}$ Stem and bark harvest + burning. Same as BL$_2$ except the residue was burned (B).

Aboveground biomass and nutrients retained by each harvesting treatment are given in Table 3.

Table 3. Aboveground biomass and nutrients retained by each harvesting treatment

	Biomass retained (t ha^{-1})	Nutrient (kg ha^{-1})				
		N	P	K	Ca	Mg
BL$_1$	9.9	82	6.8	126	79	27.9
BL$_2$	36.0	196	22.4	261	226	69.6
BL$_3$	62.1	310	38.0	395	373	111.3

Treatment BL_0 would have only negligible amounts of residue and nutrients associated with slash and litter.

The seedlings were planted in pits in February 1997 and a complete NPK fertiliser applied 3 months later at a rate of 100 g $tree^{-1}$. All dead trees were replaced in December 1997. The stand was weeded twice each year by manual hoeing.

Tree growth was measured at the end of the first and second growing seasons. All trees were measured, but only the data on trees from the initial planting (excluding the replanted seedlings) is reported. Results include: survival rate, diameter at breast height or base diameter, height, crown width and biomass in tree components. Analysis of variance and Duncan's Multiple Range test were used to determine the statistical significance of the treatments.

Aboveground biomass measurements (including stem, bark, branches and leaves) were made based on one plant in all plots in year 1 (January 1998) and in the protective rows in five plots in block I in year 2 (January 1999). Regression equations predicting the biomass of the various components of a Chinese fir tree on its base diameter and height were developed (Table 4).

Results and Discussion

The overall survival of seedlings planted in February 1997 was poor because of harsh site conditions and competition from weeds. The dead trees were replaced after 10 months but there were large differences in tree size between the two plantings. As noted earlier, the growth and the survival of the February 1997 planting only is reported here.

After two seasons of growth, the treatments had a statistically significant effect on survival, diameter, height, crown width and biomass of Chinese fir (Table 5). Survival was in the range 61-79% and was particularly low in the whole tree harvest (BL_1) and burning (BL_2B). The double slash plots (BL_3) had the

Table 4. The regression of biomass of various organs of a single Chinese fir plant on base diameter and height at age two years

Organs	Regression equation	R	n	Range of base diameter (cm)	Range of height (m)
Branches	WB=8.450429*DG^1.850987*H^0.4358788	0.8654	24	0.640-3.65	0.50-2.00
Stem	WS=11.45523*DG^1.457363*H^1.378857	0.9880	24	0.640-3.65	0.50-2.00
Bark	WBK=4.33395*DG^1.592445*H^0.3286018	0.9730	24	0.640-3.65	0.50-2.00

DG-diameter at ground level (cm); H-tree height (m).

Table 5. Effects of treatments on the growth of Chinese fir after two growing seasons

Treatment	Survival rate (%)	Base diameter (cm)	Height (m)	Crown width range (m)	Biomass in trees (g $tree^{-1}$)
BL_0	76bc	3.2bc	1.60a	1.06ab	457a
BL_1	62ab	2.8a	1.45a	1.00a	372a
BL_2	67abc	2.9ab	1.50a	1.03ab	399a
BL_3	79c	3.4c	1.80b	1.18b	567b
BL_{2B}	61a	3.1ab	1.55a	1.04ab	428a

Values in a column followed by the same letter are not significantly different (alpha=0.05).

Table 6. Effects of treatments on the biomass of tree components of Chinese fir after two growing seasons

Treatment	Leaves	Branches	Stem (g tree^{-1})	Bark	Tree
BL_0	196b	93a	135a	32b	457a
BL_1	163a	74a	109a	26a	372a
BL_2	174ab	80a	116a	28ab	399a
BL_3	230c	115b	184b	38c	567b
BL_{2B}	184ab	87a	127a	30ab	428a

Values in a column followed by the same letter are not significantly different (alpha=0.05).

largest trees and 79% survival. This may have been at least partially due to the mulching effect in the first growing season that inhibited understorey competition and at the same time improved soil moisture retention. The apparent (although not statistically significant) slightly better growth of the complete removal treatment (BL_0) may also be due to the reduction of competing vegetation. The marginally poorer growth and survival in the whole tree harvest treatment (BL_1) may also be the result of greater understorey competition than in the other plots. The treatments affected the biomass of leaves, branches, stem and bark in a similar manner as the total growth (Table 6). The tree components were consistently and significantly largest on double slash plots (BL_3). The leaf and bark components were significantly larger on the complete removal treatment (BL_0) compared to the whole tree harvest (BL_1) treatment.

These results are similar to those after one season of growth (Fan *et al.* 1999a, 1999b) except that the biomass of the trees in the complete removal treatment was no longer significantly greater than that in all other treatments with the same amount of slash retained. It is noteworthy that the burning treatment has had no significant effect on the growth of the trees at this stage. The relatively high mortality that occurred at the site during the first year may have confounded the early results. Preliminary observations indicate that the replacement planting may catch up with the others during the stand establishment period. Data from future measurements will be used to explore more fully these issues as well as the long-term effects of treatments.

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11

Site Management and Productivity of *Acacia mangium* in Humid Tropical Sumatra, Indonesia

C.K. Mok[1], L.C. Cheah[1] and Y.K. Chan[1]

Abstract

PT. Riau Andalan Pulp and Paper (RAPP) is establishing plantations in Riau province, Sumatra, Indonesia for sustainable wood supply for a pulp mill. *Acacia mangium* is the dominant species planted and is grown on a seven-year rotation. Since 1993, RAPP's plantation development activities have increased dramatically with an annual planting programme of about 35 000 hectares. The plantation area is planned to reach 270 000 hectares by 2002. This paper describes the study plan for research on inter-rotational site productivity and management of *A. mangium*. The experiment will test on-site effects of different treatments of organic matter or aboveground biomass management. The objective is to develop more sustainable management practices through in-depth understanding of processes affecting soil and tropical forest plantation productivity in the long-term. Growth of the previous *A. mangium* stand in relation to climate, terrain and soil is discussed. Harvesting and treatment applications are planned for April 2000.

Introduction

PT. Riau Andalan Pulp and Paper (RAPP) is a pulp and paper producing subsidiary of Asian Pacific Resources International Holdings (APRIL). It uses residual hardwood from logged-over forest concessions for pulp while establishing *Acacia* plantations for a sustainable, long-term wood supply. The land allocated for plantations is either logged-over forest, belukar or grassland in Riau province, Sumatra, Indonesia. *Acacia mangium* Willd. is the main species planted and grown on a seven-year rotation. Plantation-grown wood will progressively replace wood from native forest concessions as raw material for the pulp mill. The mill needs 6 million m^3 of wood annually to provide fibre for 1.3 million t yr^{-1} of pulp. Starting in 1993, RAPP plantation development has increased dramatically. For the period 1997/1998, the annual planting programme of RAPP and its associated companies was over 35 000 ha. Its plantation area is planned to reach 270 000 ha by year 2002.

Research is in progress to develop seeds and clones of superior genetic quality, and improved plantation silvicultural practices for sustainable wood production. Since 1995, a government 'no burn' policy has been enforced in the company's plantation development. Initially it was problematic but more efficient extraction of utilisable wood from the site has made it easier for planting and tending. It is envisaged that even with a high level of planting practices and field management, some land degradation will occur with short rotation plantations over the long-term. This is particularly likely to occur in this humid tropical environment with high annual radiation, temperature and rainfall. The soils are highly weathered and low in fertility and must be managed in accordance with their capabilities. Retention of adequate organic matter to maintain soil structure, water and nutrient supply is essential. This is very critical as RAPP's large-scale pulp production requires a sustained supply of superior quality wood.

The objective of this study is thus to obtain an in-depth understanding of the processes controlling short-rotation forest plantation productivity in the long-term.

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It will measure the impact of selected management practices that could reduce the impact of tree harvesting and establishment practices and mitigate any adverse effects on the soil. The research is part of the CIFOR network project on site management and productivity in tropical plantation forests.

