Site Management and Productivity in Tropical Plantation Forests

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Proceedings of Workshops
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E.K. Sadanandan Nambiar

CIFOR
CENTER FOR INTERNATIONAL FORESTRY RESEARCH

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This proceeding is based on scientific outcomes from more than a decade of collaborative research by the net-work partners. It marks the end of the Phase I of this long-term research program. It is hoped that the program will continue to the next phase as a significant contribution to the science and practice of sustainable plantation forestry. The success of this project has been possible due to the commitments of all partners towards shared goals.

It is a pleasure to acknowledge the special contributions of some contributors. Christian Cossalter, formerly CIFOR, championed, supported and managed the project during the first 7 years (1995-2002) with great dedication. Takeshi Toma continued that tradition of active participation and support from CIFOR from 2003 to 2006. Markku Kanninen's support and advice enabled the work to continue to this outcome from 2006. David Kaimowitz, former Director General of CIFOR, has encouraged us greatly. Allan Tiarks (retired from USDA Forest Service) was one of the founding scientist. He made significant contributions in many ways and even after his retirement continued to provide valuable scientific contributions. Jacques Ranger (INRA) contributed much to the soil science aspects of the project.

Japan Official Development Assistance generously supported the workshop, including travel assistance to partners to workshop held in China (2003) and Brazil (2004). The outstanding secretarial support of Rosita Go from the beginning to this day to the coordination of the network activities, workshops, and preparation of proceedings have been invaluable. John Turnbull provided high quality technical editing of this proceedings. Ms. Maarit Kallio supervised the production of this proceedings.

E.K. Sadanandan Nambiar

Group photo from the seventh workshop held on November 2006 at CIFOR, Bogor, Indonesia. (Photo: Widya Prajanthi)

Introduction:
Sustained Productivity of Plantation Forests in the Tropics: a Decade of Research Partnership

E.K.S. Nambiar[1]

Plantation Forests in Context

Plantation forests are renewable natural resources primarily managed for growing wood for a range of purposes. Their role in providing ecosystem services including carbon sequestration and landscape rehabilitation is receiving increasing recognition. Estimates of the area under planted forests vary considerably depending on the definition and their intended purpose, production or protection or both. The share of wood supply from planted forests is set to increase; according to some estimates from the present 50% to 75% by 2050. Per capita consumption of wood is also increasing in highly populous countries where economies are growing rapidly. This is particularly the case in India and China. The plantation resource is expanding at an annual rate of about 2.5 million ha largely in subtropical and tropical environments in Asia and South America and to a much lesser extent in Africa. Governments of these nations regard plantation forestry and the associated fibre and wood-based industries as a part of their economic development agendas and encourage investment through various incentives.

Most plantations in the tropics are to provide wood for fibre-based industries and their development is responsible for significant economic, environmental and social impacts. A detailed analysis of these issues is not within the scope of this paper, but the experience in South Africa and Vietnam, two partners in this network project, are illustrative examples. Shackleton *et al.* (2007) described the situation in South Africa. Plantations there cover approximately 1.35 million ha, 76% of which are privately owned and managed. In 2002, planted forests produced 17 million m^3 of commercial roundwood worth 3.3 billion Rand. This resource drove diverse forest product industries with an annual value of 13.3 billion Rand. Of this, 81% came from exports and is equal to 7.3% of national GDP. The forest sector employs 66 000 people directly and they support an estimated 300 000 dependants. Although there was no estimate given, there would have been substantial indirect employment though diverse routes of the economy. South African forest industry has developed successful outgrower programmes with individual landholders, whose land area only averages 1-3 ha, and institutional owners of woodlots. Many forest plantation owners permit animal grazing and the gathering of firewood, mushrooms, honey. However, these contributions need to be evaluated against environmental costs. Most productive plantations are in relatively high rainfall regions and catchment-scale planting can reduce stream flow.

Vietnam exports annually timber products valued at US$ 1.5 billion, but to service this industry 80% of the roundwood is imported, costing about US$ 1 billion (Forest Science Institute of Vietnam personal communication). Recently, I visited a furniture manufacturing business in South Vietnam that employs some 4000 people directly. This is one example of the many wood-based, small-scale forestry and forest products enterprises in Vietnam providing employment and valuable support to the local economy. The Government of Vietnam is committed to improving the nation's wood growing capacity through a 5-million-hectare reforestation programme.

Most plantation expansion is based on exotic species with potential for high growth rates so they can be grown and harvested on short rotations. This means their impact on the

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ecosystem, including soils, is also large. Although tropical soils in general are no more fragile than soils elsewhere, the land available for forestry generally has soils with low fertility and prone to degradation if subjected to poor and exploitive management practices. The environments are characterised by high rainfall, monsoonal climates, prolonged dry periods and high temperatures. In the early 1990s, our knowledge of the impacts of management and the research required to support large-scale changes in land use were in their infancy. Consequently, there were many uncertainties about the sustainable production of the expanding forestry plantations and their apparent risks was a topic of much public debate.

Project Objectives

The broader issues of sustainability in plantation forests include biological, economical, environmental and social components and their interactions. The relative importance of each component may depend on the region where forestry is expanding. All these issues cannot be addressed in a single project and this project was not designed to examine all the complex issues of sustainability. It was conceptualised and focused on providing scientific evidence to address concerns about sustainable production, a central aspect of sustainability in the holistic sense. Based on discussions with potential partners from several countries, the main project objectives were agreed during 1994-95. The rationale, approach and details of the project's development are described by Nambiar and Kallio (2008).

The major objectives were to:

- evaluate the impacts of soil and site management practices on the productivity of successive rotations of plantations- impacts to be measured as productivity and pertinent changes in soil;
- develop management options for maintaining or increasing productivity in a form which can be applied by local managers and facilitate adoption; and
- strengthen local institutional capacity to respond to new problems and opportunities.

To achieve these objectives it was necessary to seek out partners who had the commitment for long-term research on plantation sustainability, capacity for allocating sufficient area with security, and able to cover experimental costs at their respective sites. The research plan also stipulated that each site should aim to produce a self-contained results and its value should not be dependent on the success or failure of other sites.

Central to the research plan was the concept of a collaborative network. Each unit would undertake well-designed, process-oriented, self-contained, on-site research that was linked to the network. The field research included a set of common *core* treatments and diverse *optional* treatments. The optional treatments were based on the experience of local researchers and managers and designed to address specific local needs and practices.

This partnership established 16 experimental sites (10 eucalypt, 4 acacia and 2 conifers) typical of commercial forestry in regions represented by the partners. Sites are located in Australia, Brazil, Congo, China, India, Indonesia, South Africa and Vietnam. They cover a range of biophysical environments and forest management conditions. Details of site-specific treatments and results are described in individual papers in this proceedings. Analysis and interpretation of the results and management options for improving productivity are described in 12 papers.

Workshops and Reviews

Active and regular interaction between partners and review of progress were key factors that contributed greatly to the success of this network. This was fostered through regular and well-organised workshops hosted by partner organisations. Papers presented at the workshops were reviewed and published systematically in three previous proceedings. Workshops were held in Kuala Lumpur, Malaysia (1995), Petermaritzburg, South Africa (1998), Kerala, India (1999), Pointe Noire, Congo (2001), Guangzhou, China (2003), Piracicaba, Brazil (2004) and Bogor, Indonesia (2006).

Experimental sites were established between 1995 and 2002. At the time of the last workshop (2006) all the eucalypt sites had completed one rotation and had been harvested. Experiments have been re-established on all of them for the third rotation. Acacia sites are approaching harvest but the conifer sites will continue over their rotation period of about 30 years.

This Proceedings

This proceeding is a compilation of papers first presented at the 2004 workshop in Brazil that have been updated with the latest information and discussions in the 2006 workshop. We consider that this marks the Phase 1 of this long-term study. Papers describing the results from each site (or location where there are more than one sites) have been complemented with three synthesis papers. These include modelling productivity, trends of impacts on soils, and a general synthesis of core generic results, science and impacts. Appendix 1 included in these proceedings gives a full list of publications, including postgraduate theses, arising from this network. These contributions are based on more than a decade of work by 60-70 researchers from a wide range of scientific and cultural backgrounds. They come from countries in very different stages in their plantation forestry development. I hope the contents of the proceedings will serve all those interested in the science and practice of sustainable plantation forestry.

References

Nambiar, E.K.S. and Kallio, M.H. 2008. Increasing and sustaining productivity in tropical forest plantations: making a difference through cooperative research and partnerships. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 205-228. Center for International Forestry Research, Bogor, Indonesia.

Shackleton, C.M., Shackleton, S.E., Buiten, E. and Bird, N. 2007. The importance of dry woodland and forests in rural livelihood and poverty alleviation in South Africa. Forest Policy and Economics 9: 558-577.

Field discussion in the Brazilan site of CIFOR's network on site management and productivity in tropical plantation forests (the 6th workshop of CIFOR's network on site management and productivity in tropical plantation forests), Brazil. (Photo: Takeshi Toma)

Effects of Slash and Litter Management Practices on Soil Chemical Properties and Growth of Second Rotation Eucalypts in the Congo

P. Deleporte[1,2], J.P. Laclau[2], J.D. Nzila[3], J.G. Kazotti[1,4], J.N. Marien[1,2], J.P. Bouillet[2], M. Szwarc[2], R. D'Annunzio[5] and J. Ranger[6]

Abstract

Effects of slash and litter management practices on soil fertility and eucalypt growth were studied over a full rotation. Soil properties were compared to a depth of 1 m before harvesting the previous stand and at 1, 3 and 8 years after harvest management treatments. Stand overbark volume ranged from 84 m^3 ha^{-1} to 161 m^3 ha^{-1} seven years after planting depending on slash and litter management treatments. Burning increased stand growth in the first year after planting, but reduced the mean annual increment by 13% at seven years of age compared to harvesting only stemwood. There was a significant decrease in exchangeable Ca and Mg concentrations in the 0-10 cm soil layer one year after establishment in all treatments, and concentrations then remained about the same until the end of the rotation. There were no significant effects of slash and litter management treatments on organic carbon content, total N and exchangeable cation concentrations in soil below 10 cm. In the surface layer (0-10 cm), organic carbon content, total N, exchangeable Mg and Na concentrations were significantly lower under the residue-removed treatment compared to the treatment with the highest amount of slash and litter one year after treatment establishment but differences between these treatments were no longer significant at three years of age. Highest concentrations of exchangeable Ca and Mg were in the burning treatment at eight years of age. Stand volume at the end of the rotation was not significantly correlated with soil C and nutrient concentrations in any soil layer at any time after treatment establishment. By contrast, the volume of the 7-year-old stands was highly correlated with the mass and the nutrient contents of litter and slash above the mineral soil at planting. The study highlights the crucial role of organic matter management in the sustainability of fast-growing plantations in this tropical sandy soil and the need to take into account the amount of slash and litter from the previous rotation when determining site-specific fertiliser inputs.

Introduction

Commercial eucalypt plantations have been established since 1978 in herbaceous savannas covering the littoral plains of the Congo. However, a 6-month dry season coupled with sandy soils result in relatively low wood production (15-20 m^3 ha^{-1} yr^{-1}) in comparison to commercial eucalypt plantations in other regions (Nambiar *et al.* 2004). An increase in biomass production of 20-30% is expected with new clones developed

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by the breeding program in the Congo but there are concerns about the sustainability of these plantations in soils with very low amounts of bio-available nutrients (Safou-Matondo *et al.* 2005). Ecological consequences of afforestation have been studied extensively in this area, including soil macrofauna dynamics (Mboukou-Kimbatsa *et al.* 1998), changes with time in understorey floristic composition (Loumeto and Huttel 1997), soil nitrogen mineralisation (Nzila *et al.* 2002), biogeochemical cycling of nutrients (Laclau *et al.* 2003a, 2003b, 2003c, 2005), and water consumption (Nouvellon *et al.* 2006).

Soil carbon dynamics require particular attention since organic matter is the main source of fertility in tropical sandy soils (Feller and Beare 1997, Fisher and Binkley 2000). Organic matter content of littoral savannas in the Congo is extremely low (< 1%) due to the coarse, sandy texture of the soils and probably the impact of annual burning over several centuries (Schwartz *et al.* 1996, Bird *et al.* 2000). Carbon fluxes within eucalypt ecosystems were studied from eddy covariance methods (Nouvellon *et al.* 2006), isotopic studies (Trouvé *et al.* 1994), soil respiration monitoring (Epron *et al.* 2006) and regular stand inventories using a chronosequence approach (Saint-André *et al.* 2005). An experiment was set up in 1998 to quantify the effects of slash and litter management practices on soil properties, tree nutrition and growth (Bouillet *et al.* 1999). A strong effect of slash and litter management treatments was observed on the early growth of trees (Bouillet *et al.* 2000), nutrient accumulation in the stands, and soil chemical properties (Nzila *et al.* 2004). The objective of this paper is to synthesise key knowledge from the experiment as a whole and to assess the potential of soil analysis to gain insights into processes responsible for large differences in eucalypt growth in a sandy tropical soil.

Material and Methods

Location and Site Description

The study site is located on the coastal plains near Pointe-Noire, Congo (4°S, 12°E). The climate is subequatorial with a rainy season from October to May and a dry season from June to September. Mean annual rainfall is about 1200 mm and mean annual temperature is 25°C with seasonal variations of about 5°C. Climatic conditions and soils have been described in Laclau *et al.* (2000). Soils are Ferralic Arenosols (FAO classification), very deep and characterised by a homogeneous sandy texture, acidity, limited available nutrients, and very low levels of exchangeable cations, organic matter and cation exchange capacity.

Stand Description

The experiment was described in detail by Bouillet *et al.* (1999). Before establishment of the first rotation, the original savannah was burnt, and two months later, regrowth was treated with glyphosate. The soil was ripped along planting lines. Trees were planted in April 1990 at a spacing of 4.0 m x 4.7 m. The planting stock was *Eucalyptus* PF1 clone 1-41. This clone comes from natural crosses between two or three individuals of *Eucalyptus alba* (mother tree) and unidentified eucalypt hybrids (father tree) from a Brazilian arboretum. Fertiliser was applied at planting 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 three years after planting. At harvesting in January 1998 the stand had a mean height of 26.1 m, a basal area of 12.9 m^2 ha^{-1} and a standing volume of 129 m^3 ha^{-1}. The second rotation crop was planted in April 1998 using the same clone. Spacing was 2.65 m x 4.70 m (803 stems ha^{-1}), superimposed on the previous rows. Fertiliser (15.6 kg N ha^{-1}, 15.6 kg P ha^{-1}, and 25.2 kg K ha^{-1}) was applied at planting. No additional fertiliser was applied. Weeds were controlled with glyphosate. The stand was harvested in March 2006 when 7.9 years old.

Experimental Design and Methods

The experimental set up at the harvest of the first rotation had a complete randomised block design with four replications. Each plot had a gross area of 0.26 ha (204 trees) and an inner plot of 0.15 ha (120 trees) with two border rows. The treatments were:

BL_0 All aboveground organic residues (slash, litter and understorey) removed from the plot.

BL_1 Whole-tree harvest. All aboveground components of the commercial trees

	(diameter at breast height >11 cm) were removed.
BL$_2$	Stemwood + bark harvested. Only the commercial-sized boles (top-end over-bark diameter >2 cm) and associated bark were removed.
BL$_3$	Double slash. All the trees were logged as in the BL$_2$ treatment. The residues of the treatment and that of BL$_1$ were distributed on the ground.
BL$_4$	Stemwood harvested. Only the commercial-sized boles, were removed after debarking,
BL$_5$	BL$_4$ + slash and litter burnt.

Diameter at breast height (DBH) and height of all the trees in the inner plots were measured annually. Tree volume overbark was calculated from a taper equation established from a sample of 792 trees of the same clone in the Congo (Gomat 2006).

Litter Decomposition

Before harvesting, 20 litter samples were taken within a 50 cm x 50 cm frame in each treatment plot in blocks 1 and 3. They were oven-dried (65°C) and weighed bulked within plot for chemical analysis (120 pooled samples in total). Amounts of residues retained at the harvest in each plot were estimated from allometric equations of biomass and nutrient content established before harvesting and applied to the inventory (Bouillet *et al.* 1999). Litter decomposition was assessed in the BL$_1$, BL$_2$, BL$_3$, and BL$_4$ treatment plots of blocks 1 and 3 by placing nets (50 cm x 50 cm) over the original organic residues to prevent the input of new material. Twelve samples were collected in each plot from September 1998 to September 1999 to quantify remaining biomass. Three composite samples were pooled for mineral content estimation and an exponential model for decomposition rate was fitted (Olson 1963).

Biomass and Nutrient Content in the Stands

Twelve trees of the previous stand, distributed in six basal area classes defined from an inventory were sampled before harvesting to develop predictive models for biomass and nutrient content of the stands (Bouillet *et al.* 1999). Trees were separated into components: leaves, living branches, dead branches, stemwood and stembark. Diameters, lengths and weights were measured in the field. Subsamples were taken from all the compartments for water content measurements and chemical analysis. Allometric equations were established in each treatment as polynomials of diameter at breast height and height to predict biomass and nutrient contents aboveground. The equations were applied to the inventories to estimate the aboveground biomass and nutrient contents of trees in the BL$_0$, BL$_3$, BL$_4$ and BL$_5$ treatments, one year and three years after planting.

Soil Sampling

Soils were intensively sampled to study the relationships between stand growth and soil chemical properties. Soil samples were taken before harvesting the first rotation at depths 0-10, 10-20, 20-50, 50-70 and 70-100 cm. Four samples were collected at different distances from the trees for each treatment, block and depth. The soils were resampled at 1, 3 and 8 years after treatment establishment in blocks 1 and 3 at about 25-50 cm from the initial locations. Sampling was carried out at 8 years of age just before clear-cutting the stands (second rotation).

Two series of chemical analysis were performed for organic C, total N, and exchangeable element concentrations to assess changes in soil chemical properties over the whole rotation. The first series of 99 soil samples were taken before harvesting the previous stand and 1 and 3 years after treatment establishment (0-10 cm and 10-20 cm layers) was analysed in 2003. The second series of 215 samples collected before harvesting the previous stand and when the current stand was 3 and 8 years old was analysed in 2006. Only the samples collected in the blocks 1 and 3 of the experiment were analysed. Chemical analyses were performed on samples taken in 4 plots before harvesting the previous stand (corresponding to the location of BL$_0$ and BL$_3$ in blocks 1 and 3), and in BL$_0$, BL$_3$, BL$_4$ and BL$_5$, at 1, 3 and 8 years of age. Soils were air-dried, sieved through 2 mm and roots were removed by hand and stored in plastic boxes hermetically sealed in a dark room. Individual analyses were performed on the four samples taken per plot at each date in the layers 0-10 cm and 10-20 cm. One bulk sample per plot per block and per depth was analysed at each sampling date for the deeper soil layers. Only the chemical analyses performed in 2006 were used in the present paper. Nutrient contents in soil layers one year after treatment establishment were assessed from chemical analyses performed in 2003. Nutrient stocks in the 0-100 cm soil layer were computed from data obtained from the 2006 analysis set (mean content for each depth and treatment) and bulk density measured in sites located in a radius of 500 m from the present experiment. Mendham *et al.* (2003) have observed differences in soil bulk density according to the amount of residues retained at the soil surface under *E. globulus* plantations in Australia. However, an extensive sampling in the area of the present experiment showed a low spatial variability and similar values under native savanna and eucalypt plantations (Laclau 2001, Landais 2003). Therefore, mean values of bulk density per layer were used to calculate nutrient stocks.

A major limitation to the interpretation of temporal series of soil analysis is that: (1) soil properties can be altered over the storage period and (2) slight laboratory procedure changes between the series of analysis can obscure small changes in nutrient contents or induce a systematic bias. To check soil storage and laboratory methods did not induce a bias in the present study, exchangeable cations were analysed in 2006 in 27 samples already analysed in 2003, and in the same set of samples stored from 2002 to 2006 either in Montpellier, France or in the Congo.

Chemical Analyses

In plant samples, N was determined by thermic conductivity after combustion (FP-428) and P, K, Ca, Mg, using an ICP sequential spectrophotometer (JY 24) after digestion by hydrofluoric acid and double calcination. Ash content of all forest floor samples was determined by combustion for 4 hours at 450°C. Values of litter biomass were corrected to eliminate the effect of remaining soil particles.

In soil samples, exchangeable Ca, Mg, Mn, Na, Fe, H and Al contents were determined by ICP spectrometry (JY 38 Plus) after cobaltihexamine extraction. Cation Exchange Capacity (CEC) was measured at soil pH after cobaltihexamine extraction. Organic carbon content was determined by dry combustion (NF ISO 10694) and total N by colorimetry after Kjeldhal digestion.

Statistical Analyses

Weighed regressions were computed at each age in BL_0, BL_3, BL_4 and BL_5 to establish treatment-specific allometric equations predicting biomass and nutrient content within each tree component from DBH and height. The equations were applied to the inventories to assess biomass and nutrient contents per hectare. Two-way ANOVA were performed on stand and soil characteristics at each age to test the block and treatment effects. Differences between treatments were tested using the Bonferroni test. The repeated measures option of the GLM statement in SAS was used to test the effects of blocks, treatments, age from planting, and the interactions between the main factors, on the concentrations of elements in each layer (SAS 1998). Only the chemical analysis performed in 2006 (before harvesting the first rotation and 3 and 8 years after treatment establishment) in the BL_0 and BL_3 treatments were computed to avoid a bias due to the chemical analysis series. Pearson correlation coefficients were computed in SAS between mean stand volume at 7 years in BL_0, BL_3, BL_4, BL_5 and: (1) organic C, total N, exchangeable cation concentrations in the 0-10 cm layer, 1, 3 and 8 years after planting, and (2) stocks of these elements in the mineral soil down to a depth of 1 m at the same ages. Pearson correlation coefficients were also calculated between stand volume at 7 years of age in BL_0, BL_1, BL_2, BL_3, and residue dry matter, N, P, K, Ca and Mg contents in the slash and litter at planting. A 5% level of significance was used.

Results

Slash Deposition and Decomposition

Slash and litter management treatments led to significant differences in slash and litter mass at the soil surface ranging from 0 t ha^{-1} in BL_0

to 46.5 t ha^{-1} in BL$_3$ (Table 2). The amount in the BL$_1$ treatment was about half that of BL$_2$ and BL$_4$, and a third of that in BL$_3$ (Table 2). Sequential samplings showed a 50% loss in slash and litter mass occurred within 6 to 8 months after clearcutting irrespective of treatment. Most leaves and bark had decomposed and the remaining slash was mainly dead branches (data not shown).

Mineral content of slash varied with time, depending on the nutrient concerned. Potassium and P were released rapidly during the decomposition process, but Ca was released slowly (Fig. 1). Nitrogen and Mg releases were intermediate and followed mainly changes in dry matter amounts. The amount of nutrients released during slash and litter decomposition varied considerably between treatments. Maximum values (329 kg N ha^{-1}, 41

Table 1. Summary of analysis of variance of stand characteristics by treatment and block

	Treatments		Block		SE
	df	F	df	F	
Harvest residues					
Slash and litter mass (t ha^{-1})	3	1185.1**	1	158.4**	0.22
N (kg ha^{-1})	3	270.8**	1	76.4**	3.6
P (k ha^{-1})	3	5393.1**	1	133.6**	0.1
K (kg ha^{-1})	3	18068.9**	1	7.1*	0.2
Ca (kg ha^{-1})	3	214.6**	1	12.0**	1.1
Mg (kg ha^{-1})	3	497.7**	1	4.0	0.5
Stand characteristics					
	Tree growth				
11 months					
Height (m)	5	3.03*	3	3.175	0.08
DBH (cm)	5	3.83*	3	3.284	0.11
Volume (m^3 ha^{-1})	5	3.27*	3	3.084	0.3
36 months					
Height (m)	5	8.48**	3	4.177*	0.17
DBH (cm)	5	9.01**	3	2.530	0.16
Volume (m^3 ha^{-1})	5	8.40**	3	3.279	2.0
84 months					
Survival rate (%)	5	1.31	1	0.172	0.5
Height (m)	5	25.87**	1	0.774	0.18
DBH (cm)	5	21.25**	1	0.014	0.18
Volume (m^3 ha^{-1})	5	24.40**	1	0.056	3.5
	Nutrient content				
11 months					
N (kg ha^{-1})	3	10.39**	3	3.71	2.1
P (k ha^{-1})	3	29.94**	3	3.94*	0.2
K (kg ha^{-1})	3	16.07**	3	3.73	0.7
Ca (kg ha^{-1})	3	38.42**	3	3.71	0.8
Mg (kg ha^{-1})	3	70.90**	3	3.87*	0.6
36 months					
N (kg ha^{-1})	3	24.29***	3	1.17	11.7
P (k ha^{-1})	3	37.50***	3	1.00	1.5
K (kg ha^{-1})	3	27.57***	3	1.17	4.1
Ca (kg ha^{-1})	3	41.94***	3	0.92	4.3
Mg (kg ha^{-1})	3	34.88***	3	1.07	2.3

Significant effects are indicated with asterisks (***$p \leq 0.001$; **$p \leq 0.01$; * $p \leq 0.05$) and standard errors are given (SE).

Table 2. Mass and nutrient contents of the forest floor and slash deposited at the soil surface in BL$_1$, BL$_2$, BL$_3$, and BL$_4$ at the harvest of the previous stand in 1998. Slash and litter above the mineral soil was removed in BL$_0$ plots before planting and organic matter mass, N, P, K, Ca and Mg contents were therefore zero. Burning of slash and litter was almost complete in BL$_5$ and N, P, K, Ca and Mg contents in ash deposited at the soil surface were not quantified

	Treatments			
	BL$_1$	BL$_2$	BL$_3$	BL$_4$
Slash and litter mass (t ha^{-1})	13.7^{d}	25.2^{c}	46.5^{a}	31.4^{b}
N (kg ha^{-1})	114.8^{d}	212.3^{c}	369.4^{a}	249.7^{b}
P (k ha^{-1})	7.6^{d}	18.6^{c}	43.2^{a}	28.5^{b}
K (kg ha^{-1})	11.0^{d}	40.8^{c}	100.8^{a}	62.9^{b}
Ca (kg ha^{-1})	33.2^{c}	43.2^{c}	94.8^{a}	78.6^{b}
Mg (kg ha^{-1})	18.2^{d}	26.4^{c}	59.0^{a}	45.3^{b}

Letters ^{a}, ^{b} and ^{c} indicate significant differences ($p < 0.05$) between treatments according to Bonferroni test.

Table 3. Mean height, diameter at breast height (DBH) and mean annual increment (MAI) of trees in the different treatments, at 11, 24, 36, 48, 62, 72 and 84 months after installation of the experiment

	Treatments					
	BL$_0$	BL$_1$	BL$_2$	BL$_3$	BL$_4$	BL$_5$
11 months						
Height (m)	4.9^{b}	4.9^{b}	5.0^{b}	5.6^{ab}	5.3^{ab}	5.8^{a}
DBH (cm)	4.8^{b}	4.9^{b}	5.1^{b}	6.0^{a}	5.6^{ab}	6.2^{a}
MAI (m^3 ha^{-1} yr^{-1})	4.7^{b}	4.8^{b}	5.4^{b}	8.0^{a}	6.7^{ab}	8.7^{a}
36 months						
Height (m)	12.7^{b}	13.9^{ab}	14.8^{a}	15.9^{a}	15.4^{a}	15.1^{a}
CBH (cm)	28.0^{c}	31.2^{bc}	33.8^{ab}	37.7^{a}	35.8^{ab}	34.8^{ab}
MAI (m^3 ha^{-1} yr^{-1})	10.9^{c}	14.3^{bc}	17.7^{abc}	22.6^{a}	20.4^{ab}	18.7^{ab}
84 months						
Survival rate (%)	99.6^{a}	97.1^{a}	98.8^{a}	99.2^{a}	99.6^{a}	99.2^{a}
Height (m)	20.2^{c}	21.9^{bc}	22.6^{ab}	24.4^{a}	23.6^{ab}	23.0^{ab}
DBH (cm)	11.7^{c}	13.1^{bc}	14.0^{ab}	15.4^{a}	14.7^{ab}	13.8^{abc}
MAI (m^3 ha^{-1} yr^{-1})	12.0^{c}	15.6^{bc}	18.0^{ab}	23.0^{a}	20.9^{ab}	18.1^{ab}

Letters ^{a}, ^{b} and ^{c} indicate significant differences ($p < 0.05$) between treatments according to Bonferroni test.

kg P ha^{-1}, 99 kg K ha^{-1}, 73 kg Ca ha^{-1} and 52 kg Mg ha^{-1}) were reached in BL$_3$ 20 months after the initial harvest.

Tree Growth and Biomass Accumulation

The amount of organic matter left at the soil surface after the harvest of the previous stand had a significant effect on tree growth throughout the rotation (Table 1). Growth differences among treatments were observed by age 1 year and increased with stand age (Fig. 2). The survival rate at 84 months of age was >97% and did not influence the comparisons between treatments (Table 1). Ranking was the same throughout the development of the stands, except for BL$_5$. Burning the slash and litter increased early tree growth as the greatest height, DBH and aboveground biomass were measured in BL$_5$, 11 months after planting. However, growth in this treatment slowed compared to treatments where high amounts of organic matter were retained at the soil surface (BL$_3$ and BL$_4$) from 2 years onwards. Poorest growth was observed in BL$_0$ at 11 months and the differences with other treatments increased throughout the rotation (Fig. 2). At 3 years, total aboveground biomass was 40% lower in BL$_0$ than in BL$_3$ and BL$_4$ (19.9 t ha^{-1} *vs* 35.0 t ha^{-1}), and BL$_5$ was no longer the most productive treatment (29.8 t ha^{-1}). The mean annual increment (MAI) was 30% lower in BL$_0$ than in the treatment representative of commercial silviculture (BL$_4$) at 11 months of age and 43% lower 84 months after planting.

Nutrient Contents in the Stands

Slash and litter management treatments had a large effect on nutrient contents in the aboveground biomass from the first year of growth (Fig. 3). Amounts of P, K, Ca and Mg in BL$_0$ were only half of those in BL$_3$, 1 and 3 years after

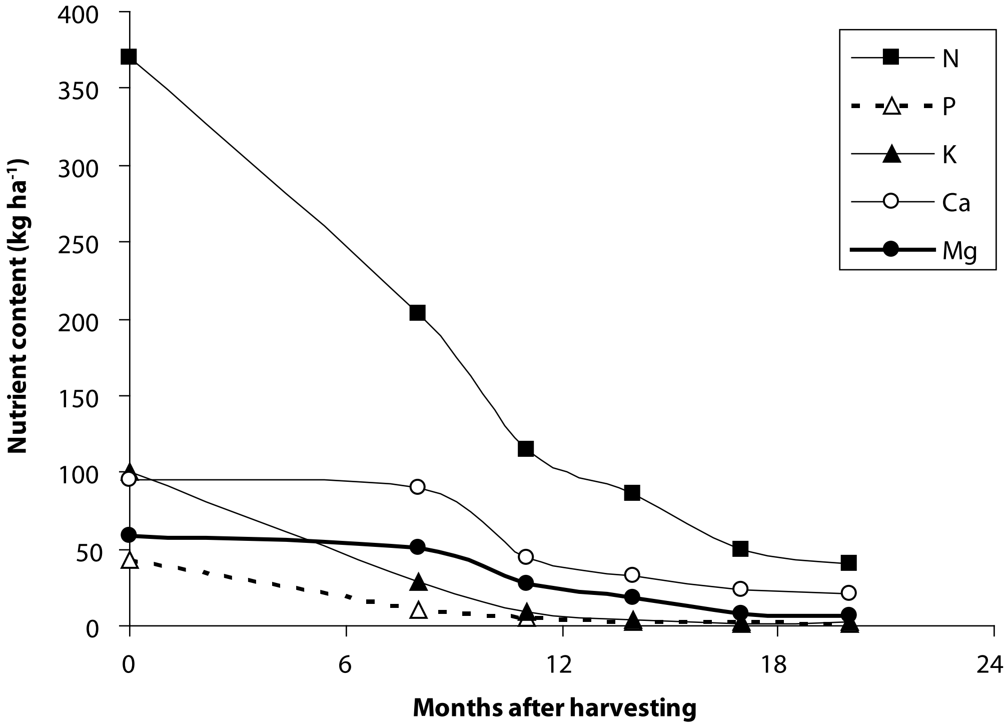


Figure 1. Time-course of nutrient content in the organic matter above the mineral soil over 20 months after harvesting in BL$_3$

planting. Effects of treatments on N accumulation in the trees were different to the other nutrients since the N content in BL_5 was significantly higher than in BL_0, BL_3 and BL_4 1 year after planting, but about 40% lower than in BL_3 and BL_4 after 3 years (Fig. 3). Nitrogen, P, K, Ca and Mg contents in the aboveground biomass were not significantly different between the treatments where litter and slash were removed (BL_0) or burnt at the site (BL_5) at 3 years of age. The higher amount of organic matter left at the soil surface in BL_3 than in BL_4 led to an increase in N (13 kg ha^{-1}), P (3 kg ha^{-1}), K (13 kg ha^{-1}), Ca (22 kg ha^{-1}) and Mg (6 kg ha^{-1}) in the aboveground biomass (Fig. 3).

Nutrient Contents in the Soils

Comparison of soil analyses performed in 2003 and in 2006 on the same set of 27 samples showed significant differences in exchangeable Ca, K, Na, Al and H concentrations as well as for the effective CEC values (Table 4). By contrast, storage conditions from 2003 to 2006 did not modify significantly the values of organic C, total N, exchangeable Mg concentrations, as well as the saturation rate estimations. Even when element concentrations were significantly different between the series of chemical analyses, the discrepancies on mean values were lower than 0.03 cmol$_c$ kg^{-1} (except for exchangeable Al).

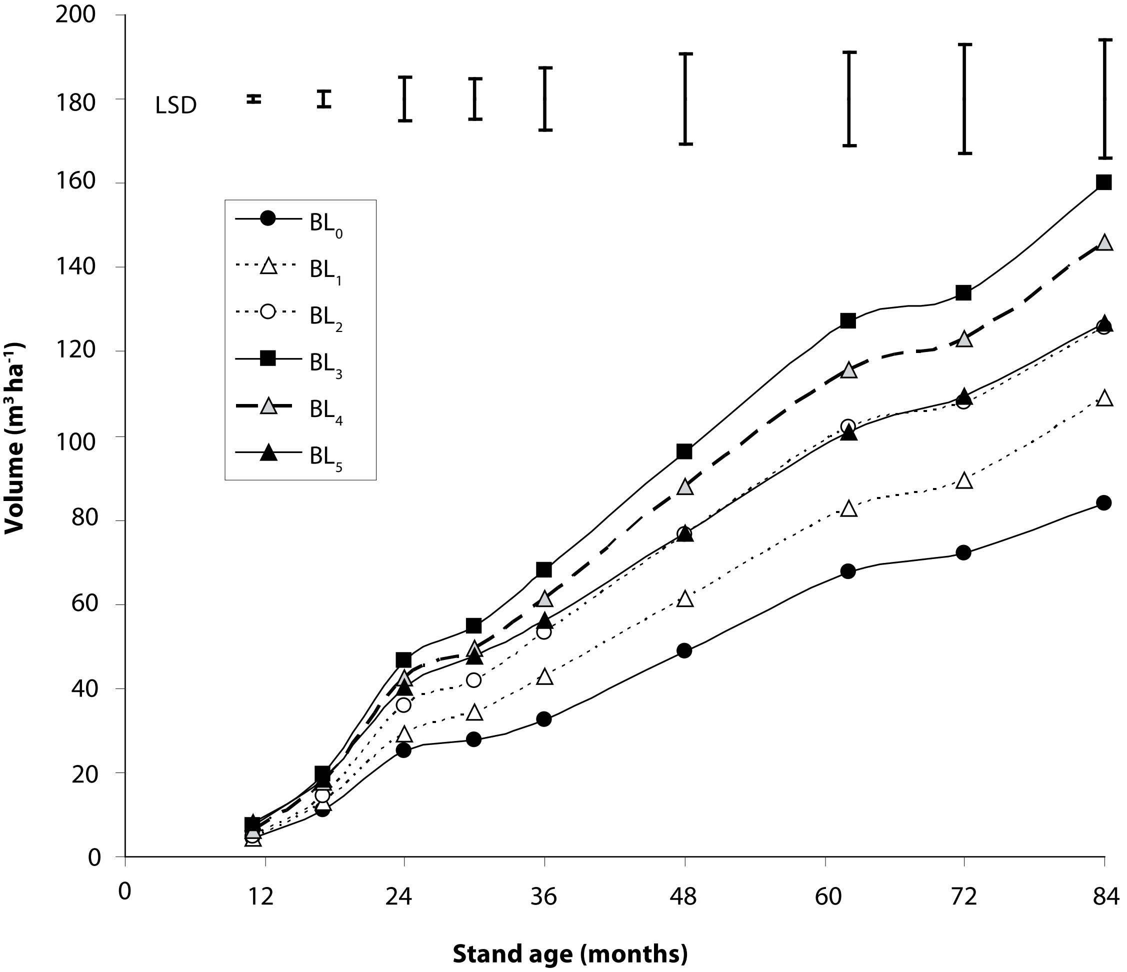
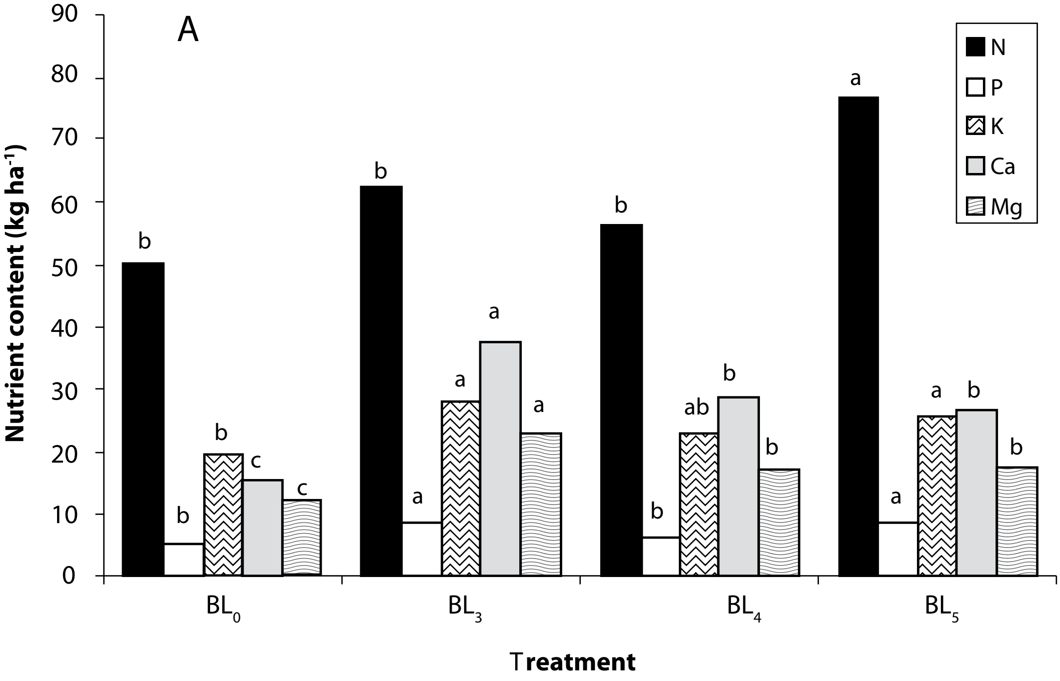


Figure 2. Mean volume development for all treatments. Vertical bars represent the least significant difference (*p*=0.05) for each measurement



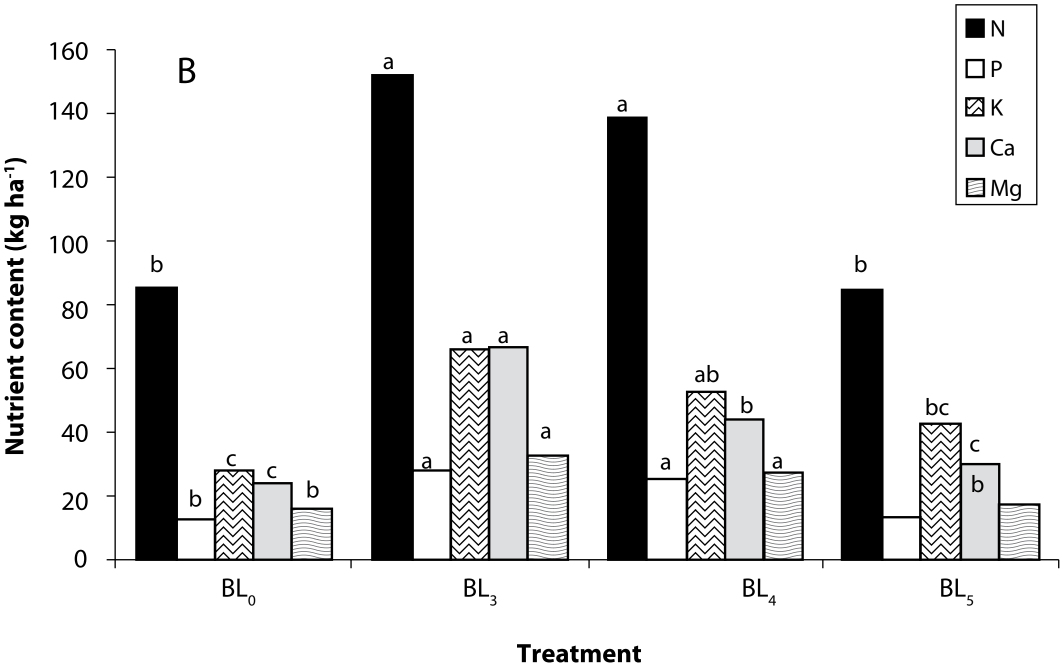


Figure 3. Nutrient content aboveground in BL_0, BL_3, BL_4 and BL_5 at 11 months (A) and 36 months (B) after planting. Different letters between treatments for the same nutrient indicate significant differences at 5% (Bonferroni test)

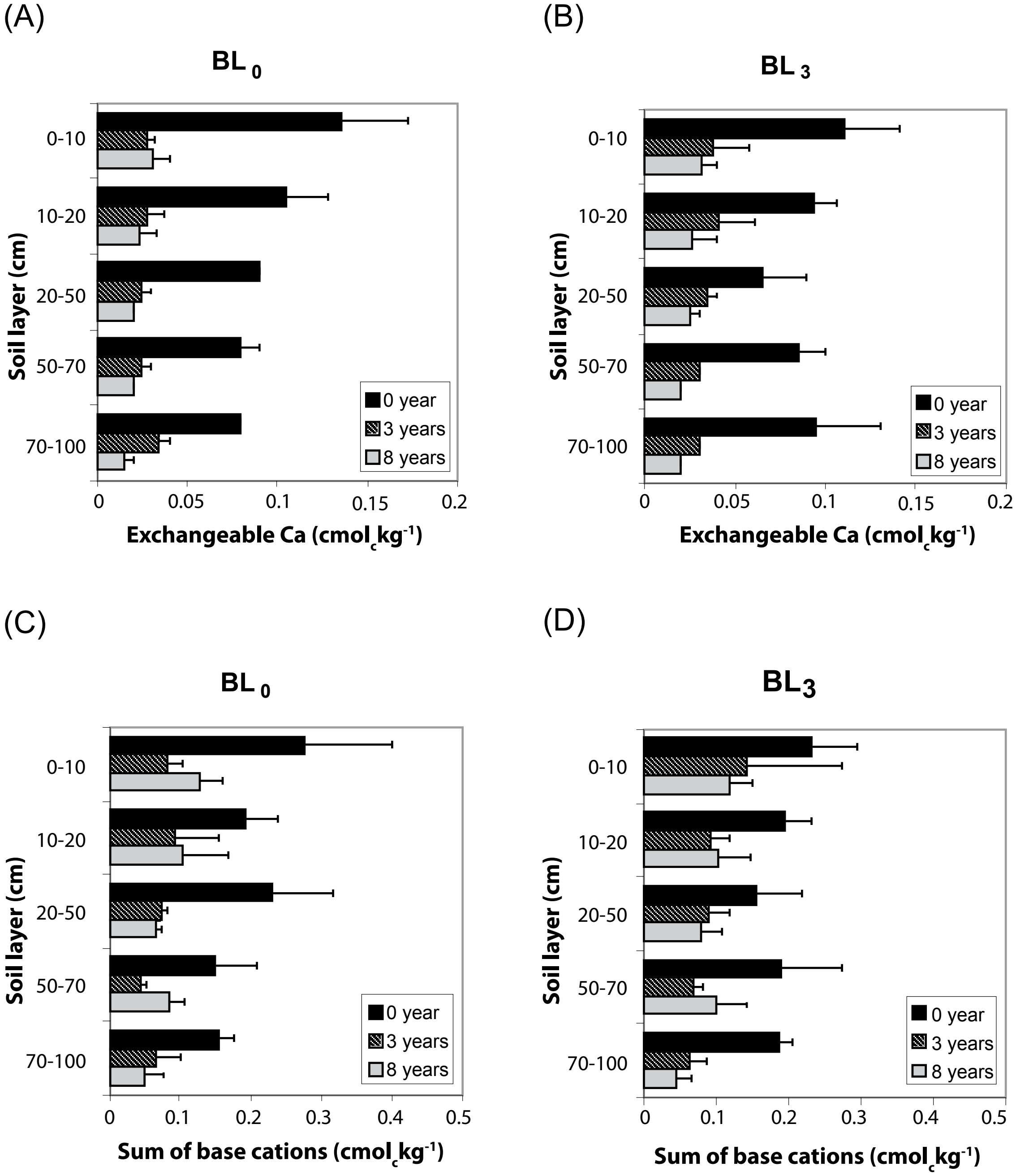


Figure 4. Changes in exchangeable Ca concentrations with stand age in BL_0 (A) and BL_3 (B), and changes in the sum of exchangeable bases concentrations with stand age in BL_0 (C) and BL_3 (D). Horizontal bars equal 1 standard deviation (*n*=8 in the soil layers 0-10 cm and 10-20 cm; *n*=2 in the layers 20-50 cm, 50-70 cm and 70-100 cm)

Table 4. Comparison of soil analysis performed in 2003 and 2006 for the same set of 27 soil samples randomly selected in the first series of analyses and submitted to different storage conditions. Mean concentrations for the 27 samples are indicated

Soil properties	Series 1 Samples analysed in 2003.	Series 2 Samples re-analysed in 2006. Stored in Congo.	Series 3 Samples re-analysed in 2006. Stored in France.
Organic C (g kg^{-1})	5.40 a	5.44 a	
Total N (g kg^{-1})	0.331 a	0.327 a	
Exchangeable Ca (cmol$_c$ kg^{-1})	0.050 b	0.077 a	0.070 a
Exchangeable Mg (cmol$_c$ kg^{-1})	0.037 a	0.035 a	0.034 a
Exchangeable K (cmol$_c$ kg^{-1})	0.023 b	0.036 a	0.028 ab
Exchangeable Na (cmol$_c$ kg^{-1})	0.016 b	0.026 a	0.033 a
Exchangeable Al (cmol$_c$ kg^{-1})	0.278 b	0.323 a	0.193 c
Exchangeable H (cmol$_c$ kg^{-1})	0.088 a	0.079 b	0.061 c
Sum of base cations (cmol$_c$ kg^{-1})	0.125 b	0.170 a	0.165 a
ECEC (cmol$_c$ kg^{-1})	0.438 c	0.634 a	0.587 b
Saturation Rate (%)	28.3 a	27.1 a	27.8 a

Letters ^{a}, ^{b} and ^{c} indicate significant differences ($p < 0.05$) between series according to Bonferroni test.