Location and Site Description

The RAPP forest concessions are located 1^0 N and 1^0S of the equator at elevations below 400 m asl on undulating to hillocky plains in Riau province, Sumatra. The research site is *ca* 10 km northeast of Baserah town. It is between latitude 0^0 20' 46"S and longitude 101^0 47’ 04"E and latitude 0' 20'37"S and longitude 101^0 49'31"E at an altitude of *ca* 100 m. The terrain and soil type are representative of most RAPP forest concessions. The existing stand of *A. mangium* has grown satisfactorily and is near harvestable age.

The climate in the region is warm humid tropical with mean annual temperature of 27^0C, with small seasonal variations, average maximum temperature 32^0C, average minimum temperature 23^0C, and high humidity 78-100%. Mean annual rainfall over 10 years is 2700 mm. The wetter months, October to May, have monthly average of 230 mm. The drier months, June to September, can have less than 60 mm per month.

Mean annual rainfall in the Baserah area from 1996 to 1998 was 2305 mm falling in 107 days. January, June and July were low rainfall months with mean monthly precipitation less than 100 mm and four to six raindays (Table 1). The other nine months had mean monthly rainfall of 153-365 mm and eight to fourteen raindays. In 1997, the annual rainfall was 1910 mm. but there were six months with rainfall of between 17 and 69 mm due to El Nino and a five-month consecutive dry period (June-October) affected tree growth.

An automatic weather station is being established close to the experimental site to obtain daily, weekly and monthly data for rainfall, temperature, humidity and solar radiation.

The research site has undulating to rolling terrain. Most slopes are 4-8% but some are 9-15%. The geology consists of Pleo-Pleistocene sediments comprising sandstones, siltstones, mudstones, tuffites and fine-grained tephra. They are low in weatherable minerals and contain kaolinitic clays.

An upland soil, ‘type C’ and an alluvial soil, ‘AL’ are found in the project area. The alluvial soil is associated with low-lying areas and stream valleys and is derived from recent riverine alluvium. The soil is deep but poorly drained and very variable in texture. It is classified as a Typic Tropofluvent (USDA), Dystric

Table 1. Rainfall in Baserah Sector, 1996 to 1998

Month	Year						Mean	
	1996		1997		1998			
	mm	Days	mm	Days	mm	Days	mm	Days
January	50	7	47	3	107	9	68	6
February	305	15	148	8	144	6	199	10
March	395	13	472	17	228	8	365	13
April	301	14	354	17	237	10	297	14
May	49	4	200	10	324	15	191	10
June	161	5	53	3	78	5	97	4
July	159	5	23	1	108	9	97	5
August	317	10	17	1	389	13	241	8
September	265	12	41	2	161	14	156	9
October	312	15	69	4	90	6	157	8
November	265	13	336	9	251	9	284	10
December	80	13	150	8	229	10	153	10
Total	2659	126	1910	83	2346	114	2305	107

Fluvisol (FAO) and Alluvial Distrik (Indonesian Classification System). The upland soil is a Typic Hapludult (USDA), a Ferric Acrisol (FAO) and a Podsolik Ortoksik (Indonesian Classification System). It is the dominant soil in RAPP's forest concessions.

Soil type C has a dark yellowish brown sandy clay loam to clay loam topsoil, generally less than 10 cm thick. The matrix is made up of moderate, coarse to medium subangular blocky structures with friable to firm consistencies when moist. This horizon is commonly underlain by strong brown clay with structures of moderately-coarse subangular blocky becoming moderately-coarse angular blocky with depth. Below 70 cm many light brownish grey, brownish yellow and red mottles are present. The soil typically has firm consistency to at least 110 cm depth.

Chemically the soils are acidic with pH (KCl) below 4.0 (Table 2). The N and C contents of the topsoil are medium but tend to become low to very low with depth. The cation exchange capacity is low, reflecting the kaolinitic nature of the clay minerals. Except for the surface layer (0-9 cm), the base saturation is very low, less than 10% throughout the profile. Available P is also very low. Physical and chemical properties of soil type C sampled at the experimental site are given in Table 2.

Soil samples will be collected from each plot after treatment application but before planting. Samples will be taken from 10 points in each plot at 0-10, 10-20 and 20-40 cm and bulked by depth. Air-dried subsamples will be used to determine particle size distribution by the pipette method and for chemical analysis. Chemical analyses of soil samples (< 2 mm fraction) from each plot will include pH (water), organic C (potassium dichromate), total N (kjeldhal digestion/distillation), total P, K, Ca, Mg (25% HCl), available P (Bray II), exchangeable K, Ca, Mg (ammonium acetate, pH 7), and exchangeable Al.

Bulk density measurements will be made on undisturbed core samples of known volume from five points in each plot at 0-10, 10-20 and 25-35 cm depth for dry weight determination at 105^{0}C. Infiltration rate to define initial soil surface condition will be measured

Table 2. Physical and chemical properties of soil type C

Parameter	Depth (cm)			
	0-9	9-50	50-68	68-110
Particle size %				
- Coarse sand	20	8	8	5
- Fine sand	16	8	8	5
- Silt	31	25	20	20
- Clay	33	59	64	70
pH - H_20	4.1	4.2	4.3	4.4
- KCl	3.8	3.6	3.5	3.5
N (%)	0.32	0.13	0.12	0.10
C (%)	2.56	0.90	0.67	0.46
Phosphorus (µg g^{-1}):				
- Total P (25 % HCl)	266	116	86	26
- Available P (Bray II)	1.33	0.47	0.40	0.76
CEC, pH7 (c mol kg-1 soil)	16.5	14.6	16.8	22.0
Exchangeable cations: (c mol kg^{-1} soil)				
- K	0.41	0.24	0.18	0.30
- Ca	2.52	0.49	0.26	0.13
- Mg	1.64	0.73	0.54	0.56
- Na	0.16	0.12	0.13	0.14
Total K, 25 % HCl (µg g^{-1})	464	427	389	439
Base saturation (%)	28.7	10.8	6.6	5.1

before and after felling. Cylinders 10-15 cm diameter will be placed over the litter sampling square and pushed into the soil to 3 cm depth. The rate of decrease of the water level in the cylinder is the infiltration rate of the soil. There will be further soil sampling and analysis in year 3 of the experiment.

Stand Establishment and Maintenance

The research site was originally scrubland (*belukar*) with a very low wood volume. It was slashed and felled and the slash spread mechanically. *A. mangium* seedlings of Claudie River provenance from northern Queensland were planted in November 1993 at 3 x 2 m spacing, 1667 trees ha^{-1}. The seedlings were 8-10 weeks old, grown in polybags, and planted in pits 20 x 20 x 20 cm. Blanking was completed within one month after planting.

Triple superphosphate (100 g) was applied in the planting hole and after planting, 20 g (9.2 g N) urea was broadcast 20 cm from the stem. This was to encourage rapid development of roots and establishment of the seedling. Fertiliser application after planting is not normally carried out.

Noxious weeds and woody regrowth were controlled for 18 months or to canopy closure whichever was earlier. Manual weeding to maintain a 50-100 cm radius, weed-free circle around the plant was carried out during the first three to six months. Chemical spot spraying was done post-planting with glyphosate for lalang (*Imperata cylindrica*), paraquat dichloride (gramoxone) for grasses, sedges and brackens, and a cocktail of paraquat and 2.4-D amine for mixture of grasses, broadleaved herbs and woody saplings.

Pests and diseases have not been a very serious threat to the plantations so far. The initial planting density allows for some losses due to pests and diseases, windthrow and other causes. Singling was carried out four to six months after planting, when the trees were 1.5-2.0 m tall, and again at eight to twelve months of age.

Tree Growth

Tree growth data are available from permanent sampling plots, tree enumeration and diameter measurements of trial plots.

Permanent sampling plot

To monitor rate of stand growth, permanent sample plots (PSP) are established at age 1.5-2.0 years with one plot to about 500 ha. The *A. mangium* PSP 30 of 0.02 ha located in compartment EO2 of Baserah is in the trial area. It was established 3 May 1995 with latest measurement 7 February 1999.

The number of stems per hectare declined from a full stocking of *ca* 1650 trees at three years to 1200 in the fifth year (Table 3). However, at 5.3 years the mean height was 23.8 m and mean diameter was 16.8 cm. The total volume (under bark) increment averaged 55.2 m^3 ha^{-1} yr^{-1} and is still rising.