The large difference in slash and litter amounts between treatments (from 0 to 46.5 t ha^{-1}) led to significant changes in organic C, total N, exchangeable Mg and Na concentrations in the 0-10 cm soil layer sampled at 1 year (Table 5). Organic C and total N concentrations were significantly lower in BL$_0$ than in BL$_4$ and exchangeable Mg concentration and saturation rate were significantly lower in BL$_0$ than in the other treatments. Soil chemical properties were not significantly modified by slash and litter management treatments beyond a depth of 10 cm whatever the stand age (data not shown). Differences between treatments in soil C and nutrient concentrations were no longer significant at 3 years, however. A significant effect of treatments appeared in the 0-10 cm soil layer 8 years after planting: concentrations of exchangeable Ca and Mg were significantly higher in BL$_5$ than in BL$_0$, BL$_3$ and BL$_4$.

A highly significant age effect was observed (p<0.01) in the 0-10 cm and 10-20 cm soil layers for exchangeable Ca and Mg contents as well as for the sum of exchangeable base cations. The age x treatment interaction was only significant for exchangeable Ca and Mg concentrations in the 0-10 cm soil layer (Table 5). Largest changes in nutrient concentrations throughout the rotation were from 0 to 3 years after treatment establishment for exchangeable Ca concentrations down to a depth of 1 m (Fig. 4). The same pattern occurred for the other base cations but was less pronounced. From age 3 to 8 years, the concentrations of all exchangeable cations analysed remained about the same in all the soil layers. Organic C, total N, exchangeable K and exchangeable Na concentrations were not significantly different 0, 3 and 8 years after installation of the experiment in the 0-10 cm and 10-20 cm soil layers.

Despite extensive sampling it was not possible to detect a clear influence of the slash and litter management treatments on the stocks of most elements in the soil (Table 6). The highest temporal changes were observed for exchangeable

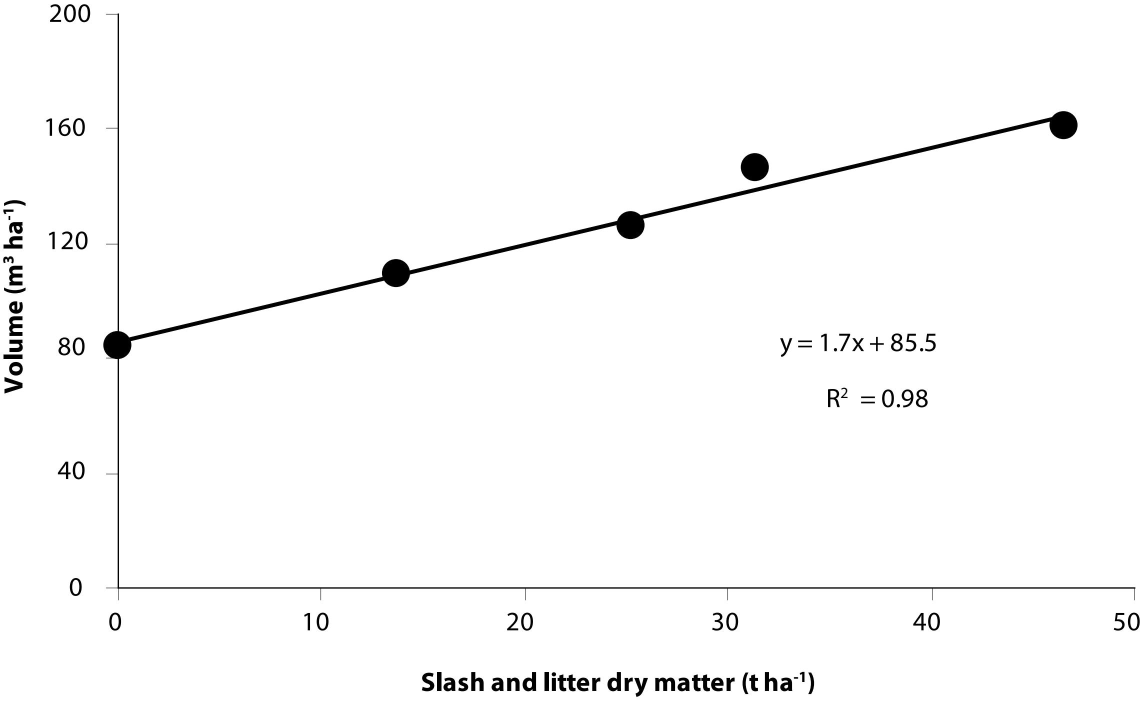


Figure 5. Relationship between slash and litter dry matter at treatment establishment and stand volume at seven years of age in the BL_0, BL_1, BL_2, BL_3 and BL_4 treatments

Ca. The amount of exchangeable Ca in the mineral soil down to a depth of 1 m was about 65% lower 3 years after treatment establishment than at the end of the previous rotation. The corresponding reduction for K and Mg was about 50%. Stocks of exchangeable K, Ca, Mg and Na remained about the same from 3 to 8 years and were about 150 kg ha^{-1} (K), 80 kg ha^{-1} (Ca), 25 kg ha^{-1} (Mg) and 80 kg ha^{-1} (Na) to a depth of 1 m. Even if treatments led to large differences in C and N inputs at the soil surface, changes in organic C and total N stocks in the mineral soil were low. A trend of decreasing organic C and total N with stand age was observed but this trend was not significant.

Relationship between Tree Growth and Nutrient Contents in Soils and Harvest Residues

There was no relationship between stand volumes at 7 years in all treatments with any of the soil properties measured in the 0-10 cm soil layer, nor with stocks of these elements in the soil to 1 m depth, irrespective of the age of the stand when soils were sampled. By contrast, a highly significant correlation ($p<0.01$) was observed between stand volume and the amount of slash and litter retained (Fig. 5). Similarly, stand volume correlated strongly with the amounts of N, P, K, Ca and Mg contents in organic matter (R range 0.96-0.99).

Table 5. Summary of analysis of variance of soil chemical attributes in 0-10 and 10-20 cm depths. Repeated measures analysis were performed for the BL_0 and BL_3 treatments and two-way ANOVA at each age were made for the BL_0, BL_3, BL_4 and BL_5 treatments

	Treatments		Block		Stand age		Interaction[1]	
	df	F	df	F	df	F	df	F
Repeated measures analysis								
Soil layer 0–10 cm								
C (g kg^{-1})	1	0.02	1	19.1**	2	1.4	2	1.1
N (g kg^{-1})	1	0.1	1	34.7**	2	0.7	2	0.5
K (cmol$_c$ kg^{-1})	1	0.8	1	0.02	2	0.9	2	0.9
Ca (cmol$_c$ kg^{-1})	1	2.1	1	12.5**	2	99.3**	2	3.7*
Mg (cmol$_c$ kg^{-1})	1	0.3	1	46.5**	2	9.6**	2	6.0*
Na (cmol$_c$ kg^{-1})	1	0.3	1	0.3	2	1.5	2	1.1
Soil layer 10–20 cm								
C (g kg^{-1})	1	0.2	1	9.5**	2	2.2	2	1.0
N (g kg^{-1})	1	1.0	1	16.7**	2	3.4*	2	0.8
K (cmol$_c$ kg^{-1})	1	0.1	1	0.6	2	0.4	2	0.8
Ca (cmol$_c$ kg^{-1})	1	0.2	1	1.0	2	81.1**	2	1.9
Mg (cmol$_c$ kg^{-1})	1	2.1	1	6.0*	2	33.7**	2	2.7
Na (cmol$_c$ kg^{-1})	1	0.1	1	1.3	2	4.4*	2	1.4
1 year after treatment establishment (soil layer 0–10 cm)								
C (g kg^{-1})	3	3.2*	1	21.9**			3	8.8**
N (g kg^{-1})	3	4.6*	1	22.3**			3	7.0**
K (cmol$_c$ kg^{-1})	3	0.8	1	6.6*			3	4.6*
Ca (cmol$_c$ kg^{-1})	3	1.4	1	0.4			3	1.4
Mg (cmol$_c$ kg^{-1})	3	5.2**	1	3.0			3	5.6**
Na (cmol$_c$ kg^{-1})	3	4.5*	1	0.7			3	0.3
3 years after treatment establishment (soil layer 0–10 cm)								
C (g kg^{-1})	3	1.3	1	9.8**			3	10.4**
N (g kg^{-1})	3	1.1	1	7.0*			3	6.5**
K (cmol$_c$ kg^{-1})	3	0.5	1	0.04			3	0.9
Ca (cmol$_c$ kg^{-1})	3	1.9	1	0.2			3	1.8
Mg (cmol$_c$ kg^{-1})	3	2.8	1	2.6			3	0.6
Na (cmol$_c$ kg^{-1})	3	0.5	1	1.9			3	1.3
8 years after treatment establishment (soil layer 0–10 cm)								
C (g kg^{-1})	3	0.5	1	8.7**			3	7.3*
N (g kg^{-1})	3	0.7	1	15.8**			3	6.2**
K (cmol$_c$ kg^{-1})	3	0.04	1	0.00			3	0.2
Ca (cmol$_c$ kg^{-1})	3	6.8**	1	0.5			3	2.3
Mg (cmol$_c$ kg^{-1})	3	12.5**	1	0.1			3	2.3
Na (cmol$_c$ kg^{-1})	3	1.4	1	0.5			3	0.2

Significant effects are indicated with asterisks (**$p \leq 0.01$; * $p \leq 0.05$).

[1] Treatment x Date for repeated measures analysis and Treatment x Block for the ANOVA at each age.

Table 6. Organic carbon (OC) and nutrient stocks in the soil (0-100 cm) before harvesting the first rotation, and at 3 years and 8 years after establishment of the site management experiment (second rotation)

Soil characteristics	Years after harvesting	BL_0		BL_3		BL_4		BL_5	
		Block 1	Block 3	Block 1	Block 3	Block 1	Block 3	Block 1	Block 3
OC (t ha^{-1})	0	53.1	45.5	47.6	44.8				
	3	54.4	40.8	50.6	45.8	47.1	49.6	47.8	44.9
	8	45.0	40.0	40.8	40.9	41.9	42.8	42.1	38.4
Total N (kg ha^{-1})	0	3090	2420	3050	2950				
	3	3150	1990	3120	2340	2640	2580	2600	2300
	8	2090	1950	2240	2190	2200	2320	2000	2260
Exc. Ca (kg ha^{-1})	0	267	260	315	179				
	3	88	77	98	95	92	76	72	59
	8	60	55	74	60	61	149	75	105
Exc. Mg (kg ha^{-1})	0	50	42	43	23				
	3	23	13	27	18	20	25	28	15
	8	14	39	19	31	19	33	23	35
Exc. K (kg ha^{-1})	0	357	196	269	148				
	3	133	135	137	134	103	124	167	127
	8	121	101	140	154	150	168	80	322
Exc. Na (kg ha^{-1})	0	78	94	126	133				
	3	74	93	94	84	72	72	91	107
	8	94	62	82	52	58	69	67	270

Discussion

Influence of Inter-rotation Management Practices on Stand Growth

Stand productivity was substantially influenced by slash and litter management treatments on this Ferralic Arenosol. Moreover, growth response to the treatments was higher than in other experiments of the CIFOR network (see this volume). Stand basal area was 73% higher in BL_3 than in BL_0 at the end of the eucalypt rotation in Congo, compared to 41% higher in Brazil, 35% in South Africa and 22% in India-Kayampoovam (Saint-André *et al.* 2007). Tree volume at the grey sand site in Australia was 40-60% higher in BL_3 treatment than in the BL_0 from year 3 (Mendham *et al.* 2003). The impact of slash and litter management on productivity was much lower in other experiments in India and on the red earth site in Australia. A general pattern of relative decrease in tree response to slash and litter management practices when soil fertility is correspondingly high was observed in the network of experiments (Saint-André *et al.* 2007). The influence of slash and litter management practices on stand productivity has also been observed for other forest species under temperate climatic conditions. A common experimental design encompassing a wide range of climate, site conditions, and forest types in northern America showed that forest-floor removal improved seedling survival and increased growth in Mediterranean climates, but reduced growth on productive, nutrient-limited, warm-humid sites (Fleming *et al.* 2006).

The main processes influencing tree growth response to slash and litter management practices are likely to be related to soil microclimate and nutrient availability. Changes in soil moisture and soil temperature according to slash and litter management treatments were observed in *E. globulus* plantations (O'Connell and Grove 1999, Mendham *et al.* 2003). A mulching effect reducing soil evaporation was likely to increase soil water content in the top soil when slash and litter from the previous rotation were retained (Matthews 2005). Soil moisture and soil temperature were not monitored in the present experiment, but the lack of significant differences in N mineralisation *in situ* from 7 to 24 months after planting between treatments suggests soil microclimate may not have been strongly modified (Nzila *et al.* 2002). The low air vapour pressure deficit during the whole year (air humidity >80%) associated with a rapid infiltration of rainfall in this sandy soil are unlikely to pose severe limitations to early tree growth due to soil evaporation. The highest aboveground biomass at 11 months after planting was observed in BL_5 where all organic matter had been removed by the burning. The large difference in tree growth between BL_0 and BL_5 during the first year after planting showed the great influence of burning on nutrient availability. Thereafter, slash decay, litterfall and canopy development of the stands led to similar conditions for soil evaporation between treatments. We conclude that the large effect of site management treatments on tree growth (Fig. 2) observed throughout the whole rotation was mainly as a result of modifications to nutrient availability and not related to water availability in soil.

Slash Management Effects on Soil Carbon and Nutrients

Phosphorus content (Duchaufour and Bonneau 1959) at the end of the first rotation of an adjacent stand was estimated at 392 kg ha^{-1} in the top 1 m of soil and 2720 kg ha^{-1} down to a depth of 6 m, where eucalypt roots were observed (Laclau 2001). Therefore, P amounts in slash and litter were very much lower than in the mineral soil and were unlikely to strongly influence tree growth after planting. Soil P availability is relatively high in this region and response to soluble P fertiliser is not common (Bouillet *et al.* 2004).

Carbon, N, K, Ca and Mg contents in slash and litter representing the current harvest practice (BL_4) amounted to 31% of organic C, 9% of N, 25% of K, 32% of Ca and 112% of Mg of pools in the top 1 m of soil prior to harvest (Tables 2 and 6). Despite this, C and nutrients in the soil were little influenced by the treatments. Significant changes in total N and base cation concentrations were observed the first year after treatment establishment but only in the 0-10 cm soil layer and not at year 3 (Table 5). The lowest organic carbon, total N and base cation concentrations in the upper layer 1 year after treatment establishment were observed in the BL_0 treatment. Only the exchangeable cation pools in the soil could supply the high nutrient requirement for canopy and fine root development at this stage. The highest concentrations of exchangeable Ca and Mg in the 0-10 cm soil layer of the BL_5 treatment at 1 year were a result of the mineralisation of nutrients occurring during burning that increased their amount in the topsoil as observed by Mendham *et al.* (2003) in Australia. This finding is consistent with the best initial tree growth in the BL_5 treatment.

Exchangeable K, Ca and Mg concentrations in the 0-20 cm soil layer (about 0.03 $cmol_c$ kg^{-1}) were at the lowest end of a range of optimum nutrient values for tree growth indicated by Gonçalves *et al.* (1997) for soils representative of those used for eucalypt plantations in tropical Brazil. Stocks of organic C, total N, exchangeable K, Ca and Mg in the 0-20 cm soil layer of the BL_0 treatment in the present study amounted to only 19%, 17%, 36%, 2% and 7%, respectively, of those measured at 7 years of age in the same treatment established on a Rhodic Ferralsol in Australia, and 21%, 27%, 72%, 2%, 5% on a Haplic Podzol (Mendham *et al.* 2003). Input-output budgets established in Congo's eucalypt plantations for the first rotation after planting were approximately balanced for K, Ca and Mg as a result of the high nutrient use efficiency of the clone and the low quantities removed with stemwood at the harvest (Laclau *et al.* 2000, 2005). However, the extremely low concentrations of exchangeable Ca and Mg in the soil of the present experiment suggest that, whatever the harvest slash and litter management treatment and considering the considerable decrease down to a depth of 1 m after planting the second rotation, these elements in the ecosystem need closely monitoring.

Conclusions

Production of clonal eucalypt plantations established on sandy soils low in fertility in the Congo ranged from 84 m^3 ha^{-1} to 161 m^3 ha^{-1} seven years after planting, depending on the slash and litter management practices during the inter rotation period. Production could be accurately predicted from the dry matter of slash and litter at planting. This study highlights the importance of taking into account the nutrient pools in harvesting residues as well as the history of the plots to enable site-specific fertiliser inputs.

Most nutrients in slash and litter were mineralised during the first two years after harvesting and this supply was crucial from the first months of growth. Differences in nutrient quantities in this pool might account for the effects of treatments on tree growth throughout the rotation. However, the large differences in C and nutrient inputs between the treatments had little impact on soil-nutrient pools.

This experiment demonstrated the great positive influence of: (1) debarking stems in-field and spreading the bark; (2) retaining stem tops on the site; (3) avoiding slash burning; and, (4) reducing the delay between stand harvesting and crop planting. Such practices are currently used in Congolese eucalypt plantations. The large decrease in base cation concentrations in this soil showed that fertilisers will need to be applied to maintain high stand productivity.

Current knowledge on nutrient bio-availability in tropical forest soils remains limited. Manipulation of ecosystems including contrasted slash and litter management practices, non-limiting nutrient inputs, and fertilisation experiments should help in better assessments of pools of available nutrients in tropical plantation forests. Among the areas of forest ecosystem functioning not addressed in this study, root activity in deep soil horizons requires particular attention. Root systems are very deep in eucalypt plantations established on highly weathered soils and the capacity of the considerable volume of soil to buffer effects of management practices remains little understood. Physiological processes involved in nutrient uptake and nutrient retranslocations within trees are key issues in the future to improve forest management practices.

After clearcutting of the second rotation in February 2006, the trial was replanted identically in May 2006 to the same spacing and with the same clone. The same treatments were applied at the same locations. Only the BL_2 treatment was modified to manage a coppice stand. This new trial will study the cumulative effects of slash and litter management practices on tree growth over successive rotations.

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References

Bird, M.I., Veenendaal, E.M., Moyo, C., Lloyd, J. and Frost, P. 2000. Effect of fire and soil texture on soil carbon in a sub-humid savanna (Matopos, Zimbabwe). Geoderma 94:71–90.

Bouillet, J.P., Nzila, J.D., Ranger, R., Laclau, J.P. and Nizinski, G. 1999. Sustainability of *Eucalyptus* plantations in the Equatorial Zone, on the Coastal Plains of the Congo. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa, 13-21. Center for International Forestry Research, Bogor, Indonesia.

Bouillet, J.P., Nzila, J.D., Laclau, J.P. and Ranger, R. 2000. Effects of site management on *Eucalyptus* Plantations in the Equatorial Zone, on the Coastal Plains of the Congo. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 11-20. Center for International Forestry Research, Bogor, Indonesia.

Bouillet, J.P., Safou-Matondo, R., Laclau, J.P., Nzila, J.D., Ranger, J. and Deleporte, P. 2004. Pour une production durable des plantations d'eucalyptus au Congo : la fertilisation. Bois et Forêts des Tropiques 279: 23-35.

Duchaufour, P. and Bonneau, M. 1959. Une nouvelle méthode de dosage du phosphore assimilable dans les sols forestiers. French Association of Soil Science Bulletin 4: 193-198.

Epron, D. *et al*. 2006. Soil carbon balance in a clonal *Eucalyptus* plantation in Congo: effects of logging on carbon inputs and soil CO_2 efflux. Global Change Biology 12:1021–1031.

Feller, C. and Beare, M.H. 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69-116.

Fisher, R.F. and Binkley, D. 2000. Ecology and management of forest soils. Wiley, New York, USA. 489p.

Fleming, R.L. *et al*. 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of Long-Term Soil Productivity sites. Canadian Journal of Forest Research 36:529-550.

Gomat, H.Y. 2006. Etablissement de tarifs individuels de cubage sur et sous écorce à partir de profils en long des tiges. Application à 5 clones de *Eucalyptus*. DEA Sciences Biologiques, University Marien Ngouabi, Brazzaville, Congo. 30p.

Gonçalves, J.L.M., Barros, N.F., Nambiar, E.K.S. and Novais, R.F. 1997. Soil and stand management for short-rotation plantations. *In:* Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests, 379-418. ACIAR Monograph No. 43. Australian Centre for International Agriculture Research, Canberra.

Gonçalves, J.L.M., Poggiani, F., Stape, J.L., Serrano, M.I.P.S., Mello, S.L.M., Mendes, K.C.F.S., Gava, J.L. and Benedetti, V. 1999. Eucalypt plantations in the humid tropics: São Paulo, Brazil. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa, 5-12. Center for International Forestry Research, Bogor, Indonesia.

Laclau, J.P. 2001. Dynamique du fonctionnement minéral d'une plantation d'eucalyptus. Effet du reboisement sur un sol de savane du littoral congolais; conséquences pour la gestion des plantations industrielles. Thèse de Doctorat, INA-PG, Paris. 146p.

Laclau, J.P., Bouillet, J.P. and Ranger, J. 2000. Dynamics of biomass and nutrient accumulation in a clonal plantation of *Eucalyptus* in Congo. Forest Ecology and Management 128:181-196.

Laclau, J.P., Deleporte, P., Ranger, J., Bouillet, J.P. and Kazotti, G. 2003a. Nutrient dynamics throughout the rotation of *Eucalyptus* clonal stands in Congo. Annals of Botany 91:879-892.

Laclau, J.P., Ranger, J., Bouillet, J.P., Nzila, J.D. and Deleporte, P. 2003b. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo. 1. Chemical composition of rainfall, throughfall and stemflow solutions. Forest Ecology and Management 176:105-119.

Laclau, J.P., Ranger, J., Nzila, J.D., Bouillet, J.P. and Deleporte, P. 2003c. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo. 2. Chemical composition of soil solutions. Forest Ecology and Management 180:527-544.

Laclau, J.P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-André, L., Marlet, S. and Bouillet, J.P. 2005. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo. 3. Input–output budgets and consequences for the sustainability of the plantations. Forest Ecology and Management 210:375–391.

Landais, D. 2003. Etudes quantitatives et qualitatives du carbone séquestré dans le sol après afforestation au Congo-Brazzaville. DESS Sciences de l'Environnement, University Louis Pasteur, Strasbourg, France. 33p.

Loumeto, J.J. and Huttel, C. 1997. Understory vegetation in fast-growing tree plantations on savanna soils in Congo. Forest Ecology and Management 99:65-81.

Matthews, S. 2005. The water vapour conductance of *Eucalyptus* litter layers. Agricultural and Forest Meteorology 135:73-81.

Mboukou-Kimbatsa, I.M.C., Bernhard-Reversat, F. and Loumeto, J.J. 1998. Change in soil macrofauna and vegetation when fast-growing trees are planted on savanna soils. Forest Ecology and Management 110:1-12.

Mendham, D.S., O'Connell, A.M., Grove, T.S. and Rance, S.J. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management 181:357-372.

Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) 2004. Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, Center for International Forestry Research, Bogor, Indonesia. 226p.

Nouvellon, Y., Saint-André L., Bouillet, J.P. and Hamel, O. 2006. Carbon sequestration in fast-growing tree plantations. ULCOS Project Report – First Phase SP7 - WP 1.2. Technical Report N° 5. CIRAD, France. 44p.

Nzila, J.D., Bouillet, J.P., Laclau, J.P. and Ranger, J. 2002. The effects of slash management on nutrient cycling and tree growth in *Eucalyptus* plantations in the Congo. Forest Ecology and Management 171:209-221.

Nzila, J.D., Deleporte, P., Bouillet, J.P., Laclau, J.P. and Ranger, R. 2004. Effects of slash management on tree growth and nutrient cycling in second-rotation *Eucalyptus* replanted sites in the Congo. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 15-30. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M. and Grove, T.S. 1999. Eucalypt plantations in south-western Australia. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa, 53-59. Center for International Forestry Research, Bogor, Indonesia.

Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44:322-331.

Raison, R.J., Khanna, P.K. and Woods, P.V. 1985. Mechanisms of element transfer to the atmosphere during vegetation fires. Canadian Journal of Forest Research 15:132-140.

Safou-Matondo, R., Deleporte, P., Laclau, J.P. and Bouillet, J.P. 2005. Hybrid and clonal variability of nutrient content and nutrient use efficiency in *Eucalyptus* stands in Congo. Forest Ecology and Management 210:193-204.

Saint-André, L., Thongo M'Bou, A., Mabiala, A., Mouvondy, W., Jourdan, C., Roupsard, O., Deleporte, P., Hamel, O. and Nouvellon, Y. 2005. Age-related equations for above- and below-ground biomass of a Eucalyptus hybrid in Congo. Forest Ecology and Management 205:199-214.

Saint-André *et al*. 2007. Slash and litter management effects on *Eucalyptus* productivity: a synthesis using a growth and yield modelling approach. [These proceedings].

SAS 1998. SAS/STAT user's guide. Release 6.03 Edition. SAS Institute, Cary, North Carolina, USA. 2018p.

Schwartz, D., de Foresta, H., Mariotti, A., Balesdent, J., Massimba, J.P. and Girardin, C. 1996. Present dynamics of the savanna-forest boundary in the Congolese Mayombe : a pedological, botanical and isotopic (^{13}C and ^{14}C) study. Oecologia 106:516-524.

Trouvé, C., Mariotti, A., Schwartz, D. and Guillet, B. 1994. Soil organic carbon dynamics under *Eucalyptus* and *Pinus* planted on savannas in the Congo. Soil Biology and Biochemistry 26:287-295.

Impact of Site Management Practices on Growth of Eucalypt Plantations in the Monsoonal Tropics in Kerala, India

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Abstract

Impacts of slash management, nitrogen (N) and phosphorus (P) fertilising, weed management and legume cover-cropping on productivity of *Eucalyptus grandis* and *E. tereticornis* plantations were evaluated. Two sites typical for each species were selected and experiments planted in 1998. Trees were harvested at age 6.5 years in 2005. Slash management had no significant impact on productivity. Overall growth rates across treatments in slash management plots were 31.7-49.1 m^3 ha^{-1} yr^{-1} in *E. grandis* and 14.8-16.4 m^3 ha^{-1} yr^{-1} in *E. tereticornis* plantations. These productivity rates were higher than achieved in the previous rotation (41-143% for *E. tereticornis* and 57-252% for *E. grandis*). The increase is attributed to good quality genetic material and improved establishment of the plantations. Weed management increased yield by 76-149% in *E. tereticornis*. Cover-cropping with legumes, such as *Pueraria* and *Stylosanthes,* improved tree volume by up to 20% at one *E. tereticornis* site (Punnala) that was deficient in soil nitrogen. Reponses to N and P fertiliser varied across sites. Nitrogen application improved stem volume of *E. tereticornis* at Punnala and *E. grandis* at Surianelli. In general, the rate of application of N for maximum growth varied from 60 to 187 kg N ha^{-1} depending on site. Response to P fertiliser was small and transient. It is possible to increase volume growth of *E. grandis* by up to about 50% and *E. tereticornis* by up to about 270% over the current production levels as a base line by a combination of optimum site practices, especially weed control and nutrient addition. Slash management had little effect on soil cations at any site two years after establishment. Soil anaerobic N and N released during a long-term aerobic incubation were significantly higher in slash-retained plots compared to those without slash suggesting slash retention may improve N status of soils. Retention of slash is recommended for improving site nutrient capital since the need for conservation of organic matter and nutrients in these soils is critical. To improve and maintain productivity of eucalypt plantations in Kerala we also recommend using good quality planting stock, adoption of site management practices which conserve nutrients, judicious application of fertilisers, weed control and legume cover cropping (especially in N deficient soils).

Introduction

Eucalypt plantations in tropical and subtropical environments can be highly productive (Smethurst *et al.* 2003), but this potential productivity is seldom achieved in eucalypt plantations in India where the average yield is 6-10 m^3 ha^{-1} yr^{-1} (Lal 2003). In Kerala, the range is 7-9 m^3 ha^{-1} yr^{-1} with the south-west having lower productivity than most of India (Jayaraman and Krishnankutty 1990, Nair *et al.* 1997). India has over 8 million ha of short rotation eucalypts (FAO 2001) but at the current low productivity levels these plantations

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cannot meet India's growing demands for pulp and fuelwood.

Low plantation productivity is due to poor genetic stock, weed competition, diseases, water stress and low nutrient status of soils (Sharma *et al.* 1985, Ghosh *et al.* 1989, Kallarackal and Somen 1997). In Kerala the main eucalypts grown are *Eucalyptus tereticornis* (at lower elevations) and *E. grandis* (at 1000-2000 m asl). Rotation length is generally 6-7 years. Poor productivity has resulted in abandonment of eucalypt cultivation in parts of the state shrinking the total area of the state-owned plantations by almost half (to 25 000 ha) in about 10 years (Anon 2000). However, there has been an increase in private holdings. Most land currently available for growing eucalypts is degraded due to a long history of low inputs and poor management over successive rotations. It is a significant challenge to meet the forecast demand of 350 000 t annually, an extra 300 000 t over the current production from plantations in Kerala. In contrast to Kerala, other parts of the country (mainly mid and northwest India) are increasing their eucalypt area, especially with the availability of clonal planting material. Here, small areas under eucalypt are a source of revenue for local farmers and larger areas are owned either by the Government or the private pulp wood industries (Das and Rao 1999, Lal 2003).

Fast growth rates of eucalypts result in high nutrient demand and potentially high rates of nutrient export from wood and biomass harvest. Long-term studies elsewhere have shown that improvements in productivity can be achieved through use of genetically superior planting stock and adoption of site management practices such as slash management, nutrient addition and weed control (Nambiar 1996, Tiarks *et al.* 2000). The aim of the present study was to evaluate the impact of management of site resources, nutrients and water to improve and sustain productivity of eucalypt plantations in Kerala state. Previously in this series, we have reported tree crop biomass, nutrient stores and nutrient export from the previous rotation, as well as the impact of harvest residue management on soil nutrient stores and effect of site management practices on tree growth at age 4 years (Sankaran *et al.* 2004). In this paper we report on the impact of slash management, nutrient addition, weed control and legume cover cropping on tree volume at full rotation and implications of these results on overall productivity and sustainability of eucalypt plantations in Kerala.

Location, Climate and Site Description

The research was located at four sites that represented two geographic regions where eucalypts are planted in Kerala, the undulating coastal plains (< 1000 m asl) and high ranges (1000-2000 m asl). At the low elevation sites, *E. tereticornis* was typically established on ex-degraded moist deciduous forests while in the high ranges the species was planted either on ex-grassland sites, or after clearing of natural shola forests. Kerala State is located between latitudes 8.2°-12.8° N and between the Arabian Sea and the Western Ghat mountain ranges in south India. Rainfall, previous land use and soil characteristics at the four experimental sites are detailed in Table 1. The geographical position of the sites and information on stocking density (stems ha^{-1}) and basal area of the original plantations are given in Sankaran *et al.* (2004). The climate is tropical warm humid with two monsoon periods, the southwest monsoon (the main monsoon), which starts in early June and extends until October and the northeast monsoon, which brings occasional rains from December to February. The dry season begins in March and continues through May. Mean atmospheric temperature is 27°C (range 20-42°C) and relative humidity ranges between 64% (Feb-March) and 93% (June-July).

Experiments were established at four sites, two planted with *E. tereticornis* and two with *E. grandis*. The parent material of soils at these sites was saprolite or saprolitic colluvium derived from Precambrian granites and gneiss. The soils are broadly classified as ferralsols (details in Sankaran *et al.* 2000). The two *E. tereticornis* sites (Kayampoovam and Punnala) are located in the foothills of Western Ghats. The *E. grandis* sites (Surianelli and Vattavada) are located in the high ranges of the Western Ghats. Stands at all

Table 1. Selected climate and soil characteristics (0-10 cm) of each of the site

Species	*E. tereticornis*		*E. grandis*	
Site name	Kayampoovam	Punnala	Surianelli	Vattavada
Annual rainfall (mm)	2700	2000	3000	1800
Altitude (m)	120	150	1280	1800
Previous land use	Moist deciduous forest	Moist deciduous forest	Grassland	Semi-evergreen forest
First planted	1977	1977	1968	1958
Previous rotations	1 seedling and 1 coppice (2 rotations)		1 seedling, 2 coppice and 1 seedling (3 rotations)	
Age of previous rotation at harvest (yr)	7	7	7	7
Soil texture	Light to medium clay	Sandy loam to clay loam	Medium clay to sandy loam	Clay loam to medium clay
pH (1:5 water)	5.3	5.1	4.8	5.3
Total C (mg g^{-1})	21.5	43.6	40.9	52.3
Total N (mg g^{-1})	1.83	2.89	2.49	4.50

sites were harvested in May-July 1998 to establish these experiments.

Experimental Design

Five experiments were established at each site during June-September 1998. A summary of experiments is provided in Table 2. Details of the treatments have also been reported earlier (Sankaran *et al*. 2000, 2004). Each experiment is a randomised block design with 3-6 treatments and four replicates. The plot size is 20 m x 20 m, tree spacing 2 m x 2 m with 100 trees per plot (36 measurement trees). At Kayampoovam, 18 m x 18 m plots were used, with 25 measurement trees. The *E. grandis* stands were thinned to 1667 stems ha^{-1} at age 2 years. All treatments except the burn only (B) received starter fertiliser (100 g $tree^{-1}$ N:P:K, 17:7:14). The treatments with N fertiliser received the rates shown in Table 2 in both years 1 and 2, and at 50% (*E. tereticornis*) and 33% (*E. grandis*) of this rate in year 4. Total P fertiliser applications were split over four doses in the first 2 years (Table 2). Weeds were controlled by hand. Basal dressing of P was 63 kg ha^{-1} (P4) in the N experiment, and that of N was 187 kg ha^{-1} in the P experiment (N4). The legume understorey treatment at the *E. tereticornis* sites were the perennial *Mucuna bracteata* DC. and *Pueraria phaseoloides* (Roxb.) Benth. and the annual *Stylosanthes hamata* Taub. Additional P fertiliser (42 kg P ha^{-1}) was applied to all the plots in the legume experiment.

Tree Growth

Tree stem diameter and height were measured regularly from 3 months after planting through to harvest at 6.5 years. Stem volume (*v*) was calculated using the equation $v = {}^{1}/_{3}\Pi r^2 h$, where *r* was the radius at the tree ground level (projected from the diameter measured at breast height) and *h* was the height of the tree to the small end diameter of 1 cm. Standing volume was calculated

Table 2. Details of experimental sites and treatments

Experiment	Sites	Treatments
Slash and litter	4 sites	Burn (BS), zero slash (BL_0), single slash (BL_1), double slash (BL_3), leaf slash only (L), and burn without starter fertiliser (B)
N fertiliser	4 sites	5 rates N1, N2, N3, N4, and N5 giving 0, 18, 60, 187 and 375 kg N ha^{-1} respectively
P fertiliser	4 sites	5 rates P1, P2, P3, P4, and P5 giving 0, 6.3, 21, 63, and 131 kg P ha^{-1}, respectively
Weed control	4 sites	No weed control except around tree base (NW), 1 m strip weed control (SW), complete weed control (CW)
Legume cover cropping	*E. tereticornis* 2 sites	*Mucuna* (M), *Pueraria* (P), *Stylosanthes* (S) or control (C, equivalent to the CW treatment)

as the sum of the stem volumes, expressed per ha. A strong relationship was found between standing volume and recovered merchantable volume harvest.

Soil Properties

Soils were assessed for treatment effects on pH, exchangeable cations and available N. Nine cores (0-20 cm) were collected from each plot and separated into 0-5, 5-10, and 10-20 cm depth ranges. The 9 subsamples were aggregated to a plot level for analysis. Soil pH was measured in 1:5 water extracts (Rayment and Higginson 1992). Exchangeable cations were assessed as solution Ca^{2+}, Mg^{2+} and K^{+} in filtrate after shaking 5 g dry soil (<2 mm) with 100 mL of 1M ammonium chloride for 1 hour (Rayment and Higginson 1992).

Soil net N mineralisation was assessed in three ways; net N released during an anaerobic incubation of disturbed soil (anaerobic N), net N released during an aerobic incubation of undisturbed cores under optimal soil moisture and constant temperature (N mineralisation index), and N released in a long-term laboratory incubation of repacked soil. Methods for these were as follows

N mineralisation index

In each plot, 18 steel cores (44 mm diameter) were pushed into the ground to 20 cm depth, removed, stored in laboratory at 4°C until extraction. For each plot, one set of 9 cores (the 'initial' set) was extracted as soon as practicable. The other set of 9 cores (the 'final' set) was incubated aerobically for 28 days in the laboratory at about 25°C (average temperature only, as laboratory was not strictly temperature controlled) and then extracted. For extraction, the soil core was pushed out and split into the 0-5 cm, 5-10 cm, and 10-20 cm depth ranges. Soil from the 9 cores at each depth was mixed to represent the plot. Soil samples (20 g moist weight) were shaken end-over-end with 60 ml of 1M KCl extracting solution, and then filtered. Extracts were analysed colourimetrically for ammonium and nitrate concentrations. The N mineralisation index was calculated as the rate of increase in soil mineral N content (μg N g $soil^{-1}$ day^{-1}) by subtracting the initial extractable N from the final extractable N.

Anaerobic N

Sieved (<5mm) soil (20 g, moist weight) was incubated with 30 ml water for 7 days at 40 °C and extracted by adding 30 ml of 2M KCl, shaking for 1 hour and filtering. Anaerobic N is the difference in ammonium concentration in the extracts between the pre- and post-incubated samples, expressed as μg N g $soil^{-1}$.

Long-term incubation

To assess slash treatment effect on N mineralisation in the laboratory, a long-term (392 day) laboratory incubation was undertaken under controlled temperature (25°) and moisture (-25 kPa matric potential) conditions, with leaching of the mineralised N at regular intervals. Soils (0-10 cm) were collected from the experimental plots 2 years after treatment installation. The leaching intervals were initially relatively close, but the time interval increased as the N mineralisation rate slowed. A more detailed description of the leaching methodology is in Mendham *et al.* (2004).

Statistical Analysis

Treatment effects on stand volume at each time and for each experiment were assessed using single-factor analysis of variance (Genstat 5 1987). Duncan's multiple range test was applied to determine which means were different amongst the treatments. For the incubation study, a nested design was used to test for treatment effects, with sites used as replicates.

Results

Tree Growth

Slash management

Slash management did not significantly affect standing volume at any of the 4 sites. At harvest at 6.5 years, standing volumes for *E. tereticornis* were 111 m^3 ha^{-1} at Kayampoovam and 87 m^3 ha^{-1} at Punnala. The volume at the *E. grandis* sites was higher, with averages of 190 m^3 ha^{-1} at Surianelli and 360 m^3 ha^{-1} at Vattavada. At all sites, the productivity was much higher than in the previous rotation (Table 3), with productivity increases between 41% and 252% (Table 3). These are attributed to use of improved genetic stock and improved management.

The data for tree height, diameter (at 130 cm), basal area and survival of trees in the slash treatment plots are shown in Table 4.

Effects of nitrogen application on standing volume

Response to N application varied between sites (Fig. 1). Application of N increased stem volume of *E. tereticornis* at Punnala and *E. grandis* at Surianelli. There was an early response to N at the other two sites, which did not continue beyond ages 2-3 years. At the *E. tereticornis* site, 187 kg of N ha^{-1} gave the maximum response (54% and 64% increase over control), and the corresponding N rate for *E. grandis* was 60 kg N ha^{-1}.

Table 3. Comparison of previous vs current (mean of slash treatments) plantation productivity

Species	Site	Productivity (m^3 ha^{-1} yr^{-1}) Previous rotation	Productivity (m^3 ha^{-1} yr^{-1}) Current rotation	Productivity increase (%)
E. tereticornis	Kayampoovam	11.6	16.4	41
	Punnala	6.1	14.8	143
E. grandis	Surianelli	9.0	31.7	252
	Vattavada	31.3	49.1	57

Table 4. Tree height, diameter, basal area and survival- mean across slash treatments

Species	Site	Height (m)	Diameter at breast height (cm)	Basal area (m^2 ha^{-1})	Survival (%)
E. tereticornis	Kayampoovam	14.6	10.0	16.6	82.2
	Punnala	13.6	8.9	13.4	81.0
E. grandis	Surianelli	18.7	13.3	24.0	93.9
	Vattavada	23.7	16.9	39.3	95.6

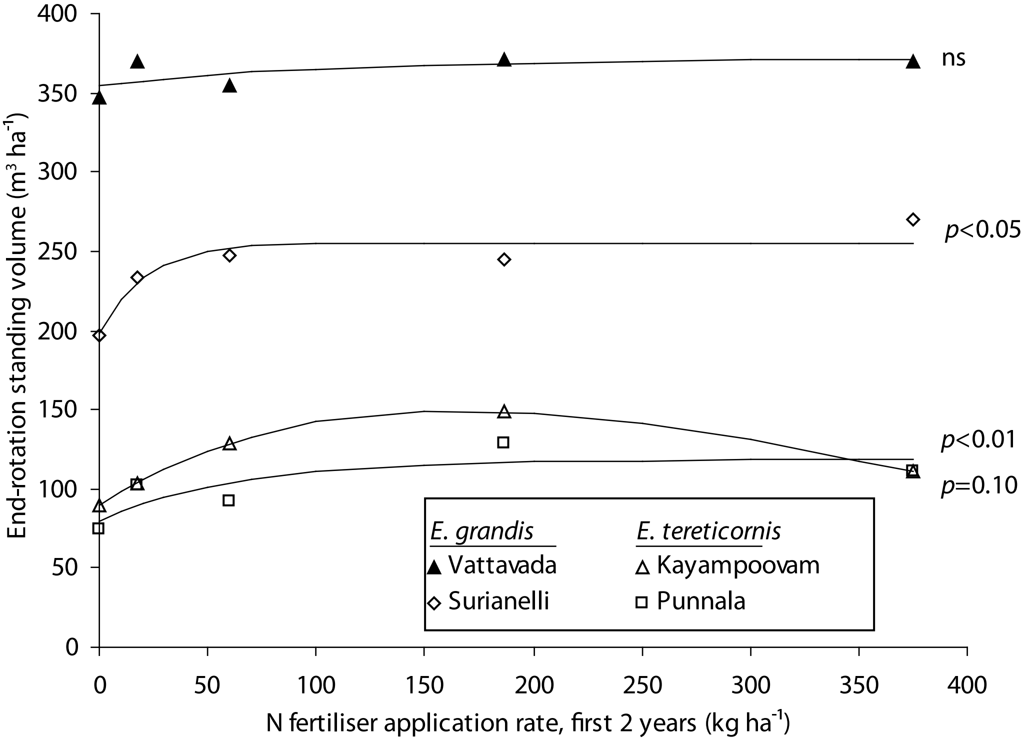
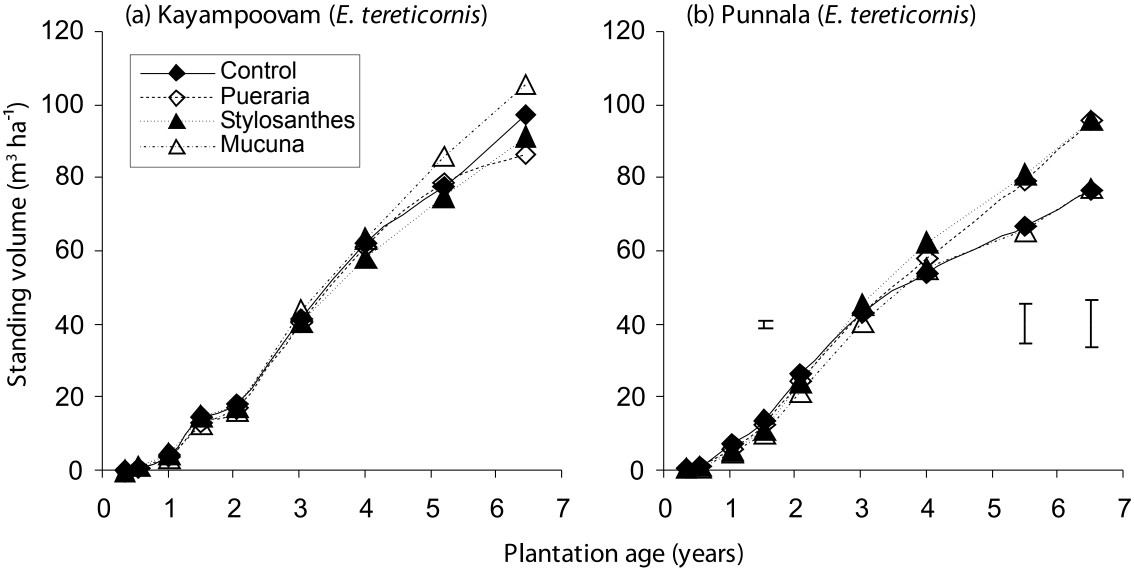


Figure 1. Standing volume response to N fertiliser at the end of the rotation. Probability (P) values represent the significance of the exponential regression

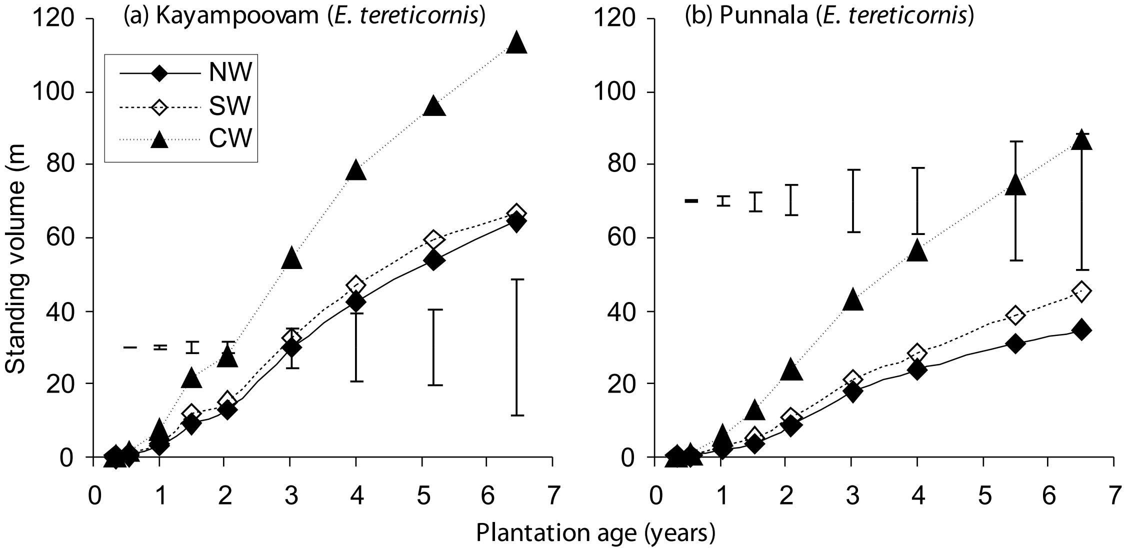
Table 5. Soil exchangeable cation concentration ($cmol_c$ kg^{-1})

	K		Ca		Mg	
Sites	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
Kayampoovam	0.47	0.55	9.83	8.60	2.51	2.78
Punnala	0.35	0.30	2.08	1.64	1.52	1.03
Surianelli	0.51	0.33	3.21	0.83	2.58	1.02
Vattavada	1.13	1.03	24.30	13.2	7.13	3.71



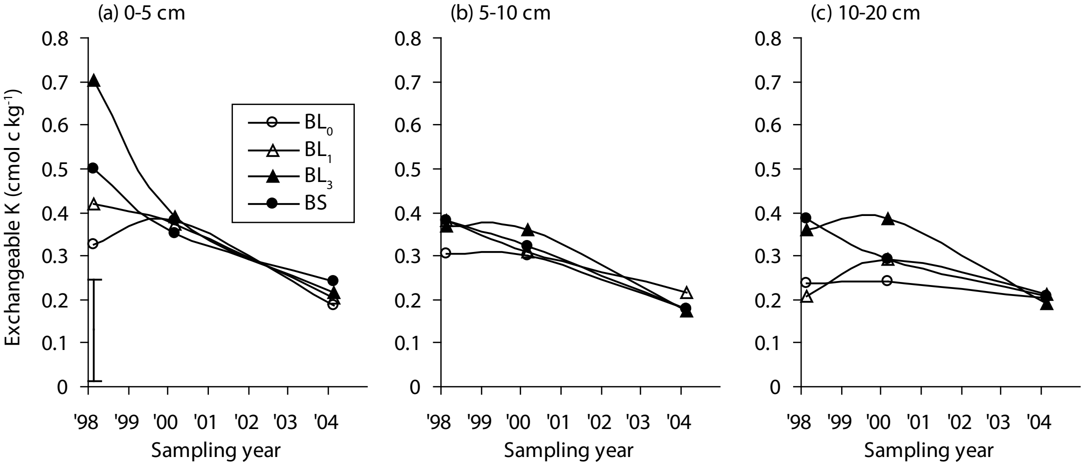
Bars show LSD where treatment differences were significant.

Figure 2. Effect of legume intercropping on *E. tereticornis* standing volume



Bars show LSD where treatment differences were significant.

Figure 3. Effect of weeding treatment on standing volume in *E. tereticornis*



Bar shows LSD where treatment difference was significant.

Figure 4. Impact of treatment on soil exchangeable potassium over time at Punnala

Effect of phosphorus application on standing volume

A significant increase in standing volume (32 m^3 ha^{-1} over control) was recorded in the *E. tereticornis* plantation at Punnala for the first 4 years, but there were minimal responses at the other sites beyond 1 year of age. As the results are not significant they are not presented here.

Effect of legume cover cropping in E. tereticornis

Legume cover cropping with *Peuraria* and *Stylosanthes* improved productivity only at the Punnala *E. tereticornis* site (Fig. 2). The pattern of response was interesting, with a significant growth depression at 18 months, and a reversal thereafter leading to an increase of 20% in tree standing volume at the end of the rotation (Fig. 2). The *Mucuna* cover crop caused approximately 20% mortality in trees at Punnala by smothering them. This resulted in no productivity difference between it and the weeded control although individual trees were larger in the *Mucuna* treatment which compensated for the loss of tree numbers. Legume cropping had no effect on plantation productivity at Kayampoovam site.

Effect of weed management on standing volume

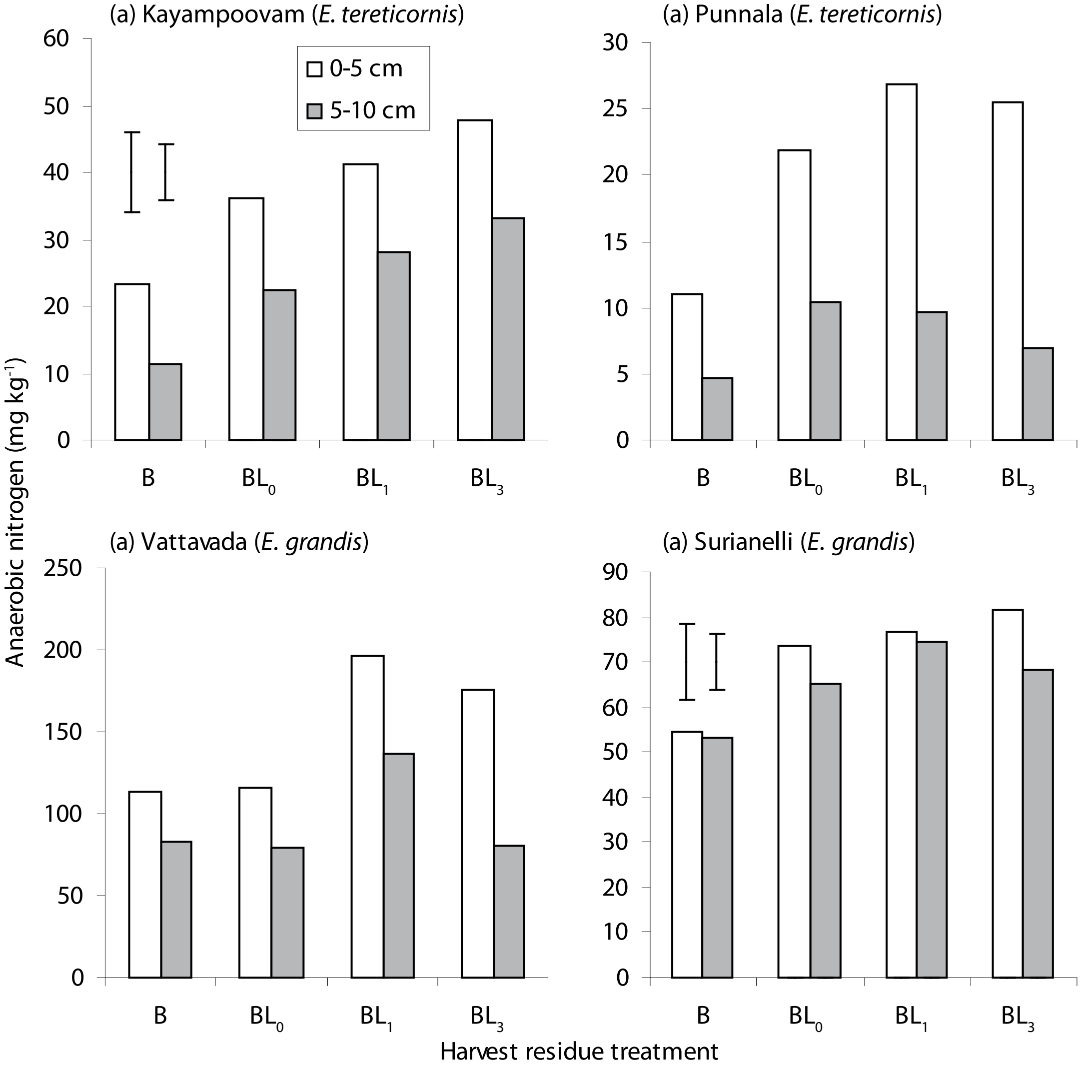
Effects of weed control on growth at the two *E. tereticornis* sites are shown in Figure 3. Complete weeding (CW) increased volume by 76% over the control in *E. tereticornis* at Kayampoovam and by 149% in Punnala. Strip weeding was not very effective and standing volume was not significantly improved over the control treatment at any of the sites. The effect of weeding was mostly non-significant in the *E. grandis* plantations.

Treatment Effects on Soil Properties

Effects of slash manipulation on soil cations were assessed in 2000 (at age 2 years). There were no significant effects on K, Ca or Mg at the 0-5 cm, 5-10 cm or 10-20 cm soil depths, so only the mean values are presented in Table 5. Vattavada had the highest concentration of each of the cations. Punnala and Surianelli both had relatively low Ca concentration. The time-course of soil K was examined in at Punnala, the site with the lowest exchangeable K (Fig. 4), where slash retention resulted in a significant increase in surface (0-5 cm) exchangeable potassium at establishment (1998). There were no other significant treatment effects on exchangeable cations. The time course of exchangeable K showed a steady decline at all three depths over the 6 years.

Impact of Slash Management on N Mineralisation – Field and Laboratory Studies

Slash treatment had no significant effect on N mineralisation index at any of the sites at 2 years.



Bars show LSD where treatment differences were significant within each depth.

Figure 5. Anaerobic nitrogen production in the laboratory measured in soils collected from field under to slash treatments for 2 years

There was, however, an effect of slash treatment on anaerobic N, with an increasing trend from B (Burn), BL_0, BL_1 to BL_3 treatments especially at 0-5 cm depth at all sites (Fig. 5). The differences in values were significant for Surianelli and Kayampoovam ($p<0.01$) indicating that anaerobic N was higher in BL_1 and BL_3 plots compared to the other slash treatments.

Cumulative data for N release from laboratory incubated soils, collected from the four experimental plots showed that plots with slash retained released significantly higher N than those with slash and litter removed (Fig. 6).

Predicting Response to N Fertiliser

Tree responses to N fertiliser application across the four sites were significantly correlated with N mineralisation index (0-5 cm) at 2 years after establishment (Fig. 7a). Anaerobic N was not correlated with response to N fertiliser (Fig. 7b).

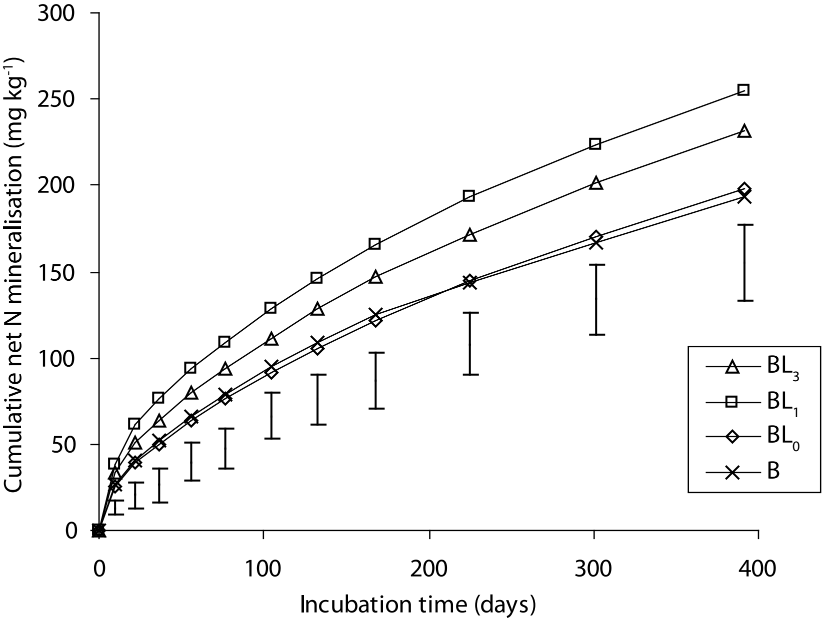


Figure 6. Effect of slash management on N release in the laboratory incubation - data combined from all sites. Treatment differences were significant at each time, with bars showing the LSD between treatments

Discussion

The overall standing volume (across treatments) in *E. grandis* (31.7-49.1 m^3 ha^{-1} yr^{-1}) was higher than that in *E. tereticornis* plantations (14.8-16.4 m^3 ha^{-1} yr^{-1}). However, in both cases, the productivity was markedly higher than those achieved in the previous rotation (41-143% for *E. tereticornis* and 57-252% for *E. grandis*). Productivity was mostly higher, or in a few cases similar, to productivity of several *E. tereticornis* (8-18 m^3 ha^{-1} yr^{-1}) plantations in moist tropical /subtropical zones in India (Chaturvedi 1983, Rawat and Negi 2004, Dogra and Sharma 2005). Productivity achieved in *E. grandis* plantations was significantly higher than for other *E. grandis* plantations in Kerala (Singh *et al.* 1988, Tandon *et al.*1988). The reasons for the improvement include use of enhanced genetic material and attention to management. However productivity rates of *E. tereticornis* plantations are still significantly lower than the biological potential of the genus. Potential reasons for this include: (1) *E. tereticornis* is a naturally low yielding species susceptible to several fungal diseases (Sharma *et al.* 1985), and (2) the sites available for planting *E. tereticornis* in Kerala are generally very degraded, with low fertility and/or shallow soils which can become water stressed (Kallarackal and Somen 1997). Species choice can be managed to improve yield, and studies are currently being carried out to identify a species suitable for lower elevations in the state.

Slash retention in plantations helps conserve the site nutrient capital, retain moisture, and reduce erosion, all of which contribute to favourable growing conditions for plants (Haywood *et al.* 2003). Although we did not observe a productivity response to slash retention, increases in eucalypt productivity due to slash retention have been reported, especially on low fertility sites (Mendham *et al.* 2003, Gonçalves *et al.* 2004, Nzila *et al.* 2004, Xu *et al.* 2004). Lack of response on our sites partly is due to the small amount of slash remaining at the low fertility sites such as

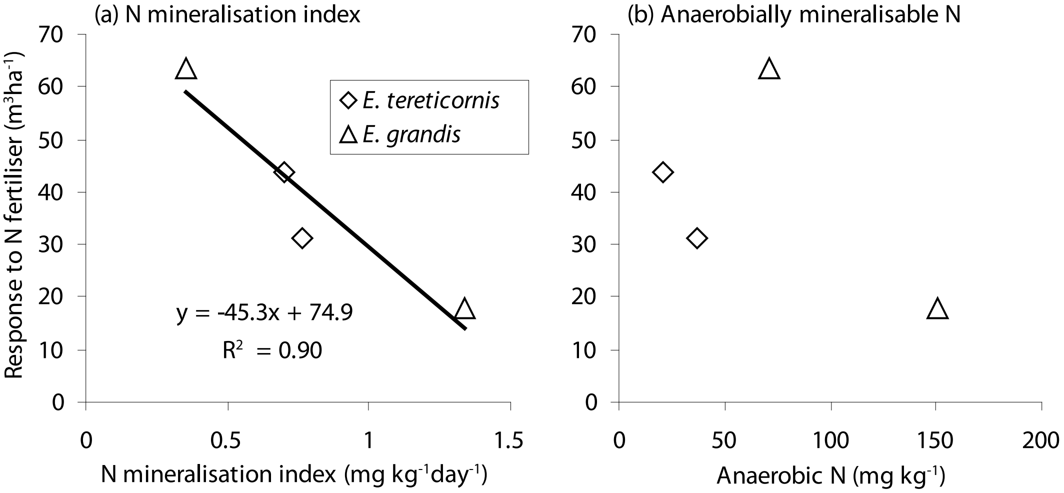


Figure 7. Relationship between response to N fertiliser at 5 years and soil nitrogen mineralisation index (a) and anaerobic nitrogen (b), measured in 0-5 cm soil at 2 years after establishment

Punnala and Surianelli. For example, the total slash weight varied from 6-19 t ha^{-1} across all four sites (Sankaran *et al.* 2000), compared to 31-51 t ha^{-1} for the two sites of *E. globulus* in Western Australia (harvested at 10 years of age) (Mendham *et al.* 2003). Whilst Vattavada had a relatively high amount of slash, the inherent soil fertility was also was high (Sankaran *et al.* 2004), thus potentially masking any nutritional benefit from the slash.

There were no significant changes in exchangeable soil cations to 20 cm depth at 2 years after planting at any of the sites, probably because the quantities of cations in the slash were relatively low (Sankaran *et al.* 2005). However, there was a general decline in exchangeable K, similar to that observed in *E. globulus* plantations in south-western Australia, which is probably associated with uptake by the growing plantation (O'Connell *et al.* 2000).

Many studies have shown significant responses to N and P fertiliser application in plantations (e.g. Cromer *et al.* 2002, Gonçalves *et al.* 2004, Xu *et al.* 2004, 2005) similar to our results. Nitrogen was the most limiting nutrient, with large responses in both *E. tereticornis* and *E. grandis*. However, the responses to fertiliser were quite variable across the sites, suggesting that there were inherent differences in the nutrient supply characteristics of soils. We found a significant relationship between soil supply of nitrogen (N mineralisation index) and standing volume response, independent of species. This demonstrates that there is potential for targeting fertiliser applications to more responsive sites, but the relationship currently relies upon only four sites so is not ready to be implemented in practice.

Impacts of slash treatment on the N mineralisation index were also minimal, but we found that cumulative N mineralisation in a more sensitive laboratory experiment was significantly higher in the slash retained treatments, supporting similar field observations by O'Connell *et al.* (2000) in *E. globulus* plantations. Thus slash retention is likely to yield benefits at the lower fertility (N responsive) sites in the future.

Legume cover cropping potentially has multiple benefits for eucalypt plantation cultivation, including fixation of atmospheric N, diversification of products to include fodder, as well as weed control and minimisation of leaching losses (Malik *et al.* 2001). Tian *et al.* (2001) found *Peuraria phaseoloides* accumulated 150-250 kg N ha^{-1} within 4-18 months of growth, 68% of which was derived from atmosphere when grown on soils low in P and K, and 87% when soil P and K supply was sufficient. They also found that *Peuraria* roots capture nutrients deep in the soil and *Peuraria* fallow can reduce decline of soil organic matter and increase N concentrations in particulate soil organic matter. Some or all of these benefits may be conferred through legume intercropping in eucalypt plantations. Choice of legume species is critical since climbers like *Mucuna* can smother trees if left unmanaged, a situation that resulted in 20% mortality in our experiment at Punnala. Non-climbing legumes (*Peuraria* and *Stylosanthes*) significantly improved standing volume at Punnala, the *E. tereticornis* site that had a strong response to N fertiliser. However, at Kayampoovam, where soils are shallow, lack of response to legume cover cropping may have been due to a water limitation. This site also showed only a relatively small response to applied N. Mendham *et al.* (2004) investigated effect of residues of *Mucuna*, *Pueraria* and *Stylosanthes* on soil N supply through long-term laboratory incubation studies. They showed cover cropping by these legumes in the early phase of plantation growth may be a useful mechanism to enhance soil N supply and optimise the synchrony between N supply and N uptake. They also reported the effect of legumes on N dynamics may vary markedly with legume species. Beneficial effects of intercropping eucalypts with leguminous trees such as *Acacia mearnsii*, *A. holosericea* and *Albizia falcataria* have been reported by DeBell *et al.* (1997), Forrester *et al.* (2004) and Xu *et al.* (2004), and are a potential option for improving N fertility of sites.

Weeds compete with trees for site resources (water, nutrients, light) and adversely effect wood yield (Nambiar and Sands 1993, Little 2002). Weeding alone can improve plantation productivity substantially in *E. tereticornis* plantations (Fig. 3). The mechanism for improved productivity through weed control is probably different at the two sites, with Kayampoovam a more water-stressed site (due to shallow soil depth), and Punnala a more nutrient-stressed site, indicated by the strong response to N fertiliser. During the dry period, the predawn leaf water potential at Punnala reached a minimum value of -1.0 Mpa (indicating low water stress), whereas at Kayampoovam the value reached almost -2.5 Mpa, suggesting these trees were quite water stressed. Responses to weeding in *E. grandis* were generally not significant and the reasons for this could be different for both the sites. At Vattavada, a highly fertile site, weeding improved plantation productivity over the initial 1.5 years and thereafter there was no response. This could be ascribed to the early canopy closure, which is characteristic of *E. grandis* plantations. However, at Surianelli, an ex-grassland site with low soil fertility, the lack of response to weeding may be an unreliable result, because most of the weeded plots were subject to wild elephant damage killing about 25% of the trees in the fully weeded treatment. Presence of weeds in non-weeded plots restricted access by elephants, so fewer trees were lost to elephant damage in that treatment.

Conclusions and Management Impacts

A number of cultural practices in combination can be employed to improve productivity of eucalypt plantations in Kerala. Using good quality planting stock and careful attention to establishment techniques are the key factors in achieving good productivity. In addition, it is possible to improve yields (76-149%) through weed control in *E. tereticornis* as shown by this study. Nitrogen fertiliser application combined with weeding resulted in an increase of up to 60% on responsive sites. Legume cover cropping has potential to improve productivity by up to 20% on N-deficient sites. Slash retention is important for retaining nutrients on site, even if a direct increase in growth cannot be measured. As the productivity has been increased markedly through improved management, it is likely that slash removal will have a greater impact in future rotations.

Based on the overall results from this study and related research on genetics, Kerala Forest

Research Institute (KFRI) has recommended a package of practices for the local forest managers (KFRI 2005). These experiments were also used as demonstrations for forest managers and decision makers in the State. Some of the recommendations have been implemented operationally.

This project enhanced the capacity of KFRI's scientists, research fellows and technical staff through training in project planning and implementation, methodologies for measurements and sample collection, data collation and analyses, soil and plant analyses, handling of sophisticated analytical instruments and preparation of scientific papers. Four project scientists were trained at CSIRO (Perth); three in modern techniques in soil and plant analyses and one in data analyses and interpretation. Field staff at project sites also received training in a range of forest operations. There has therefore been flow-on benefits in both the science capacity building and forestry operations.

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References

Anon. 2000. Forest Statistics, 2000. Kerala Forest and Wildlife Department, Government of Kerala, Thiruvananthapuram, India. 115p.

Chaturvedi, A.N. 1983. *Eucalyptus* for farming. UP Forest Bulletin No. 84. Forest Department, Lucknow, India.

Cromer, R.N., Turnbull, C.R.A., La Sala, A.V., Smethurst, P.J. and Mitchell, A.D. 2002. *Eucalyptus* growth in relation to combined nitrogen and phosphorus fertilizer and soil chemistry in Tasmania. Australian Forestry 65:256-264.

Das, S.K. and Rao, C.N. 1999. High yield eucalypt clonal plantations of Andhra Pradesh Forest Development Corporation Ltd.- a success story? Indian Forester 125:1073-1081.

DeBell, D.S., Cole, T.C. and Whitesell, C.D. 1997. Growth, development and yield of pure and mixed stands of *Eucalyptus* and *Albizia*. Forest Science 43:286-298.

Dogra, A.S. and Sharma, S.C. 2005. Performance of *Eucalyptus* species and provenances in south-west Punjab. Indian Forester 131:1521-1528.

FAO. 2001. Global forest resources assessment 2000. Main report. FAO Forestry Paper No. 140, FAO, Rome.

Forrester, D.I., Bauhus, J. and Khanna, P.K. 2004. Growth dynamics in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. Forest Ecology and Management 193:81-95.

Ghosh, S.P., Kumar, B.M., Kabeerathumma, S. and Nair, G.M. 1989. Productivity, soil fertility and soil-erosion under cassava-based agroforestry systems. Agroforestry Systems 8:767-782.

Gonçalves, J.L.M., Gava, J.L. and Wichert, M.C.P. 2004. Sustainability of wood production in eucalypt plantations of Brazil. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, July, 2001 Congo and February, 2003, China, 31-43. Center for International Forestry Research, Bogor, Indonesia.

Haywood, J.D., Golz, J.C., Sayer, M.A.S. and Tiarks, A.E. 2003. Influence of fertilization, weed control, and pine litter on loblolly pine growth and productivity and understorey plant development through 12 growing seasons. Canadian Journal of Forestry Research 33:1974-1982.

Jayaraman, K. and Krishnankutty, C.N. 1990. A data bank for forestry sector in Kerala, Research Report No. 66. Kerala Forest Research Institute, Peechi, Kerala, India.

Kallarackal, J. and Somen, C.K. 1997. Water use by *Eucalyptus tereticornis* stands of differing density in southern India. Tree Physiology 17:195-203.

Kerala Forest Research Institute. 2005. Improving eucalypt productivity in India. Information Bulletin. Kerala Forest Research Institute, Peechi, Kerala, India. 11p.

Lal, P. 2003. Clonal *Eucalyptus* plantations in India. *In*: Turnbull, J.W. (ed.) Eucalypts in Asia: conference proceedings, Guangdong, China, 7-11 April, 2003, 16-21. ACIAR Proceedings No.111. Australian Centre for International Agricultural Research, Canberra.

Little, K.M. 2002. The response of eucalypt hybrid clone to weed control and burning. *In*: Proceedings of the International Symposium on *Eucalyptus* Plantations, 1-6 September 2002, 160-173. Guangdong, P.R. China.

Malik, R.K., Green, T.H., Brown, G.F., Beyl, C.A., Sistani, K.R. and Mays, D.A. 2001. Biomass production of short rotation bioenergy hardwood plantations affected by cover crops. Biomass and Bioenergy 21:21-33.

Mendham, D.S., O'Connell, A.M., Grove, T.S. and Rance, S.J. 2003. *Eucalyptus* residue management effects on soil carbon and nutrient stores and on growth of second rotation eucalypts. Forest Ecology and Management 181:357-372.

Mendham, D.S., Kumaraswamy, S., Balasundaran, M., Sankaran, K.V., Corbeels, M., Grove, T.S., O'Connell, A.M. and Rance, S.J. 2004. Legume cover cropping effects on early growth and soil nitrogen supply in eucalypt plantations in south-western India. Biology and Fertility of Soils 39:375-382.

Nair, K.S.S., Jayaraman, K. and Chacko, K.C. 1997. Productivity of teak and *Eucalyptus* plantations in Kerala. Final Report of Research Project 250/1996. Kerala Forest Research Institute, Peechi, Kerala, India.

Nambiar, E.K.S. 1996. Sustained productivity of forests is a continuing challenge to soil science. Soil Science Society of America Journal 60:1629-1642.

Nambiar, E.K.S. and Sands, R. 1993. Competition for water and nutrients in forests. Canadian Journal of Forest Research 23:1955-1968.

Nzila, J.D., Deleporte, P., Bouillet, J.P., Laclau, J.P. and Ranger, J. 2004. Effects of slash management on tree growth and nutrient cycling in second rotation *Eucalyptus* replanted sites in the Congo. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, July, 2001 Congo and February, 2003, China, 15-30. Center for International Forestry Research, Bogor, Indonesia

O'Connell, A.M., Grove, T.S., Mendham, D. S. and Rance, S.J. 2000. Effects of site management in eucalypt plantations in south-western Australia. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: a progress report: workshop proceedings, 7-11 December, 1999, Kerala, India, 61-71. Center for International Forestry Research, Bogor, Indonesia.

Rawat, V. and Negi, J.D.S. 2004. Biomass production of *Eucalyptus tereticornis* in different agroecological regions in India. Indian Forester 130:762-770.

Rayment, G.E. and Higginson, F.R. 1992. Australian laboratory handbook of soil and water chemical methods. Australian Land Survey Handbook Series. Inkata Press, Melbourne and Sydney, Australia. 330p.

Sankaran, K.V. *et al*. 2000. Effects of site management on *Eucalyptus* plantations in the monsoonal tropics: Kerala, India. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: a progress report: workshop proceedings, 7-11 December, 1999, Kerala, India, 51-60. Center for International Forestry Research, Bogor, Indonesia.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kumaraswamy, S., O'Connell, A.M., Grove, T.S. and Mendham, D.S. 2004. Improved productivity of eucalypt plantations through site management practices in the monsoonal tropics - Kerala, India. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, July, 2001 Congo and February, 2003, China, 61-76. Center for International Forestry Research, Bogor, Indonesia.

Sankaran, K.V., Grove, T.S., Kumaraswamy, S., Manju, V.S., Mendham, D.S. and O'Connell, A.M. 2005. Export of nutrients in plant biomass following harvest of eucalypt plantations in Kerala, India. Journal of Sustainable Forestry 20:15-36.

Sharma, J.K., Mohanan, C. and Florence, E.J.M. 1985. Disease survey in nurseries and plantations of forest tree species grown in Kerala. KFRI Research Report No. 36. Kerala Forest Research Institute, Peechi, India, 268p.

Singh, S.B., Prasad, K.G., Gupta, G.N. and Subramanian, V. 1988. Cause of decline of *Eucalyptus grandis* in Nagarampara, Kerala-a survey note. Journal of Tropical Forestry 4:259-268.

Smethurst, P., Baillie, C., Cherry, M. and Holz, G. 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. Forest Ecology and Management 176:531-542.

Tandon, V.N., Pande, M.C. and Rajendra Singh. 1988. Biomass estimation and distribution of nutrients in five different aged *Eucalyptus grandis* plantation ecosystems in Kerala. Indian Forester 114:184-199.

Tian, G., Hauser, S., Koutika, L.S., Ishida, F. and Chinau, J.N. 2001. *Pueraria* cover crop fallow systems: benefits and applicability. *In*: Tian, G., Ishida, F., Keatinge, D., Karsky, R. and Wendt, J. (eds.) Sustaining soil fertility in West Africa. Proceedings of a symposium at Minneapolis, USA, 5-9 November 2000, 137-155. SSSA Special Publication (USA), No. 58. Soil Science Society of America, Madison, Wisconsin, USA.

Tiarks, A., Elliott-Smith, M. and Stagg, R. 2000. Loblolly pine (*Pinus taeda*) plantations in semitropical southeastern United States. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 101-103. Center for International Forestry Research Bogor, Indonesia.

Xu, D.P., Yang, Z.J. and Zhang, N.M. 2004. Effects of site management on tree growth and soil properties of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong Province, China. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, July, 2001 Congo and February, 2003, China, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Xu, D., Dell, B., Malajczuk, N. and Gong, M. 2005. Effects of phosphorus application on productivity and nutrient accumulation of a *Eucalyptus urophylla* plantation. Journal of Tropical Forest Science 17:447-461.

Harvesting of experimental plantations of *Eucalyptus grandis* (7-yr-old) at Surianelli, Kerala, India. (Photo: K.V. Sankaran)

Effects of Site Management on Tree Growth, Aboveground Biomass Production and Nutrient Accumulation of a Second-rotation Plantation of *Eucalyptus urophylla* in Guangdong Province, China

D.P. Xu[1], Z.J. Yang[1] and N.N. Zhang[1]

Abstract

Effects of site management practices on tree growth, aboveground production and nutrient accumulation of a second rotation of *Eucalyptus urophylla* plantation on degraded soils in southern China were evaluated. In terms of tree growth, aboveground biomass production and nutrient accumulation, treatments where branch and leaf slash was retained and *Acacia holosericea* was intercropped between tree rows were better than the treatment where only branch and leaf slash was retained. The treatment where branch and leaf slash was doubled was better than the treatment where branch and leaf slash was cleared, but not significantly ($p<0.05$) better than the treatment where all aboveground organic matter was removed and weeds were periodically controlled because of reduced weed competition. Intercropping with N-fixing trees increased tree growth and productivity 90 months after planting. Application of N, P and K fertilisers on this poor soil increased tree growth much more than that obtained by harvest residue management alone. Coppice trees grew better than replanted trees. At the high level of fertiliser application, coppice and replanted trees grew at the similar rate. Mean annual increment of coppice trees was much higher than that of replanted trees because there were two stems in the coppice treatment. Yield decline was marked in the second rotation without genetic improvement of the growing stock and some input of fertilisers. Harvest residue retention, adequate fertilisation and coppice regeneration are recommended as operational practices for eucalypt plantations in south China.

Introduction

The approximately 1.5 million hectares of eucalypt plantations in south China have been mainly established in the last 15 years. Soils on most sites available for eucalypt plantations were degraded by former land practices. Plantation productivity on these poor sites is very low (5-10 $m^3 ha^{-1} yr^{-1}$) and variable compared with eucalypt plantations in other countries (Brown *et al.* 1997). On these sites, trees commonly have very small crowns and grow slowly after age 4 years (Xu 1997). Consequently trees are harvested after a short rotation period (3-6 years). More seriously, productivity appears to be declining with successive rotations in some areas due to poor management. Some reports relate the low productivity to poor soil fertility (Dell and Malajczuk 1994, Xu and Dell 1997) including low available soil P (Wang and Zhou 1996). Serious soil erosion (>13 t $ha^{-1} yr^{-1}$) after plantation establishment, associated nutrient loss in some areas (Xu *et al.* 1999) and organic material (slash

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and litter) harvest by local communities (Xu 1996) may be contributing factors. Fertilisation in the first one or two years after planting is common practice (Wang and Zhou 1996, Zhong *et al.* 1999), but the rates used are generally insufficient to prevent tree growth stagnating in mid-rotation (3-4 years old). Low soil P is the main limitation to high plantation productivity (Xu *et al.* 2001). Like most trees, eucalypts have the capacity to acquire available nutrients from the soil and to conserve them in biomass. The withdrawal of many nutrients from the biomass, through efficient internal cycling during the formation of heartwood, is an effective strategy for maximising the use of limited nutrient pools by eucalypt plantations (Florence 1996, Saur *et al.* 2000). But in south China eucalypts are harvested before nutrient cycling becomes a significant source of nutrients for new growth. Therefore, improved practices for conserving soil and retaining slash on site are needed to improve soil chemical and physical properties and improve nutrient cycling, and support to sustained or increased productivity of eucalypt plantations.

The goal of this research is to develop options for site management that will sustain or improve productivity of eucalypt plantations over succession rotations in south China. More specifically, the objectives are to explore the relationship between site management practices and productivity of *Eucalyptus urophylla* S. T. Blake over succession rotations in two experiments by studying the impacts of:

- different harvesting intensity, site management and intercropping with N fixing trees on soil physical and chemical properties, tree growth, biomass accumulation and nutrient cycling; and
- stand re-establishment practices and fertiliser application on tree growth and productivity.

Early response of harvest residue retention and intercropping with N fixing trees on tree growth and nutrient status of young trees was reported by Xu *et al.* (2004). This paper reports the impact of site management practices on tree growth, biomass and nutrient accumulation in a full rotation.

Materials and Methods

Site details have been described by Xu *et al.* (1998, 2000b, 2004). Key information is reproduced here.