Table 3. Stems ha^{-1}, mean height, mean diameter, volume, MAI and CAI trend with age of *Acacia mangium* in PSP 30 Baserah

Age (yr)	Density (stems ha^{-1})	Mean height (m)	Mean diameter (cm)	Volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	CAI (m^3 ha^{-1} yr^{-1})
1.5	1667	7.9	8.9	36.4	24.3	0.0
2.2	1667	11.5	11.0	76.9	35.0	57.8
2.7	1667	14.2	11.7	105.5	39.1	57.3
3.2	1633	17.0	13.0	150.0	46.9	89.1
3.7	1533	18.7	14.0	176.9	47.8	53.6
4.2	1400	20.2	14.8	192.7	45.9	31.7
4.7	1267	22.4	15.8	216.8	46.1	48.2
5.3	1200	23.8	16.8	246.1	46.4	58.6

The mean (MAI) and current (CAI) annual increments (total stem volume under bark) declined in year 4 probably due to five consecutive dry months in June-October 1997 associated with El Nino. Both MAI and CAI have increased again at 5.3 years.

Tree enumeration

In September 1999, the number of living trees in all except three of the experimental plots was 200-300. Plots 1 to 6 in block IV have lower numbers due probably to localised site effects

Tree diameter

The diameter breast height over bark (dbh) of living trees measured in September 1999 had a mean of 16.0 cm with a maximum of 38.5 cm (Fig. 1). This is close to the average diameter (16.8 cm) of PSP 30. Variation in mean dbh between blocks was small (Table 4).

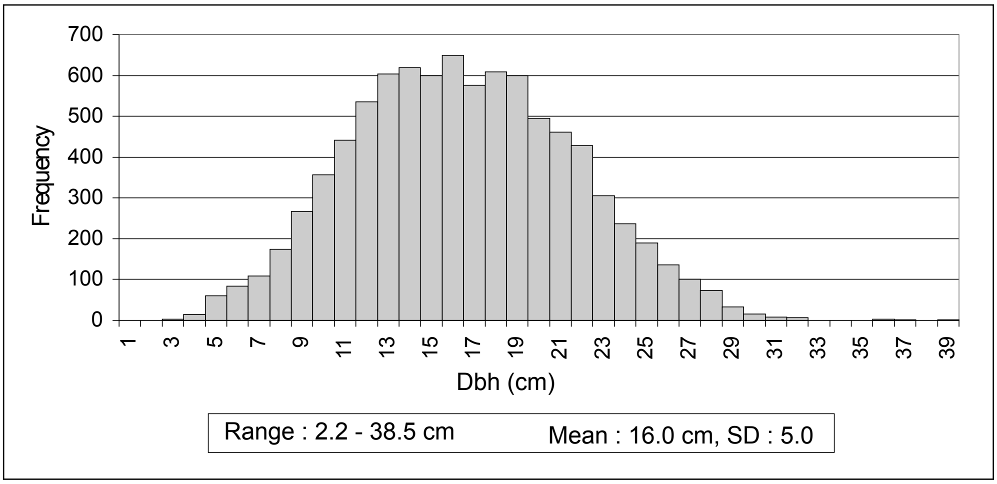
Block IV with the highest mean dbh (16.5 cm) has the lowest total number of living trees, (Table 4). In Block II this is reversed, highest number of living trees but smallest mean dbh (15.6 cm). This relationship between the number of living trees and diameter growth is as expected.

On the basis of the dbh frequency distribution 84-91% of living trees in each block are between 8-24 cm diameter. Only 1.2% of the experimental trees are multistemmed so the impact on stand dbh distribution is minimal.

Table 4. Number and diameter of living trees in each block

Block	Number of living trees		Diameter (cm)	
	Plot mean	SD	Plot mean	SD
I	263	16	16.1	4.8
II	274	17	15.6	4.9
III	248	16	15.9	5.2
IV	208	14	16.5	5.6
V	261	16	15.9	4.9

Figure 1. Diameter distribution of living trees in experimental plots



Understorey Vegetation

Grass species observed in most plots were *Digitaria wallichiana*, *Panicum repens*, *Scleria sumatrensis* and *Panicum sarmentosum*. The two common ferns were *Stenochlaena palustris* and *Pteridium esculentum*. Shrubs were mainly *Clidemia hirta*, *Melastome* sp., *Ageratum conyzoides*, *Elettariopsis curtisi*. Trees included *Celastrus* sp., *Macaranga* sp., *Mezzettia lepotoda*, *Santiria rubiginosa* and *Vitex* sp.

Experimental Details

The experimental design and core treatments will conform to those of CIFOR network project (Tiarks *et al.* 1999).

Experimental design will be a randomised complete block with five replicates. The five core treatments are summarised below together with the two optional treatments of special interest to RAPP. One optional treatment, BL_4, is on-site manual debarking with stem wood removed. The other, BL_5 is manual debarking on site with manual stacking and wood transported by forwarder along access placed at 15 m intervals.

Each block will have seven experimental treatments. However, the five replicates of core treatment standing crop (SC) will be a single continuous block as they will not be harvested (Fig. 2). The six remaining treatments will be allocated at random to plots 1 to 6 in each replicate.

A treatment plot will be 48 x 48 m with an internal plot of 32 x 32 m for growth measurements and sampling. The buffer area is to be used for biomass harvest and chemical analysis sampling. The gross plot size of standing crop is slightly smaller, 50 x 40 m, so as to obtain a continuous single block away from other plots. The 35 plots will be laid out in five replications on soil type C in an area of 15.4 ha (Fig. 2). Four of the plots are entirely on 9-15% slopes, and 12 plots partly on 4-8% and partly on 9-15% slope. The remaining 19 plots are on 4-8% slopes.

Core treatments:

BL0	All crop trees with bark, understorey vegetation, slash and litter removed.
BL1	Whole-tree harvest. All crop trees with bark (tops, branches and slash) removed to BL_3. Understorey vegetation and litter retained.
BL2	Merchantable tree harvest. Commercial wood and bark removed. Tops, branches and slash, understorey vegetation and litter retained and evenly distributed.
BL3	Double slash. Commercial wood and bark removed. Non-commercial residues from BL_1 brought in and distributed evenly, adding to the slash already present.
SC	Standing crop retained undisturbed.

Optional treatments:

BL4	Commercial felling, all commercial wood without bark removed. Bark, tops, branches, slash, understorey vegetation and litter retained.
BL5	Manual felling, all commercial wood minus bark transported by forwarder. Bark, tops, branches, slash, understorey vegetation and litter retained.

Measurement

Measurements to be recorded are described below.

Pre-harvest Biomass and Nutrients

Standing trees

Twenty five trees will be randomly sampled by diameter class with two to four trees per diameter class for estimating mass of wood and bark in main stem, branches including bark separated into < 1 cm, 1-5 cm and > 5 cm, young phyllodes (‘leaves’) separated from fully mature phyllodes, if not separable they can be bulked, flower, pods and seeds if any.

For stem biomass, each sampled tree will be felled. After measuring its length to diameter 7 cm, the stem will be cut into four sections of equal length. Fresh weight of each stem section will be determined.

A 5 cm thick disc will be cut from the middle of each stem section and discs pooled from different trees to obtain four replicated samples within each height class. There will be four such pools of discs, one for each section length. Discs will be cut into pies of 30^0 size, and bulked by height class. They will be subsampled to obtain four replicated samples from each height class for basic density determination of wood and bark after oven drying at 105^0C. Another four subsamples are for nutrient (N, P, K, Ca, Mg) determinations after oven drying at 70^0C.