Site Description

The experimental site is located in Yangxi county, 5 km from Zhilong town (21°43'N, 111°35'E), Guangdong province. The site is 20 to 50 m above sea level on a small hill with a slope of about 5°. Main features of the climate are: mean annual rainfall 2178 mm, maximum daily rainfall 242 mm, annual mean temperature 22.0°C, maximum temperature 37.0°C, minimum temperature 2.1°C, mean temperature in the coldest month 15.0°C, mean temperature in the hottest month 28.0°C and annual mean humidity 81%. The soil is a lateritic red soil (Ultisol) over granite. The soil profile is over 2 m deep with about 20 cm A horizon and deep B horizon and low in available nutrients. Both total and available nutrient concentrations in the soil are low compared with undisturbed forest soils in south China.

The site is typical for eucalypt plantations planted on degraded soils in south China. As a result of high bulk densities and nutrient deficiencies, *E. urophylla* cannot grow well without soil cultivation and fertilisation. Soil erosion from the site was very serious (13 t ha^{-1} yr^{-1}) in the first rotation after site preparation and tree planting (Xu *et al.* 1999). In 1991, the original vegetation of mixed shrubs with scattered *Pinus massoniana* Lamb. was cleared and topsoil (0-20 cm) was cultivated by a tractor to establish a first rotation plantation of *E. urophylla*. Spacing for the plantation was 2 m x 3 m (1666 trees ha^{-1}). At planting, 100 g of a NPK fertiliser (15.0% N; 6.5% P; 8.3% K) was applied per tree into the planting hole as basal fertiliser. In 1992 when trees were 12 months old, 150 g of a NPK fertiliser with the same composition was applied into two small holes on opposite sides 30 cm from each tree.

Experimental Design and Layout

There were two adjacent experiments with separate but complementary objectives and experimental designs.

Experiment 1: impact of harvest intensity and intercropping with Acacia

Impacts of different harvest intensities and intercropping on site productivity are being measured following the harvest of a first-rotation *E. urophylla* plantation. The experimental design was a randomised complete block with five treatments and four blocks. The treatments were:

BL_o	All aboveground organic residue was removed from the plot before planting (all aboveground tree components, litter and understorey).
BL_1	Whole tree harvest (all aboveground tree components removed from the plot and slash distributed on BL_3).
BL_2	Stem and bark harvest (trunk with bark and wood removed) remaining branches and foliage distributed evenly over the plot.
BL_3	Double slash (same as BL_2 plus the slash from BL_1, distributed evenly over the plot).
BL_4	Stem and bark harvest plus intercropping with *Acacia holosericea* A. Cunn. ex G. Don.

Each plot is 360 m^2 in area with 60 trees (6 x 10) spaced at 2 m x 3 m. The designated harvest intensity was applied to each plot as it was harvested in March 1997.

Planting holes (40 x 40 x 30 cm deep) were prepared midway between the previous rows and at the same spacing as the former plantation (2 x 3 m). Fertilisers: 50 g urea (46% N), 40 g KCl (40% K) and 150 g superphosphate (6.4% P) were placed in each hole. On 8 April 1997, 4-month-old seedlings, grown from seeds collected from the same plantation, were planted to establish the second rotation (2R) experimental stand. Coppice from the first rotation stumps was removed every 2-3 months. Weeds in the BL_0 treatment were cut and removed from the plots before planting, and in the following year cut weeds were left on the site twice. No weed control was applied in the other treatments. In the BL_4 treatment, seedlings of *A. holosericea* were planted between rows of eucalypt seedlings. They were not fertilised directly.

Soil samples from each plot were collected before tree planting, and after tree planting and after tree harvest (90 months). Five cores (3 cm in diameter) in fixed positions in each plot were taken. Each core was separated into 3 layers (0-10, 10-20 and 20-40 cm) and bulked into a mixed soil sample for each layer. Available N (hydrolysable N) was analysed by 1 M NaOH hydrolysis and H_3BO_3 absorption method (Cornfield 1960) and exchangeable K was analysed by 1 M NH_4OAc extraction and flame photometry.

Tree height and stem diameter of 60 trees in each plot were measured annually. Dry matter production in each plot was estimated using allometric equations relating diameter to dry matter. Equations were derived by destructively sampling trees. Eighteen trees were selected to cover all diameter classes and harvested in first rotation (R1) and 12 trees covered all diameter classes were harvested after this experimental rotation (R2). After measuring tree height, each tree was separated into leaves, branches, stem-bark and stem-wood.

The equation, Ln (Y)=a+b Ln (X), was fitted for each tree component' where Y= biomass (oven dry basis), a and b=constants and X=diameter at breast height over bark. The equations were applied to each tree and summed on a plot basis.

Stem volume of a tree was calculated by the equation: Volume = 0.42 basal area x height (Simpson and Mo 1989).

Immediately after tree felling the fresh weights of stem, leaf and branch were measured in the field. Discs (2 cm thick) were removed from each 3 m of stem, the bark and wood was separated, weighed, and broken into small pieces and dried at 80°C to constant dry weight (approx. 48 hours). The canopy was partitioned into two equal strata by crown depth and samples consisting of 20% (diameter of branches > 10 cm)-30% (diameter of branches <10 cm) of leaf and branch were taken. They were weighed, and subsamples (approx. 500 g) of each component were removed for dry weight determination. Samples of leaf, branch, stem-bark and stem-wood from each tree were analysed for nutrient concentration.

In each plot, five 1 m^2 sample plots were used to collect the understorey and litter. Fresh weight of understorey and litter was determined on site. A sample (approx. 500 g) of each component was dried at 75°C for 48 hours to constant dry weight. Bulk samples from 5 sample plots in the main P treatment plots were processed for chemical analyses (Chen *et al.* 1994).

Methods for soil, plant and litter analysis have been described previously (Xu *et al.* 2000b). Nutrient accumulation for each of the different components of the trees was estimated by the equation: nutrient content = biomass x average nutrient concentration.

All data on tree height, diameter, volume and dry weight were analysed using a two-way analysis of variance (ANOVA) and the means were compared using Newman-Keuls Critical Range Test where the ANOVA showed that there were significant differences between means ($*p<0.05$) by the software 'Statistica'.

Experiment 2: impact of different re-establishment methods and fertiliser application.

The experimental design was a split plot with three treatments (fertiliser), two subtreatments (regeneration method) and 4 blocks. The main treatments were:

F_0 No additional fertiliser.
F_1 Low fertiliser, N 76.7 kg ha^{-1}, P 16.0 kg ha^{-1} and K 53.4 kg ha^{-1}.
F_2 High fertiliser, N 153.3 kg ha^{-1}, P 32.0 kg ha^{-1} and K 106.7 kg ha^{-1}.

The two subtreatments were:

C Coppice.
S Seedlings replanted.

For the seedling treatment, planting holes (40 x 40 x 30 cm deep) were prepared between first rotation stumps. Seedlings were raised from the same batch as Experiment 1 and planted in April 1997.

For the coppice treatment, trees were harvested in March 1997 and the experiment was laid out soon after. New coppice was thinned to two stems per tree in July 1997. The slash and litter management were as for Experiment 1, BL_2. Two additional subplots were added in each block to compare the effects of different site management when no fertiliser was added. They were BL_0 and BL_3). There were 72 trees in each plot (6 x 12) and 36 trees in each subplot. The spacing was 2 m x 3 m. The area of each plot was 432 m^2. As in Experiment 1, the designated slash management was applied in March 1997 and any coppice removed at 3-monthly intervals.

Trees in F_1 plots were fertilised in the planting hole with 25 g urea, 40 g KCl and 150 g superphosphate per tree and 25 g urea per tree was applied into two small holes 30 cm from both sides of a tree 3 months after planting. In the coppice subplots, 50 g urea, 40 g KCl and 150 g superphosphate $tree^{-1}$ were applied in the same way. Both the seedling and coppice plots received 50 g urea and 40 g KCl one year after planting. The F_2 trees received 50 g urea, 40 g KCl and 150 g superphosphate per seedling and a further 50 g urea and 40 g KCl months after replanting. The F_2 coppice plots received 100 g urea, 80 g KCl and 150 g superphosphate at the same time as refertilisation seedlings (3 months after planting). One year after planting, 100 g urea, 80 g KCl and 150 g superphosphate per tree were applied to seedling and coppice F_2 subplots. Foliar sampling was carried out in the same way as for Experiment 1.

Results

Tree Growth

The slash treatments significantly ($p<0.001$) affected tree heights. At 90 months, tree height increased as more residue was retained (BL_1, BL_2 and BL_3). The difference between BL_1 and BL_2 was not significant but the trees on the BL_3 plots were significantly taller than trees on the BL_1 and BL_2 plots. The effect of BL_0 treatment was an exception, the trees in those plots had the same height as BL_1 plots, presumably because of the repeated weed control applied to the BL_0 plots in the first year. Trees on the BL_4 plots were not significantly different in height from the trees on the BL_2 plots, indicating that interplanting with *Acacia holosericea* did not increase the height growth of the eucalypts.

Tree diameters responded to the treatments in a similar pattern to heights. At 69 months, tree diameter in BL_3 was higher than that in BL_1 and BL_0, but was not significantly different from that in BL_2. At 90 months, tree diameter in BL_4 was higher than that in BL_1, BL_0 and BL_2, but was not significantly different from that in BL_3. Tree diameter increased faster in BL_4 than other treatments in the late stage of this rotation, indicating that intercropping with *A. holosericea* had a positive impact on tree diameter growth towards the end of the rotation.

At 90 months, BL_3 and BL_4 were the best treatments in terms of stand volume and BL_1 was the poorest (Fig. 1). There was no difference between BL_0 and BL_2. From 46 to 90 months, stand volume in BL_4 increased faster than that in BL_3. This indicates that the double slash increased tree growth in the early stages and the residue from intercropping with *A. holosericea* in BL_4 increased tree growth in the late stage of the rotation. Mean MAI of all treatments in the second rotation was about 6 m^3 ha^{-1} yr^{-1}, much lower than average productivity (around 20 m^3 ha^{-1} yr^{-1}) of commercial eucalypt plantations in south China. Stand volume of the second rotation plantation at 90 months was lower than that (8.3 m^3 ha^{-1} yr^{-1}) in the first rotation at 72 months old. The low MAI in the second rotation was partly due to low tree survival rate. Survival rate in the first rotation was 89%, and 78% in the second rotation.

At 90 months of age, dry weight of wood and total aboveground biomass in BL_4 were higher than that in BL_1, BL_0 and BL_2 (Table 2). Wood and total aboveground biomass in BL_3 were higher, but not significant than that in BL_0, BL_1 and BL_2. Dry wood production in BL_3 was 3.84 t ha^{-1}, about 14% higher than that in BL_1. Wood mass in

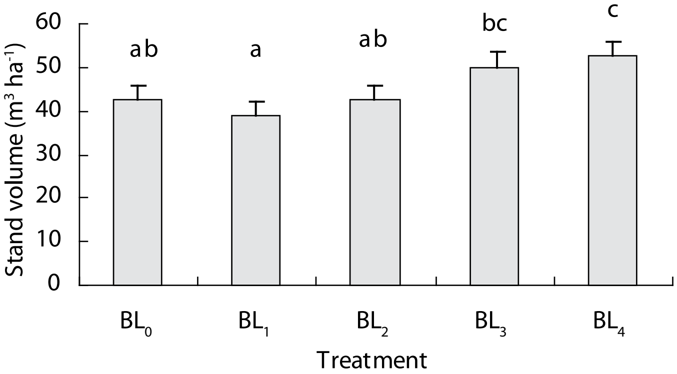

Figure 1. Stand volume of *E. urophylla* plantation at Yangxi at 90 months. Means of the treatment with same letter are not significantly different at p=0.05 using Newman-Keuls critical range. Test bars = one standard error).

Table 1. Effect of different harvest residue treatments on tree height and diameter at 90 months

Treatments	BL_0	BL_1	BL_2	BL_3	BL_4
Height (m)	10.57 ab	10.12 a	10.62 ab	11.42 c	11.19 bc
Diameter (cm)	8.56 ab	8.16 a	8.69 ab	9.21 bc	9.54 c

Means of the treatment with same letter in each row are not significantly different at p=0.05 using Newman-Keuls critical range test.

Table 2. Aboveground biomass of different tree components in different treatments

Treatments	Stemwood	Bark	Branches	Leaves	Total
			(t ha^{-1})		
2R BL$_0$	25.8 a	4.2 a	2.9 a	1.2 a	34.1 a
BL$_1$	24.4 a	4.1 a	2.8 a	1.1 a	32.4 a
BL$_2$	25.9 a	4.2 a	2.9 a	1.2 a	34.2 a
BL$_3$	29.6 ab	4.8 a	3.3ab	1.3 ab	39.1 ab
BL$_4$	32.6 b	5.1 a	3.6 b	1.5 b	42.7 b
1R	30.0	5.2	3.0	2.1	40.3

Means of the treatment with same letter in each column are not significantly different at p=0.05 using Newman-Keuls critical range test. 1R=previous rotation.

Table 3. Nutrient accumulation by aboveground biomass in different treatments

Treatments	N	P	K	Ca	Mg
			(kg ha^{-1})		
2R BL$_0$	62.01 a	3.81 a	35.07 a	68.81 a	6.63 a
2R BL$_1$	59.51 a	3.67 a	33.83 a	66.96 a	6.41 a
2R BL$_2$	62.08 a	3.82 a	35.08 a	68.74 a	6.63 a
2R BL$_3$	71.00 ab	4.36 ab	40.09 ab	78.48 ab	7.58 ab
2R BL$_4$	77.23 b	4.73 b	43.45 b	84.58 b	8.20 b
1R	99.90	7.64	45.97	52.38	15.80

Means of the treatment with same letter in each column are not significantly different at p=0.05 using Newman-Keuls critical range test. 1R=previous rotation.

BL$_4$ was 6.79 t ha^{-1}, about 26% more than that in BL$_1$. Dry wood production and aboveground biomass in BL$_4$ in this rotation was higher than in the previous rotation. However, the period of this rotation was 18 months longer than the previous rotation. Therefore, leaf biomass in this rotation was lower than the previous rotation as trees were older. Average branch biomass in this rotation was slightly higher than that in the previous rotation.

The accumulation of N, P, K and Mg by aboveground biomass in this rotation was lower than the previous rotation (Table 3). However, Ca accumulation in the previous rotation was lower than in this rotation. The low uptake of N, P, K and Mg by aboveground biomass indicated that the supply of soil P in this rotation was lower than that in the previous rotation. The accumulation of N, P, K, Ca and Mg in BL$_4$ was higher than that in BL$_1$, BL$_2$ and BL$_0$.

Experiment 2: Impacts of re-establishment method and fertiliser application on tree growth

The effect of fertilisation on growth of replanted trees was highly significant (p<0.001) (Fig. 2). It dramatically increased tree height and diameter growth at all measurement times. In coppice trees, there was a small but significant (p<0.05) effect of fertiliser on growth before 31 months. Tree height in F$_2$ was higher than in F$_0$ and F$_1$ but this difference decreased as trees grew older. At 46, 57, 69 and 90 months, there was no significant difference between CF$_0$, CF$_1$ and CF$_2$, and trees in the three treatments were almost the same height (Fig. 3).

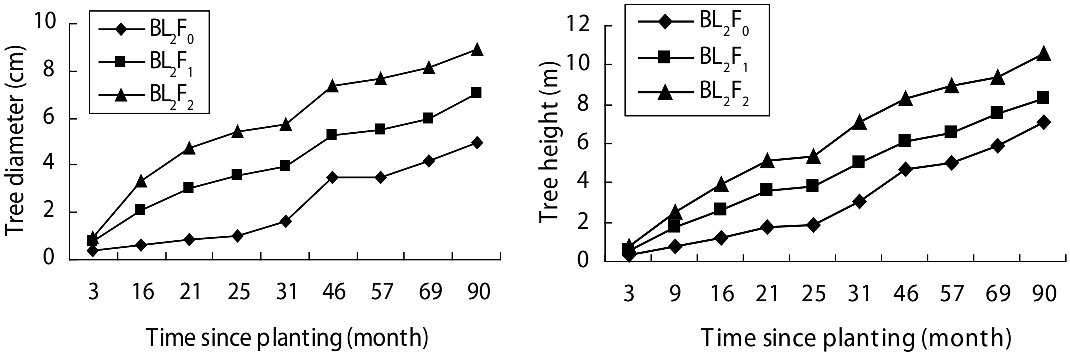

Figure 2. Effect of fertilisation on height and diameter growth of planted trees. First two diameter measurements were at 0.1 m height, the later were at 1.3 m

Up to 90 months of age, coppice trees were larger than the replanted trees and there was an interaction ($p<0.001$) between fertilisation level and regeneration method (Fig. 4). In both tree height and diameter, the difference between coppice and replanted trees was greatest in F_0 (about 4.3 m in height and 4.5 cm in diameter) but the advantage of coppicing declined with fertiliser application (Figs. 2, 3).

There was a significant difference ($p<0.001$) between replanting and coppice in stand volume at 90 months. Coppice stand volume was much higher than replanted trees because there are two stems for one coppice and initial size of coppice stems was larger than replanted seedlings. Stand volume of F_2 was much higher than that in F_0 and F_1 in replanted trees but not in coppice (Fig. 4). MAI of coppice was 17.0 m^3 ha^{-1}, similar to that in previous plantation.

There was no significant difference among BL_1, BL_2 and BL_3 without fertilisation (Fig. 3). Without fertilisation, trees in BL_0 treated plots grew faster than trees in BL_3 and BL_2 plots at an early stage. This was because weeds in BL_0 plots were regularly controlled in the first year while no weed control was applied to the BL_3 and BL_2 plots. 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. Although this is a confounding effect not anticipated in our experimental approach, the results highlight the importance of good weed control on stand growth. However, tree growth in BL_3 increased in the late stage of the rotation. Productivity of the plantation without fertilisation was very low and would not be acceptable in commercial operations.

There was no significant difference in the three fertilisation treatments of coppice regeneration (CF_0, CF_1 and CF_2). This lack of fertilisation response of the coppice plantation was contrasted with the response of trees in replanting treatments (BL_2F_0, BL_2F_1 and BL_2F_2). There was a significant difference in the three fertilisation treatments in the replanted treatments. There was no significant difference in the three treatments with different slash retention treatments and same fertilisation treatment (BL_0F_0, BL_2F_0 and BL_3F_0). This indicated that slash retention alone could not increase tree growth and adequate fertilisation was required.

Discussion

Increased nutrients resulting from slash and litter also increased stand volume at full rotation length (Table 1) confirming the results during the earlier stages of stand growth (Xu *et al.* 2004). This also led to greater aboveground biomass and nutrient accumulation (Tables 2, 3). Branch and leaf residue retention (BL_2) increased stand volume by 25% and double slash (BL_3) increased stand volume by 41% over whole tree harvest

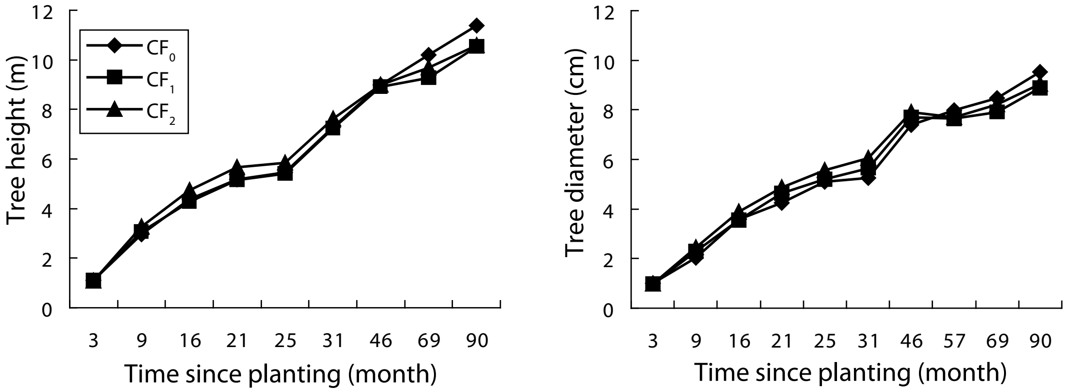

Figure 3. Effect of fertilisation on height and diameter growth of coppice trees. First two diameter measurements were at 0.1 m height, the later were at 1.3 m.

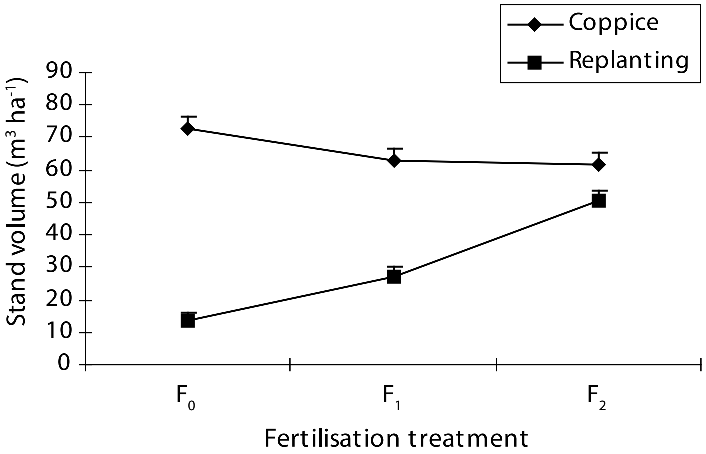

Figure 4. Effect of fertilisation on stand volume of planted trees and coppice 90 months after re-establishment

(BL$_1$). This result was similar to the experiment for coppice of *E. saligna* x *E. robusta* hybrid in Brazil (Miranda *et al.* 1998), but the effect of slash on productivity in this study was smaller compared to the 86% increase in production on the windrows of slash found in Brazil. The reason for the small effect in this study could be the small amount of slash compared with other studies. Before the 1980s, almost all harvest residue and understorey and litterfall on the soil surface in eucalypt plantations in southern China were collected as firewood, and this practice continues even today. This, along with serious soil and nutrient runoff, due to inappropriate site cultivation (Xu *et al.* 2000a), partly explains why soil degradation and productivity decline of eucalypt plantations have been so common in southern China. Slash retention alone was not sufficient to increase productivity to a high level on this low productive land with relatively small amount of slash. At this experimental site the MAI of the previous plantation was much higher than the average MAI across all treatments in second rotation. Although double slash (BL$_3$) increased MAI by 41% over all aboveground biomass harvest treatment (BL$_1$), MAI was 8.3 m^3 ha^{-1} yr^{-1} lower than in the first rotation. The fertilisation regime in second rotation experiment was less than that applied in the first rotation to avoid the response to fertiliser overshadowing the effects of retaining harvest residue. Although slash retention helped it was not enough to raise production to a high level on this degraded site. An appropriate fertiliser application program could be more important than harvest residue retention to substantially improve the productivity. However, slash retention and increased litter production in the next rotation will conserve large amounts of nutrients and could reduce nutrient input by fertilisation. The increment of the nutrients uptake by aboveground biomass of trees in second rotation through slash retention was much less than the amount of nutrients left on site in slash (Table 4). This suggests that most of the nutrients from slash decomposition were not taken up by the trees.

Weed control significantly affected productivity at this site. As noted earlier, BL_0 alone was weeded regularly in the early stage 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 in BL_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 in the early stage of the plantation. Weed control has not been an important problem in eucalypt plantations in southern China in the past because of total soil tillage and understorey harvest. However, weeds should be controlled if new site preparation methods are adopted for soil fertility conservation and there is much less understorey removal. More study is needed to develop appropriate weed control options.

Intercropping with *Acacia* increased growth of the eucalypts in late stage of the second rotation. This could be the effect of increasing N supply in topsoil after decomposition of litterfall and fine roots and nodules of the acacia. If rotation lengths become shorter, intercropping is probably not a viable management option. More study is needed to validate potential productivity increases from an intercropping system involving eucalypts and acacias.

Coppice growth was better than growth of replanted trees in the second rotation after 90 months. There was interaction between regeneration method and fertilisation level. Response of coppice trees to fertilisation was much lower than replanted trees and also lower than the response reported by Miranda *et al.* (1998) in Brazil. Well-developed root systems probably helped the coppice to utilise soil nutrients better than the smaller root systems of the planted trees. At the same time, coppice could also use the nutrients remaining in the root system from the previous rotation. It is recommended that coppice should be adopted for second rotation of eucalypt plantations unless improved genetic material is available for planting.

Fertilisation increased productivity substantially. It is suggested that the level of fertilisation in plantations on degraded lands should be high

Table 4. Comparison of nutrient content in slash and litter left on site before and in aboveground biomass of trees in second rotation

Treatments	BL_1	BL_2	BL_3	BL_1	BL_2	BL_3
	Nutrients in slash and litter of 1R (kg ha^{-1})			Nutrients in aboveground tree biomass in 2R (kg ha^{-1})		
N	52.7	93.8	133.6	59.5	62.8	71.0
P	2.3	5.1	7.8	3.7	3.8	4.4
K	8.8	28.3	46.4	33.8	35.1	40.1
Ca	25.4	42.7	61.0	67.0	68.7	78.5
Mg	8.5	14.6	20.8	6.4	6.6	7.6

enough to achieve reasonable productivity. The amount of fertiliser used in F_2 was similar to the amount used in first rotation and seems high enough to raise nutrient concentrations to a level suggested by other fertiliser experiments in China, e.g. Xu *et al.* (2001). In this high fertilisation treatment with slash retention (BL_2F_2) growth was only 67% the MAI in first rotation. This indicates that an increased nutrient supply by fertilisation is necessary to prevent yield decline in the second rotation on this degraded site.

This study has demonstrated the impact of slash retention on available nutrient supply at the early stage of plantation and tree growth in a rotation. It is well known in south China that harvest residue should be left on site to ensure nutrient cycling. However, it is remains difficult in practice to keep the harvest residue on site as people other than the plantation owner collect it. The key point for the plantation owner is how to keep the harvest residue on site and to find an efficient way to break up harvest residue and incorporate it into the soil.

This study also showed that intercropping an acacia in a eucalypt plantation can increase the growth of the eucalypts. Currently, it is common practice on poor sandy soils in south China to establish a mixed plantation with two rows of eucalypt trees and one row of acacias. More study is needed to optimise this practice.

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References

Brown, A.G., Nambiar, E.K.S. and Cossalter, C. 1997. Plantations for the tropics - their role, extent and nature. *In*: Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests, 1-19. Monograph No.43. Australian Centre for International Agriculture Research, Canberra.

Chen, Z., Chang, H. and Wang, B. 1994. Studies on biomass and production of the lower sub-tropical evergreen broad-leaved forest in Heishiding natural reserve, China. VI. Distribution, biomass and production of roots. Journal of Tropical Ecology 10:273-279.

Cornfield, A.H. 1960. Ammonium released on treating soil with N sodium hydroxide as a possible means of predicting the nitrogen-supplying power of soils. Nature 187: 260-261.

Dell, B. and Malajczuk, N. 1994. Boron deficiency in eucalypt plantations in China. Canadian Journal of Forest Research 24: 2409-2416.

Florence, R.G. 1996. Ecology and silviculture of eucalypt forests. CSIRO, Melbourne, Australia.

Miranda, G.A., Barros, N.F., Leite, H.G. and Teixeira, L.C.J.L. 1998. Producão de povoamentos de eucalipto em regime de talhadia, em funcão da adubadcão e da distribuicão da galhada da rotacão anterior, no Vale do Jequitinhonha-MG. Revista Árvore 22: 307-314.

Saur, E., Nambiar, E.K.S. and Fife, D.N. 2000. Foliar nutrient retranslocation in *Eucalyptus globulus*. Tree Physiology 20: 1105-1112.

Simpson, J. and Mo, Q. 1989. Long-term fertiliser responses in eucalypts at Dongmen. *In*: Proceedings of the 4th Technical Exchange Seminar on China-Australia Afforestation Project at Dongmen, 40-52. Nanning, Guangxi, China.

Wang, H.R. and Zhou, W.L. 1996. Fertiliser and eucalypt plantations in China. *In*: Attiwill, P.M. and Adams, M.A. (eds.) Nutrition of eucalypts, 389-397. CSIRO, Melbourne, Australia.

Xu, D.P. 1997. An approach to nutrient balance in tropical and south subtropical short rotation plantations. *In*: Yang, C. (ed.) Forest soil, 78-87. Science and Technology Publishing House, Beijing.

Xu, D.P. 1996. Soil degradation, a key factor in restraining productivity of tropical tree plantations in south China. *In*: Proceedings of IUFRO Conference on Effects of Environmental Factors on Tree and Stand Growth, Dresden, Germany, 251-158. University of Dresden, Germany.

Xu, D. and Dell, B. 1997. Importance of micronutrients for productivity of plantation eucalypts in east Asia. *In*: Kikkawa, J. *et al.* (eds.) Overcoming impediments to reforestation. Proceedings of 6th International BIO-REFOR Workshop, Brisbane, Queensland, December, 1997, 133-138. BIO-REFOR, University of Tokyo, Tokyo.

Xu, D.P., Bai, J.Y. and Dell B. 2000a. Overcoming the constraints to productivity of eucalypt plantations in southern China. *In*: Proceedings of International Workshop on Mycorrhizas in Forestry, Guangzhou, China, September 1998, 150-162. China Forestry Publishing House, Beijing.

Xu, D.P., Liu, Y. and Yang, Z. 1999. Soil erosion control by vegetation restoration in southern China. *In*: Proceedings of International Symposium on Soil Erosion and Dryland Farming, Xian, China, September 1997, 256-268, Soil Society of America, USA.

Xu, D.P., Yang, Z.J., Chen, M.H. and Chen Q.D. 1998. Plantation of *Eucalyptus urophylla* S.T. Blake in Guangdong province, China. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 16-20 February 1998, Pietermaritzburg, South Africa, 31-38. Center for International Forestry Research, Bogor, Indonesia.

Xu, D., Yang, Z., Dell, B., Gong, M. 2000b. Effects of site management on tree growth, soil properties and nutrient availability of second rotation plantation of *Eucalyptus urophylla* in Guangdong Province, China. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 31-40. Center for International Forestry Research, Bogor, Indonesia.

Xu, D., Dell, B., Malajczuk, N., Gong, M. 2001. Effects of P fertilisation on productivity and nutrient accumulation in a *Eucalyptus grandis* x *E. urophylla* plantation in southern China. Forest Ecology and Management 161: 89-100.

Xu, D.P., Yang Z.J. and Zhang, N.N. 2004. Effects of site management on tree growth and soil properties of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.), Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Zhong, C., Gong, M., Chen, Y., Wang, F. and Chen, Y. 1999. Productivity of eucalyptus plantations in southern China: mycorrhizal fungi and fertilisers. *In*: Kikkawa, J. *et al*. (eds.) Overcoming impediments to reforestation: proceedings of 6th International BIO-REFOR Workshop, Brisbane, Queensland, December, 1997, 236-246. BIO-REFOR, University of Tokyo, Tokyo.

Plantation in China. (Photo: Christian Cossalter)

Soil Fertility and Growth of *Eucalyptus grandis* in Brazil under Different Residue Management Practices

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Abstract

Silvicultural operations such as soil preparation, logging residue management and application of fertilisers can influence soil fertility, hence nutrient uptake and tree growth. This paper reports effects of site management practices of minimum and intensive cultivation of the soil on the growth of *Eucalyptus grandis* and on soil fertility. The experimental site is characterised by seasonal soil water deficits and very low soil fertility. Effects of complete harvest residue removal, residue retention and residue burning were assessed. Highest productivities were obtained where residues were retained or burned and the lowest where all residues (slash, litter and bark) were removed. Results highlight the temporary, but large, nutrient release due to burning and the effect of forest residues on tree growth. In the 0-5 cm soil layer temporary variations were found in organic C and N, exchangeable cation contents and pH only except for burned residues treatment where variations in the (5-10 cm) layer were found. No modification of soil properties was found in 10-20 cm layer. The organic C in 0-5 cm layer of the treatment where all residues were removed was about 0.4% (4 g kg^{-1}) lower than that in the original eucalypt stand one month after harvesting. Variation in organic C content in the different treatments correlated with the variation in organic N content. Soil pH changed little in the different treatments. Burning resulted in loss of 82% of biomass, 86% of N, 60% of P, 49% of K, 11% of Ca, 29% of Mg and 84% of S. In this treatment, there were considerable and gradual increases in exchangeable Ca and Mg and a decrease in exchangeable Al to 10 cm depth. Exchangeable K initially increased up to 0.8 years after harvesting and later decreased. Over a 21-month period, the largest rates of N mineralisation were found in the standing crop treatment (77 kg ha^{-1} N), followed by the treatment where the residues were retained with minimum disturbance of the site (58 kg ha^{-1} N). Removal or burning residues inhibited N mineralisation (45 and 28 kg ha^{-1} of N respectively). High N mineralisation rates are one reason why most Brazilian eucalypt plantations have little or no response to N fertilisation. Different residue management treatments had pronounced effects on tree growth. Retention of all residues on soil or burning had similar growth at age 8.7 years. However, there was high nutrient loss in the burning treatment. Removal of all residues reduced stem biomass productivity (30%) compared to retention of all residues. Results indicate residue management has a major effect on soil fertility and nutrient store of the ecosystem, and that some practices can compromise the sustainability of forest productivity in the short term.

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

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in soils that are commonly loamy latosols and quartzipsamments (sandy soils). Little is known about potential impacts caused by different residue management practices on yield sustainability over successive rotations of eucalypt stands, particularly with respect to soil fertility. Usually, soil fertility decline is caused by management that does not conserve soil and site resources, damages soil physical and chemical characteristics, and applies insufficient or unbalanced fertiliser. The problem is more serious with fast-growing genotypes that have high nutrient demand and uptake capacity and consequent high nutrient export when harvested.

During site preparation, harvesting residues can be burnt or mixed with surface soil (e.g. conventional ploughing) or retained on the soil surface with restricted soil disturbance (e.g. 'minimum cultivation' in lines or spots). The need to disturb less soil by providing more cover and protection, to improve weed control and to reduce costs has led to a progressive increase in the use of minimum cultivation practices during the last fifteen years (Gonçalves *et al.* 2002). Many managers have accepted minimum cultivation as a good alternative to maintaining or increasing soil fertility in the long term as it reduces nutrient and organic matter losses and preserves crucial physical properties.

In the subtropics and tropics the presence of different amounts of litter and logging residues have affected eucalypt productivity to different degrees, depending on water and nutrient availability (e.g. Du Toit *et al.* 2004, Nzila *et al.* 2004, O'Connell *et al.* 2004, Sankaran *et al.* 2004 and Xu *et al.* 2004). In these studies retaining harvesting residues increased the efficiency of water and nutrient use in eucalypt stands under water and nutritional stress by reducing losses and providing nutrients in available forms that corresponded with tree demand. Minimum cultivation techniques have been accepted as a good alternatives to maintain or increase soil fertility in the long term because it reduces the nutrient and organic matter losses and preserves crucial physical properties such as permeability (root growth, infiltration, aeration) (Gonçalves *et al.* 2002, Stape *et al.* 2002, Xu and Dell 2003).

The present study aims to evaluate and compare soil fertility in eucalypt stands in Brazil established under different systems of forest residue management.

Material and Methods

Description of the Experimental Area

The study was carried out in a commercial plantation of *Eucalyptus grandis* Hill ex Maiden (Coffs Harbour provenance), Itatinga district, São Paulo state, Brazil; latitude 23°00' S, longitude 48°52' W, and altitude 750 m. Before plantations were established 'Cerrado', the native vegetation typical of the area, occupied these sites. The eucalypt stand was seven years old at the beginning of the study. Climate of the area is Cwa, according to the classification of Köeppen, i.e. mesothermic with a dry winter, the mean temperature for the coldest month (July) is less than 18°C, and for the hottest month (January) more than 22°C. Mean annual precipitation is 1579 mm, 57% falling from December to March. There is no pronounced water deficit. The soil type of the area is characterised as a Typic Hapludox (Haplic Ferralsol, FAO classification), loamy, dystrophic. The site is gently undulating. Some soil physical and chemical characteristics are shown in the Table 1. The climate, soil and vegetation are representative of extensive areas planted with eucalypts on the São Paulo plateau.

Site Preparation

The experimental treatments consisted of operational practices designed to provide a range of disturbances of different intensities on the soil and harvest residues, as follows:

SC Standing crop, left intact; *E. grandis* plantation (7 years-old) established by seedlings;

BL_0 Clearfell the stand; aboveground matter including the tree crop, understorey, slash and litter were removed;

BL_1 Clearfell the stand. Whole-stemwood harvested. All the bark, understorey, slash and litter were retained with minimum disturbance to site; and

$SL_{(b)}$ Clearfell the stand and harvest stemwood. All residues were distributed on the soil and burnt.

Table 1. Soil physical and chemical attributes before trial establishment

Depth	Clay	Silt	Sand	Bulk density	pH in	C	N	P-resin	Exchangeable cations			
									K	Ca	Mg	Al
cm		%		g dm^{-3}	CaCl$_2$	g kg^{-1}		mg kg^{-1}		cmol$_c$ kg^{-1}		
0 – 10	20	3	77	1.25	3.5	15.2	1.8	6.0	0.04	0.17	0.15	1.45
10 – 20	20	3	77	1.25	3.6	10.5	1.0	4.5	0.03	0.14	0.12	1.15
20 – 30	22	2	76	1.30	3.7	9.3	0.9	3.0	0.03	0.09	0.06	1.20
30 – 50	22	2	76	1.30	3.8	4.6	0.5	3.0	0.02	0.05	0.03	1.10
50 – 100	24	2	74	1.31	3.8	1.5	0.2	2.0	0.02	0.05	0.03	1.12

The experiment used a randomised complete block design, with 4 replicate plots of 726 m^2 with 121 trees.

The stand was clearfelled in July 1995 and treatments were applied by August 1995. Treatments BL$_0$, BL$_1$ and SL$_{(b)}$ were completed after the clearfelling and seedlings for the new plantations were planted in September 1995 at a spacing of 3.0 x 2.0 m. Seedlings were raised in a commercial nursery from seeds of *E. grandis* (Coffs Harbour provenance).

Seedlings were planted in furrows 30 cm deep. They were 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. The trial was weeded twice, the first 3 months after planting and, the second 4 months later.

Tree Growth

Height and diameter (breast height) were measured periodically and stand volume calculated. To estimate the biomass and nutrient uptake, five trees were sampled per plot, each tree representing a particular size class distribution. One tree from each of the 16 plots was selected with stand mean diameter at breast height and mean height. These trees were sampled destructively periodically for 8.7 years. The samples provided values of stemwood, and wood density. Total fresh stem and foliage biomass were determined for each tree and representative subsamples (ranging from 200 to 1500 g) of each component were taken for moisture determination (dried at 65°C) to calculate total dry mass.

Soil Sampling and Analytical Procedures

Soil samples were collected at 0-5, 5-10 and 10-20 cm depths with an auger, 1, 6, 10, 26 and 84 months after harvesting. Ten single soil samples per plot were collected in a diagonal transect. These samples were combined into compound samples, which were air-dried, homogenised, pounded to break up clods, and sifted (2 mm sieve). The soil pH was determined in CaCl$_2$ 0.01 mol L^{-1} (1:5 extracts). Available P, and exchangeable Ca, Mg, and K were displaced by ion-exchange resins. Calcium and Mg in the extracts were determined by atomic absorption spectrometry and K by flame photometry. Procedures used for these analyses are described in Raij *et al.* (2001). Determinations of C and total N were made using dry combustion (1050°C; LECO CN 2000) (Nelson and Sommers 1982). Soil textural analysis used the pipette method for clay content; the sand content was determined by sieving, while the silt content was determined by the difference between sand and clay content (Embrapa 1997). The volumetric ring method was used for bulk density determination by weighing and drying; the soil particle density was determined using the volumetric flask method (Embrapa 1997).

N Mineralisation

Nitrogen mineralisation dynamics were measured in treatments SC, BL$_0$, BL$_1$ and SL$_{(b)}$ using the methodology of Raison *et al.* (1987). Soil cores were contained *in situ* in 6 PVC tubes (40 cm long and 5 cm diameter). Soil was incubated (± 50 days), sequentially sampled and mineral nitrogen was measured. The soil cores were segmented in 0-5, 5-15 and 15-30 cm depths.

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

Loss of Nutrients from Harvest Residues by Burning

To establish the mass and nutrient content of residues before and after burning, a small experiment, similar to treatment BL_1, was established within a large plot of 1000 m^2, in a randomised complete block design with 4 replicate subplots of 1 m^2. The following treatments were assessed: (1) control – all harvest residues were not burnt; (2) all harvest residues were collected and burned on a metal foil. From these results the loss of nutrients by volatilisation was estimated.

Residue materials were dried at 65°C for 48 h, weighed and ground to pass a 1.0 mm sieve using a Willey mill. Residue samples were digested for determination of total nutrient concentration using concentrated H_2SO_4 for total N and concentrated HNO_3+$HClO_4$ (2:1 v/v ratio) for other macronutrients (Sarruge and Haag 1974). Nitrogen was determined by Kjeldhal distillation (TE036/01-Tecnal). After digestion by nitric and perchloric acids, the concentrations of Ca and Mg were determined by atomic absorption spectrometry (Perkin Elmer AAnaLYST 100), K by flame emission spectrometry (B462-Micronal), and P by UV spectrometry (U2001-Hitachi).

Statistical Analysis

The results were analysed using analysis of variance. Two-way ANOVA was used to test the variation in soil characteristics between treatments and times, by each depth. Whenever the ANOVA indicated a significant difference between the means ($p<0.05$), these were compared using the least significant difference (LSD) starting from the multiple range test (Tukey HSD) for mean separation analysis. The statistical program used in the analyses was Statgraphics Plus for Windows (1995).

Results and Discussion

Soil Nutrient Store

Temporary variations in organic C and N, exchangeable cation contents and pH occurred in 0-5 cm soil samples in treatments where all residues were maintained (BL_1), removed (BL_0) and burned (SL_b). Variations in these properties in the 5-10 cm depth occurred only in the SL_b treatment (Tables 2, 3 and 4). No modification was found in the next layer (10-20 cm; data not shown).

Organic C in SC, BL1 and BL0 did not vary significantly between sampling times. When the residues were removed, organic C in the 0-5 cm layer was about 0.4% (4 g kg-1) lower than that found where the eucalypt stand was maintained (SC) one month after harvesting. This drastic decrease in organic C suggests that labile C in this layer was high. Probably, the increase of soil temperature and moisture (Gonçalves *et al.* 1999) promoted the temporary acceleration of organic matter decomposition after harvesting and residue removal. The organic C content in the different treatments was correlated with organic N content (r = 0.95; $p = 0.01$). In the BL0 treatment a decrease of available P with the time was recorded (Table 3) whereas the exchangeable bases increased with time up to a depth of 10 cm. Poor tree growth in BL0, and subsequent low nutritional demands, was probably the main cause of this effect. Soil pH changed little with time within each treatment (Tables 3 and 4). In the 0-5 cm layer, in most of the samples, the pH ranged between 3.7 and 3.9. There was no clear trend of effects among treatments.