Phyllodes will be stripped off branches and separated into young and fully mature groups. Each group will be subsampled for dry weight determination and for nutrient determination. Branch and twig biomass

Figure 2. PT. Riau Andalan Pulp and Paper trial site

PT. RIAU ANDALAN PULP & PAPER

RAPP – CIFOR PROJECT
SECTOR BASERAH
CMPT E02

Soil type	Hectare of soil units by slope (%)				Total area	
	0-3	4-8	9-15	>15	Ha.	%
C – Deep, well drained medium over fine textured soils with friable topsoil and firm subsoil. Colours are yellowish brown to strong brown	-	11.8	3.6	0.7	16.1	95.3
AL – Deep, poorly drained soils with variable textures, occurring in stream valleys.	0.8	-	-	-	0.8	4.7
Total	0.8	11.8	3.6	0.7	16.9	100

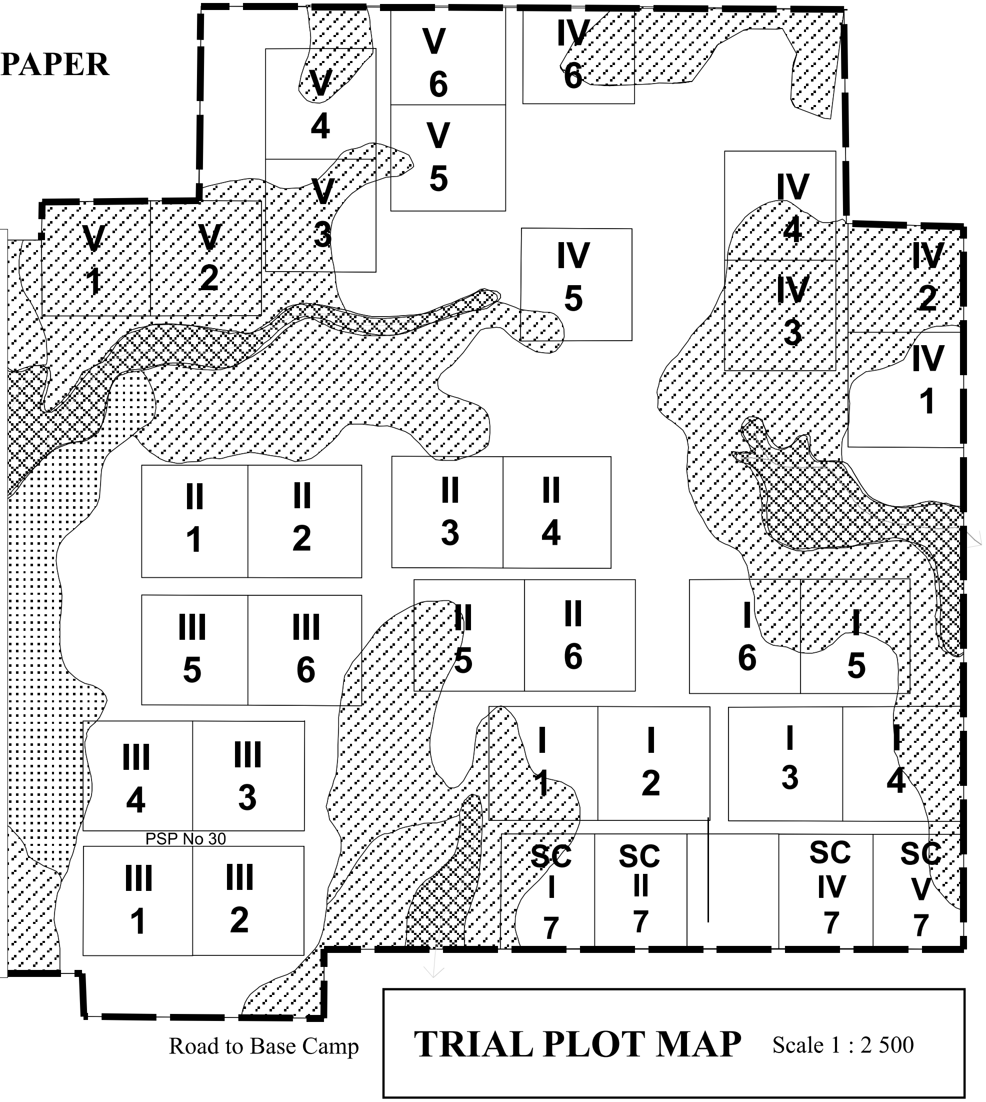
Legends

AL 0-3% SC

C 4-8% Standing Crop

C >15% Plot No. 1 to 7

C 9-15 % Block No. I to V



and nutrient determinations will be carried out in the same manner as for phyllodes.

Understorey biomass and nutrients

On each plot, the dominant species, composition and biomass of the understorey will be determined from five subplots of 1 m^2, and separated into grasses, herbs and shrubs. After weighing, samples will be bulked by block and representative subsamples taken for dry weight and nutrient determinations.

Litter on forest floor

The litter will be sampled down to the mineral soil surface from five subplots used in understorey sampling. It will be separated into phyllodes, branches (wood and bark), twigs, stem (wood and bark), seeds, pods and stalks, and each component oven dried to obtain dry weight. The litter will then be bulked for all blocks by each component and subsampled for N, P, K, Ca, Mg determinations. A portion of each subsample will be ashed at 500^0C to express biomass and nutrient values on ash-free basis.

Tree Growth

Height and diameter of trees on each treatment plot will be measured at 6-monthly intervals until 24 months and then annually during the rotation. Volume and biomass equations will be developed from sample trees so that they can be estimated from diameter data. Stand nutrition up to canopy closure is to be monitored by collecting phyllode samples for nutrient analysis at 6-monthly intervals.

Trial Implementation and Management

After sampling the biomass of standing trees, understorey and litter, the stand will be clearcut using chainsaws with manual removal of wood from the plot except for the treatment where a forwarder is to be used to transport the wood.

Close supervision will ensure directional felling is carried out for easier access and work in treatment plots. Areas, 6-10 m wide, have been planned between blocks and plots to allow easy access so as to minimise site disturbance and ensure wood extraction from the research areas is unimpeded.

The trial plots will be planted with a mixture of selected clonal *A. mangium* at 3 x 3 m spacing. In order not to mask effects of organic matter treatments, minimal amounts of fertiliser will be applied to the plants at planting and none after planting.

A detailed file on the trial is to be kept together with a file to record all measurements, operations, costs and events that may affect the productivity of the experimental plantings. The trial will run for at least one rotation of seven years.

Acknowledgements

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12

SHORT COMMUNICATION 1

Nutrient Cycling in a Short Rotation *Eucalyptus* Plantation and an Adjacent Savanna in Congo

J.P. Laclau[1], J. Ranger[2], J. de D. Nzila[3] and J.P. Bouillet[1]

Introduction

Since 1978, 42 000 hectares of clonal plantations have been established on a former savanna in a 50 km radius around Pointe-Noire. Their main purpose is the production of pulpwood. Research on the sustainability of these plantations is a priority because they are grown on a short rotation on soils with small reserves of available nutrients. Among several studies focussing on this goal, the biogeochemical cycle was assessed in a clonal plantation of a eucalypt hybrid and in a native savanna for 1.5 years. This hybrid comes from natural crosses between two or three individuals of *Eucalyptus alba* Reinw. ex Blume (female parent) and a group of poorly identified *Eucalyptus* hybrids from a Brazilian arboretum (male parent). They are thought to be the result of crosses between *E. grandis*, *E. robusta*, *E. urophylla* and *E. botryoides* (Delwaulle 1989). In the savanna, the biomass of the grass *Loudetia arundinacea* (Hochst.) Stend. amounts to 80% of the total aerial biomass throughout the year.

The aim of the study was to characterise the nutrient dynamics in both ecosystems and to establish nutrient budgets. This study is complementary with the Congo experiment within the framework of the CIFOR network ‘Site management and productivity in tropical forest plantations’ (Bouillet *et al.* 1999). This research will provide information on the impact of silvicultural practices on soil fertility and should contribute to more efficient fertiliser practices for a sustainable yield of the commercial plantations around Pointe-Noire.

Materials and Methods

At the start of the study, the amounts of nutrients were assessed in the 6-year-old eucalypt plantation, savanna, litter layer and soil. The eucalypt stand and the savanna had an area of about five hectares and were located adjacent to each other. The eucalypt plot was planted in January 1992 on the savanna. The nutrient accumulation was measured using a chronosequence approach for the same eucalypt clone (Laclau *et al.* 2000) and every month during one year in the savanna (between two annual fires). The other measurements were carried out in plots of 0.25 ha in both ecosystems as follows: litterfall (with 15 litter traps), precipitation (with three gutters in an open area), throughfall (with three replicates of three gutters in the eucalypt stand and four replicates of collectors on the savanna floor), stemflow (with collars around 10 trunks), solution beneath the litter layer (collected by four sets of nine narrow lysimeters) and soil solution (collected with four replicates of tension lysimeters at the depths of 15 cm, 50 cm, 1 m, 2 m, 3 m, 4 m in the savanna and at the same depths plus 6 m in the eucalypt stand). The dry deposition in the atmospheric inputs of Cl and S were assessed assuming canopy interactions were negligible. Chloride was used as a tracer to calculate dry deposition for Ca, and S was used as a tracer for the other elements. A hydrological model was used to assess the seepage

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fluxes. The monitoring of soil moisture with TDR probes during one year allowed validation of this model.

Samples of solutions were collected weekly in all the collectors (rainfall, throughfall, stemflow, and soil solution up to the depth of 6 m), samples were then stored at 4°C, and bulked every 4 weeks for chemical analyses. The solutions were filtered in Pointe-Noire and pH and SO_4^{2-} (by colorimetry) were measured as quickly as possible. The samples were then acidified with H_2SO_4, and sent to the CIRAD laboratory in France where nitrate, ammonium and chloride were measured by colorimetry and total Si, P, K, Ca, Mg, Na, by ICP emission spectroscopy. In the plant samples, N was analysed by acid-base volumetry after Kjeldahl mineralisation, P by cold colorimetry from the Murphy and Riley reagents, and K, Ca, Mg and Na by spectrophotometry in the IRD laboratory of Pointe-Noire. After a pedological description, soil was sampled for each horizon down to a depth of 6 m in three pits in the eucalypt stand and one pit in the savanna. Each replicate of sample was analysed separately. Elements were determined by ICP in the CIRAD laboratory.

Errors in the estimate of the main fluxes of the input-output budgets (Table 3) were calculated as follows: (1) atmospheric depositions, 50% of measured values, to take into account the difficulty of assessing dry depositions; (2) starter fertilisation, 5% of the composition of the fertiliser; (3) deep drainage, sum over one year of twice the standard error calculated every month; (4) harvest, confidence interval (p=0.95) of the values predicted by the nutrient content tables and (5) annual fire, twice the standard error between the replicates. Errors in the estimate of the budgets were calculated as the sum of the error of each flux, considering that the errors of determination of each flux are independent.

Results and Discussion

Amounts of Nutrients in the Compartments of the Ecosystem

We considered that the depth of soil involved in the nutrition of the stands was 6 m in the plantation and 2 m in the savanna. The density of roots beyond these depths was extremely low. Although the main characteristics of the soil were similar in both plantation and savanna, the amounts of P, K, Ca and Mg available are higher in the soil below the eucalypt probably because of the difference in depth of soil explored by roots (Table 1). The amounts of total N were high but isotopic studies in this soil have shown the presence of stable and ancient organic matter of forest origin. Mean residence time of organic matter is low in the upper soil horizons and increases with depth to about 8200 B.P. (Trouvé 1992).

The amount of biomass in plantation is about 11 times that of savanna. The aerial part of the savanna vegetation was entirely accumulated after fire and reached a maximum at the end of the rainy season about 8 months after the fire. In the eucalypt plantation, the amounts of nutrients in the forest floor are large compared with the accumulation in the stand, particularly N, Ca and Mg. In contrast they were very low in the savanna floor due to the annual fires.

The Nutrient Use Efficiency (kg of dry matter / kg of nutrient accumulated in the biomass) is much higher in the eucalypt stand than in the savanna for N, P, K and Mg. The very low accumulation of K, Ca and Mg in the eucalypt stand (between 47 and 71 kg ha^{-1}) is probably due to the very low availability of exchangeable cations in the soil.

Nutrient Fluxes

Only the nutrient fluxes in solution and in the litterfall are presented here.

The atmospheric inputs of N, P, K, Mg and S are very low (< 5 kg $ha^{-1}yr^{-1}$). The high inputs of Na and Cl (Table 2) might be explained by the short distance from the sea (10 km). In Congo, the marked enrichment of Ca in the rains indicates the presence of a large amount of aerosols from local or African desert sources (Lacaux *et al.* 1992). A foliar uptake of N was observed in both the eucalypt and the savanna. The foliar leaching of P, K and Mg was more pronounced in the savanna. A dense network of fine roots in the forest floor allowed quick uptake of nutrient in the eucalypt ecosystem. The high fluxes of N, P and Mg in the eucalypt litterfall indicate a very active biological cycle in this ecosystem. In contrast, in the savanna nutrient fluxes in litterfall were very low.

There was very little leaching of N, P, K, Ca and Mg by deep seepage (< 1 kg ha^{-1} yr^{-1} except N below the savanna). Higher seepage fluxes were measured for Na and Cl below the savanna.

Table 1. Biomass and amounts of nutrients in the different compartments of the eucalypt plantation and the native savanna

	Biomass	Nutrients (kg ha^{-1})							
	t ha^{-1}	N	P	K	Ca	Mg	Na	Cl	S
Eucalypt plantation									
Stand (6-yr-old)	95.6								
Stem wood	6.5	115.6	16	34.2	15.4	11.5	32.3	37	7.5
Stem bark	3.8	20.7	9.8	12.6	23.8	17.6	16.2	22	1.5
Leaves	9.6	56.3	3.9	11.9	6.7	7.7	9.6	3.6	4.4
Branches	23.0	21.5	5.0	6.3	6.5	5.1	7.3q	5.9q	1
Underground parts(1)	138.5	33.7	3.1	6.4	9.6	5.5	-	-	-
Total	11.4	248	38	71	62	47	> 65	> 69	> 14
Forest floor		81	4	6	33	18	12	-	-
Soil(2)									
0 - 15 cm		775	65	19	38	12	10		
15 - 50 cm		1552	110	39	80	18	12		
50 - 200 cm		2695	690	91	397	60	43		
200 - 600 cm		8292	1826	305	997	180	125		
Total to 6 m depth		13300	2700	450	1510	270	190		
Savanna ecosystem									
Stand (8 months after fire)									
Aboveground parts	4.2	22.1	3	7.6	4.1	7	1.5	4.3	2.2
Underground parts(1)	8.4	72.7	4.1	8.3	1	3.4	4.9	-	-
Total	12.6	95	7	16	5	10	6	> 4	> 2
Savanna floor	0.3	3.6	0.2	0.3	1.3	1	0	0.3	0.2
Soil(2)									
0 - 15 cm		574	45	36	54	13	16		
15 - 50 cm		1159	96	98	101	24	46		
50 - 200 cm		3084	472	130	374	60	120		
Total to 2 m depth		4800	610	260	530	100	180		

(1) Na, Cl and S not measured in underground parts.

(2) N total, P available with Duchaufour and Bonneau methodology (1959) and exchangeable cations.

Input-output Budgets

The study of biogeochemical cycles is still in progress and the assessment of several fluxes will be improved i.e. atmospheric deposits, weathering. Thus only the main trends should be considered at this stage (Table 3).

The savanna ecosystem has been known to occur in this area for about 3000 years (Schwartz 1992) and so the input-output budgets should be balanced to explain the sustainability of this savanna. The presence of a leguminous plant (*Eriosema erici-rosenii* R.E. Fries, Schewed) in the coastal savannas of Congo might explain the stability of the nitrogen cycle if a symbiotic fixation of about 20 kg ha^{-1} yr^{-1} occurs. The total biomass of this legume was about 800 to 1000 kg ha^{-1} at the end of the rainy season. In a savanna dominated by *Loudetia simplex* in Ivory Coast, the nitrogen fixation (mainly non-symbiotic) was estimated at 12 kg ha^{-1} year-1 and allowed balancing of the budget (Abbadie *et al.* 1992). The Congolese savanna studied here has apparently no actual or potential non-symbiotic N fixing activity (Le Mer and Roger 1999) but the high biomass of the leguminous species might account for an input of nitrogen in the ecosystem sufficient to compensate for the losses. The budgets of the other nutrients are nearly balanced taking into account the estimated errors of determination of the fluxes.