In SL_b, organic C in the 0-5 cm layer increased soon after burning and decreased 6 and 10 months after harvesting before increasing again after 26 months (Table 3). Apparently, there was eluviation of C in soluble form or particles (ash, charcoal), since an increase in C was found in 5-10 cm layer at 10 months after harvesting (Table 4). The great amount of ash and particles of charcoal produced by burning 38.9 t ha^{-1} of forest residues (23.7 t ha^{-1} of litter, 8.9 t ha^{-1} of bark and 6.3 t ha^{-1} of harvest slash) together with the soil porosity would have promoted this effect. In this treatment considerable and gradual increase of exchangeable Ca and Mg and decrease of exchangeable Al up to 10 cm of depth was found (Tables 3 and 4). Exchangeable K initially increased up to 0.8 years after harvesting and later decreased, probably due to the leaching and tree uptake since the growth rate in SL_b was relatively high.

As discussed, burning forest residues (litter, bark, and harvest slash) initially elevates soil fertility in the upper soil layers. However, at the ecosystem nutrient pool level, nutrient losses are very large and should negatively influence long-term soil fertility. In this study we found losses of 82% of biomass, 86% of N, 60% of P, 49% of K, 11% of Ca, 29% of Mg and 84% of S by burning (data not shown). Export of these nutrients from the system must have been primarily from volatilisation and aerial ash transport. Applying these percentages to original nutrient concentrations in biomass, losses per hectare would be 245 kg of N, 17 kg of P, 55 kg of K, 38 kg of Ca, 15 kg of Mg and 11 kg of S.

It is important to note the high losses of nutrients considered non-volatile, such as P and K. Cotton and Wilkinson (1988) affirmed that P is volatilised when temperatures exceed 360°C. Moreover, nutrient losses through water and wind erosion will be higher because some of the mineralised nutrients are exposed on the soil surface after burning. In this situation, a significant part of the nutrients can be removed by winds, surface flow, and water infiltration that will transport larger amounts of soluble nutrients.

N Mineralisation

Over a 21-month period, the largest rates of N mineralisation were found in the SC treatment (standing crop, 77 kg ha^{-1} of N), followed by BL_1 treatment (minimum disturbance, 58 kg ha^{-1} of N; Table 5). When all residues were removed N mineralisation decreased to 45 kg ha^{-1} of N. The smallest rate of 28 kg ha^{-1} of N mineralisation was found in treatment where residues were

Table 2. Summary of analysis of variance of soil chemical attributes by treatment, sampling date and interaction in 0-5 and 5-10 cm depths

Chemical attribute	Treatments		Sampling date		Interaction		SE
	df	F	df	F	df	F	
			0-5 cm layer				
pH in $CaCl_2$	3	17.2*	4	5.2*	12	1.8^{ns}	0.18
C (g kg^{-1})	3	3.8*	4	3.1**	12	0.6^{ns}	6.84
N (g kg^{-1})	3	4.1*	4	2.8**	12	0.5^{ns}	0.63
P-resin (mg kg^{-1})	3	7.5*	4	4.8*	12	1.8*	2.10
K (cmol$_c$ kg^{-1})	3	6.4*	4	4.2**	12	1.6*	0.04
Ca (cmol$_c$ kg^{-1})	3	5.3**	4	6.3**	12	1.1^{ns}	0.29
Mg (cmol$_c$ kg^{-1})	3	3.8*	4	2.5*	12	1.2^{ns}	0.18
Al (cmol$_c$ kg^{-1})	3	16.7**	4	10.8**	12	2.3*	0.18
			5-10 cm layer				
pH in $CaCl_2$	3	3.6*	4	13.3**	12	0,8^{ns}	0.10
C (g kg^{-1})	3	2.8*	4	18.0**	12	0.9^{ns}	5.83
N (g kg^{-1})	3	3.2*	4	16.1**	12	0.7^{ns}	0.67
P-resin (mg kg^{-1})	3	1.7^{ns}	4	4.1*	12	1.1^{ns}	2.50
K (cmol$_c$ kg^{-1})	3	4.2**	4	21.6**	12	3.0*	0.03
Ca (cmol$_c$ kg^{-1})	3	1.0^{ns}	4	11.8**	12	1.7^{ns}	0.09
Mg (cmol$_c$ kg^{-1})	3	4.1^{*8}	4	11.9**	12	2.7^{ns}	0.05
Al (cmol$_c$ kg^{-1})	3	6.3**	4	11.5**	12	2.6^{ns}	0.14

Significant effects are indicated with asterisks (**$p \leq 0.01$; * $p \leq 0.05$).

Table 3. Chemical attributes of surface soil layer (0-5cm) at different sampling time after harvesting

Treat.	Month after harvesting	pH in $CaCl_2$	C	N	P-resin	Exchangeable cations			
						K	Ca	Mg	Al
			(g kg^{-1})		(mg kg^{-1})	(cmol$_c$ kg^{-1})			
SC	1	3.4 aA	18.3 bB	1.9 cB	7.2 aB	0.05 aA	0.18 cdA	0.16 aA	1.52 aA
	6	3.8 bAB	16.4 bB	1.4 aAB	8.0 aB	0.08 bA	0.17 bcA	0.12 aA	1.32 aB
	10	3.7 bA	13.2 aA	1.3 aA	6.9 aA	0.08 bA	0.19 dA	0.18 aAB	1.53 aB
	26	3.8 bA	16.6 bA	1.7 bABC	6.7 aAB	0.05 aA	0.18 cdA	0.18 aA	1.30 aB
	84	3.8 bA	17.4 bB	1.9 cB	6.2 aB	0.05 aA	0.15 aA	0.13 aA	1.45 aB
BL_1	1	3.6 aC	17.8 aB	1.7 bB	4.3 aA	0.09 aB	0.40 aB	0.08 aA	1.64 cA
	6	3.7 aA	17.0 aB	1.5 aB	12.7 bC	0.09 aA	0.47 aB	0.13 abA	1.24 bB
	10	3.7 aA	16.4 aA	1.6 aA	8.0 abA	0.12 bB	0.38 aB	0.27 bB	1.29 bA
	26	3.9 bAB	19.4 bAB	2.0 cBC	5.7 aA	0.12 bB	0.76 bB	0.31 bB	0.93 aA
	84	4.0 bB	20.1 bB	2.3 dB	4.7 aAB	0.13 bB	0.70 bB	0.30 bB	0.83 aA
BL_0	1	3.7 aD	14.0 abA	1.1 abA	6.1 abB	0.08 aAB	0.36 aB	0.08 aA	1.63 cA
	6	3.9 aB	12.0 abA	1.0 aA	5.9 aA	0.08 aA	0.31 aB	0.15 aA	1.55 bcC
	10	3.8 aB	10.7 aA	1.1 abA	6.8 bA	0.17 bC	0.40 aB	0.14 aA	1.34 bA
	26	4.0 bB	14.6 bA	1.4 bA	4.5 aA	0.26 cC	0.66 bB	0.48 bC	0.97 aA
	84	3.9 aA	12.0 abA	1.0 aA	4.0 aA	0.20 bD	0.58 bB	0.35 bB	0.95 aA
SL_b	1	3.5 aB	22.2 bC	2.1 bB	7.1 aB	0.09 aB	0.47 aB	0.11 aA	1.63 dA
	6	3.8 bAB	16.8 aB	1.6 aB	9.4 aB	0.12 abB	0.41 aB	0.21 abA	1.02 aA
	10	3.8 bB	14.9 aA	1.5 aA	8.1 aA	0.29 dD	0.60 abC	0.25 abB	1.34 cA
	26	3.8 bA	24.7 bB	2.4 bC	6.8 aB	0.15 bcB	0.78 bcB	0.40 bcBC	1.35 cB
	84	3.8 bA	28.0 C	2.9 cC	7.0 aB	0.17 cC	0.90 cC	0.48 cC	1.20 bB

Means followed by different minuscule letters in the column indicate significant differences among sampling date within treatment, and means followed by different capital letters in the column indicate significant differences among treatments by Tukey test ($p = 0.05$).

burnt. The contribution of litter was very small, less than 5% of the total N mineralised (Table 5). The largest amount of N mineralised was found in the treatments where the soil organisms had more substrate to process. 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, therefore experiencing high temperature and humidity fluctuations (Gonçalves *et al.* 1999), besides the reduction of substrate quality for the soil microorganisms. In the second case, more pronounced effects of temperature increase of the surface soil would have caused considerable reduction of microbial biomass.

High rates of N mineralised over the first six months after harvesting in the SC treatment is probably related to the clearfelling of the adjacent plots to the standing crop for installation of the other treatments. Because of the clearfelling, lateral solar radiation penetrated the SC plots and caused

Table 4. Chemical attributes in 5-10 cm soil layer at different sampling time after harvesting

Treat.	Month after harvesting	pH in $CaCl_2$	C	N	P-resin	Exchangeable cations			
						K	Ca	Mg	Al
			(g kg^{-1})		(mg kg^{-1})		(cmol$_c$ kg^{-1})		
SC	1	3.6 aA	10.0 aA	1.1 aA	5.8 aB	0.03 aA	0.17 aA	0.10 aAB	1.39 bA
	6	3.9 bAB	9.4 aA	1.0 aA	6.2 aB	0.05 abA	0.15 aA	0.12 aA	1.12 abA
	10	3.9 bB	7.3 aA	0.8 aA	6.6 aA	0.07 bA	0.17 aA	0.13 aA	1.07 aA
	26	4.0 bB	9.6 aAB	1.0 aA	5.5 aAB	0.04 abA	0.13 aA	0.13 aA	1.44 bB
	84	4.0 bB	9.3 aA	0.8 aA	4.8 aA	0.03 aA	0.12 aA	0.10 aA	1.35 bB
BL_1	1	3.8 aB	8.8 aA	0.9 aA	7.1 bB	0.05 aA	0.25 bB	0.13 aBC	1.48 bAB
	6	3.9 abAB	8.0 aA	0.8 aA	6.6 abB	0.08 abA	0.26 bB	0.18 aB	1.38 bB
	10	3.9 abB	7.9 aA	0.8 aA	5.9 abA	0.08 abA	0.13 aA	0.17 aA	1.10 aA
	26	4.0 bB	7.6 aA	0.8 aA	6.6 abB	0.12 cB	0.13 aA	0.13 aA	1.10 aA
	84	4.0 bB	8.2 aA	0.7 aA	5.0 aA	0.09 bB	0.12 aA	0.10 aA	1.08 aA
BL_0	1	3.8 aB	8.8 abA	0.9 abA	3.4 aA	0.05 aA	0.38 aC	0.09 abA	1.49 aAB
	6	4.0 bB	7.5 aA	0.9 abA	4.1 aA	0.07 abA	0.20 aAB	0.08 aA	1.58 aC
	10	3.8 aA	7.3 aA	0.7 aA	6.9 bA	0.11 bB	0.23 aA	0.13 bA	1.35 aB
	26	4.0 bB	12.7 bBC	1.1 bA	4.5 abA	0.12 bB	0.21 aA	0.13 bA	1.48 aB
	84	3.9 abAB	10.0 abA	0.8 abA	4.0 aA	0.09 bB	0.19 aA	0.11 aA	1.59 aC
SL_b	1	3.6 aA	9.6 abA	0.9 aA	5.5 abB	0.09 aB	0.42 bC	0.14 aC	1.61 cB
	6	3.8 aA	8.8 aA	0.8 aA	8.7 cC	0.13 bB	0.44 bC	0.20 bB	1.10 aA
	10	3.8 aA	13.5 bB	1.4 bB	6.6 bA	0.23 cC	0.17 aA	0.25 cB	1.33 abB
	26	3.7 aA	15.2 bC	1.5 bB	4.8 aA	0.14 bB	0.13 aA	0.33 dB	1.59 bcB
	84	3.8 aA	17.8 bB	1.5 bB	4.0 aA	0.12 abC	0.15 aA	0.30 dB	1.52 bcC

Means followed by different minuscule letters in the column indicate significant differences among sampling date within treatment, and means followed by different capital letters in the column indicate significant differences among treatments by Tukey test ($p = 0.05$).

a soil temperature increase (Gonçalves *et al.* 1999), which would cause an increase in the N mineralisation rate.

The largest N mineralisation occurred in the 0-15 cm soil layer (> 65%). In the old stand (SC), the amount of N mineralised in this layer was larger, about 90% of the total N (Table 5). The largest N mineralisation rates and treatment differences were found in the first year after clearfelling as a direct effect of the treatments in exposing soil (Fig. 1). Soil N mineralisation, around 40 kg ha^{-1} over the first 8 months in the minimum disturbance treatment (BL_1), explains partially the lack or small response to nitrogen fertilisation observed in Brazilian eucalypt plantations (Barros *et al.* 1990, Gonçalves and Barros 1999). Forest residues also constitute an important complementary source of N (Table 5). Average annual N demand for maximum eucalypt growth is around 50 kg ha^{-1} (Gonçalves *et al.* 2004).

Table 5. Total-N mineralised over the first 21 months of growth

Treatments	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_b	-	16 (57)	3 (11)	9 (32)	28

Values between brackets are the percentages in relation the total.

Table 6. Nutrient concentration, biomass and nutrient content in the accumulated forest-floor of a eucalypt stand before and 6 months after harvesting and replanting

Treatments	Biomass⁽¹⁾	N	P	K	Ca	Mg
				(g kg^{-1})		
Before harvesting		7.9	0.4	1.5	8.8	1.0
6 months later		7.2	0.3	1.6	8.7	1.0
	(t ha^{-1})			(kg ha^{-1})		
Before harvesting⁽¹⁾	23.7 (1.8)	187	9.5	36	209	24
6 months later⁽¹⁾	15.6 (1.9)	112	4.5	25	135	16

(1) Values in parentheses are the standard errors.

Table 7. Stand characteristics at the harvest of the first rotation (79 months of age) and the second rotation (77 months of age)

	First rotation	Second rotation			
	Commercial silviculture	Worst treatments (BL_0)	Commercial silviculture (BL_1)	Mean of all treatments⁽¹⁾	Best treatments⁽²⁾ (BL_1)
Stocking density (trees ha^{-1})	1620	1630	1650	1630	
Height (m)	20.8	19.6	22.4	20.5	
DBH (cm)	12.0	11.6	12.8	12.3	
Basal area (m^2 ha^{-1})	19.5	17.8	25.0	22.9	
Volume (m^3 ha^{-1})	192.5	176.2	276.7	249.6	

(1) Treatments: BL_1 (all residues retained), BL_2 (only understorey and litter retained), BL_0 (all residues removed), SL_b BL_1 (all residues burned).

(2) Best treatment = commercial silviculture.

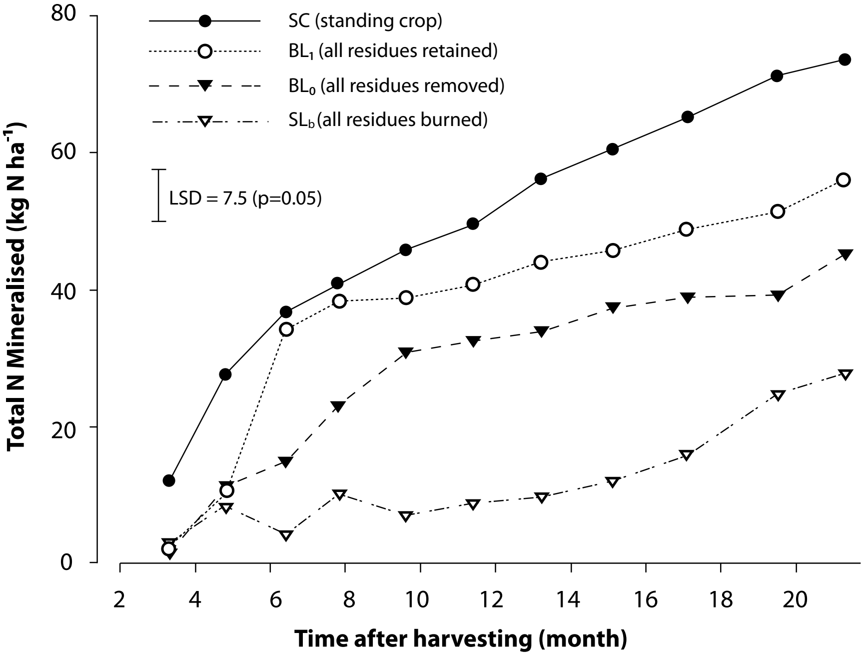
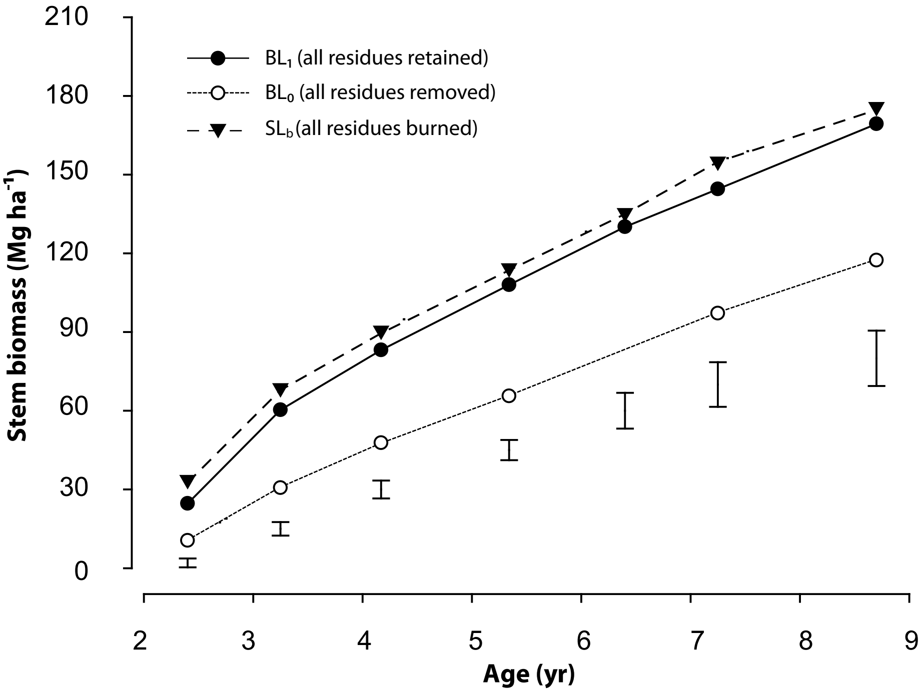


Figure 1. Total-N mineralised in 0-30 cm soil layer over the first 21 months after harvesting



Bars represent the least significant differences at $p < 0.01$

Figure 2. Stem biomass (with bark) over 8.7 years in relation to treatments

Researchers have observed that extensive eucalypt plantations rarely respond to nitrogen fertilisation under tropical and subtropical conditions (Barros *et al.* 1990, Gonçalves *et al.* 1997, Herbert and Schönau 1990, Xu and Dell 2003). This is because the several natural sources of N, mainly the organic N mineralisation, are enough to meet tree demands (Gonçalves and Barros 1999, Gonçalves *et al.* 2001). However, due to the high outputs of N (Reis *et al.* 1987, Bennett *et al.* 1997, Gonçalves *et al.* 1997, Stape 2002), and the possible exhaustion of the reserves of mineralisable organic N, intensively managed forests may respond to N fertilisation after successive rotations (Gonçalves *et al.* 2001, Xu and Dell 2003), mainly on sites with low levels of soil organic matter (Herbert and Schönau 1989). Input-output budgets at the ecosystem level and field trials in Congo showed consistently that N fertilisation must increase over successive rotation to sustain the growth of eucalypt plantations (Laclau 2001). Deficiency of N is closely related to exhaustion of mineralisable C, since N and C dynamics are closely related (McGill and Christie 1983). Hence, practices that increase the stocks of soil organic N should be encouraged, e.g. by using symbiotic fixers.

Effect of Site Management on Productivity

Different residue management treatments profoundly affected growth of *E. grandis* stands (Fig. 2). Treatments where all residues were retained on soil (BL_1) or burned (SL_b) grew at a similar rate at 8.7 years of age. Removal of all residues caused a productivity reduction of 52 t ha^{-1} (30%) of stem biomass compared to the treatment where all residues were retained (contrast $BL_1 - BL_0$). The importance of the residues on the productivity of soils with low fertility is very clear. Comparable residue management studies on sites with soils low in fertility showed similar trends in Australia (O'Connell *et al.* 2004) and Congo (Nzila *et al.* 2004).

The apparent cause of the large growth reduction when residues are removed is related to Ca and P deficiency, nutrients that are contained in great amounts in forest residues (Table 6) or in their ashes. The Ca and P in these soils are below the levels needed for eucalypts on loamy soils (Gonçalves *et al.* 2004). In this trial there were no limestone applications and the P rate (13 kg ha^{-1}) is considered low. In similar soils, Gonçalves *et al.* (1996) recommend 26 kg ha^{-1} of P.

It is probable that reduced N mineralisation, which was found when all residues were removed, was not the main cause of the reduced growth, or growth in the treatment where all residues were burnt (SL_b) and the rates of N mineralisation were very low (Fig. 1) would have been much lower. Ashes of residues produced in this treatment also were not a good source of N for the trees because most of N is volatilised to the atmosphere with burning, as was demonstrated.

Higher volume growth of trees in the early years after burning the residues (SL_b), highlights the temporary effect due to the high initial availability of nutrients released by burning and mineralisation. However, this management practice has undesirable effects on the total nutrient store and can reduce productivity over subsequent rotations.

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References

Barros, N.F., Novais, R.F. and Neves, J.C.L. 1990. Fertilização e correção do solo para o plantio de eucalipto. *In*: Barros, N.F. and Novais, R.F. (eds.) Relação Solo-Eucalipto, 127-186. Ed. Folha de Viçosa, Viçosa, Brazil.

Bennett, L.T., Weston, C.J. and Attiwill, P.M. 1997. Biomass, nutrient content and growth response to fertilisers of six-year-old *Eucalyptus globulus* plantations at three contrasting sites in Gippsland, Victoria. Australian Journal of Botany 45:103-121.

Bremner, J.M. 1965. Soil nitrogen. *In*: Bartholomew, W.V. and Clark, F.E. (eds.) Agronomy 10:93-149.

Cotton, F.A. and Wilkinson, G. 1988. Advanced inorganic chemistry. Wiley, New York, USA.

Du Toit, B., Dovey, S.D., Fuller, G.M. and Job, R.A. 2004. Effects of harvesting and site management on nutrient pools and stand growth in a South African eucalypt plantation. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 31-43. Center for International Forestry Research, Bogor, Indonesia.

Embrapa. 1997. Manual de métodos de análise de solo. 2nd ed. Embrapa Centro Nacional de Pesquisa de Solos, Rio de Janeiro. 212p.

Gonçalves, J.L.M. and Barros, N.F. 1999. Improvement of site productivity for short-rotation plantations in Brazil. Bosque 20: 89-106.

Gonçalves, J.L.M., Stape, J.L., Wichert, M.C.P. and Gava, J.L. 2002. Manejo de resíduos vegetais e preparo de solo. *In*: Gonçalves, J.L.M. and Stape, J.L. (eds.) Conservação e cultivo de solos para plantações florestais, 131-204. IPEF, Piracicaba, Brazil.

Gonçalves, J.L.M., Barros, N.F., Nambiar, E.K.S. and Novais, R.F. 1997. Soil and stand management for short-rotation plantations. *In:* Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests, 379-418. Monograph No. 43. Australian Centre for International Agriculture Research, Canberra.

Gonçalves, J.L.M., Mendes, K.C.F.S. and Sasaki, C.M. 2001. Mineralização de nitrogênio em ecossistemas florestais naturais e implantados do estado de São Paulo. Revista Brasileira de Ciência do Solo 25(3): 601-616.

Gonçalves, J.L.M., Poggiani, F., Stape, J.L., Serrano, M.I.P.S., Mello, S.L.M., Mendes, K.C.F.S., Gava, J.L. and Benedetti, V. 1999. Eucalypt plantations in the humid tropics: São Paulo, Brazil. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa, 5-12. Center for International Forestry Research, Bogor, Indonesia.

Gonçalves, J.L.M., Raij, B. and Gonçalves, J.C. 1996. Florestais. *In*: Raij, B.V., Cantarella, H., Quaggio, J.A. and Furlani, A.M.C. (eds.) Recomendações de adubação e calagem para o Estado de São Paulo, 245-259. 2nd ed. Instituto Agronômico de Campinas and Fundação IAC., Campinas, Brazil.

Gonçalves, J.L.M., Stape, J.L., Benedetti, V., Fessel, V.A.G. and Gava, J.L. 2004. Evaluation of minimum and intensive soil preparation regarding fertility and tree nutrition. *In*: Gonçalves, J.L.M. and Benedetti, V. (eds.) Forest nutrition and fertilization, 13-64. IPEF, Piracicaba, Brazil.

Herbert, M.A. and Schönau, A.P.G. 1989. Fertilising commercial forest species in southern Africa: research progress and problems (part 1). South African Forestry Journal 151:58-70.

Herbert, M.A. and Schönau, A.P.G. 1990. Fertilising commercial forest species in southern Africa: research progress and problems (part 2). South African Forestry Journal 152:34-42.

Laclau, J.P. 2001. Dynamique du fonctionnement minéral d'une plantation d'*Eucalyptus*. Effets du reboisement sur un sol de savane du littoral congolais; conséquences pour la gestion des plantations industrielles. D.Sc. thesis. Institut National Agronomique Paris-Grignon, Paris. 148p.

McGill, W.B. and Christie, E.K. 1983. Biogeochemical aspects of nutrient cycle interactions in soils and organisms. *In*: Bolin, B. and Cook, R.B. (eds.) The major biogeochemical cycles and their interactions, 271-301. Wiley, New York, USA.

Nelson, D.W. and Sommers, L.E. 1982. Total carbon, organic carbon and organic matter. *In*: Page, A.L., Miller, R.H. and Keeney, D.R. (eds.) Methods of soil analysis: chemical and microbiological properties, Part 2, 539-579. American Society of Agronomy, Madison, USA.

Nzila, J.P., Deleporte, P., Bouillet, J.P., Laclau, J.P. and Ranger, J. 2004. Effects of slash management on tree growth and nutrient cycling in second-rotation *Eucalyptus* replanted sites in the Congo. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 15-30. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove, T.S., Mendham, D.S., Corbeels, M., McMurtrie, R.F., Shammas, K. and Rance, S.J. 2004. Impacts of inter-rotation site management on nutrient stores and fluxes and growth of eucalypt plantations in southwestern Australia. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 77-91. Center for International Forestry Research, Bogor, Indonesia.

Raij, B. van, Andrade, J. C., Cantarella, H. and Quaggio, J.A. 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico, Campinas, Brazil. 285p.

Raison, R.J., Connell, M.J. and Khanna, P.K. 1987. Methodology for studying fluxes of soil mineral-N *in situ*. Soil Biology Biochemistry 19: 521-530.

Reis, M.G.F., Barros, N.F. and Kimmins, J.P. 1987. Acúmulo de nutrientes em uma seqüência de idade de *Eucalyptus grandis* W. Hill (ex - Maiden) plantado no cerrado, em duas áreas com diferentes produtividades, em Minas Gerais. Revista Árvore 11:1-15.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kumaraswamy, S., O'Connell, A.M., Grove, T.S. and Mendham, D.S. 2004. Improved productivity of eucalypt plantations through site management practices in the monsoonal tropics: Kerala, India. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 61-76. Center for International Forestry Research, Bogor, Indonesia.

Sarruge, J.R. and Haag, H.P. 1974. Análises químicas em plantas. ESALQ, Departamento de Química, Piracicaba, Brazil. 56p.

Stape, J.L. 2002. Production ecology of clonal *Eucalyptus* plantations in northeastern Brazil. PhD thesis, Colorado State University, USA. 225p.

Stape, J.L., Andrade, S., Gomes, A.N., Krejci, L.C. and Ribeiro, J.A. 2002. Definição de métodos de preparo de solo para silvicultura em solos coesos do litoral norte da Bahia. *In*: Gonçalves, J.L.M. and Stape, J.L. (eds.) Conservação e cultivo de solos para plantações florestais, 259-296. IPEF, Piracicaba, Brazil.

Statgraphics Plus. 1995. Statgraphics Plus for Windows, Version 1.4 ed. Statistical Graphics Corporation, Rockville, Maryland, USA.

Xu, D. and Dell, B. 2003. Nutrient management of eucalypt plantations in South China. *In*: R-P. Wei and D. Xu (eds.) *Eucalyptus* Plantations – Research, Management and Development : proceedings of an international symposium, on eucalypt plantations. 1-6 September 2002, Guangzhou, Guangdong, Peoples Republic of China, 269-289. World Scientific, Singapore.

Xu, D.P., Yang, Z.J. and Zhang, N.N. 2004. Effects of site management on tree growth and soil properties of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Effects of Slash and Site Management Treatments on Soil Properties, Nutrition and Growth of a *Eucalyptus grandis* Plantation in South Africa

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Abstract

Effects of site and slash management treatments on soil chemical properties, soil water contents, foliar nutrient levels and stand productivity were studied for a full rotation in a stand of *Eucalyptus grandis* in South Africa. Site management treatments included slash removal, slash retention, slash burning and fertilisation at establishment. Soil water content fluctuated seasonally but was similar across all treatments at a given time. For each treatment, soil pH, exchangeable cations and P all increased initially before returning to levels similar to those at the start of the rotation. Slash burning had the most pronounced, but temporary, influence on soil properties, causing significant increases in exchangeable Ca, Mg and acid-extractable P at one year of age. Foliar macronutrient concentrations, leaf area development and initial volume growth rate were significantly increased by both slash burning and fertilisation. Slash removal resulted in the lowest levels of exchangeable cations and phosphorus in the soil throughout the rotation. This was reflected in the reduced uptake and foliar levels of these elements as well as N, resulting in retarded leaf area development and inferior volume production. However, apart from the slash removed treatment the effect of the various treatments on stand growth was not significant compared to the control at 5.5 years of age. Although stand growth in this rotation was higher than that projected for a similar stage of growth in the previous rotation, this was probably due to improved genetic material and site management in this current rotation and highlights difficulties in comparing productivity from one rotation to the next. The decrease in soil water content and leaf area after canopy closure, suggest tree growth is most likely to benefit from improved nutrition in the period before canopy closure when nutrient demands are high.

Introduction

Intensive silviculture is commonly practised in southern African eucalypt plantations to increase productivity and its effectiveness has been demonstrated by several empirical experiments (Schönau 1984, 1989). Silvicultural regimes encompass various forms of slash management, site preparation, pest or browsing control where necessary, fertilisation at establishment and intensive weed control up to canopy closure. Slash disturbance occurs where machines are used for harvesting by crushing and mixing slash with soil. Slash burning is restricted to non-sensitive sites under special circumstances. South African research has demonstrated that the productivity in unthinned, short rotation eucalypt plantations can be significantly improved by several operations: Appropriate cultivation before stand establishment improved basal area by between 11 and 52% over that of manual pitting (Smith *et al.* 2000); while it had more erratic responses under re-establishment conditions (Smith *et al.* 2001). Vegetation management

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improved volume growth by 29 to 122% (Wagner *et al.* 2006). Fertilisation at establishment improved mean annual increment by 3.1 to 10.9 m^3 ha^{-1} yr^{-1} (Herbert 1996). However, the results to date are largely empirical and the mechanisms responsible for these improvements in stand productivity have not been studied in detail in southern Africa. Intensive site management practices may have a large impact on the nutrient dynamics and the productivity of forest stands (Fölster and Khanna 1997, Gonçalves *et al.* 1997, Fisher and Binkley 2000, Nzila *et al.* 2004, O'Connell *et al.* 2004). This study aimed to evaluate effects of slash and site management on the growth of *Eucalyptus grandis* and on soil properties related to site fertility.

Materials and Methods

The Karkloof trial site is located at 29° 24'S and 30° 12'E at an altitude of 1260 m above sea level. The mean annual precipitation of 950 mm falls mainly in summer (October-April). Long-term mean monthly minima for the coldest month (June) and the warmest month (January) are 3.7°C and 14.8°C while the corresponding maxima are 19.0°C and 25.0°C. The soil is derived from dolerite and shale parent materials. It has a humus-rich (70 g kg^{-1} organic C), clayey A horizon (zero to 0.2 m depth) overlying a yellow-brown clayey B1 horizon (0.2 to 0.4 m), and a red, clayey B2 horizon which grades into weathered shale at approximately 0.9 m depth, on average. The A, B1 and B2 horizons have mean bulk densities of 0.97, 1.21 and 1.35 Mg m^{-3}, respectively. The site was converted from grassland to an *E. grandis* plantation in 1964. The first crop was harvested in 1973 and was followed by three coppice crops (harvested in 1973, 1982 and 1991). More details on the climatic conditions at the site, the land-use history, as well as the soil physical and chemical properties have been published earlier (du Toit *et al.* 2000, 2004, du Toit 2003).

Experimental Design and Treatments

The first rotation stand was clear-felled at age seven years in December 1998. The experimental layout of the trial and adjacent monitoring plots has been described by du Toit *et al.* (2000). The trial has a randomised block design with four replications. Results from six of the treatments are discussed in this report, and those treatments are:

BL_0	Slash removed: all harvesting residue (including bark, branches and foliage) and litter layer manually removed.
BL_2	Regular slash: harvesting residue retained and broadcast.
BL_3	Double slash: harvesting residue and litter from the BL_0 plots were added to BL_2 and redistributed.
SB	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 (BL_2), plus addition of 90 g of mono-ammonium phosphate per tree, applied in two spots close to the seedlings. This dose provided 16.6 kg nitrogen (N), 33.3 kg phosphorus (P), 0.7 kg zinc (Zn), 1.1 kg calcium (Ca); 2.4 kg magnesium (Mg) and 2.0 kg sulphur (S) per hectare.

Eucalyptus grandis seedlings from improved seed were planted in February 1999, at the same initial spacing (2.44 x 2.44 m, i.e. 1680 stems ha^{-1}) as the first rotation.

Soil Chemical Changes

Topsoil samples (0-10 cm depth) were collected in January 1999, immediately before trial establishment, and again at approximately one, two and seven years of stand age (March 2000, February 2001 and May 2006, respectively). The initial sample set was taken with a conventional soil auger and consisted of four soil cores per plot that were bulked for analysis. Subsequent samples were taken with a Beater-auger. This soil Auger, originally designed by Dr. Beater, collects a thin diameter core 20 cm deep, with a bag attachment that facilitates the collection and bulking of several core samples. The underlying concept is to minimise errors by adequately covering spatial variability. Forty soil cores (bulked into four samples each made up from 10 cores) were collected per plot. The samples were air-dried and ground to pass through a 2 mm sieve. Soil pH was determined in both water and 1 M KCl using a soil solution ratio of 1:2.5. The ΔpH was calculated as pH(KCl) minus pH(H_2O). Exchangeable cations were extracted in 1 M ammonium acetate and their concentrations were determined with atomic absorption spectroscopy. Extractable acidity was determined by titration after extracting with 1 M KCl. Organic carbon was determined with the Walkley-Black method of wet oxidation (Nelson and Sommers 1996). Total N was determined by the Kjeldahl method (Bremner 1996). Available P was estimated by extracting with 0.03 M NH_4F in 0.1M HCl (Bray and Kurtz 1945) and P was determined colourimetrically (molybdenum blue).

Soil Water Measurements

Single neutron probe tubes were inserted into two replications of the BL_0, BL_2, BL_3, SB and SD treatments. Neutron count was recorded at 0.2, 0.3, 0.4, 0.5, 0.6 and 0.8 m below the soil surface. Gravimetric samples were taken in predetermined calibration zones on each measurement day and together with measurements of bulk density the count ratios were converted to volumetric water content. Water retention curves were determined on undisturbed core samples on a tension table for high matric potentials and a pressure membrane extractor for low matric potentials (-100 to -1500 kPa). The field capacity of the soil (-10 kPa tension) and the wilting point (-1500 kPa tension) were determined from the water retention curve and corresponded to volumetric soil water contents of 45% and 25%, respectively.

Measurement of Stand Growth

Tree height, stem diameter at breast height (dbh) and survival were measured at approximately three-monthly intervals during the first two growing seasons and at longer intervals thereafter. Volume and mean annual increment (MAI) were calculated from dbh and height measurements using equations (Coetzee 1992), cited in Bredenkamp (2000). The volume refers to utilisable stemwood volume up to a thin-end diameter of 5.0 cm. The leaf area of individual trees was determined by destructive sampling and leaf scanning from planting up to 1.3 years. The regressed leaf areas of individual trees per plot were summed and divided by the ground area to determine leaf area index (LAI). The term plant area index is used to describe the optical estimate of LAI before it has been corrected to reflect the true LAI (Dovey and du Toit 2006). After canopy closure, plant area index was estimated optically, using two Li-Cor™ plant canopy analysers. All measurements were taken on windless days, under uniform sky conditions, and with the sun at a low angle (Li-Cor 1992). The relationship between plant area index and LAI varied with age. Relationships appropriate to the stand age class (developed from Dovey and du Toit 2006) were used to convert LAI from plant area index readings at different intervals between 1.8 and 5.5 years of age.

Destructive harvesting of 20 ± 3 trees (selected across all treatments) was carried out at 0.3, 0.5, 0.8, 1.0, 1.8 and 3.0 years of age. Subsamples of foliage were collected from bulk leaf samples of each individual sample tree and analysed for nutrient concentration (Kalra and Maynard 1991). The dried material was ground, dry ashed and dissolved in 0.6 M HCl, filtered and diluted to an appropriate level with deionised water. Concentrations of Ca and Mg were determined by atomic absorption spectroscopy while flame emission spectroscopy was used for potassium (K). The concentration of P was determined spectrophotometrically (molybdenum blue method). The concentration of N was determined by the Kjeldahl procedure with selenium as a catalyst (Nicholson 1984).

All data were analysed using a standard ANOVA procedure after appropriate transformation on the dependent variables where necessary (McConway *et al.* 1999). Plot means were used for the statistical analysis of soil data.

Results

Soil Water Content

Changes in volumetric water contents and rainfall events are shown in Fig. 1. Soils in the treatments with slowest (BL_0) and fastest initial growth rates (SB), as well as the control were selected. Fig. 1 shows large seasonal fluctuations in water content with higher values in summer than in winter. Water contents are particularly low in the late winter/early spring periods (0.7 and 1.7 years). The peak in the water content that occurred in the third summer (at 1.8 years) was much lower than the previous summer peak. Water contents between treatments were largely similar, but from approximately 1.0 year, small but consistent differences in water content appeared, with treatment SB having the lowest values.

Changes in Soil pH and the Exchange Complex

For clarity, the figures in this section contain only those treatments where large and significant differences from the control (regular slash, BL_2) were observed. Treatment SF is not included because it received localised placement of fertiliser. Significant increases in pH (H_2O) occurred between planting and 2 years of age for all treatments before declining to initial levels at seven years (Fig. 2a). Slash burning induced a greater increase in topsoil pH (H_2O and KCl) than in other treatments (Fig. 2a and 2b). The ΔpH was similar across all treatments at a given time, and became significantly more negative by year 2 (by approximately one unit) (Fig. 2c). The effective cation exchange capacity (ECEC) increased at year one for all treatments, the highest increase (2.1 cmolc kg^{-1}) was due to slash burning (Fig. 2d). This effect results from changes in exchangeable base cations and extractable acidity. Slash burning increased the sum of the base cations significantly by approximately 3.0 cmolc kg^{-1} at year 1 but this effect declined by 2 years of age, remaining constant thereafter (Fig. 2e). Extractable acidity mirrored this trend, decreasing by approximately 0.9 cmolc kg^{-1} at age 1 year (Fig. 2f). The double slash treatment also showed a significant increase in the sum of exchangeable bases at 1 year of age, but this change was smaller in magnitude than that of the burnt treatment. Neither extractable acidity nor total base cation levels changed significantly over time in slash removed, broadcast, slash disturbed and fertilised treatments. By 7 years of age, the burnt and double slash treatments had significantly lower levels of extractable acidity and significantly higher base cation levels than the slash removed treatment (Fig. 2e and 2f).