In the eucalypt plantation the outputs of P, K and Mg are only slightly higher than the inputs and the Ca budget is positive. However the nitrogen budget deficit is large (18 kg ha^{-1} yr^{-1}) even though the total N available in

Table 2. Main fluxes of nutrients in a eucalypt plantation and a native savanna (*in italics*)

	Flux	N-NH$_4^+$	N-NO$_3^-$	P-PO$_4^{3-}$	K$^+$	Ca^{2+}	Mg^{2+}	Na$^+$	Cl$^-$	S-SO$_4^{2-}$
	(mm)	(kg ha^{-1} yr^{-1})								
Atmospheric	1414	1.4	2.9	0.3	2.8	13.4	1.4	7.1	28.5	3.6
inputs		*(1.4)*	*(2.9)*	*(0.3)*	*(2.8)*	*(14.5)*	*(1.4)*	*(7.1)*	*(32.6)*	*(3.6)*
Throughfall	1289	1.0	1.5	1.0	5.8	15.8	3.3	15.2	26.0	3.5
	(1207)	*(1.5)*	*(0.4)*	*(3.5)*	*(17.2)*	*(11.5)*	*(9.7)*	*(6.2)*	*(32.6)*	*(3.6)*
Stemflow	19	0.0	0.0	0.1	0.3	0.3	0.2	1.5	2.5	0.1
Litterfall(a)		38.6		3.0	3.3	18.6	17.8			
		(4.1)		*(0.2)*	*(0.4)*	*(1.5)*	*(1.1)*			
Leaching beneath	1308	1.2	1.3	2.9	5.2	8.4	4.9	26.3	28.5	5.8
the forest floor	*(1207)*	*(1.4)*	*(0.3)*	*(6*	*(13.2)*	*(27.5)*	*(8.7)*	*(13.2)*	*(28.3)*	*(8.6)*
Deep 4 m	336	1.3	0.1	0.05	0.4	0.5	0.3	1.4	7.4	2.3
drainage at	*(699)*	*(1.5)*	*(1.1)*	*(0.04)*	*(0.8)*	*(0.6)*	*(0.3)*	*(8.6)*	*(15)*	*(2.6)*
the depth of:										
6 m	293	0.7	0.1	0.06	0.2	0.4	0.3	1.1	4.6	1.3

(a) N in litterfall refers to total N.

Table 3. Input-output budgets (without weathering) in the eucalypt plantation and native savanna (in italics) in Congo

	Nutrients (kg ha^{-1} yr^{-1})				
Input	N	P	K	Ca	Mg
Atmospheric deposition	4.3 ± 2.1	0.3 ± 0.15	2.8 ± 1.4	13 ± 6.5	1.4 ± 0.7
	(4.3 ± 2.1)	*(0.3 ± 0.15)*	*(2.8 ± 1.4)*	*(14 ± 7)*	*(1.4 ± 0.7)*
Fertilisation	5.1 ± 0.3	2,2 ± 0.1	6.9 ± 0.3	0	0
	(0)	(0)	(0)	(0)	(0)
Weathering	-	-	?	?	?
Symbiotic fixation	(20)(2)				
Output					
Deep drainage	0.8 ± 1.0	0.06 ± 0.05	0.2 ± 0.2	0.4 ± 0.3	0.3 ± 0.3
	(2.6 ± 2.4)	*(0.04 ± 0.07)*	*(0.8 ± 1.4)*	*(0.6 ± 0.6)*	*(0.3 ± 0.3)*
Harvest (1)	27 ± 9	4.1 ± 2.8	9.9 ± 7	5.0 ± 2.8	3.2 ± 1.6
Annual fire	*(22 ± 14)*	*(2.0 ± 1.8)*	*(2.4 ± 3.7)*	*(3.0 ± 5.9)*	*(2.7 ± 2.4)*
Budgets	-18.4 ± 12.4	- 1.7 ± 3.1	-0.4 ± 8.9	7.6 ± 9.6	-2.1 ± 2.6
	(0 ?)	-1.7± 2.0	-0.4 ± 6.5	10.4 ± 13.5	-1.6 ± 3.4

(1) Eucalypt stands are harvested every 7 years in the Congo. Pulpwood de-barked and firewood harvested.

(2) Estimated to balance the N budget in the savanna.

the 50 cm of surface soil is 2300 kg ha^{-1}. In the 15 cm of surface soil where most of the mineralisation occurs the pool of total N is very low (< 800 kg ha^{-1}). The removal of *Eriosema erici-rosenii* in the eucalypt stands by weeding reduces N input, which is of concern for the sustainability of the nitrogen nutrition in the plantations.

Conclusion

There is very little leaching loss of nutrients under eucalypt plantations and savannas. This may be the result of a high uptake by the stands of nutrient inputs. However the nutrient budgets showed a potential deficit of nitrogen in the eucalypt ecosystem. These results indicate that regular fertilisation is necessary to achieve a high yield and for the sustainability of these plantations.

The large quantity of nutrients in the forest floor and in litterfall highlights the importance of the management of organic matter for the sustainability of high production eucalypt plantations.

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SHORT COMMUNICATION 2

Loblolly Pine (*Pinus taeda*) Plantations in the Semitropical Southeastern United States

A. Tiarks[1], M. Elliott-Smith[1] and R. Stagg[1]

Introduction

In the United States, the majority of publicly owned forest land is managed by the Forest Service, an Agency within the U.S. Department of Agriculture. The laws and regulations that guide the Forest Service requires that no management activity, including wood production, will permanently impair the productivity of the land. In partnership with the National Forest Management, the research arm of the Forest Service developed a national research plan to install studies within major forest types and physiographic regions (Powers *et al.* 1990). The project has a set of broad objectives. In particular it aims at understanding how management-induced changes in soil porosity and organic matter affect the long-term site productivity. This parallels the core objectives of CIFOR's network project (Nambiar *et al.* 1999).

In the southeastern region of the United States, loblolly pine (*Pinus taeda* L.) growing on coastal plain soils represents a productive forest type and makes a major economic contribution to the region. However, many of the soils are infertile with low water-holding capacities and low levels of organic matter. In addition, heavy equipment used for logging and site preparation may compact the soils and leave logging residue unevenly distributed or removed from the site. Following the experimental protocols of the national study, study sites were located on National Forests in Louisiana and Mississippi to measure the impacts of organic matter removal and soil compaction on the productivity of the following rotation. Some of the results are reported here.

Methods

The studies are located on soils with two levels of natural fertility. The study in Louisiana is located on soils relatively high in bases, while in Mississippi the soils are lower in bases and nutrient storage capacity. The Louisiana site is located on the Kisatchie National Forest (31°40'N, 92°30'W) where mean annual rainfall is 1450 mm and average daily temperature ranges from 15°C in January to 34°C in July. The harvested stands were 50-60-year-old loblolly pine plantations that had been thinned several times. The understorey consisted of small hardwood trees and bushes even though the stands had been prescribed burnt on a regular basis. The Mississippi site is located on the De Soto National forest (31°30'N, 89°00'W) where mean annual rainfall is 1430 mm and average daily temperature ranges from 8°C in January to 27°C in July. The stands harvested for the study were 55-year-old slash pine (*Pinus elliottii* Engelm.) plantations with a grass understorey. The Mississippi stands had been thinned and prescribed burned.

The study is replicated at three locations in each state. At each location, the treatments consist of three levels of organic matter removal which are:

BL_0 All aboveground residue, understorey and litter removed.

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BL_1 All aboveground parts of pines removed during harvest.

BL_2 Only bole removed, with all logging slash retained.

Each 0.4 ha plot is split into two equal parts: weeds were allowed to develop on one half (H_0) and herbicide applied to the other (H_1). A compaction treatment was applied at each site with levels of zero, moderate and severe. Only the results from the uncompacted plots are reported here to conform to the treatments used in the "Site management and productivity in tropical forest plantations' study (Nambiar *et al.* 1999).

In both states, the plots were planted with genetically improved loblolly pine seedlings at a spacing of 2.5 x 2.5 m, so in Mississippi slash pine was replaced with loblolly pine. Total tree height and diameter at breast height (dbh) were measured at age 5 years. Total volume (under bark) was calculated using the equation developed by Schmitt and Bower (1970). Analysis of variance was used to test for significant differences and Duncan's multiple-range test was used to separate means.

Soil samples were taken from the 0-10 cm depth from 15 randomly located spots in each plot before harvesting. The samples were bulked by plot and air-dried for chemical analysis. Chemical properties of soils are shown in Table 1 as means of the three locations within each of the two states. The soil series differs by location in Louisiana, so the variability in properties is higher compared to Mississippi where the same soil series is at all three locations.

Results

In Louisiana, the retention of logging residue did not have a significant effect on the growth of the loblolly pine by age 5 years. Weed control did have a statistically significant effect ($P<0.001$) increasing the height from 3.90 m on the untreated plots to 4.73 m on the herbicide-treated plots. Weed control increased the dbh from 4.9 to 7.0 cm and total volume was increased from 7.4 to 16.0 m^3 ha^{-1}.

In Mississippi, data from plots not compacted during harvest are shown in Table 2. Retaining organic matter on site increased growth of the newly established plantation. Without weed control, the trees on the BL_1 plots were 0.16 m taller than trees on the BL_0 plots (Table 2). Leaving all of the aboveground organic matter on the plots (BL_2) increased the height by an additional 0.39 m. The effect of leaving organic matter on the site was even greater when weeds were controlled as indicated by a significant organic matter retention by herbicide interaction. By age 5 years on weeded plots, the trees on BL_2 plots were 0.45 m taller than on the BL_1 plots and 0.97 m taller compared to the BL_0 treatment. A similar increase in dbh occurred as the amount of organic matter retained increased. The combined increase in height and dbh resulted in more than doubling of the volume from 4.4 m^3 ha^{-1} for the BL_0H_1 plots to 9.3 m^3 ha^{-1} on the BL_2H_1 plots.

Table 1. Soil chemical properties of the 0-10 cm layer of the study sites before harvest

Parameter	Location and species			
	Louisiana Loblolly pine		Mississippi Slash pine	
pH	4.7	(0.3)[3]	5.1	(0.2)
OC (g kg^{-1})[1]	12.3	(2.7)	12.8	(1.3)
P Bray2 (mg kg^{-1})	3.1	(1.2)	2.0	(0.7)
K exchangeable (c mol kg^{-1})[2]	0.12	(0.07)	0.05	(0.02)
Ca exchangeable (c mol kg^{-1})	2.46	(1.64)	0.62	(0.29)
Mg exchangeable (c mol kg^{-1})	1.07	(0.69)	0.28	(0.13)
Na exchangeable (c mol kg^{-1})	0.07	(0.03)	0.06	(0.02)
CEC (c mol kg^{-1})	9.86	(6.23)	2.88	(0.64)

[1] OC determined by combustion; [2] Bases extracted with 1M $BaCl_2$; [3] Standard deviations in parentheses.

Table 2. Effect of logging residue retention and herbicide treatments on the growth of loblolly pine at age 5 years in Mississippi

Treatment	Height (m)	dbh (cm)	Volume (m^3 ha^{-1})
BL_0H_0	2.80a	3.0a	3.5a
BL_1H_0	2.96ab	3.2a	3.9a
BL_2H_0	3.35ab	3.8ab	4.9a
BL_0H_1	3.00ab	3.6a	4.4a
BL_1H_1	3.52ab	4.4ab	6.6ab
BL_2H_1	3.97b	5.4b	9.3b

Values in a column followed by the same letter are not significantly different (alpha=0.05).

Discussion and Conclusions

Because of the importance of the nutrients in explaining the results, soils are being sampled at greater depths as the plantation develops. Samples have been collected to a depth of 30 cm at age 5 years and are being collected to a depth of 180 cm as the plantations reach 10 years old. The plot size was selected to be large enough so that reliable measurements of pine growth and changes in soil properties can be made throughout the planned 60+ year rotation on these public forests. While these results should be used to adjust management practices, the guidelines should be considered tentative until results from later stages in the rotation are obtained

On soils with higher levels of bases and other nutrients in Louisiana, the pines did not respond to the slash retention treatments. When weeds were controlled, the volume growth increased dramatically. On sites with lower levels of P and bases, pine growth was increased as more of the organic matter was retained on site. The increase was greater when weeds were controlled in addition to organic matter retention. However, with weed control, the pine volume on the Louisiana site was 72% greater than the best treatment in Mississippi. The greater growth occurred in Louisiana even though more of the precipitation falls during the growing season in Mississippi. The amount of N available to the pines has not been measured, but was probably higher on treatments where organic matter was retained, contributing to the growth differences. Both low and high nutrient soils can be found in the two states because the differences are due to local geology and other soil forming processes. The soil characteristics which distinguish the different responses of these two sites are available in soil surveys. These surveys, as well as local knowledge of the soils, should be used in tailoring management practices to the site.

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Summary of the Third Workshop in Kerala, India

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Introduction

An important feature of this network project is the opportunity for all the participants to meet for sharing results and ideas at reasonable intervals at one of the project locations. We met at Kuala Lumpur (Malaysia) for the first workshop, which discussed and agreed upon the core objectives, formalised the project plan and the strategy for implementation. At the second meeting held in Pietermaritzburg (South Africa), the workshop reported on locations of sites, progress in installation, methods and early results from some sites. This third workshop hosted by the Kerala Forest Research Institute (India) was the first since the experiments at most of the sites have been installed. Thus by December 1999, experiments have been in progress for more than four years in southwestern Australia and Brazil and for few months at Subanjeriji, Sumatra (Indonesia). A second site in Sumatra is in the planning stage and completion of the field experiment is expected in late 2000. This span of time between experiment installations is an added variable, which will pose some challenges when we attempt to synthesise and integrate results. However, it also presents an immediate opportunity for sharing experience.

In this summary we have brought together the main progress achieved which provides a framework for reviewing the scope of the study. One of our core goals is to ensure that each site is designed as a complete, stand-alone study. The results from each can be independently interpreted, reported in publications and applied to improve forest management.

The information presented to this workshop can be grouped into following categories:

- the amounts of biomass and nutrients accumulated by the stand in the previous rotation;
- the amounts of slash and litter removed or retained after the various treatments had been applied;
- the early growth of the experimental (replanted) stands;
- preliminary results from process level studies, which will be useful in understanding the results; and
- five contributions of current research complementary to the project, two of which are included in this proceedings.

In addition, the comprehensive field notes provided by Kerala Forest Research Institute gave detailed accounts of the experiment and results on the four sites in Kerala.

Productivity of the Previous Stand

The information on rates of accumulation of biomass in Table 1 is based on the results presented at the second and third workshops. Caution is required in comparing the rate of accumulation by short rotation stands (7-9 years) with those in long rotation, which, as in the case of *Pinus elliottii* in Queensland, was thinned. Furthermore the harvested eucalypt sites in Kerala and South Africa are 2 - 3 rotation coppice crops. Continued coppicing is known to lead to decreased productivity. The rate of accumulation of above ground biomass by the trees was 34.4 t ha^{-1} yr^{-1} on the highest producing site, Manjimup, southwestern Australia. This was about seven times the rate of accumulation on the lowest producing site at Punalla, Kerala. The wide range of rates of biomass accumulation at these plantations sites, even within short rotation crops of eucalypts, shows that the partners have implemented the project on a broad range of sites. It is important to note the four-fold difference in productivity between four sites in Kerala because large differences in productivity between

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Table 1. Location, species, aboveground standing biomass of the previous rotation stand, rate of accumulation of that biomass and response to the residue treatments by the new plantation

Country - site	Species	Previous rotation stand				Experimental stand response
		Age (yr)	Tree biomass[1] (t ha^{-1})	Tree biomass (t ha^{-1} yr^{-1})	Age (months)	
Australia						
Queensland	*Pinus elliottii*	29	232.0	7.9	39[2]	Trend for increased growth with increasing residue
Southwestern Australia						
Manjimup	*Eucalyptus globulus*	8	275.0	34.4	48	Early growth differences disappeared
Busselton	*Eucalyptus globulus*	8	98.0	12.3	48	BL_3 largest, but not statistically significant
Brazil						
Itatinga	*Eucalyptus grandis*	7	140.3	20.0	39	BL_0 smallest
P.R. China						
Fujian	*Cunninghamia lanceolata*	29	197.4	6.8	24	BL_3 largest; growth rate of BL_0 slowing with time
Guangdong	*Eucalyptus urophylla*	6	44.0	6.3	31	BL_1 shortest, BL_0 received some weeding
Congo						
Pointe-Noire	*Eucalyptus hybrids*	8	117.0	14.7	18	Trend for increasing growth with increasing residue
India, Kerala						
Kayampoovam	*Eucalyptus tereticornis*	7	63.0	9.1	12	No effect
Punalla	*Eucalyptus tereticornis*	7	33.7	4.9	12	No effect
Vattavada	*Eucalyptus grandis*	7	141.9	20.1	12	No effect
Surianelli	*Eucalyptus grandis*	7	43.5	6.2	12	No effect
Indonesia						
Sumatra	*Acacia mangium*	9	146.4	NA	NA	-
South Africa						
Natal	*Eucalyptus grandis*	7	140.3	20.0	8	Trend for increasing growth with increasing residue

(1) Standing biomass only.