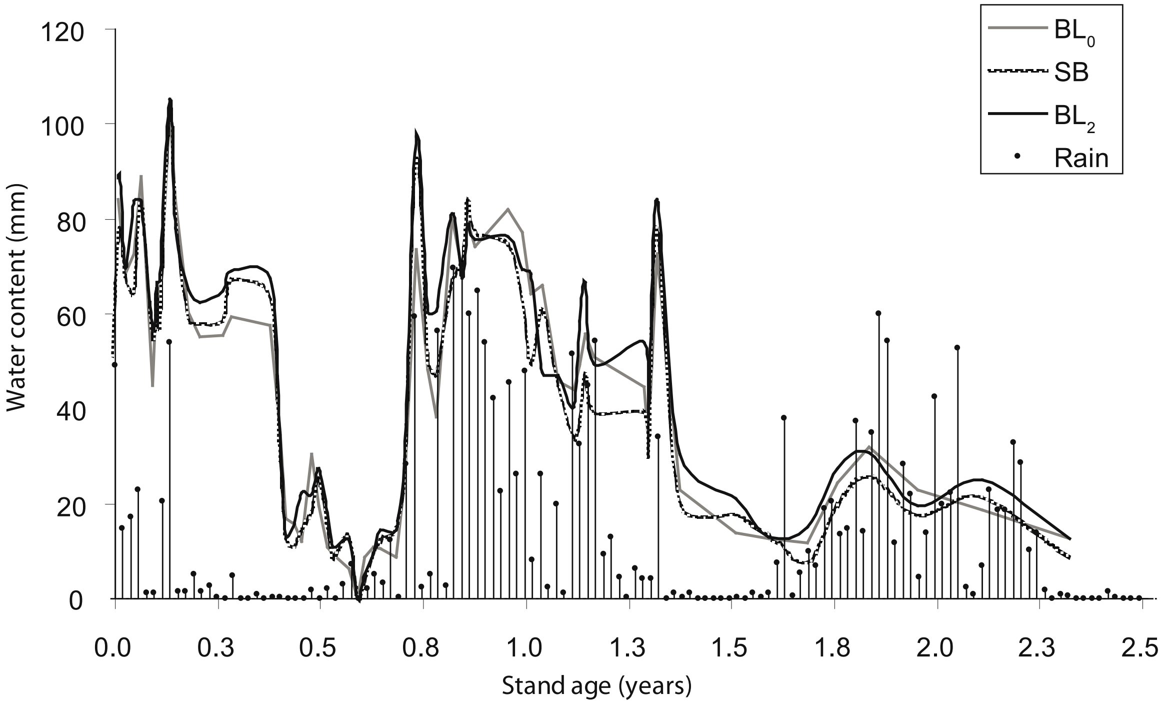
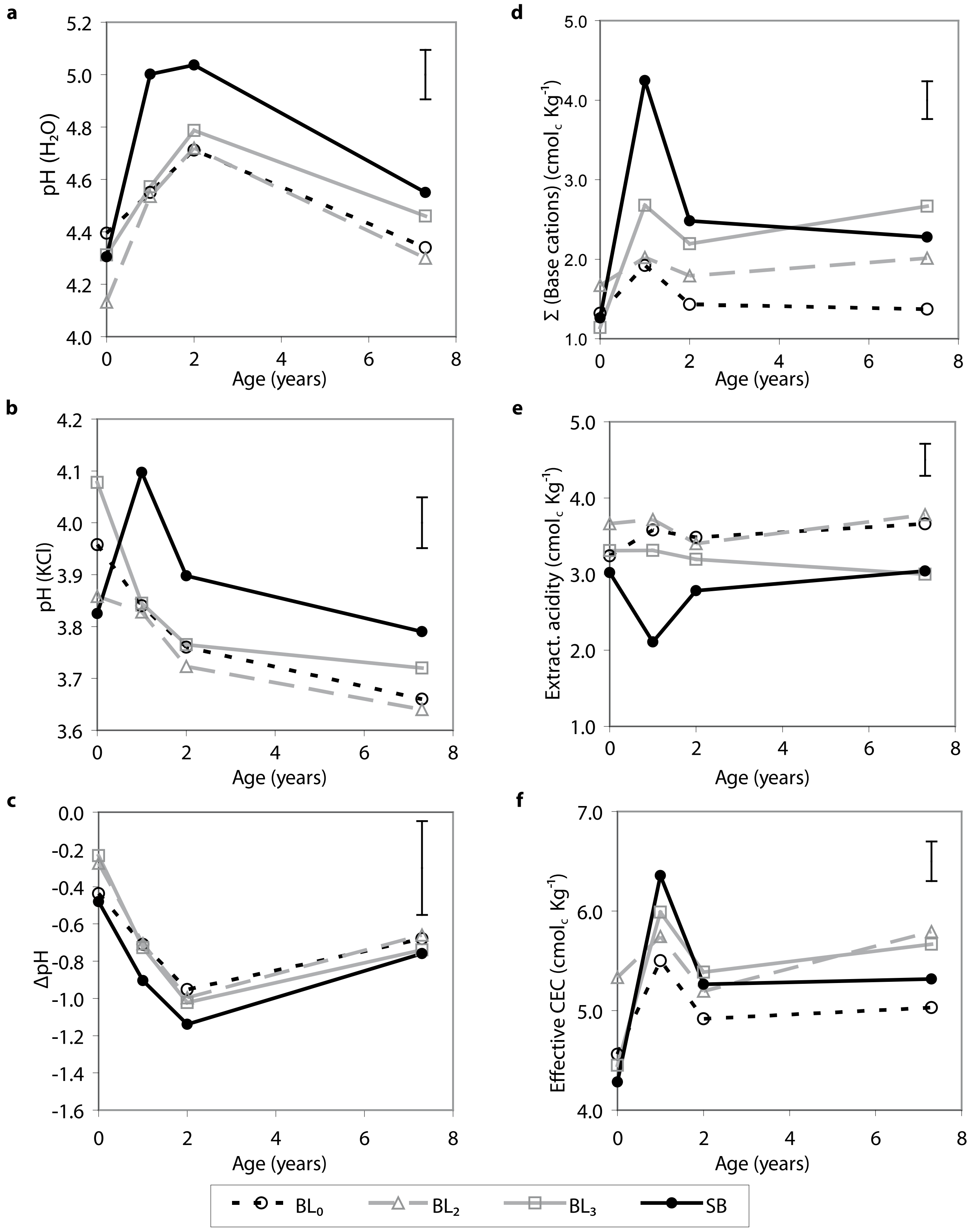
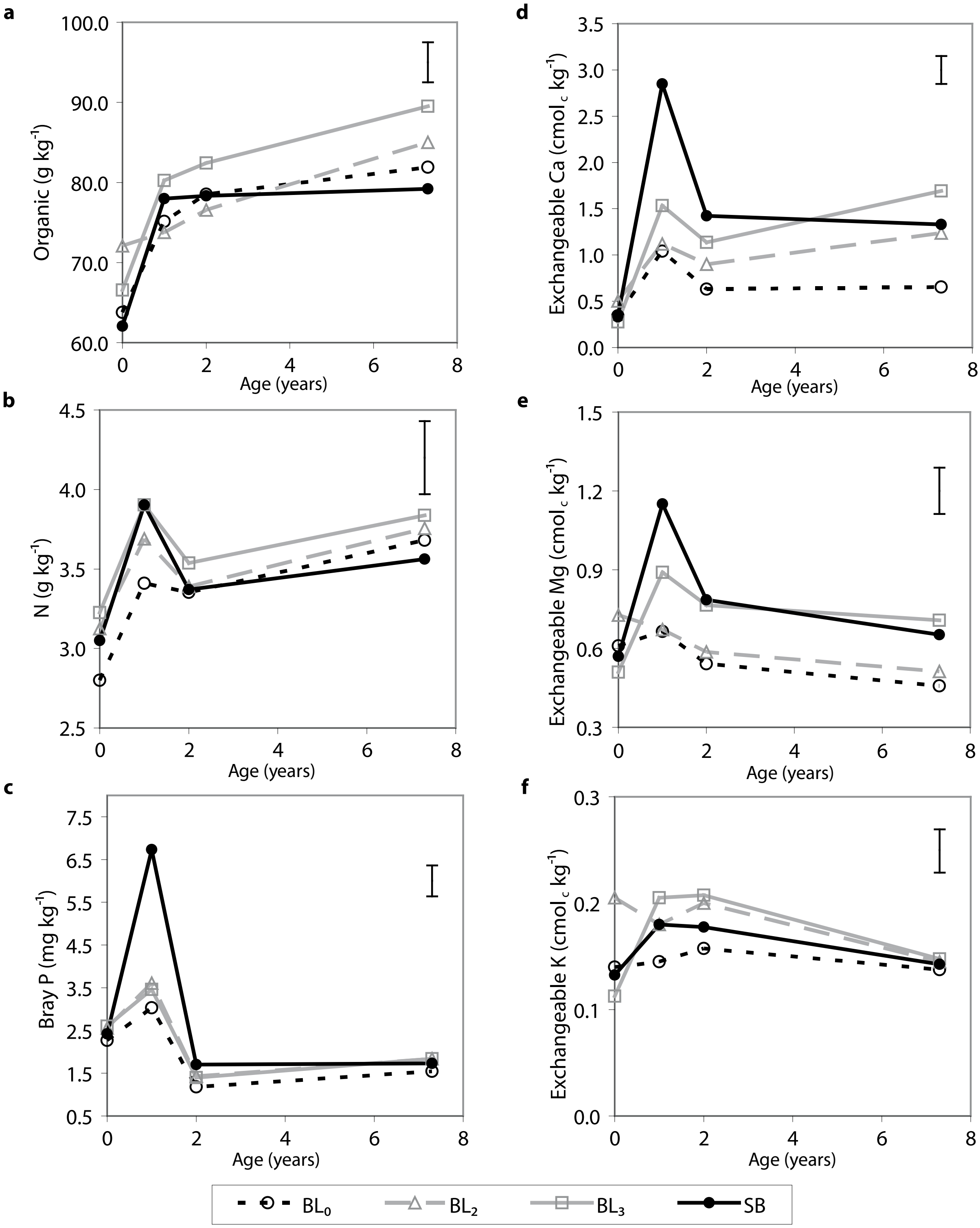


Figure 1. Fluctuations in soil water content of the entire soil profile for selected treatments over the first three growing seasons. Rainfall events are shown as vertical lines capped with dots



Error bars ($p < 0.05$) are shown as vertical lines in the top right corner.

Figure 2. Changes in soil chemical properties of the topsoil (0-10 cm) over time for selected treatments



Error bars (p <0.05) are shown as vertical lines in the top right corner.

Figure 3. Changes over time in (a) total soil organic C, (b) total soil N, (c) acid extractable P (d), exchangeable K (e) exchangeable Ca, and (f) exchangeable Mg for selected treatments

Changes in Topsoil Organic Carbon and Macronutrient Levels

Organic carbon (OC) increased on average by 10.8 g kg^{-1} from planting to year one (Fig. 3a), the maximum increase (15.9 g kg^{-1}) occurred with slash burning. From 1 to 7 years, OC levels increased in all treatments but more so with slash retention. If slash was burnt, OC level remained static over the rotation. At the end of the rotation (5.5 years) soil under double slash had 89 g kg^{-1} OC compared to 79 g kg^{-1} under burning. The total N values in all treatments increased during year 1 from an average of 3.1 to an average value of 3.7 g kg^{-1}, and thereafter remained at similar levels to rotation end. Phosphorus levels in the slash burnt treatment increased highly significantly at year 1 while all other treatments recorded small increases. By year 2, P levels across all treatments declined to similar (but slightly lower) levels than those recorded at time zero, and thereafter remained unchanged until year 7. Exchangeable K did not differ significantly with time and there were no time by treatment interactions (Fig. 3d). Levels of exchangeable Ca and Mg (Fig. 3e and f) followed a similar trend following slash burning: They increased temporarily, but highly significantly, following burning by approximately 2.4 and 0.6 $cmol_c$ kg^{-1} for Ca and Mg respectively. A smaller but still significant increase was also recorded at year 1 in the double slash treatment. In general, exchangeable Ca and Mg remained at statistically similar levels from year 2 to year 7. Soil analyses did not reveal any changes that were significantly different from the control for treatment SD over time.

Foliar Nutrient Concentrations

Changes in some foliar nutrient levels during the first three years of growth are shown in Table 1. Nutrient concentrations fluctuated during the first year after planting. High levels of N were recorded across treatments, especially the slash disturbed and fertilised treatments, at 3 months of age, although these levels are not uncommon for *E. grandis* (Boardman *et al*. 1997). There were no significant ($p < 0.05$) differences between treatment foliar nutrient levels at 3 and 6 months. Significant differences in N, P, K and Ca concentrations were recorded at 9 months: the control, slash disturbed and fertilised treatments had significantly higher concentrations of N, P and K than the slash removed and burnt treatments (Table 1). However, by 12 months, the slash burnt treatment had the highest concentration of N and P in the foliage and slash removed treatment the lowest. Differences between treatments in foliar concentrations of P and Ca were still significant at 12 months, with the slash removed treatment recording the lowest levels (Table 1). Some significant differences in foliar nutrient levels between treatments persisted beyond one year of age.

Stand Growth

Development of LAI is shown in Fig. 4. Details of the early response in LAI amongst treatments have been reported (du Toit and Dovey 2005). Onset of spring rains at 8 months stimulated canopy development and growth. Treatments with high nutrient availabilities (slash burnt, fertilised and to a lesser extent, slash disturbed) developed maximum LAI more rapidly and reached a higher peak LAI (range 4.6-4.9) than the control (4.4). LAI was slower to develop in the slash-removed treatment and peaked at 3.9 which was significantly lower than that of the other treatments. The difference in LAI between the fast-growing treatments (SB and SF) and the slash-removed treatment (BL_0) was significant from 0.5 to 2.3 years (Fig. 4).

Details of the early tree height, ground level diameter and LAI responses have been reported (du Toit *et al*. 2000). Stem volume growth over time is shown in Fig. 5. For clarity in presentation, we omitted the slash disturbed and fertilised treatments which showed similar growth to the slash burnt treatment. The low volume in the double slash treatment (Fig. 5) can be ascribed to the low stand density, resulting from early frost damage (Table 2). Stem volume development follows a sigmoid curve, reaching the maximum current annual increment around 3 years of age. The curves diverge in the early growth phase (up to approximately 3 years of age), reflecting the same treatment ranking as was observed for the LAI. Of the treatments with similar stocking (>1450 trees ha^{-1}), volume in the slash removed treatment was significantly lower than all other treatments for all measurement events (Fig. 5).

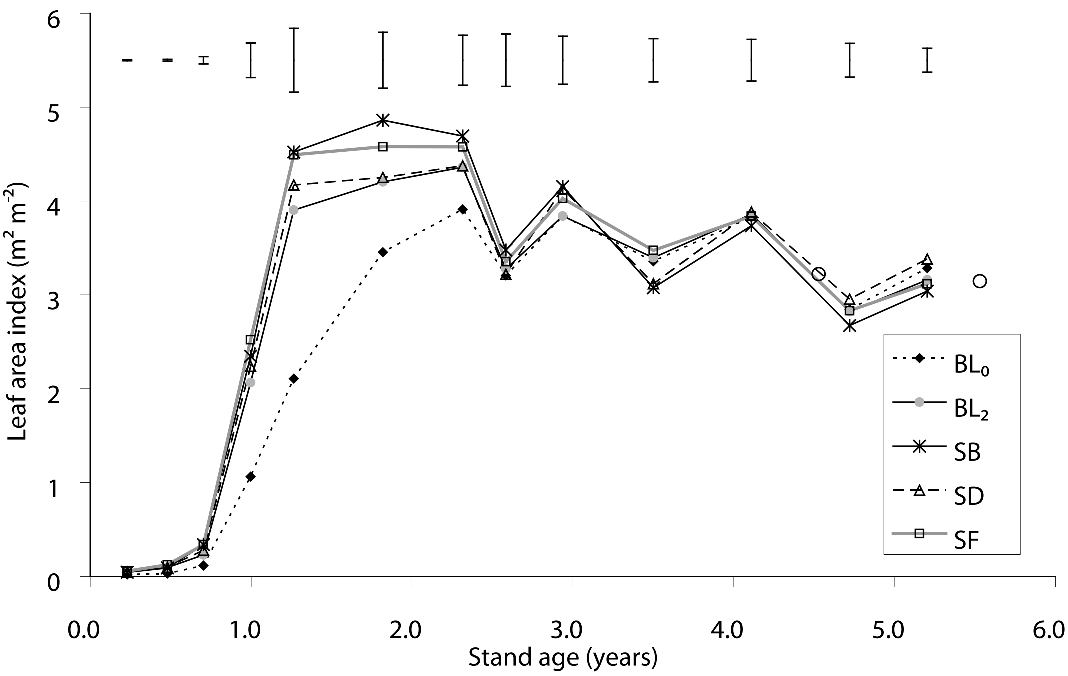
Table 1. Foliar macronutrient concentrations during the first three years of growth after planting

Age (yr)	Time of year (month)	Nutrients	Treatments (all values in percentages of dry mass at 65°C)				
			BL$_0$	BL$_2$	SB	SD	SF
0.25	May	N	3.47 a	3.63 a	3.24 a	4.02 a	4.02 a
		P	0.15 a	0.19 a	0.16 a	0.18 a	0.19 a
		K	0.91 a	1.18 a	0.92 a	1.20 a	0.92 a
		Ca	0.64 a	0.66 a	0.62 a	0.67 a	0.64 a
		Mg	0.33 a	0.29 a	0.33 a	0.31 a	0.31 a
0.5	Aug	N	2.91 a	3.24 a	2.90 a	2.92 a	3.20 a
		P	0.14 a	0.16 a	0.16 a	0.14 a	0.16 a
		K	0.62 a	0.70 a	0.66 a	0.62 a	0.72 a
		Ca	0.56 a	0.81 a	0.64 a	0.58 a	0.72 a
		Mg	0.28 a	0.31 a	0.36 a	0.26 a	0.28 a
0.75	Nov	N	2.69 a	3.37 b	2.55 a	3.21 b	3.28 b
		P	0.13 a	0.19 c	0.15 a	0.17 b	0.19 c
		K	0.60 a	0.82 b	0.68 a	0.85 b	0.86 b
		Ca	0.42 a	0.60 b	0.63 b	0.70 b	0.67 b
		Mg	0.28 a	0.31 a	0.32 a	0.28 a	0.26 a
1.0	Feb	N	2.86 a	3.04 ab	3.35 b	2.87 a	3.21 ab
		P	0.13 a	0.14 ab	0.17 c	0.14 ab	0.16 bc
		K	0.98 a	0.92 a	0.96 a	0.87 a	0.88 a
		Ca	0.82 a	1.02 ab	1.14 bc	1.35 cd	1.52 d
		Mg	0.24 a	0.28 a	0.29 a	0.25 a	0.33 a
1.8	Dec	N	2.04 ab	1.99 a	2.21 b	1.86 a	1.99 a
		P	0.13	0.11 a	0.13 b	0.11 a	0.11 a
		K	0.73 ab	0.75 b	0.64 a	0.64 a	0.75 b
		Ca	1.07 b	0.84 a	1.02 b	1.11 b	0.84 a
		Mg	0.20 a	0.23 a	0.24 a	0.27 a	0.23 a
3.0	Feb	N	2.03 ab	1.93 a	1.96 a	1.97 a	2.07 b
		P	0.11 a	0.12 ab	0.11 a	0.14 b	0.13 b
		K	0.67 a	0.67 a	0.69 ab	0.69 ab	0.73 b
		Ca	0.58 a	0.65 a	0.67 a	0.52 a	0.65 a
		Mg	0.26 b	0.23 a	0.30 c	0.23 a	0.27 b

Values within a row followed by the same letter are not significantly different ($p < 0.05$).

At 3.0 years, the fastest growing treatments (SB, SF and SD) had produced approximately 22 m^3 ha^{-1} more volume than the slowest growing (BL$_0$). The parallel nature of the curves from that point forward show that the absolute differences between treatments (and hence the rate of volume production) remained similar up to 5.5 years of age (Fig. 5).

Stand density, height and dbh, basal area, volume and mean annual increment for treatments at 5.5 years are shown in Table 2. Volume and MAI estimates for the preharvest coppice stand was calculated at age 7 years and interpolated to age 5.5 years for purposes of comparison with the current experimental stand (Table 2). Estimates show that basal area, volume and MAI in the preharvest crop, interpolated to 5.5 years, are



Open circles at 4.5 and 5.5 years are independent LAI data from destructive measurements to validate the optical measurements across plots at that stage.
Error bars (p <0.05) are shown as vertical lines for each measurement event.

Figure 4. Development of leaf area index (LAI) with age

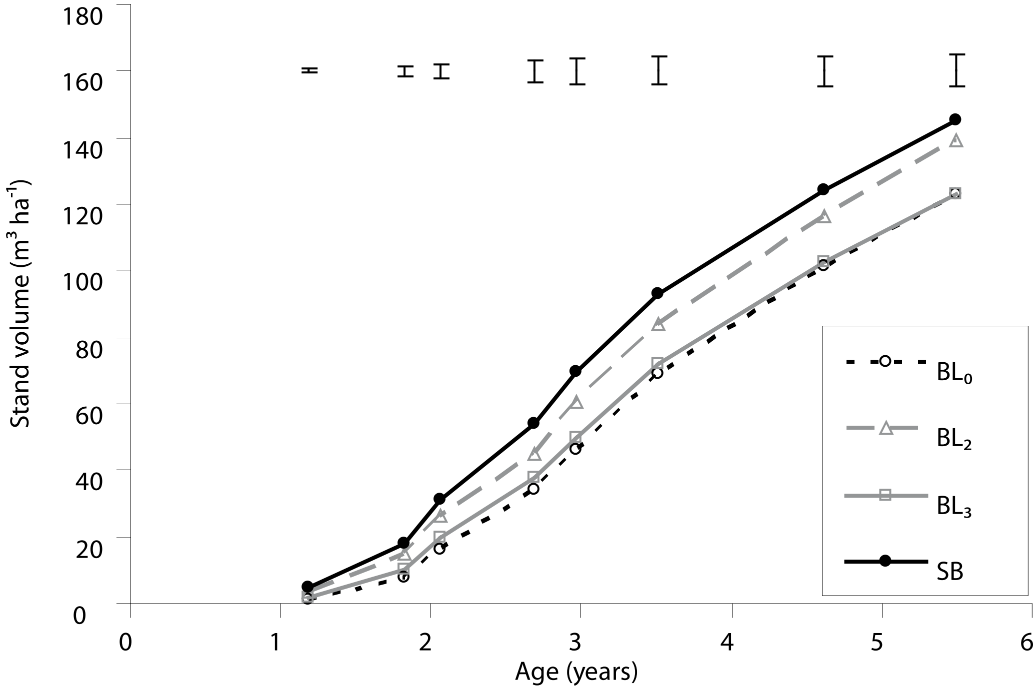
similar to the slash removed treatments of the current crop, but lower than that of all other treatments with adequate stocking. After the age 5.5 years, an unusual snowfall caused uneven damage to the stand and it was not possible to continue the study. Under normal circumstances the typical age of harvest in these plantations is about 7 or 8 years.

Discussion

Treatments had only minor effects on available soil water. Soil water content was driven primarily by rainfall and age related changes in LAI. An increase in LAI with age coincided with rapid soil water depletion despite substantial rainfall. Seasonal soil water stress caused reductions in LAI through increased litterfall. Low soil water content after age 2 years may have masked the potential influence of treatments on soil water. Water availability is likely to influence the extent and duration by which the stand can respond to changes in nutrient availability.

Changes in Soil Properties

The general increase in pH (H_2O) at 2 years of age (Fig. 2a) is likely to be due to increased decomposition of the forest floor and slash following clear felling, with subsequent consumption of acidity by organic anions and the release of base cations from the slash. Noble *et al.* (1996) aerobically incubated leaf litter of several species with an acid soil and found varying increases in pH and decreases in extractable aluminium. The magnitude of these changes correlated well with the quantity of organic anions added to soils (i.e. ash alkalinity of the litter). A temporary increase in the topsoil pH following slash burning (Fig. 2a) is commonly observed in forest soils (Ellis and Graley 1983, Khanna *et al.* 1994, Romanyà *et al.* 1994, Fisher and Binkley 2000, O'Connell *et al.* 2004). This effect has been ascribed to the combustion of organic acids and the consumption of acidity upon the release of base cations (Fisher and Binkley 2000). However, the changes in the



Error bars (p <0.05) are shown as vertical lines for each measurement event.

Figure 5. Development of volume with age

Table 2. Stand growth parameters for the pre-harvest coppice crop (clearfelled at 7 years) and the six treatments imposed on the current (seedling) crop

Treatments	Pre-harvest coppice crop		Seedling crop (all measurements at 5.5 yr)					
	Measurements at 7 yr	Estimates at 5.5 yr	BL_0	BL_2	BL_3	SB	SD	SF
Mean height (m)	18.2	-	16.2 a	17.3 b	17.4 b	17.1 b	16.9 b	17.2 b
Mean DBH (cm)	13.4	-	12.0 a	13.0 c	13.5 d	12.6 b	12.9 c	13.0 c
Basal area (m^2 ha^{-1})	23.3	19.6 (1)	19.2 b	20.3 bc	17.6 a	21.2 cd	21.9 d	21.3 cd
Volume (m^3 ha^{-1})	162	118 (1)	123 a	139 b	123 a	145 b	146 b	145 b
MAI (m^3 ha^{-1} yr^{-1})	23.2	21.4	22.2	25.2	22.3	26.3	26.4	26.3
Stocking (stems ha^{-1})	1461 (2)	>1460	1610 c	1461 b	1164 a	1628 c	1601 bc	1531 bc

(1) Estimated from 7 year measurements using equations from Coetzee (1999).
(2) 1461 stems ha^{-1} standing on 1306 stumps ha^{-1}.

topsoil were temporary because pH values in most treatments returned to initial values after some time.

Highly weathered soils rich in sesquioxides commonly display variable charge characteristics (Brady and Weil 1999) which means that the size of both the anion and cation exchange capacity (AEC and CEC) can change with soil pH. The ΔpH can be used reliably to predict the magnitude and the nature of surface charges in tropical soils (Alves and Lavorenti 2005). The largest temporary change in ΔpH and effective CEC (2.1 $\text{cmol}_c\ \text{kg}^{-1}$) occurred in the slash burn treatment, suggesting that the increase in pH was partly responsible for the increase in effective CEC. It is well established that an increase in pH (H_2O) in variable charge soils above the point of zero net charge will lead to an increase in CEC at the expense of the AEC (Bolt and Bruggenwert 1978, Brady and Weil 1999). The plantation system is vulnerable during the months following burning as there is little or no vegetation resulting in a temporary decrease in nutrient uptake and an increase in water infiltration. The mechanism responsible for increasing CEC is important as it may temporarily improve cation retention and reduce leaching of base cations and ammonium nitrogen in the period after fire. Ludwig *et al.* (1998) found a temporary increase of 1-3 $\text{cmol}_c\ \text{kg}^{-1}$ in the upper layers of an Australian podzol following intense burning of mixed eucalypt slash. Khanna *et al.* (1994) observed an increase in CEC of between 1.6 and 7.8 $\text{cmol}_c\ \text{kg}^{-1}$ in eight Australian forest soils after addition of ash combusted under laboratory conditions and found the greatest increase in CEC occurred in acid soils.

Significant differences in topsoil base cation levels between slash removed and other treatments only manifest by year 7. The likely mechanism is as follows: although slash removal diminishes the input source abruptly, rates of nutrient removal, chiefly through plant uptake, takes longer to peak and continues throughout the rotation. Differences in exchangeable base cation pools between slash removed and other treatments should therefore gradually increase with time, as observed.

An increase in OC was found across all treatments. Two factors may have contributed to this result. (1) A net influx of organic compounds in this period is likely where decomposition of the slash and humus layer is high due to the addition of new substrate and the increase in temperature following clear felling. Adams and Attiwill (1991) showed that total C in the soil solution approximately doubled in the 8-month period following clearfelling and burning of a eucalypt forest in Tasmania. (2) The non-consistent sampling technique used and the gradual transition from humus layer to mineral soil may have introduced bias in sampling. Scraping off the humus layer to expose mineral soil for sampling may be a source of variation. It was particularly difficult to find the transition between humus and mineral soil in the burnt treatment, especially after some rainfall, which resulted in movement of ash into the mineral soil. Because of the high likelihood of sampling error, we will confine our discussion on changes in organic C to the period from year 1 to 7. The mean increase in OC in all unburnt treatments from 1 to 7 years of age was 9.0 g kg-1 which has practical significance as it is quite large. Similar results have been reported elsewhere. O'Connell *et al.* (2004) showed a significant increase of approximately 15 g kg-1 in OC in double slash treatments 4 years after treatment implementation. Nzila *et al.* (2004) reported a 9% (0.4 g kg-1) increase in OC in the double slash treatment compared to 9% decrease in the slash removed treatment for 3 years after treatment implementation. The two latter authors found no significant change in the slash burn treatment, which is in agreement with our findings over the period 1 to 7 years.

Nutrient Availability and Foliar Nutrients

Significant differences in foliar nutrient levels at ages 0.75 and 1.0 imply that slash management treatments changed nutrient availability between treatments over time (Table 1). Despite rapid growth and nutrient uptake in slash removed and burnt treatments (du Toit and Dovey 2005) a decline in foliar N, P and K to levels below the adequate range (Boardman *et al.* 1997) occurred at 9 months of age (Table 1). This temporary reduction in foliar concentration in the burned treatments may be a dilution effect where growth rate exceeded nutrient uptake; the levels becoming the largest at 1 year of age. A nutrient shortfall in the slash-removed treatment may have caused the reduction in concentrations there, as this was the slowest growing treatment with the lowest uptake.

Soil analyses at 1 year showed that the slash burned treatment had significantly higher levels of total N, Bray P, exchangeable Ca and Mg than the control. This was reflected in the foliar analysis by significantly higher concentrations and contents of N, P and Ca at 1 year after planting (Table 1, du Toit and Dovey, 2005). Significant increases in foliar macronutrient concentration and content during 9 to 12 months of age were however not reflected in the soil analyses of the slash-disturbed treatment (Table 1, du Toit and Dovey 2005). It is possible that the foliar nutrient analysis techniques were able to detect subtle changes in plant available nutrient fractions compared to soil-based methods.

In summary, it appears that nutrient availabilities were temporarily increased relative to the control through burning, fertilisation (and to a lesser extent by slash disturbance), and decreased by slash removal (Table 1).

Effects of Treatments on Stand Growth

The early growth rate in fast-growing short rotation plantations is strongly dependent on growth resource availability (water, nutrients and light). Development of LAI was hampered by lack of nutrients in treatment BL_0 but improved by more abundant supplies of nutrients in the slash burnt and fertilised treatments (Table 1). Early boosts in LAI were reported for fertilised stands of *E. grandis* by Cromer *et al.* (1993) and Hunter (2001). Leaf area development was suppressed by dry conditions during the first growing season but ample water supply during the second growing season enabled treatments with sufficient nutrient supplies to increase their rates of LAI development and radiation interception (Fig. 1, Job *et al.* 2003, du Toit and Dovey 2005). Differences in volume production up to 3.0 years can be attributed to differences in LAI since the growth efficiency (stem wood production per unit of LAI) remained similar across all treatments (du Toit and Dovey 2005). The fact that LAI was similar in all treatments from 2.6 to 5.5 years of age (Fig. 4), explains why the rate of volume growth was similar across all treatments in the latter half of the rotation. The mechanism of the response observed in this experiment (improvements in LAI but not growth efficiency) underscores the importance of intensive early silviculture in an area where rainfall is often limiting.

Treatments that simulated intensive management (SF and SB) improved the productivity over that of the control by only a small margin (4.3% increase in volume) at 5.5 years, despite being significant in the first half of the rotation. Part of the reason for this is that the soil is relatively rich in organic carbon (>70 g kg^{-1}, the highest in the network) and total N (>3.2 g kg^{-1}). Saint-Andre *et al.* (2008) showed that there was a strong relationship between growth response (BL_3 - BL_0) and the value (N in the slash:N in soil). It is therefore possible that on other South African sites where the soils and the slash result in a higher ratio, greater responses to slash management will be likely compared to those reported here.

Comparison of volume growth between the previous crop and current treatments should be made with caution as changes in the genetic material or silvicultural management (adequate stocking, even spacing and intensive weed control) may be different and may mask actual changes in site production potential (Burger 1996, Smith *et al.* 2005). The fact that the control (BL_2) had a higher productivity than the pre-harvest coppice crop was expected, since some stump mortality had occurred in the coppice crop and the new crop was planted with improved genetic stock. Despite the temporary nutrient shortages induced by the slash removal treatment, it achieved approximately the same productivity as the pre-harvest crop. More intensive silviculture in the current rotation (adequate stocking, even spacing, good genetic material and intensive weed control) may have partly offset the effects of the nutrient shortages.

Conclusions and Management Implications

Intensive silvicultural management at re-establishment is a principal factor behind the high productivity of *Eucalyptus* plantations in South Africa and there is concern over the effect of these operations on soil fertility and sustainable production. Our results show that the main effect of intensive site management treatments was to change the plant-available fractions of several nutrients temporarily during the phase of active leaf area expansion, which affected the rate of LAI development and the growth rate. However, changes in key soil properties related to long-term soil fertility were not substantial for any site management treatment tested on this fine-textured, well-weathered soils and high in organic carbon. Resilience of the system was due to the large nutrient pools in the soil relative to those in the slash. Controlled moderate-intensity fires can be beneficial on similar sites where large quantities of slash tend to accumulate. They can assist the forest manager to reduce the fuel load and speed up the cycling of immobilised nutrients. However, on less resilient sites with small nutrient pools, conservation of nutrient capital in both soil and slash is important, as demonstrated by other studies in this network.

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References

Adams, M.A. and Attiwill, P.M. 1991. Nutrient balance in forests of northern Tasmania. 2. Alteration of nutrient availability and soil-water chemistry as a result of logging, slash burning and fertilizer application. Forest Ecology and Management 44:115-131.

Alves, M.E. and Lavorenti, A. 2005. Point of zero salt effect: relationships with clay mineralogy of representative soils of the Sao Paulo State, Brazil. Pedosphere 15:545-553.

Boardman, R., Cromer, R.N., Lambert, M.J. and Webb, M.J. 1997. Forest plantations. *In*: Reuter D.J. and Robinson J.B. (eds). Plant analysis: an interpretation manual. 2nd ed. 503-566. CSIRO Publishing, Collingwood, Australia.

Bolt, G.H. and Bruggenwert, M.G.M. 1978. Soil chemistry. A. Basic elements. 2nd ed. Elsevier Scientific Publishing, Amsterdam, The Netherlands.

Brady, N.C. and Weil, R.R. 1999. The nature and properties of soils. 12th ed. Prentice-Hall, New Jersey, USA.

Bray, R.H. and Kurtz, L.T. 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Science 59:39-45.

Bredenkamp, B.V. 2000. Volume and mass of logs and standing trees. *In*: Owen, D.L. (ed.) South African forestry handbook, Vol. 1, 167-174. V and R Printers, Pretoria, South Africa.

Bremner, J. M. 1996. Nitrogen-total. *In*: Sparks, D.L. (ed.) Methods of soil analysis. Part 3. Chemical methods, 1085-1121. Soil Science Society of America Book Series, No 5. Soil Science Society of America, Madison, Wisconsin, USA.

Burger, J.A. 1996. Limitations of bioassays for monitoring forest soil productivity: rationale and example. Soil Science Society of America Journal 60:1674-1678.

Coetzee, J. 1999. Growth prediction for short rotation *E. grandis* crops. ICFR Bulletin 9/99. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A. and Brown, M. 1993. Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. Forest Ecology and Management 62:211-230.

Dovey, S.B. and du Toit, B. 2006. Calibration of LAI-2000 canopy analyser with leaf area index in a young eucalypt stand. Trees - Structure and Function 20:273-277.

du Toit, B. 2003. Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa. Southern African Forestry Journal 199:15-25.

du Toit, B. and Dovey, S.B. 2005. Effect of site management on leaf area, biomass development and stand growth efficiency of a young stand of *Eucalyptus grandis* in South Africa. Canadian Journal of Forest Research 35:891-900.

du Toit, B., Esprey, L.J., Job, R.A., Fuller, G.F. and Dovey, S. 2000. Effects of site management in *Eucalyptus grandis* plantations in South Africa. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C, and Ranger, J., (eds.) Site management and productivity in tropical plantation forests: a progress report, 21-30. Center for International Forestry Research, Bogor, Indonesia.

du Toit, B., Dovey, S.B., Fuller, G.F. and Job, R.A. 2004. Effects of harvesting and site management on nutrient pools and stand growth in a South African eucalypt plantation. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds). Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 31-43. Center for International Forestry Research, Bogor, Indonesia.

Ellis, R.C. and Graley, A.M. 1983. Gains and losses in soil nutrients associated with harvesting and burning eucalypt rainforest. Plant and Soil 74:437-450.

Fisher, R.F. and Binkley, D. 2000. Ecology and management of forest soils. 3rd ed. John Wiley, New York, USA. 489p.

Fölster, H. and Khanna, P.K. 1997. Dynamics of nutrient supply in plantation soils. *In*: Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests. ACIAR Monograph No.43, 339-378. Australian Centre for International Agricultural Research, Canberra.

Gonçalves, J.L.M., Barros, N.F., Nambiar, E.K.S. and Novais, R.F. 1997. Soil and stand management for short-rotation plantations. *In*: Nambiar, E.K.S. and Brown, A.G., (eds) Management of soil, nutrients and water in tropical plantation forests. ACIAR Monograph No.43, 379-417. Australian Centre for International Agricultural Research, Canberra..

Herbert, M.A., 1996. Fertilizers and eucalypt plantations in South Africa. *In*: Attiwill, P.M. and Adams, M.A. (eds) Nutrition of eucalypts, 303-325. CSIRO Publishing, Collingwood, Australia.

Hunter, I. 2001. Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis*, *Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertilizer, at 3 years of age, in southern India. Forest Ecology and Management 144:189-199.

Job, R.A., du Toit, B. and Esprey, L.J. 2003. Estimating selected input parameters for 3-PG from an age series of *Eucalyptus grandis*. ICFR Bulletin 15/2003. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Kalra, Y.P. and Maynard, D.G. 1991. Methods manual for forest soil and plant analysis. Information Report NOR-X-319, Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Canada.

Khanna, P.K., Raison, R.J. and Falkiner, R.A. 1994. Chemical properties of ash derived from *Eucalyptus* litter and its effect on forest soils. Forest Ecology and Management 66:107-125.

Li-COR Inc. 1992. LAI-2000 Plant Canopy Analyser operating manual. Li-Cor Inc., Lincoln, North Carolina, USA. 183p.

Ludwig, B., Khanna, P.K., Raison, R.J. and Jacobsen, K.L. 1998. Modelling cation composition of soil extracts under ashbeds following an intense slash fire in a eucalypt forest. Forest Ecology and Management 103:9-20.

McConway, K.J., Jones, M.C. and Taylor, P.C. 1999. Statistical modelling using GENSTAT®. Arnold, London. 502p.

Nelson, D.W. and Sommers, L.E. 1996. Total carbon, organic carbon and organic matter. *In*: Sparks, D.L. (ed.) Methods of soil analysis. Part 3. Chemical methods, 961-1010. Soil Science Society of America Book Series No. 5. Soil Science Society of America, Madison, Wisconsin, USA.

Nicholson, G. 1984. Methods of soil, plant, and water analysis. FRI Bulletin No.70. Forest Research Institute, New Zealand Forest Service, Rotorua, New Zealand.

Noble, A.D., Zenneck, I. and Randall, P.J. 1996. Leaf litter ash alkalinity and neutralisation of soil acidity. Plant and Soil 179:293-302.

Nzila, J.D., Deleporte, P., Bouillet, J.P., Laclau, J.P. and Ranger, J. 2004. Effects of slash management on tree growth and nutrient cycling in second-rotation *Eucalyptus* replanted sites in the Congo. *In*: Nambiar, E.K.S., Ranger, J. Tiarks, A. and Toma. T. (eds.) Site management and productivity in tropical plantation forests:proceedings of workshops in Congo July 2001 and China February 2003, 15-30. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove, T.S., Mendham, D. Corbeels, M., McMurtrie, R.F. Shammas, K. and Rance, S.J. 2004. Impacts of inter-rotation site management on nutrient stores and fluxes and growth of eucalypt plantations in southwestern Australia. *In*: Nambiar, E.K.S., Ranger, J. Tiarks, A. and Toma. T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 77-91. Center for International Forestry Research, Bogor, Indonesia.

Romanya, J., Khanna, P.K. and Raison, R.J. 1994. Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. Forest Ecology and Management 65:89-103.

Saint André, L. *et al*. 2008. Slash and litter management effects on *Eucalyptus* productivity: a synthesis using a growth and yield modelling approach. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 173-188. Center for International Forestry Research, Bogor, Indonesia.

Schönau, A.P.G. 1984. Silvicultural considerations for high productivity of *Eucalyptus grandis*. Forest Ecology and Management 9:295-314.

Schönau, A.P.G. 1989. Requirements for intensive silviculture. South African Forestry Journal 150:40-49.

Smith, C.W., Little, K.M. and Norris, C.H. 2001. The effect of land preparation at re-establishment on the productivity of fast growing hardwoods in South Africa. Australian Forestry 64:165-174.

Smith, C.W., Little, K.M., Rolando, C. and du Toit, B. 2005. The plantation forestry sustainability initiative: a framework for monitoring and measuring the sustainability of intensively managed southern African forest plantations. ICFR Bulletin 08/2005. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Smith, C.W., Norris, C.H. and Esprey, L.J. 2000. The effect of land preparation at establishment on the productivity of fast growing hardwoods in the summer rainfall regions of South Africa. ICFR Bulletin 06/2000. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 31p.

Wagner, R.G., Little, K.M., Richardson, B. and McNabb, K. 2006. The role of vegetation management for enhancing productivity of the world's forests. Forestry (Oxford) 79:57-79.

Debarking of *E. grandis* in South Africa (Photo: Ben du Toit)

Impacts of Inter-rotation Site Management on Soil Nutrients and Plantation Productivity in *Eucalyptus globulus* Plantations in South-Western Australia

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Abstract

Harvest residue management impacts on soil nutrients and plantation productivity were evaluated at two contrasting second rotation *Eucalyptus globulus* plantations in south-western Australia. Soil properties and plantation productivity were monitored for a full rotation length of 10 years. Site management options applied between the crop rotations included burning, removal, and retention of single and double loads of residues, with retention of up to 100 Mg DW ha^{-1} (in the double residues at the red earth site) before planting the new crop. By 10 years, harvest residue management had no significant impact on soil stores of carbon or total N and P, but it did significantly affect the stores of exchangeable cations in the surface 0-10 cm soil. Soil nitrogen mineralisation was higher during the first few years after planting where residues were retained. Plantation productivity response to residue management varied across the two sites, with no response to residue management or nutrient application on the fertile red earth soil, and significant responses to both N addition and residue retention on the grey sand soil. Results from these and related studies including economic outcomes have been formulated and delivered as a decision support system for use by plantation growers.

Introduction

Eucalyptus globulus plantations are expanding in south-western Australia, with more than 250 000 ha on former agricultural lands, mostly by industrial companies on 10-year rotations for export wood chips. Soils in this region have a naturally low fertility, as they are formed from highly weathered and leached parent materials (McArthur 1991, Tennant *et al*. 1992). Development of agricultural systems required significant inputs of major and minor nutrients (Robson and Gilkes 1980), that improved soil fertility in these farmlands. This soil improvement, coupled with increased soil stored water gained under the agricultural phase, has enabled high growth rates (MAI 20-40 m^3 ha^{-1} yr^{-1}) in many first-rotation plantations.

The majority of the plantation estate is currently still in its first rotation (1R), but this crop is being harvested and mostly converted to second rotation (2R). An understanding of the biological impacts of inter-rotation management under this land use is recognised as critical, similar to the situation in *Pinus radiata* plantations in southern Australia (Smethurst and Nambiar 1990). Previous studies have shown that first-rotation plantations cause a decline in soil nitrogen and phosphorus availability (Mendham *et al*. 2004), as well as in soil-stored water (Mendham *et al*. 2005), suggesting that second and subsequent rotations will require more intensive management to maintain and increase productivity.

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The aim of this study was to examine the impact of harvest residue management on *E. globulus* plantation productivity and soil characteristics at two sites with contrasting soil fertility and production potential. The impacts of residue management on plantation productivity and soil properties were assessed for one full rotation (10 years) after re-establishment of the second rotation. This project had a range of objectives and significant results have been published (e.g. Mendham *et al.* 2003, O'Connell *et al.* 2004b). This paper presents an overview of the main findings in relation to plantation productivity and soil properties, building on earlier papers (O'Connell *et al.* 2000, O'Connell *et al.* 2004a) published in CIFOR proceedings.

Sites

Two sites were established on contrasting soils in south-western Australia, a higher fertility red-earth site at Manjimup, and a lower fertility grey-sand site at Busselton. Climate and soils of the sites selected for the study broadly represent the range of sites on which *E. globulus* is planted in south-western Australia. Table 1 gives details of location, climate, soil type and chemistry at each site. The climate of the zone is characterised as being Mediterranean, with hot, dry summers and cool, wet winters. The first rotation was established on ex-farmland in 1986 (red earth site), and 1987 (grey sand site), and both were harvested at age 8 years. The 1R stand at the red earth site yielded an estimated volume over bark of 366 m^3 ha^{-1}, while the stand at the grey sand site yielded about 96 m^3 ha^{-1}. The sites were both replanted with improved seedlings in mid-1994 for this experiment.