(2) Queensland: the previous stand was *Pinus elliottii* thinned at age 15.6 years; the second crop (this experiment) is a hybrid *P. elliottii* x *P. caribaea* var. *hondurensis.*

sites within a region is common in forestry. The large variation in biomass has also resulted in corresponding differences in the amount of slash and contrasting residue treatments within and between sites. Of the four sites where *Eucalyptus grandis* was harvested, three had nearly identical rates of biomass accumulations in the trees of 20 t ha^{-1} yr^{-1}. Since these sites were located in South Africa, Brazil and India, the uniform rate of productivity may indicate the strong influence of species on production when productivity is not severely curtailed by low soil fertility, as appears to be the case at Surianelli in Kerala where the rate of accumulation by the same species was less than 30% of other sites. Because several management techniques were applied as options, this possibility can be tested as the newly established stands get closer to rotation age. The available data already provides valuable information on the extent of nutrient transport, which would occur from sites in relation to harvest intensity (e.g.; whole tree vs stem only) and their impact on soil nutrient store. Thus Simpson *et al.* note (this volume) that log harvest removed 171% of the exchangeable K in soil to a depth of 120 cm. Several other papers provide estimates of potential nutrient depletion in relation to inter-rotation management practices. Overall, the range of sites, harvest impacts and soils represented in the network would allow the management options developed by the project to be applicable to many forest plantations areas in the tropics. At all sites, the new plantations have been established with the same species as in the previous rotation except in Queensland where *P. elliottii* has been replaced by *P. elliottii* x *P. caribaea* var. *hondurensis* hybrid. Thus the project now includes six species and two hybrids.

Effects of Residue Treatments on New Plantations

The core treatments applied represent the levels of biomass retained on the site, ranging from removal of all aboveground biomass to a ‘double slash’ in which logging slash from one plot is applied to another. The net amount removed or retained varied between sites depending on the productivity of the previous rotation. These treatments are designed to achieve maximum contrast in the levels of stress that can be achieved by manipulation of the logging residue and litter.

A summary of the early response of the trees to the residue treatments along with the age at the latest measurement is shown in Table 1. Of the 12 sites for which growth results are available, five showed no response to amounts of biomass retained. On the seven sites showing an effect of the treatments, the trend was always for increased tree growth as more residues were retained. The trial in South Africa showed the lowest survival in the BL_3 (double slash) plots, probably because the insulating effect of the residue allowed the formation of frost pockets. However, the increased growth rates of the surviving trees made up for the differences in survival so the biomass index was the larger than on the BL_0 and BL_2 treated plots.

At the Guangdong, China site, BL_0 plots were weeded manually and the weed biomass removed from plots in the early stages of tree establishment. Because of this at 8 months after planting, the trees are larger on this treatment than on plots where the logging residue was left (BL_2). However, by 31 months after planting, the trees on these two treatments were the same size. At the Fujian site in China, the slash treatment had a significant effect on survival of the Chinese fir, but this result should be seen in the background of generally high mortality encountered (including the block effect) at that site.

Process-based Information

The site-specific responses to the core treatments also underscore the importance of the process level studies being undertaken at most sites in developing management options for similar locations. On most of the sites intensive measurements are being made on processes that are thought to affect the productivity of the site. At all sites there are important additional (optional) treatments applied. These will be vital in explaining the results not only at that particular site but also for explaining the factors determining productivity across sites. Additional information being obtained includes decomposition of residue, N mineralisation, change in organic matter, changes in available nutrient pools and effect of site management on water relations. On some sites, the network project is a part of large integrated project including detailed studies on carbon and nutrient cycling (e.g., Congo, Queensland, southwestern Australia). On several sites, the decomposition rates of the logging residue are being measured and found to be very rapid. For example, at the Congo site, 38 to 65% of the logging residue decomposed in 6 months. The leaves and twigs, which contain the highest concentration of nutrients, were mostly decomposed with only the larger branches remaining. In Kerala, the decomposition rate followed the same pattern, with the half-life of 2 cm diameter twigs twice as long the half-life for 0.5 cm twigs. Perhaps even more important in terms of network linkages, the *E. tereticornis* residue decayed much faster than litter from *E. grandis*.

Retaining the harvest residue on site can also affect the amount of organic C in the soil. At the Guangdong site in China, increasing the amount of residue left on the plots resulted in higher amount of soil carbon from 25.3 to 31.3 t ha^{-1} in 2 years after planting. However, harvesting always reduced the soil carbon levels compared to preharvest. In another phase of organic residue decomposition, N mineralisation and the availability of other nutrients is being measured at several sites. On the southwestern Australia sites, the presence of eucalypt residue is thought to slow the formation of nitrates, which can be rapidly leached. The inhibition of nitrate formation results in the retention of more N on the site until the new crop can utilise it. Studies in Brazil are providing detailed information on the dynamics of N mineralisation over a long period under an intensive production system.

The harvest residues also form a mulch, slowing evaporation and retaining more water for the trees. On the South African site, the water content was higher in the double slash treated plots (BL_3) compared to the single slash plots (BL_2). However there was not a corresponding increase in tree growth in the first 8 months on the double slash plots. This emphasises the point that process level measurements may need to be continued though much of the rotation. In some instances water x nutrient interaction may be the key factor determining productivity. In general there has been little information provided on foliar nutrient status of young experimental trees in relation to site and /or treatments.

Network Effectiveness

As the information from all the sites become available, gaps and inconsistencies in measurements can be identified, rectified or explained. The effects of the residue treatments at each site will become clearer as the stands approach rotation age. The linkages within the network will allow a better understanding of the interaction between site and residue treatments, enhancing the utility of the results. Results from both the core and optional treatments will be needed to develop management options to maintain or increase productivity. The site-specific responses to the core treatments underscore the importance of the process level studies being undertaken in developing management options for similar locations

While the same intensive process-based studies are not being made at all sites, these studies increase the understanding of the tropical plantation ecosystem in general. More importantly, the process level studies that are ongoing at most of the sites will be the foundation for development of science-based management options to maintain and improve the productivity of tropical forest plantations. As some of the sites are located in remote areas that have little information about the soils, climate and understorey vegetation, a secondary benefit will be greater knowledge about previously neglected ecosystems. Judicious use of this knowledge can be used to prevent management strategies that will prevent future degradation of the soils. Rather, management alternatives will be developed to correct declines in productivity caused by past management. While the project is now fully functional, additional sites may be desirable to expand the network to other important ecosystems.

Because of the professionalism and high scientific calibre of the partners, the Project on Site Management and Productivity in Tropical Forest Plantations is operating successfully. At this third workshop, the attendees exchanged ideas on types of measurements that should be used and the basis for selecting a measurement, as well as the concepts that are needed to interpret the results, develop meaningful management options and transfer the information to users. These interactions showed that partners have established strong linkages and shared commitments. As previously noted, one of our core goals is to ensure that each site is designed as a complete, stand-alone study, so the results can be interpreted and applied to improve local forest management. It is clear that this objective is being achieved and in some cases partners have already formulated management recommendations. This augers well for all of us because transferring the scientific information to managers and assisting them to apply the results is a rewarding challenge.

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