Biomass and Nutrient Pools

Harvest residues remaining on site after harvest consisted of over 50 t ha^{-1} dry weight at the red earth site, and over 30 t ha^{-1} at the grey sand site (Table 2), with the largest biomass pool in leaves, followed by twigs and branches. Leaf and twigs also contained the highest quantities of nutrients, with the bark fraction containing a significant proportion of Ca.

Table 1. Location, climate, soil type, and soil chemical properties at the two sites (SE in parentheses)

	Red earth - high fertility site	Grey sand - low fertility site
Locality	Manjimup	Busselton
Location	34°20'S, 116°00'E	33°45'S, 115°07'E
Climate		
Annual rainfall (mm)	1023	825
Annual pan evaporation (mm)	524	574
Mean daily temperature (°C) - summer	17.3	19.6
- winter	10.2	12.3
Soil type (FAO 1990)	Rhodic Ferralsol	Haplic Podzol
Soil chemical properties (0-10 cm)		
pH (1:5 water)	6.00 (0.13)	4.93 (0.14)
Total C (g 100 g^{-1})	4.98 (0.84)	2.77 (0.17)
Total N (g 100 g^{-1})	0.23 (0.02)	0.14 (0.01)
Total P (g 100 g^{-1})	0.0344 (0.0032)	0.0090 (0.0017)
Bray extractable P (mg kg^{-1})	0.19 (0.02)	0.06 (0.02)
Exchangeable K ($cmol_c$ kg^{-1})	3.17 (0.73)	1.91 (0.43)
Exchangeable Ca ($cmol_c$ kg^{-1})	1.21 (0.61)	0.71 (0.59)
Exchangeable Mg ($cmol_c$ kg^{-1})	4.98 (0.84)	2.77 (0.17)

The biomass pool in harvest residues is equivalent to a significant fraction of that in the 0-20 cm soil depth, especially at the red earth site, where the quantity of residue was equivalent to 35% of soil C in the top 20 cm of soil. Nutrient pools in harvest residues were less than those in soil, but were still significant, with residue N equivalent to 10% of the surface 0-20 cm soil N pool at the red earth site, and 6% at the grey sand site (Tables 2 and 3). The quantity of cations in the harvest residues was a similar order of magnitude to the quantity held on the exchange complex in the top 20 cm of soil.

Experimental Design and Methods

Harvest Residue Management

Harvest residue management experiments were established at the two sites using a randomised block design, with treatments randomised within each of 4 blocks. The experiments incorporated the core CIFOR treatments (Tiarks *et al.* 1998) and an additional burn treatment. They were:

BL_0 all residues and litter removed;
BL_2 residues retained and uniformly distributed;
BL_3 double the quantity of residues, uniformly distributed; and
Burn residues burnt.

Table 2. Residue biomass and nutrient content (SE in parentheses)

	Biomass (Mg ha^{-1})	Nutrient content (kg ha^{-1}) N	P	K	Ca	Mg
Red earth						
Leaves	21.5 (2.4)	259.1 (33.3)	14.6 (1.7)	95.7 (13.6)	314.7 (41.6)	30.4 (3.7)
Twigs <1 cm	12.6 (1.5)	44.3 (7.1)	4.0 (0.7)	49.7 (7.2)	145.9 (22)	13.0 (1.9)
Branches	9.7 (0.6)	16.7 (4.6)	1.9 (0.4)	22.7 (2.4)	47.0 (9.1)	8.2 (0.7)
Bark	4.9 (0.8)	12.6 (2.0)	0.8 (0.1)	7.9 (1.7)	64.3 (11.7)	6.4 (1.0)
Miscellaneous	2.3 (0.6)	17.3 (4.6)	1.5 (0.4)	7.6 (2.4)	32.2 (9.1)	2.3 (0.7)
Total	51.1 (5.8)	347.2 (41.8)	22.5 (2.6)	181.1 (23.4)	597.4 (79.7)	59.4 (7.2)
Grey sand						
Leaves	13.0 (1.9)	138.0 (31.8)	8.8 (1.7)	20.8 (4.9)	198.5 (39.9)	18.8 (4.3)
Twigs <1 cm	7.6 (0.6)	24.2 (4.6)	2.9 (0.7)	14.6 (5.5)	98.5 (14.5)	10.7 (1.0)
Branches	2.8 (0.6)	4.9 (1.2)	0.7 (0.2)	4.3 (1.2)	36.4 (10.6)	3.9 (0.8)
Bark	2.7 (0.7)	6.6 (1.7)	0.5 (0.1)	5.3 (2.8)	31.5 (8.2)	3.4 (0.7)
Miscellaneous	5.3 (1.8)	45.0 (15.5)	3.1 (1.2)	11.8 (3.6)	76.1 (22.9)	10.1 (3.0)
Total	31.3 (2.9)	218.7 (42.3)	15.9 (2.3)	56.8 (8.7)	441 (66.3)	46.9 (6.7)

Table 3. Soil pools of nutrients (Mg ha^{-1}) to 1 m depth (mean of four pits per site, SE in parentheses)

	Red earth		Grey sand	
	0-20 cm	20-100 cm	0-20 cm	20-100 cm
Organic C	72.68 (11.26)	71.54 (6.93)	54.68 (2.69)	68.66 (5.17)
Total N	3.46 (0.22)	3.57 (0.33)	2.39 (0.13)	1.65 (0.18)
Total P	0.51 (0.04)	0.91 (0.07)	0.18 (0.04)	0.38 (0.04)
Exch K	0.14 (0.01)	0.44 (0.09)	0.04 (0.01)	0.03 (0.00)
Exch Ca	1.08 (0.29)	3.98 (0.46)	0.65 (0.17)	0.76 (0.36)
Exch Mg	0.11 (0.02)	0.37 (0.13)	0.12 (0.03)	0.13 (0.09)
Exch Na	0.06 (0.01)	0.20 (0.05)	0.05 (0.02)	0.08 (0.01)

Plot size was 18 m x 18 m with 40 trees per plot (stocking density of 1234 stems ha^{-1}). Seedlings were planted in July-August 1995 and received a spot application of mixed fertiliser at rates equivalent to 29 kg N ha^{-1} and 12 kg P ha^{-1}. Weed growth was controlled manually or by herbicide spray during the first 2 years after tree planting.

Height and stem diameter over bark of 18 trees in the centre of each plot were measured at regular intervals until the trees were 10 years old, i.e. just prior to harvest. Standing volume was calculated as the sum of stem conical volumes, calculated from height and diameter measurements.

Effects of harvest residue treatments on amount of soil nutrients, and on tree growth, were tested by analysis of variance at each sampling or measurement time. Use of 1R stump basal area as a covariate in the analysis of variance was highly effective in reducing experimental error and improving resolution of treatment effects. Impacts of treatment on soil properties were assessed using initial soil values for each nutrient as a covariate to account for inherent spatial variation.

Nutrient Responses

At each site, adjacent to the harvest residue experiments, two additional randomised block experiments were established to quantify response to N and P application. These provided information for interpreting the impact of harvest residue treatments on tree nutrition and growth. One experiment incorporated five rates of N (0, 40, 125, 250 and 500 kg N ha^{-1} $year^{-1}$ broadcast applied in each of the two years following planting in a randomised block design). A basal dressing of 125 kg P ha^{-1} plus other major and minor nutrients was also applied. The second experiment incorporated five rates of P (0, 20, 50, 125 and 250 kg P ha^{-1}) with a basal dressing of N (250 kg N ha^{-1} $year^{-1}$) and the same major and minor nutrients used in the N-rate experiment. Harvest residues were retained at normal levels (BL_2) across these experiments and redistributed uniformly. A further control treatment (nil N and P with basals) was equivalent to the BL_2 treatment in the harvest residue experiment. Tree growth was measured regularly in the N- and P-rate experiments up to 10 years at the responsive grey sand site, and up to 6 years in the non-responsive red earth site.

Soil Analysis

The effects of harvest residue treatments on soil nutrient properties were determined using two sampling strategies:

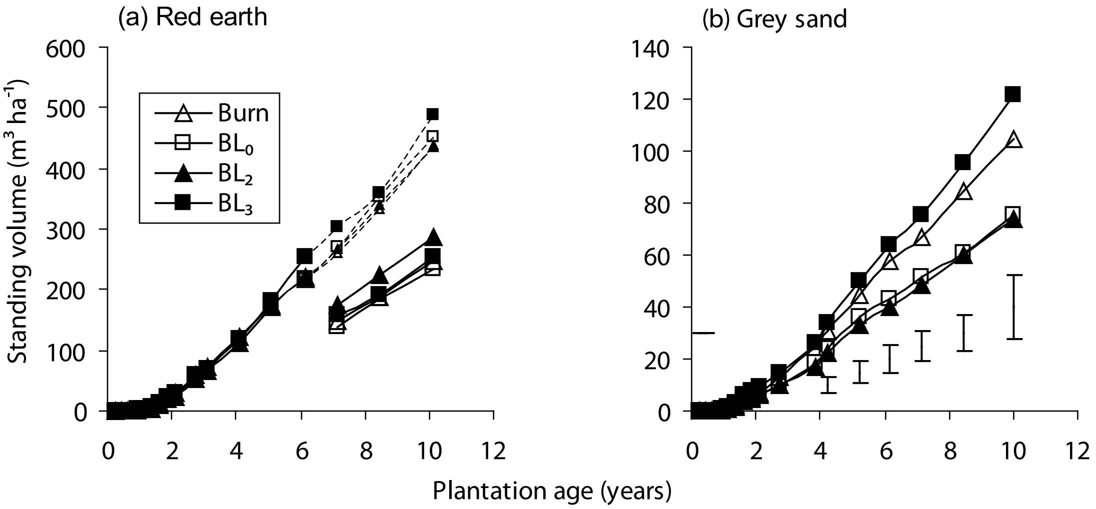
- Soil N mineralisation was assessed at monthly intervals for 5 years after experiment establishment, using the method of Raison *et al.* (1987). Briefly, 9 cores per plot were incubated *in-situ* with caps on (to prevent leaching) for 28 days, then they were transported to the laboratory and mineral NH_4^+ and NO_3^- were analysed colourimetrically after extraction with 1N KCl.
- Annual dynamics of soil pH and nutrients (total C, N, P, and exchangeable K, Ca, and Mg, see methods below) were monitored on annual surface soil (0-20 cm) collections, based on 9 cores per plot (year 9 sampling was omitted). Quantities of nutrients (kg ha^{-1}) in the <2 mm fraction were calculated from concentrations and soil bulk density.

Soil pH was measured in a 1:5 water solution. Total C was assessed on the <2 mm soil, initially using the Walkley and Black wet oxidation method (Rayment and Higginson 1992), but latterly on a Leco combustion analyser. Prior to migrating analyses across to the Leco methodology, the two methods were cross checked and gave the same results for these soils. For N and P, ground <2mm soil was digested in H_2SO_4 with H_2O_2 and the extract was analysed colourimetrically on a Lachat flow injection analyser (Rayment and Higginson 1992). Exchangeable K, Ca, Mg and Na were assessed using atomic absorption spectroscopy after extraction with a 1N NH_4Cl solution.

Results

Plantation Productivity

Effects of residue management on wood production were site dependent, with no effect at the highly productive red earth site at any time during the rotation (Fig. 1a), but a significant effect from year 4 at the grey sand site (Fig. 1b). Note



Bars show least significant difference between treatments where differences were significant ($p<0.01$)

Figure 1. Slash management impacts on plantation productivity

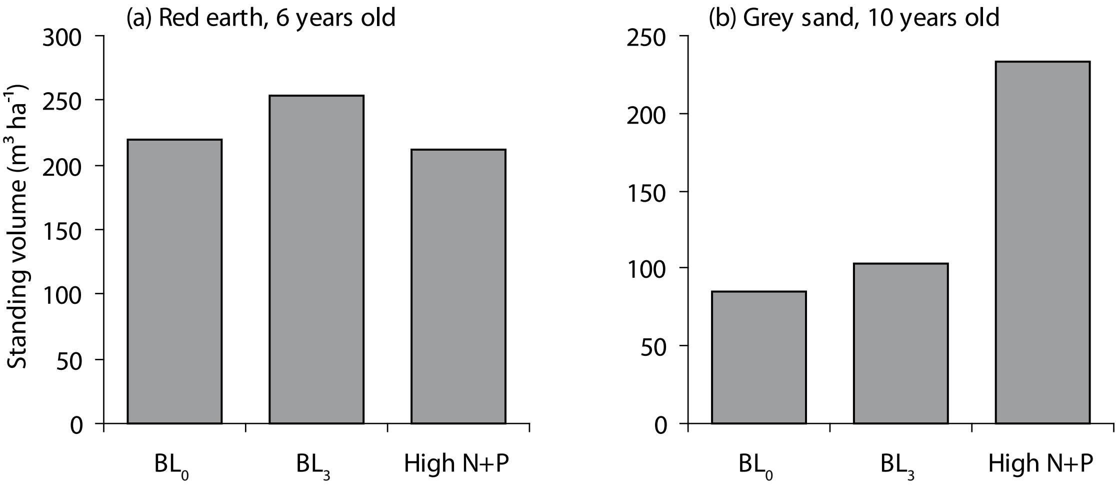


Figure 2. Harvest slash management vs high fertiliser impacts on standing volume at the red earth site at 6 years, and the grey sand site at end of rotation

that the plantation at the red earth site was operationally thinned at age 7 years, so growth of the remaining trees after age 7 years was calculated from measurements of the remaining stand and scaled up based on the pre-thinning basal area; calculated on a plot scale, but tracking the individual trees (dotted line in Fig. 1a).

To demonstrate the contrasting effects of soil fertility across the two sites, Fig. 2 compares the productivity in the zero and double residue treatments and a treatment with the high N and P fertiliser addition ($N_{250}P_{250}$). The fertiliser experiments at the red earth site were discontinued beyond age 6 years because there was no growth response to fertiliser addition from the beginning of the experiment. However, strong responses to N and P were found in the grey sand soil, with more than double the productivity due to fertilisation compared to the treatments with harvest residue manipulation (Fig. 2b).

Productivity in the double residues treatment in the second rotation at both sites was similar to that in the first rotation (Table 4), with a slightly lower productivity at the grey sand site probably due to nutritional constraints, as productivity at that site was more than double when sufficient N and P fertiliser were applied (Fig. 2).

Soil Bulk Density

Soil bulk density was assessed to ensure correct interpretation of changes in soil nutrient quantities, thus the sampling intensity was insufficient to characterise bulk density for each sampling. However, the average soil bulk density over the first 5 years of sampling showed that it was significantly lower under the residue-retained treatments at the grey sand site (Fig. 3b).

Soil C, N and P

Impacts of harvest residue management on total soil C were minimal at both soil depths with no apparent change over time with stand development (Fig. 4). Similar results were found for total soil P and N, with very few significant effects of residue management on these properties (data not shown).

Large pools of mineral N accumulated in surface soil during the first year (Fig. 5). Retention of residues attenuated this effect in the red earth soil, but not in the grey sand soil. At both sites, there was a long-term cumulative effect of residue retention on stimulating soil N mineralisation (Fig. 6), with approximate cumulative increases in soil N mineralisation of 70 kg ha^{-1} at the red earth site, and 108 kg ha^{-1} at the grey sand site.

Soil pH

Soil pH was significantly increased by residue burning on the red earth soil, and at the 10-20 cm depth in the grey sand soil (Fig. 7). These effects were transient and not generally significant beyond the first 1.5 years. However, the burn treatment maintained a higher (albeit mostly non-significant) soil pH for the remainder of the rotation. In the lower fertility grey sand soil, the effect on pH was restricted to the initial post-burn sampling, and then only in the 10-20 cm soil depth.

Soil Cations

Soil cation dynamics fluctuated more over time compared to total C, N, and P (Fig. 8). The quantity of K declined steadily during the first 3-4 years, irrespective of treatment, before stabilising and even increasing slightly (Fig. 8). In the red earth soil, trees were operationally thinned at age 7 years, which contributed to a spike in

Table 4. Comparison of first and second rotation plantation productivity

	Red earth	Grey sand
First rotation		
Age (yr)	8	8
Volume (m^3 ha^{-1})	366.2	95.6
MAI (m^3 ha^{-1} yr^{-1})	45.8	12.0
Second rotation (Double residue treatment)		
Age (yr)	10	10
Height (m)	27.5	13.5
Diameter at breast height (cm)	22.1	14.5
Volume (m^3 ha^{-1})	486.8$^{(1)}$	103.5
MAI (m^3 ha^{-1} yr^{-1})	48.7$^{(1)}$	10.3

(1) Calculated from basal area ratio of non-thinned trees at 10 years (see text)

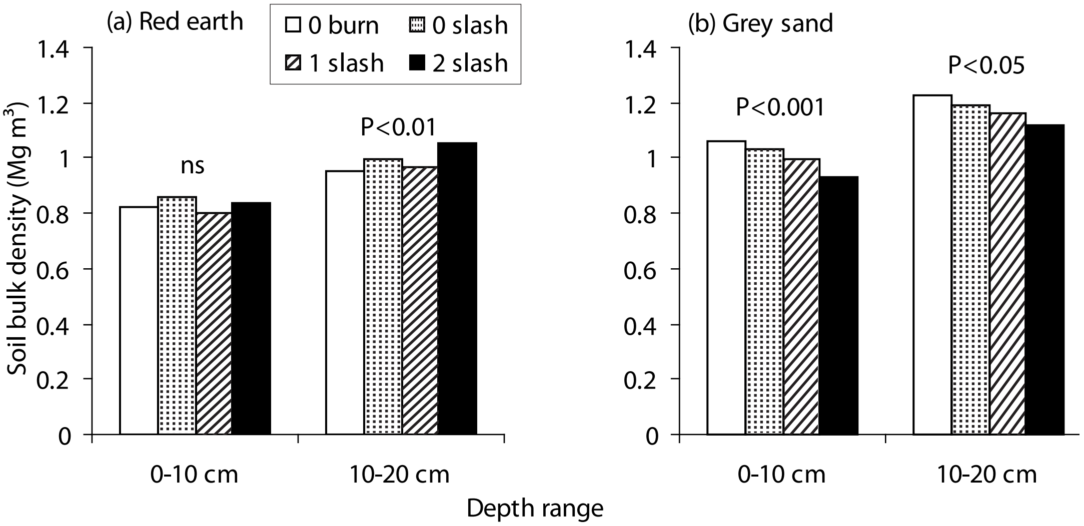
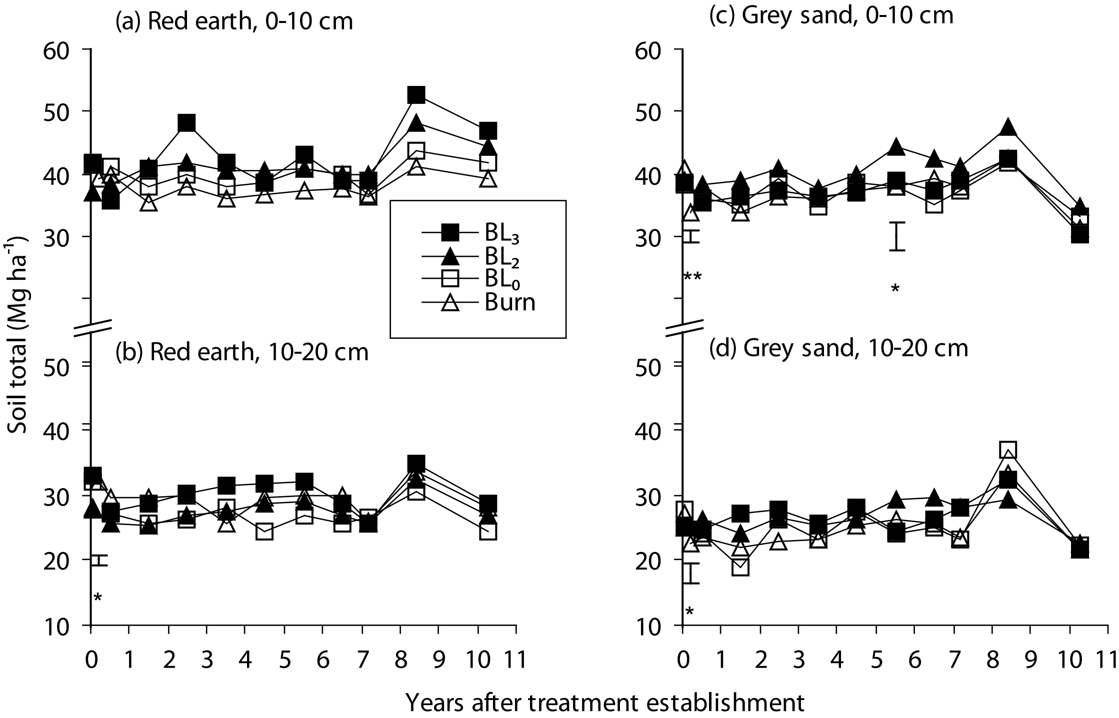


Figure 3. Differences in soil bulk density between treatments at each site (average of measurements made over the first 5 years of the rotation)



Bars show least significant difference between treatments where differences were significant, with significance indicated by * (*p*<0.05), and ** (*p*<0.01).

Figure 4. Residue management impacts on total soil carbon over the rotation

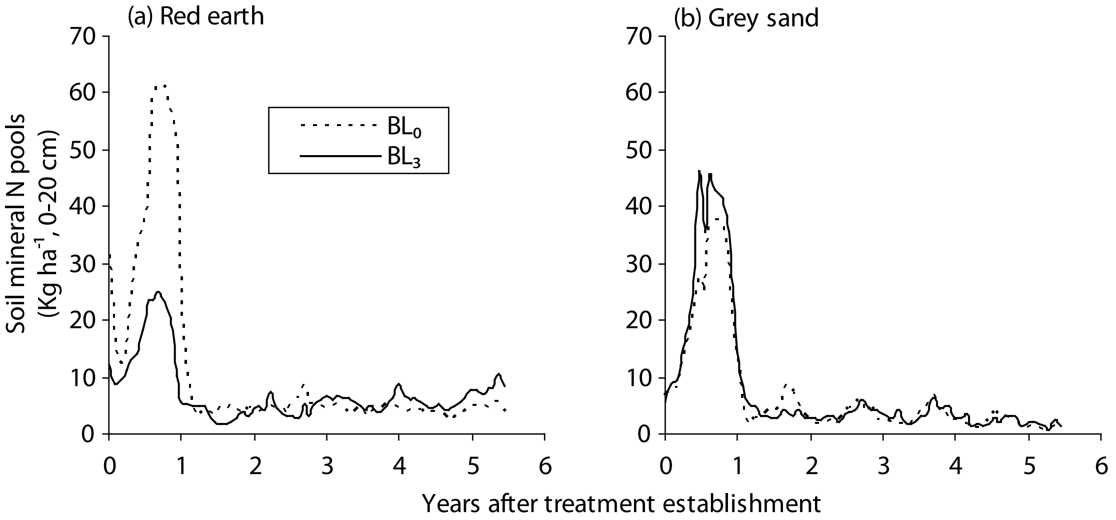


Figure 5. Residue management impacts on soil nitrogen pools (0-10 cm) in the zero and double residue treatments

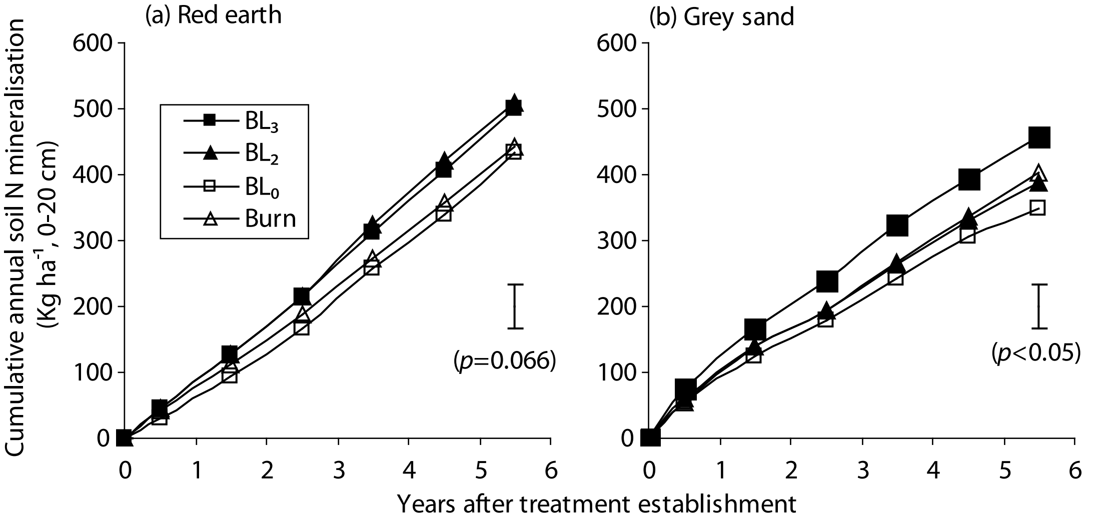
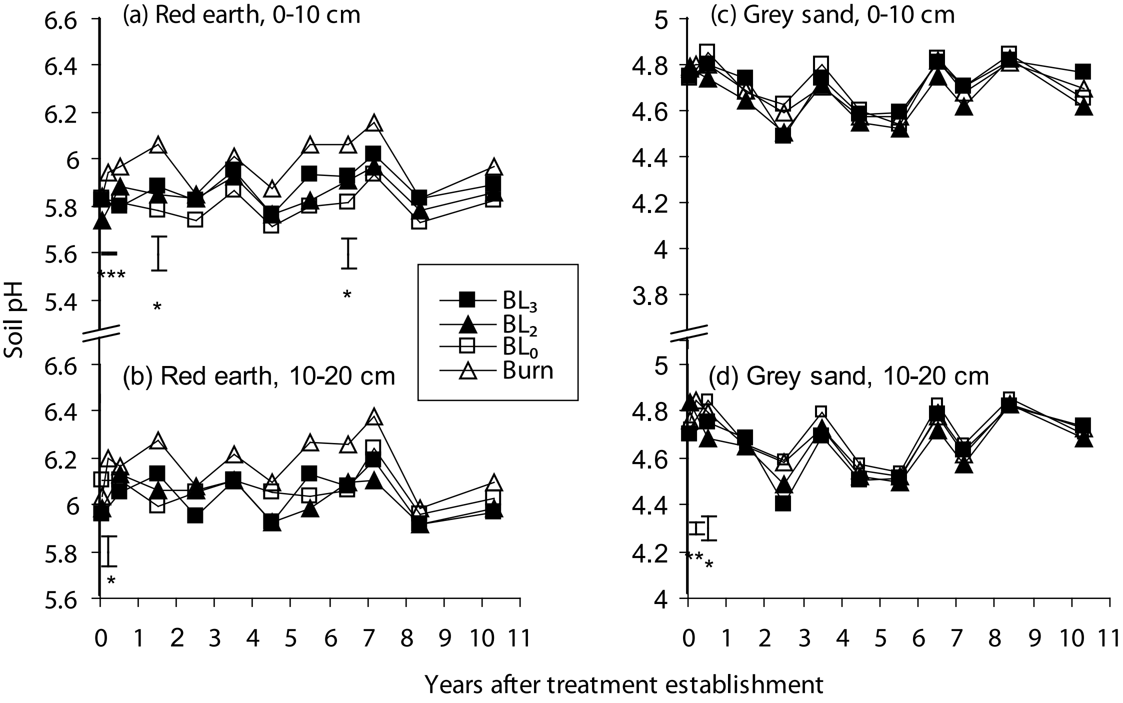


Figure 6. Residue management impacts on cumulative soil nitrogen mineralisation. Bars show least significant difference between treatments 5.5 years after planting

soil exchangeable K at both soil depths. In the measurements following thinning (8-10.3 years), soil K again declined. The impacts of treatment were relatively minor, although exchangeable K was generally lowest in the residue removed treatment (BL_0). The differences in soil K between the residue removed and residue retained (and double-residue) treatments were much less (<15 kg ha^{-1} difference between BL_0 and BL_2) than the 57-181 kg ha^{-1} of K measured in the harvest residues (Table 1).



Bars show least significant difference between treatments where differences were significant, with significance indicated by * (p<0.05), ** (p<0.01), and *** (p<0.001).

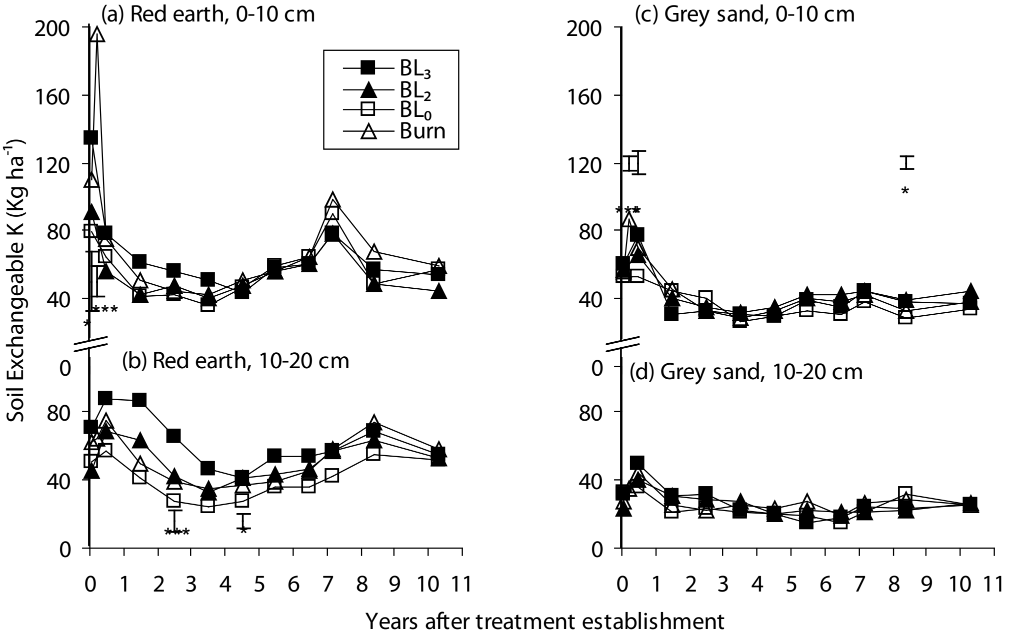
Figure 7. Residue management impacts on soil pH over the full rotation

Whilst soil exchangeable Ca also declined during the first 3-4 years, it contrasted with soil K in its response to treatment (Fig. 9). Exchangeable Ca was significantly higher in the residue retained treatments in the surface (0-10 cm) soil at both sites during the rotation. At the final sampling at the red earth site, the Burn and BL_2 treatments had around 600 kg ha^{-1} more soil Ca than the BL_0 treatment, while the BL_3 treatment had around 1000 kg ha^{-1} more Ca than the BL_0 treatment. There were no significant impacts of harvest residue management on exchangeable Ca in the 10-20 cm depth range.

Soil exchangeable Mg showed a similar response as soil Ca, with greater exchangeable Mg in the residue retained treatments, although the differences were mostly significant at the red earth site (Fig. 10).

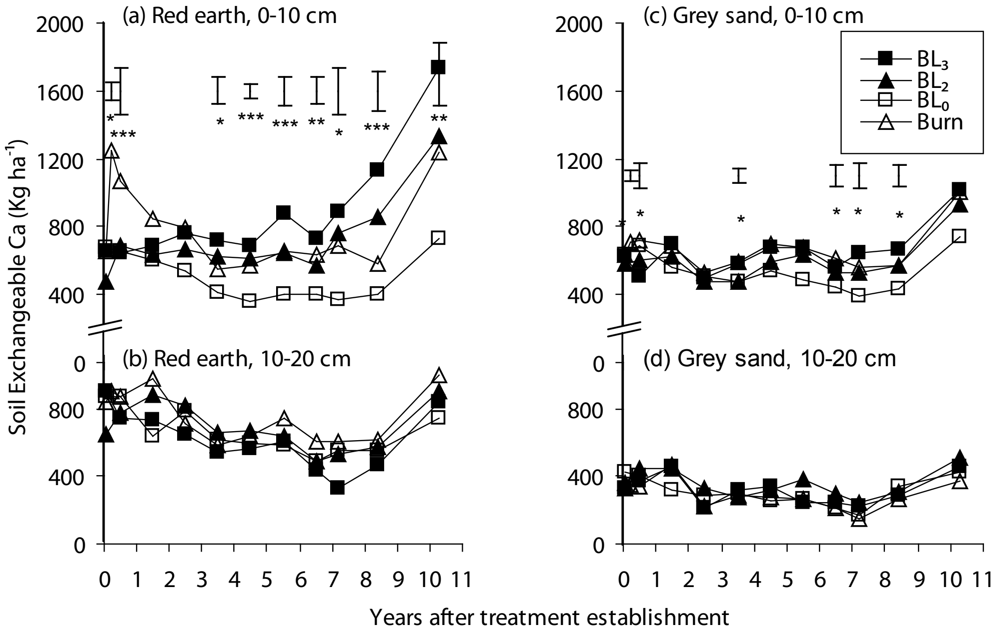
Discussion

Plantation productivity at the red earth site was high and was not influenced by residue or nutrient management. In contrast, the grey sand site was responsive to both nutrient and residue management. Productivity at the grey sand site was increased by nutrient application to approximately 250 m^3 ha^{-1}, still well below projected productivity at the red earth site of around 450 m^3 ha^{-1}. However, it is likely that later applications of N fertiliser would have increased productivity further at that site, as N application ceased at age 2 years. Lower rainfall and soil water storage capacity at the grey sand site would have restricted its potential productivity to below that of the red earth site. Standing volume calculations for 1R and 2R plantations showed that productivity in the double residues treatment had increased marginally at the high fertility site, and decreased marginally at the lower fertility site. Nutrition is the key factor resulting in lower productivity



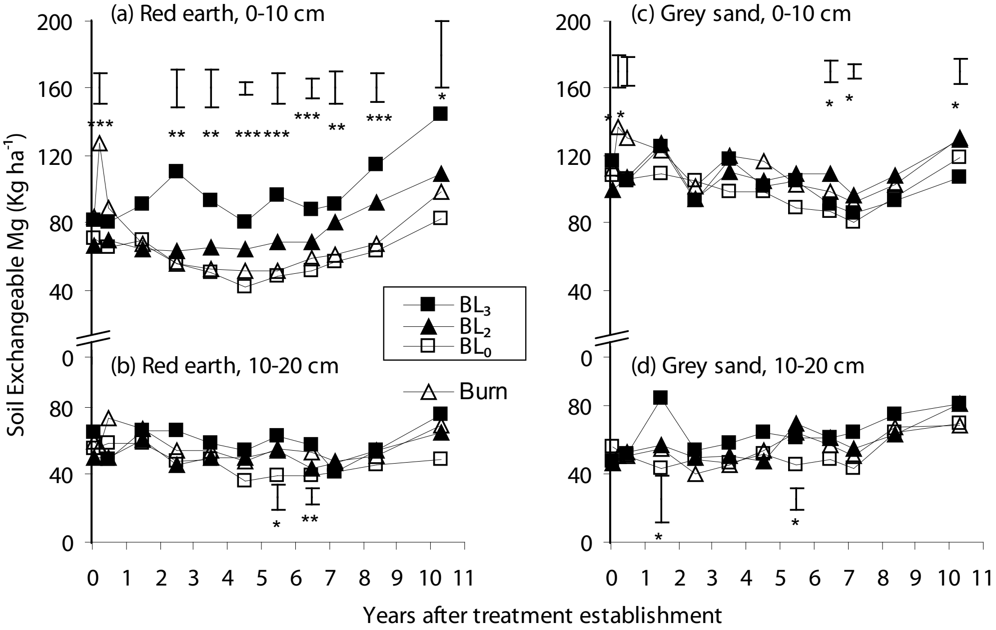
Bars show least significant difference between treatments where differences were significant, with significance indicated by * ($p<0.05$), ** ($p<0.01$), and *** ($p<0.001$)

Figure 8. Residue management impacts on soil exchangeable potassium over the full rotation



Bars show least significant difference between treatments where differences were significant, with significance indicated by * ($p<0.05$), ** ($p<0.01$), and *** ($p<0.001$)

Figure 9. Residue management impacts on soil exchangeable calcium over the full rotation



Bars show least significant difference between treatments where differences were significant, with significance indicated by * ($p<0.05$), ** ($p<0.01$), and *** ($p<0.001$).

Figure 10. Residue management impacts on soil exchangeable magnesium over the full rotation

at the grey sand site, with productivity more than doubling with high N and P application. This supports the finding of earlier studies that soil N and P availability declines under eucalypt plantations on ex-pasture soil (Mendham *et al.* 2004), and suggests that management of nutrition will become more critical in 2R plantations.

Marked impacts of residue burning on soil pH were found at both sites, but these effects were quite transient and had mostly disappeared by the end of the first year after burning. The red earth soil maintained a trend for higher soil pH during the course of the experiment in the burnt treatment compared to the unburnt treatments. This result was similar to that observed in other studies in *Eucalyptus* plantations in South Africa (du Toit *et al.* 2008).

Somewhat surprisingly, residue management had only very minor impacts on soil C, N and P, and no lasting effect by the end of the rotation. O'Connell *et al.* (2004) reported earlier a significant effect of residue management on soil C concentration, especially at the grey sand site. However, this difference in concentration was fully accounted for by (1) differences in the soil bulk density under the treatments (Fig. 3), and (2) initial concentrations of soil C across the plots prior to treatment application (this effect was removed by the analysis of covariance in Fig. 4), hence the lack of response reported here. At both sites, the double residues treatment had approximately the same quantity of C in the harvest residues as in the top 10 cm of soil, so any significant input of this into the soil would have been detected. The majority of the residues had decomposed within the first 24 months, with loss in mass of 93% of the leaves, 41% of the bark, 35% of the twigs, and 28% of the larger branches (Shammas *et al.* 2003), but none of this was detected in the soil. Nitrogen and P in residue material represented a much smaller proportion of total soil N, with these representing around 15% of the 0-10 cm soil N, and

5-20% of the 0-10 cm soil P. Additionally, N and P were retained preferentially in the decomposing harvest residues (Shammas *et al.* 2003), so their release to the soil would have been much slower, and probably intercepted at the mineral soil interface by tree roots.

Whilst total soil N pools were not influenced by residue treatment (data not shown), significant differences were detected in mineral N (Fig. 5) and N mineralisation rates (Fig. 6). Retention of residues had no impact (grey sand site) or induced lower soil mineral N pools (red earth site). Where residues were removed at the red earth site, mineral N pools increased markedly during the first year, increasing the risk of loss through leaching at the time when the young plantation had the least capacity to uptake all available N. Mineral pools remained low when tree roots fully occupied the site (after 1 year).

The stimulatory effect of residue retention on N mineralisation was consistent but was relatively small, such that only an extra 70-100 kg of N was released from the soil over the entire five years. This quantity was much lower than that originally present in the harvest residues (Table 2), supporting the hypothesis above that much of the N is intercepted as it is mineralised from the residues, prior to entering the mineral soil. Extra N released from residues enhanced plantation growth at the infertile grey sand site, but that site still required supplementary N fertiliser to achieve maximum productivity (Fig. 2). The fertile red earth site showed no growth response to either N or P fertiliser, or to residue retention.

Both residue management and stand development had significant effects on exchangeable soil cations. Over time, all of the cations assessed showed an initial depletion, coincident with the rapid canopy expansion phase up to around age 4 years, followed by replenishment in surface soil as canopies lifted and recycling started to occur through litter (Miller 1981). Leaves are the largest single store of cations (Table 2) and much of the leaf biomass is accumulated during the canopy expansion phase, so this is probably the main cause of rapid soil decline. Latterly, tree roots probably extracted exchangeable cations from deeper in the profile, which may have contributed to the increase in content in the surface layers, especially in the red earth soil that had significant stores of cations at depth (Table 3). Grey sand soil had smaller reserves at depth than the red earth soil (Table 3), and replenishment of surface soil exchangeable cations after about year 4 was generally not as evident at that site.

Residue retention greatly increased quantities of exchangeable Ca and Mg in 0-20 cm soil layer by an approximately equivalent amount to that held in residues at the beginning of the experiment, compared to the BL_0 treatment. Both Ca and Mg are relatively immobile in soil compared to K (Guo and Sims 2001), explaining the greater impact of treatment on these nutrients. Potassium is relatively mobile in both residues (Shammas *et al.* 2003) and soil (Guo and Sims 2001), and was readily leached from residues through the surface horizons early in the experiment, as shown by the early spike in surface soil exchangeable K. Thus there was a minimal effect of treatment on soil exchangeable K. It is also interesting to note that thinning at the red earth site in year 7 resulted directly in a similar spike in soil exchangeable K in the 0-10 cm depth range (Fig. 8a). This peak was most prominent in the 10-20 cm depth range in year 8, suggesting that it took about 1 year to migrate to the lower horizon.

Core residue management treatments at both sites have recently been reapplied, and the sites will be monitored into the third rotation. This will provide an insight into the degree of resilience in these systems over multiple rotations, with the hypothesis that the red earth site may start to run into nutrient limitation in the BL_0 treatment. We are also examining the impact of coppice versus seedling re-establishment, as coppice crops have a greater demand for site resources earlier in the rotation.

Impacts

One of the key industry-focussed outcomes integrating this and other studies has been the production of a decision support system, the Blue gum Productivity Optimisation System (BPOS), to assist blue gum (*E. globulus*) growers to make informed decisions regarding plantation management, and impacts on productivity and profitability. BPOS was recently released to industry and favourably received. These industry partners collectively manage around 200 000 ha of plantations. Several companies now retain slash routinely as a part of site preparation for a second rotation.

This study has also had a significant impact on science, with at least seven peer-reviewed publications directly associated with the study. The experiments have also provided a training ground for at least 2 post-doctoral fellows, 2 honours students, and a PhD student.

Acknowledgements

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References

FAO. 1990. Food and Agriculture Organization of the United Nations Soil Map of the World. Revised Legend. World Soil Resources Report 60. FAO-UNESCO, Rome.

du Toit, B., Dovey, S.B. and Smith, C.W. 2008. The effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 63-78. Center for International Forestry Research, Bogor, Indonesia.

Guo, L.B. and Sims, R.E.H. 2001. Eucalypt litter decomposition and nutrient release under a short rotation forest regime and effluent irrigation treatments in New Zealand I. External effects. Soil Biology and Biochemistry 33:1381-1388.

McArthur, W.M. 1991. Reference soils of south-western Australia. Department of Agriculture, Western Australia. 265p.

Mendham, D.S., O'Connell, A.M., Grove, T.S. and Rance, S.J. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management 181:357-372.

Mendham, D.S., Heagney, E.C., Corbeels, M., O'Connell, A.M., Grove, T.S. and McMurtrie, R.E. 2004. Soil particulate matter effects on nitrogen availability after afforestation with *E. globulus*. Soil Biology and Biochemistry 36:1067-1074.

Mendham, D.S., White, D.A., Battaglia, M., Kinal, J., Walker, S., Rance S.J., McGrath, J. and Abou Arra, S. 2005. Managing the trade-off between productivity and risk in the blue gum plantations of south-western Australia. Client Report No. 1554. CSIRO Forestry and Forest Products, Perth, Australia.

Miller, H.G. 1981. Forest fertilization : some guiding concepts. Forestry 54:157-167.

O'Connell, A.M., Grove, T.S., Mendham, D. and Rance, S.J. 2000. Effects of site management in eucalypt plantations in southwestern Australia. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 61-71. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove,T.S., Mendham, D.S., Corbeels, M., McMurtrie, R.F., Shammas, K. and Rance, S.J. 2004a. Impacts of inter-rotation site management on nutrient stores and fluxes and growth of eucalypt plantations in southwestern Australia. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 77-91. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove, T.S., Mendham, D.S. and Rance, S.J. 2004b. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in southwestern Australia. Soil Biology and Biochemistry 36:39-48.

Raison, R.J., Connell, M.J. and Khanna, P.K. 1987. Methodology for studying fluxes of soil mineral nitrogen *in situ*. Soil Biology and Biochemistry 19:521-530.

Rayment, G.E. and Higginson, F.R. 1992. Australian laboratory handbook of soil and water chemical methods – Australian Soil and Land Survey Handbook, Inkata Press, Melbourne and Sydney, Australia.

Robson, A.D. and Gilkes, R.J. 1980. Fertiliser responses (N,P,K,S, micronutrients) on lateritic soils in south Western Australia - a review. *In*: Lateritisation processes, 381-390. International Geological Correlation Programme Project No. 129. Oxford and IBH Publishing Company, New Delhi.

Shammas, K., O'Connell, A.M., Grove, T.S., McMurtrie, R., Damon, P. and Rance, S.J. 2003. Contribution of decomposing harvest residues to nutrient cycling in a second rotation *Eucalyptus globulus* plantation in south-western Australia. Biology and Fertility of Soils 38:228-235.

Smethurst, P.J. and Nambiar, E.K.S. 1990. Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. Canadian Journal of Forest Research 20:1498-1507.

Tennant, D., Scholz, G., Dixon, J. and Purdie, B. 1992. Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. Australian Journal of Experimental Agriculture 32:827-843.

Tiarks, A., Nambiar, E. and Cossalter, C. 1998. Site management and productivity in tropical forest plantations. CIFOR Occasional Paper No. 16. Center for International Forestry Research, Bogor, Indonesia.

Effects of Inter-rotation Management on Site Productivity of *Acacia mangium* in Riau Province, Sumatra, Indonesia

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Abstract

This paper reports the effect of slash management on productivity of a second rotation *Acacia mangium* plantation in Riau province, Sumatra, Indonesia after five years. The site was affected by a root rot disease and an opportunistic investigation was carried out to understand the impact of this disease on stand growth and the potential effects of treatments on fungus infection. There was no significant effect of treatments on stand volume but plots with higher levels of slash retention had a higher mean stem diameter at breast height and lower tree survival. Retention of slash and litter had no significant effect on soil organic C, total N, available P, exchangeable K, and Mg. Exchangeable Ca level increased with slash retention. Extractable P declined and soil pH increased during the experiment. Incidence of root rot confounded tree growth and there is some evidence that high organic matter retention may have increased the infection rate. Growth response to different rates of NPK fertiliser was inconclusive partly because of tree mortality and variation induced by root rot. Wood production of the second rotation crop was at least as high as in the first rotation and there was no obvious negative effect on soil properties.

Introduction

PT. Riau Andalan Pulp and Paper (RAPP) grows and manages its plantations for pulpwood on mineral soils and peat lands in Riau, Sumatra, Indonesia. By December 2005, RAPP with its Joint Venture/ Joint Operation and Community Forests (HTR) had planted about 260 000 ha of fast-growing trees including *Acacia mangium, A. crassicarpa* and *Eucalyptus* spp. Current production of the pulp mill is 2 million t^{-1} yr^{-1} consuming about 9 million m^3 yr^{-1} of roundwood (under bark).

The main species is *A. mangium* which is planted on mineral soils. Genetic improvement for this species has focused on growth rate, stem straightness and wood properties. The best genetic material is deployed through seeds and vegetative propagation for Cloned Family Forestry (CFF) based on an annual operational planting program.

Average productivity of the commercial *A. mangium* plantations is 35 m^3 ha^{-1} yr^{-1} at 7 years. Productivity variation is mainly determined by site factors including management practices and tree survival. Therefore it is crucial to determine and apply the best management practices to achieve sustainable production from short-rotation plantations.

This study started in 2001 and aimed to provide an understanding of the effects of inter-rotation site management practices on productivity. Nurwahyudi and Tarigan (2004) reported. earlier results. This paper builds on these results and focuses on:

- growth, biomass accumulation and nutrient uptake up to 5 years of stand age;
- changes in soil properties; and
- incidence of root rot disease in relation to site management.

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We also discuss how quantitative information on growth rates and nutrient cycling from this study and from other sites in the 'Site Management and Productivity in Tropical Forest Plantations' network, supported by the Center for International Forestry Research, is being used to guide inter-rotation site management practices to increase and sustain long-term productivity.

Site Description

The RAPP's plantations are located from about latitude 1°N to 1°S and from longitude 101°E to 102°E. The site description has been described in detail by Mok *et al.* (1999) and Nurwahyudi and Tarigan (2004) so only a brief description is given here.

The experimental site is located in Baserah Estate, compartment I026, about 200 km south-west of Pekanbaru, Riau province, between 101°47'04"E and 101°47'31"E and between 0°20'37"S and 0°20'46" S. It is about 100 m above sea level. Mean annual rainfall is 2460 mm distributed throughout the year with a mean monthly rainfall of 204 mm. Rainfall is higher between January and May and October to December and lower during June to September. Mean annual temperature is 27°C and mean annual relative humidity is 80% or more.The soil is classified as Typic Hapludult fine family (USDA soil taxonomy) (Tattan personal communication). It is relatively shallow and moderately well drained. The slope of the site is mainly 4-8%. The A horizon ranges from yellowish dark brown (10YR 4/4) to dark brown (10YR 4/3). Soil texture is clay loam to clay. The A horizon has low CEC, low pH, low to very low exchangeable bases and base saturation, and high Al saturation.

Stand Description

The first rotation plantation was established in 1993 using *A. mangium* seedlings of a northern Queensland provenance. Spacing was 3 m x 2 m (1667 stems ha^{-1}). Trees were fertilised with 100 g tree^{-1} of triple superphosphate (TSP) (10% P) and 20 g tree^{-1} of urea (35% N) at time of planting. Maintenance included six herbicide applications up to age 2 years. Trees were lightly pruned and singled at age 8 months. At 7 years of age this first rotation plantation had a MAI of 29 m^3 ha^{-1} yr^{-1}. Trees were harvested by a combination of manual chainsaw felling, including trimming and bucking, and the wood was moved manually to the roadside. Slash and litter were managed according to the treatment described below and by Nurwahyudi and Tarigan (2004).

The experiment (second rotation) was planted in March 2001 with *A. mangium* seedlings of Claudie River (north Queensland) provenance. Spacing was 3 m x 3 m (1111 stems ha^{-1}). Weeds were controlled as before. Trees were fertilised at planting with 20 g of TSP (10% P) and 35 g of rock phosphate (RP) (4% P) per tree. Trees were singled and pruned at age 8 months.

Slash Management Study

This trial was established as a randomised complete block design with four replications and five treatments.

Core treatments:

BL$_0$ All aboveground biomass, litter and understorey vegetation removed.

BL$_1$ Whole tree harvest. All crop trees with bark and including tops, branches and leaves were removed. Only litter and understorey vegetation retained.

BL$_2$ Commercial wood harvest with all stems of >7 cm diameter were removed. Slash (non-commercial residues), understorey vegetation and litter were retained and spread evenly.

BL$_3$ Double slash. Similar to BL$_2$ but slash from BL$_1$ brought in and distributed evenly, adding to the slash already present.

Optional treatment:

BL$_2$+bk Similar to BL$_2$ but bark removed from stems and retained on-site. This treatment represents current harvesting practice in RAPP's acacia plantations.

Nutrient Management Study

A separate trial was established in the adjacent area to determine the effect of various N,P,K fertiliser combinations on growth of *A. mangium* on second rotation site to assist in formulating an optimum fertiliser regime. Basal slash and litter management was the same as BL$_2$ treatment.

It was designed as a 3 x 4 x 3 factorial with 3 replications testing three levels of N, P, and K. Nitrogen was applied as urea (35% N), P as TSP (10% P) and RP (4% P) and K as muriate of potash (25% K). Details of this trial were reported by Nurwahyudi and Tarigan (2004).

Measurements

Tree height and diameter at breast height (DBH) were measured annually. Stand volume was estimated at plot scale. In some plots, trees suffered mortality problems. Those with survival of 55% or less were not included in the variance analysis for growth and stand volume. These were BL_1 replicate 3, BL_2 replicate 2, and BL_2+Bk replicate 4. Based on DBH class distribution, 16 buffer trees were systematically taken from BL_2 treatment plots annually for biomass assessment. Biomass components were separated into foliage, bark, branch (woody material <5 cm diameter), and stem wood (5 cm in diameter or more). Samples from each component were oven dried (75°C for 24 hours) and weighed. A regression (allometric) equation based on DBH was derived for each component. Biomass samples of each component were analysed for N, P, K, Ca and Mg.

Soil samples were taken after treatment application but before planting, and then at ages 3, 4, and 5 years from BL_0 and BL_3 and BL_2+Bk. Fifteen soil cores per plot at depths of 0-10 cm, 10-20 cm and 20-40 cm were taken. They were bulked according to depth within plots, air-dried and retained for analysis. So far only post-planting samples of the top 0-10 cm soil layer have been tested.

The experimental sites developed root rot disease in patches and in most cases trees died. We examined if any soil chemical properties were associated with root rot infection. Soil samples were taken at age 5 years from root rot sites (indicated by higher mortality) and 'root rot- free' sites (indicated by much lower or no mortality). Ten pairs of plots approximately 10 m in radius were identified distributed across the experimental area. Fifteen core samples (0-10 cm depth) from each site were taken and bulked to make one composite sample for chemical analysis.

Litterfall was collected from late June 2004 (age 3.25 years) to June 2005 (age 4.25 years) from 4 replicates of BL_2 treatment. Litter traps (1 m^2) were established, using wooden poles and mosquito net, at 4 random points per plot. Litter was collected biweekly, oven dried (75°C for 24 hours) to estimate dry weight. Samples were bulked for every four collections (2 months) and subsampled for chemical analysis for N, P, K, Ca and Mg.

Results

Tree Growth Response

Tree growth and survival data at 5 years are in Table 1. Diameter varied significantly between treatments. Slash and litter removal (BL_0) was detrimental to tree size and slash retention (BL_2+Bk) produced larger diameters in individual trees. This was partly due to lower stocking in slash retention treatments (Fig. 1).

Stand volume and mean annual increment (MAI) were not significantly different between treatments. Highest stand volume at 5 years was in BL_2+Bk and the lowest was in BL_3 but results were confounded by variability in survival. Despite a higher survival in treatment BL_0, better growth in BL_2 and BL_2+Bk eventually compensated the yield. Height and diameter growth of all treatments are higher than for trees in the first rotation at the same age.

The trend in survival to age 5 years is shown in Figure 1. Only BL_0 and BL_3 differed significantly in survival. The primary cause of mortality was root rot disease caused by *Ganoderma* sp. As trees died, gaps developed in the stand and induced more mortality by windthrow at gap edges. Whether or not the incidence or severity of root rot disease is directly related to the amount of slash retained in the plot is not clear because of high variation in the distribution of affected

Table 1. Height, DBH, volume and survival of A. mangium at age 5 years

Treatments	Height (m)	DBH (cm)	Stand volume (m^3 ha^{-1} yr^{-1})	Volume MAI (m^3 ha^{-1} yr^{-1})	Survival (%)
BL_0	24.4 a	17.4 a	210.6 a	42.1 a	85.5 a
BL_1	24.8 a	17.1 a	203.7 a	40.7 a	83.5 ab
BL_2	24.7 a	18.3 ab	212.1 a	42.4 a	78.2 ab
BL_3	23.8 a	18.8 b	187.3 a	37.5 a	68.4 b
BL_2+Bk	26.1 a	18.8 b	222.9 a	44.6 a	72.7 ab
First rotation	22.4	15.8	204.4	40.9	70

Figures followed by the same letters are not significantly different at $p = 0.05$.

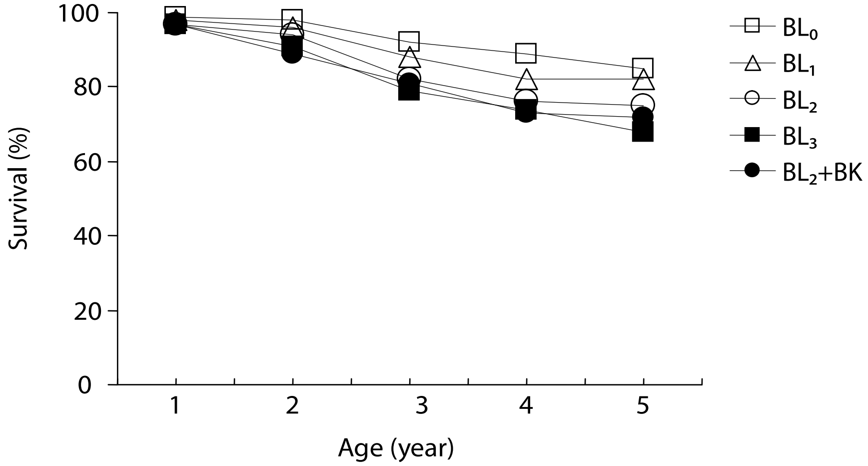


Figure 1. Survival of *A. mangium* stand in slash retention treatments

patches but there was a trend suggesting mortality was slightly higher with slash retention (Fig. 1).

Effect of Fertiliser Application at Planting on Growth

There was no significant effect of N, P, K fertiliser combinations on stand growth. This was partly due to block variations in tree mortality caused by root rot infection. However, results of three treatments are presented in Table 2 to show growth trends of extreme treatments.

There was a clear trend of improved growth rates due to fertiliser application. However we need further experiments to establish the value of intensive fertilisation in addition to the benefit of slash retention.

Stand Biomass Growth and Nutrient Content

Regression equations between DBH and all standing biomass components were established from age 1 to 5 years. At age 5 years, DBH had stronger correlation with stem and bark ($R^2 = 0.86$ and $R^2 = 0.87$ respectively) but weak correlation with leaf and branches ($R^2 = 0.59$ and $R^2 = 0.54$ respectively).

Highest biomass increment in the stand occurred from age 2 to 3 years and subsequently biomass growth began to level out (Table 3). Branches and leaf constituted almost 30% of the total biomass at age 1 year but only 12% at age 5 years. In contrast, the proportion of stem biomass increased and became the most dominant component as the

Table 2. Stand volume of *A. mangium* at age 5 years in relation to fertiliser application

Fertiliser applied	Stand volume ($m^3\ ha^{-1}$)	MAI ($m^3\ ha^{-1}\ yr^{-1}$)	Survival (%)
No fertiliser ($N_0P_0K_0$)	160	32	62
$N_1P_3K_2$ (6.9 g N + 17.3 g P + 18 g K tree^{-1})	214	43	84
$N_2P_3K_1$ (13.7 g N + 17.3 g P + 9 g K tree^{-1})	222	44	78

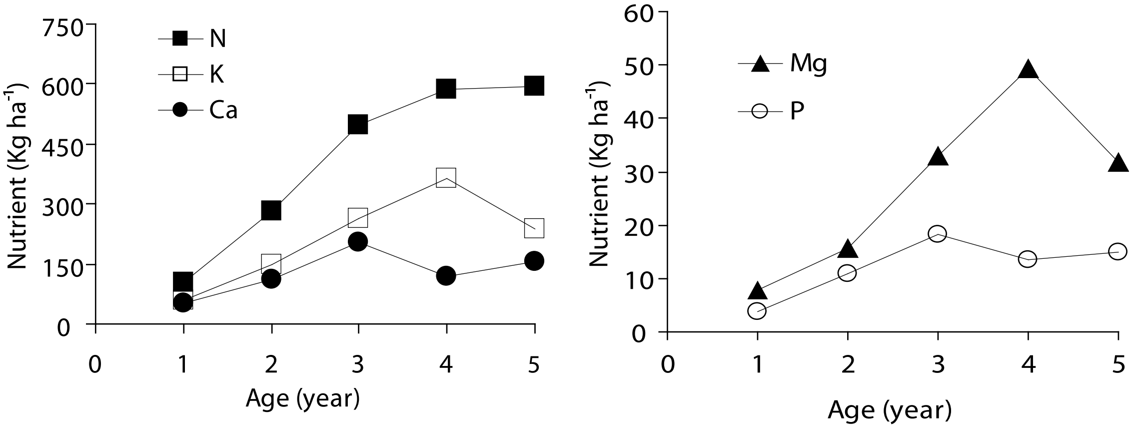


Figure 2. Nutrient content in the standing biomass of *A. mangium* from age 1 to 5 years

Table 3. Standing biomass distribution of *A. mangium*

Component	Biomass ($t\ ha^{-1}$)				
	Age (yr)				
	1	2	3	4	5
Stem	5.2 (42)	22.4 (59)	85.2 (70)	107.1 (76)	123.6 (80)
Branch	1.7 (14)	8.6 (23)	22.3 (18)	15.0 (11)	14.0 (9)
Leaf	1.7 (14)	3.3 (9)	2.4 (2)	4.9 (3)	4.8 (3)
Bark	3.7 (30)	3.7 (9)	11.9 (10)	14.5 (10)	12.0 (9)
Total	12.3	38	121.8	141.5	154.4

Numbers in brackets are percentage of total biomass.

trees grew. Canopy closed at age 2 years and leaf biomass remained constant from age 4 years.

In the standing biomass, N was the highest followed by K, Ca, Mg and P (Fig. 2). Nitrogen accumulation followed the stand biomass growth pattern but other nutrients contents, especially K and Ca, changed over time.

Litterfall and Litter Nutrient Content

For the first 14 weeks (June to September 2004) of litterfall collection, litter mass showed no significant variation between treatments (Siregar *et al.* 2004). Based on this result, litterfall was collected in the following year (June 2004 to June 2005) in treatment BL_2.

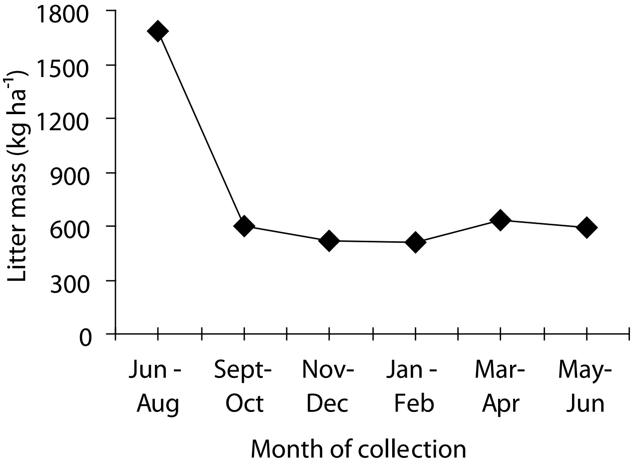


Figure 3. Litter production and under *A. mangium* from age 3 and 4 years

Table 4. Soil chemical properties of the study site after treatment application, before planting *A. mangium* plantation (from Nurwahyudi and Tarigan 2004)

Soil properties	Soil depth (cm)		
	0 - 10	10-20	20-40
pH H_2O	3.6 ± 0.04	3.61 ± 0.02	3.6 ± 0.03
pH KCl	3.42 ± 0.04	3.41 ± 0.03	3.40 ± 0.03
C org (%)	2.49 ± 0.17	1.43 ± 0.09	0.89 ± 0.05
N (%)	0.26 ± 0.02	0.18 ± 0.01	0.13 ± 0.01
C/N	9.52	7.98	6.57
Extractable P (mg kg^{-1})	3.4 ± 0.26	2.27 ± 0.21	1.73 ± 0.16
CEC pH 7 (cmol kg^{-1})	13.58	12.38	1.66
Exch. K (cmol kg^{-1})	0.35 ± 0.03	0.24 ± 0.03	0.19 ± 0.03
Exch. Ca (cmol kg^{-1})	1.03 ± 0.22	0.46 ± 0.12	0.21 ± 0.07
Exch. Mg (cmol kg^{-1})	0.81 ± 0.11	0.55 ± 0.06	0.32 ± 0.04
Exch. Na (cmol kg^{-1})	0.13 ± 0.03	0.12 ± 0.01	0.12 ± 0.01
Base saturation (%)	17.13 ± 3.28	11.29 ± 2.47	7.39 ± 1.5

Numbers following ± is SE.

Litter production at 3 to 4 years was predominantly leaves with very few flowers or pods. Because of this we bulked all litter components for weight and nutrient analysis. Figure 3 shows the seasonal difference in litterfall.

Nutrient concentration of the litter did not show large variation over time. Typical ranges were: N 1.3-1.84%, P 0.012-0.028%, K 0.54-0.63%, Ca 0.59-0.99% and Mg 0.24-0.32%. Nitrogen had the highest nutrient content in the litter, followed by Ca, Mg, P and K. The rate of return of N through litter fall followed the litterfall closely. Total amounts of nutrients returned through litterfall between ages 3 and 4 years were 71.8 kg ha^{-1} yr^{-1}of N, 2.1 kg ha^{-1} yr^{-1}of P, 0.7 kg ha^{-1} yr^{-1}of K, 24.3 kg ha^{-1} yr^{-1}of Ca and 10.5 of Mg kg ha^{-1} yr^{-1}.

Soil Chemical Properties

Some results from initial soil analyses and the amount of nutrients remaining at the site in relation to treatments reported by Nurwahyudi and Tarigan (2004) are reproduced here to help interpretation and discussion. Table 4 shows the soil chemical properties of the experimental area after treatment application before planting.

In this paper we have focused only on changes in soil properties in the top 0-10 cm layer since previous results at three years (Siregar *et al.* 2004) showed only little effect of treatments in the deeper layers. All data in this section refer to the depth of 0-10 cm soil. The amount of biomass and nutrients in the slash retained after harvest is shown in Table 5.

Soil Organic Carbon and Nitrogen

Soil organic C content did not show significant variation over time and there was no significant effect of treatments (Fig. 4A).

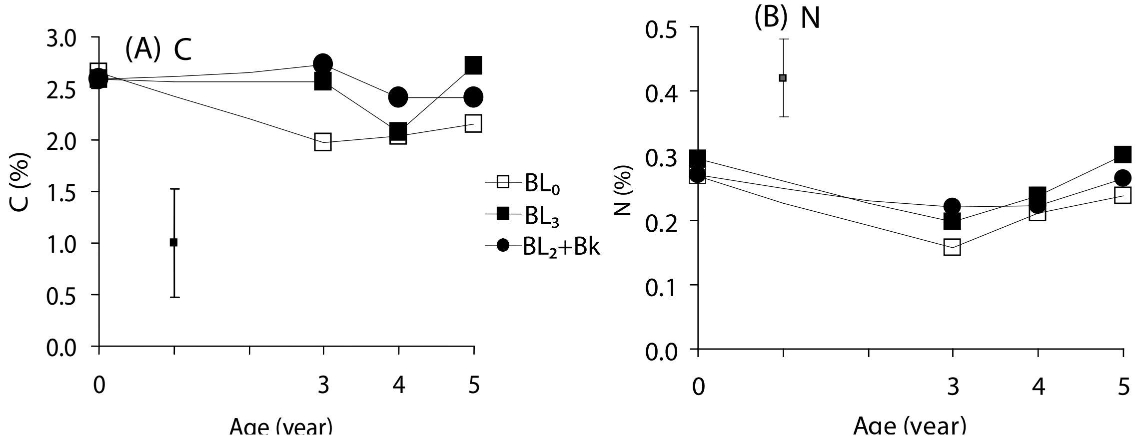
Figure 4B shows changes in soil N level over time. Total soil N decreased to age 3 years in all treatments but increased again by ages 4 and 5 years to the initial level. There was no significant effect of treatments on soil N.

Extractable Phosphorus

Figure 5A shows changes in extractable P (Bray II) over time. Soil P remained relatively steady until age 4 years and then decreased significantly in all treatments by age 5 years. Treatment BL_2 + Bk seems to have maintained higher level of P compared to even BL_3 which retained more P from slash at the site (Table 5).

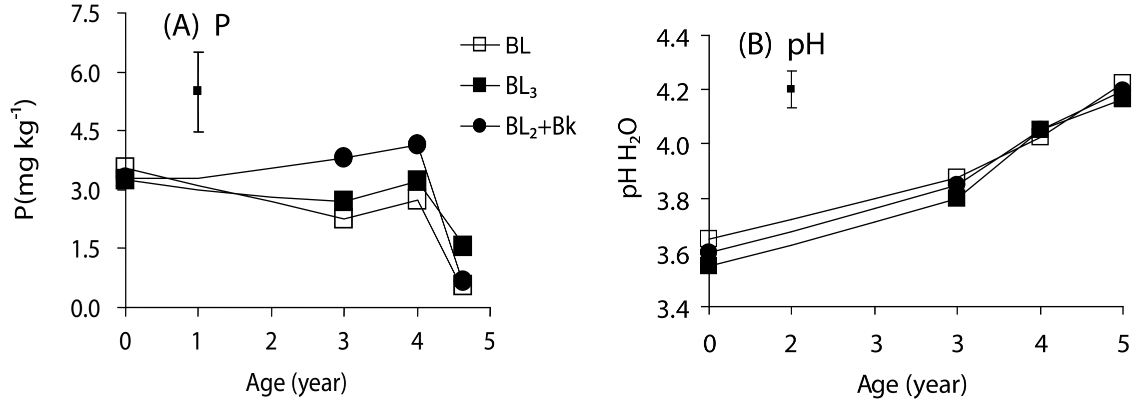
Table 5. Slash quantity and its nutrient content in relation to treatment (from Nurwahyudi and Tarigan 2004)

Treatments	Slash	Total nutrients in the slash (kg ha^{-1})				
	(t ha^{-1})	N	P	K	Ca	Mg
BL_0	0					
BL_1	38.5	515	9	87	207	50
BL_2	70.5	823	18	273	291	74
BL_2+Bk	82.4	949	21	327	382	78
BL_3	102.5	1131	27	458	375	98



Vertical bars denote standard error of means across treatments and time.

Figure 4. Soil organic C and total N under *A. mangium* stand in relation to slash retention



Vertical bars denote standard error of means across treatments and time.

Figure 5. Soil extractable P and pH under *A. mangium* stand

Soil pH

The *A. mangium* plantation did not result in soil acidification. There was a progressive increase in pH (H_2O) from time of treatment application (pH 3.4) to age 5 years (pH 4.2) regardless treatments (Fig. 5B).

Exchangeable Cations

Changes in soil exchangeable cations are shown in Figure 6. Slash treatments had no effect on K at any sampling time. But the K level fell sharply from planting to age 3 years and remain at that level (Fig. 6A).

There was a similar, but less pronounced, effect of stand age on Mg level. It is notable that Mg levels were consistently higher when slash was retained compared to when slash and litter were removed but there was little difference between treatments (Fig. 6C).

Slash and litter retention increased exchangeable Ca levels at all ages, levels being three times higher at ages 3 and 4 years (Fig. 6B). Reduction of Ca from time of treatment to age 3 years occurred only in BL_0 treatment demonstrating the negative effect of slash and litter removal on soil Ca. Cation Exchange Capacity (CEC) showed no significant change across stand age for all treatments but the contribution of slash and litter retention to increase in CEC is very clear (Fig. 6D).

Incidence of Root Rot Disease

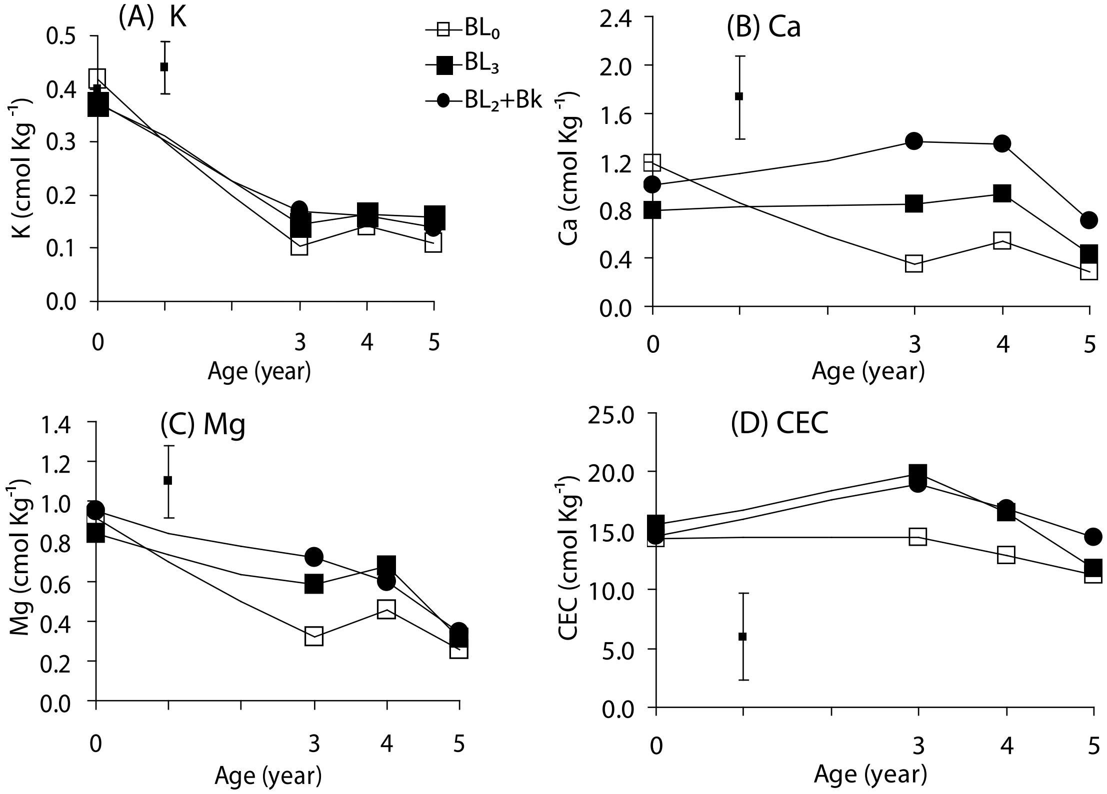
This experiment was adversely affected by soil borne fungal root rot disease. Symptoms of this disease first appeared at 4 to 6 months after planting the second rotation sites. While the root rot appeared to be the primary cause of the mortalities they were also the result of greater susceptibility of affected trees to windthrow. There was a gradual increase in mortality on the experimental site. The incidence increased as the quantity of slash retained on-site increased (Figs. 1, 7).

Deaths occurred from ages 1 to 3 years. A preliminary survey examined the possible relationship of common soil properties to disease incidence by comparing root-rot affected patches and root rot-free areas. Greater mortality in higher slash treatments compared to no or low slash provided more opportunities for data collection. There were no significant differences between patches except that soil-available P was higher in root rot-free spots than affected areas (Table 6).

Discussion

Tree growth and Stand Volume

Retention of slash on site slightly increased stem volume growth of the stand at age 5 years compared to the first rotation. The effect may



Vertical bars denote standard error of means across treatments and time.

Figure 6. Soil exchangeable cations under *A. mangium* stand K, Ca, Mg and CEC

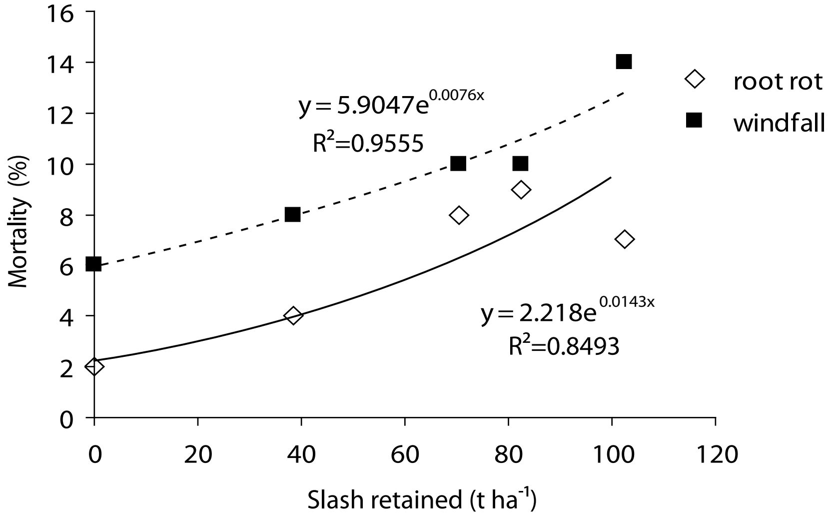


Figure 7. Relation between amount of slash retained in the plot and tree mortality due to root rot and wind fall in a 3-year-old *A. mangium* stand

Table 6. Soil properties (0-10 cm depth) in paired plots of root rot affected spots and 'root rot-free' spots under 5-year-old *A. mangium* plantation

Soil properties	Root rot-affected spot	Root rot-free spot
pH (H_2O)	4.4 (0.15)	4.5 (0.10)
pH (KCl)	3.70 (0.07)	3.72 (0.08)
Organic C (%)	2.10 (0.43)	2.30 (0.70)
Total N (%)	0.17 (0.02)	0.19 (0.04)
NH_4 (mg kg^{-1})	59.3 (32.2)	76.4 (50.7)
NO_3 (mg kg^{-1})	134.5 (22.6)	127.9 (29.0)
Extractable P (mg kg^{-1})	1.55 (0.68)	2.15 (0.42)
Exch. Ca (cmol kg^{-1})	1.11 (0.54)	0.80 (0.36)
Exch. Mg (cmol kg^{-1})	0.60 (0.18)	0.55 (0.15)
Exch. K (cmol kg^{-1})	0.16 (0.03)	0.14 (0.04)

Numbers in brackets are standard errors.

Table 7. Growth of *A. mangium* at 5 years of age on the study site

Growth	First rotation	Second rotation$^{(1)}$
Height (m)	22.4	24.8
DBH (cm)	15.8	18.1
Stand volume (m^3 ha^{-1})	204.4$^{(2)}$	207.3
MAI (m^3 ha^{-1} yr^{-1})	40.9	41.5

(1) mean of all treatments.

(2) spacing: first rotation 3m x 2m (1666 trees ha^{-1} at planting, 1166 trees ha^{-1} at 5 years); second rotation 3m x 3m (1111 trees ha^{-1} at planting, 855 trees ha^{-1} at 5 years).

diminish over time. In Queensland, Australia, the effect of treatments installed prior to planting on stem volume increment of hybrid pine (*Pinus elliottii* x *P. caribaea*) was not observed after age 6.4 years (Simpson *et al.* 2004).

Stand volume was affected by high block variations caused by mortality. Total yield of *A. mangium* is dependent on stand density; a stocking density of 566 stems ha^{-1} at 7 years yielded 202 m^3 ha^{-1} over bark while 1636 stems ha^{-1} yielded 420 m^3 ha^{-1} (Mulawarman *et al.* 2006). In Riau, the BL_2+Bk treatment, which is the current practice in RAPP, improved growth compared to slash removal at age 5 years despite its lower survival rate.

Overall growth rate (mean of all treatments) of the experimental stand and that of the previous rotation at that site shows that the second rotation crop is marginally faster growing than the previous one (Table 7) although the stocking in second rotation is lower than the first rotation. This may be due to a range of factors including better genetic material and other improved management practices. Growth of the second rotation crop was higher than the first rotation even in BL_0 (Table 1).

Effects of Site Management on Soils

Nitrogen concentration in the surface soil had declined 3 years after planting but then increased up to age 5 years (Fig. 4B). Acacias can fix 100-300 kg ha^{-1} yr^{-1} of atmospheric N depending on age and species of the trees (MacDicken 1994, Bouillet *et al.* 2008). Different residue treatments in eucalypt stands in south-western Australia affected average annual concentration of potentially mineralisable N (O'Connell *et al.* 2004). They reported that amounts of N mineralised annually in the surface 0-20 cm soil differed between treatments and this significantly greater mineralisation was associated with high residue treatments. There was a decline in potentially mineralisable N followed by a turning point at year 2-3 and then increasing potential N. This pattern may reflect an increasing contribution to potential mineral N supply from fine root turnover as the new stands develop.

Decline in extractable P during the life of this stand might have been caused by uptake of P by the young stand (15 kg ha^{-1} at 5 years) and some changes in available fractions within the soil. We do not know to what extent the extractant we used to measure P is representative of available pools. The K, Ca and Mg concentrations fluctuated up to 5 years of age (Fig. 6A to 6C). Potassium is very mobile in the soil and in high rainfall, such as at the Baserah site, may have been leached to depths below 10 cm. Lower K at age 3 to 5 years compared to planting time can be caused by rapid K mobilisation and seasonal fixation in the soil. The plant uptake is high, 236 kg ha^{-1} at 5 years (Table 8). It is possible that some K is taken up from deeper parts of the soil, an issue not investigated in this study.

Soil pH under the acacia stands increased significantly during this study. This is an important observation given popular concern that *A. mangium* would acidify the soil. For example, Noble and Randall (1998) suggested trees reduce or prevent nitrate leaching and that nitrate leaching is highly correlated with acidification rate. They also contended that removal of litter removes alkalinity leaving soil more acidic, alternatively, adding leaf litter to an acid soil and allowing it to decompose increases soil pH. This is contrary to the results of our study in which soil pH increased during the 5 years of stand growth even with complete slash and litter removal.

Stand Biomass and Nutrient Cycling

Stand volume of 223 m^3 ha^{-1} under BL$_2$+Bk (Table 1) and 222 m^3 ha^{-1} under intensive fertilisation (Table 2) corresponds to total biomass of 154 t ha^{-1} out of which stem biomass is 123 t ha^{-1} (Table 3). Based on this, we estimate that to produce a volume MAI of 44 m^3 ha^{-1} yr^{-1}, the stand has taken up 600 kg ha^{-1} of N, 15 kg ha^{-1} of P, 236 kg ha^{-1} of K, 157 kg ha^{-1} of Ca and 32 kg ha^{-1} of Mg. These figures may substantially be higher if a production goal of MAI 50 m^3 ha^{-1} yr^{-1} or more is targeted. Such an ambitious growth target will require major improvement in site management including significant addition of fertiliser, taking into account the type of changes in available P (declining over time) and exchangeable K and Ca reported here. Table 8 shows it is crucial to manage available P, K and Ca to meet uptake requirements for higher stand productivity. Also, the amount of nutrient accumulated in the biomass may not be true reflection of the plant requirement of these elements.

Table 8. Nutrient content of standing biomass of 5-year-old *A. mangium*, and soil and litterfall nutrient contents

Component	Biomass (t ha^{-1})	Nutrient amount (kg ha^{-1})				
		N	P	K	Ca	Mg
Leaf	4.8 (3)	139.2	4.3	49.3	9.5	6.7
Bark	11.8 (9)	162.8	2.4	44.9	78.3	4.5
Branch	14.0 (9)	75.6	2.9	27.9	32.6	6.6
Stem	123.6 (80)	217.5	5.3	113.9	36.3	14.1
Total standing biomass	154.2 (100)	595.2	15.0	236.0	156.7	31.8
Leaf litterfall	4.5	71.9	2.1	0.65	24.3	10.5
Soil (0-10 cm) at age 5 years		2650	0.66	54.7	142.6	41.8
Soil (0-10 cm) before planting (1)		2600	3.4	136.9	206.4	98.5

Numbers in brackets are percentage of the total standing biomass.

(1) as per method described for Table 4.

Keeping slash and bark on site (about 21% of the standing biomass) retains about 64% N, 66% P, 52% K, 77% Ca and 56% Mg of total nutrient contained in the biomass (Table 8). More fertiliser will be needed to sustain productivity if this nutrient in the biomass is not managed properly and conserved.

Ganoderma Root Rot and Soil Properties

Management of pests and diseases is a challenge for long-term sustainability in forest plantations. The causal pathogen of root rot in this case is a fungus, *Ganoderma* sp. (Mohammed *et al*. 2006). In other areas of the plantation *Phellinus* sp. has also been found to infect roots and kill trees. In South-East Asia and India, the root rot diseases can cause mortality in acacia plantations ranging from 3 to 40% (Golani 2006). However, it is difficult to control root rot as the pathogens survive on woody material in the soil (Old *et al*. 2000). They suggest removing and destroying all debris to reduce sources of inoculum. This practice would affect the site's nutrient budget so systems need to be developed to balance disease control and site productivity.

Ganoderma distribution pattern was patchy and random throughout the site and we have been unable to find a relationship with any site factors and infection. A root rot site survey in RAPP's plantations indicated more patches of root rot occurred on lower parts of a slope. This may be related to spread of the inoculum by water movement. Rimbawanto (2006) reported that spatial analysis indicated infected trees were randomly distributed initially but later tended be aggregated. This highlights the probability of vegetative spread of the fungus after initial introduction to the site. Making a direct link between slash retention treatments with root rot disease is difficult because *Ganoderma* inoculum may not be distributed uniformly across treatments.

High N may increase root rot incidence (Stone *et al*. 2004). They suggested high plant N removed C from plant defence pathways (those generating phenolics, alkaloids and phytoalexins) to support growth pathways (those generating carbohydrates) and excess N could increase disease incidence particularly if P and K are deficient. The form of N may also affect disease incidence. Root rot diseases caused by *Fusarium, Rhizoctonia* and *Aphanomyces* were reduced by NO_3^-- N and increased by NH_4^+- N, whereas the reverse was true for disease caused by *Pythium* and *Ophiobolus*. Moderate P levels tend to decrease disease incidence (*Pythium* root rot) whereas very high or low tend to increase the incidence.

Conclusions and Management Implications

RAPP's commercial plantations currently grow at a MAI in the range 22-50 m^3 ha^{-1} yr^{-1} at 5 years when planted with improved planting stock and good management practices in mineral soils. The reason for this large variation across sites is not fully understood but variations in soil, survival rate and local management are likely to be significant factors.

Results from this research show that it is possible to maintain or increase productivity of successive crops and there is no indication of any threat to soil properties. Understanding the reasons for the large variations in productivity between sites and good knowledge required to meet nutrient demand for achieving the productivity goal remain an on going challenge.

The following important information and lessons emerged from this study, including earlier reports (Nurwahyudi and Tarigan 2004, Siregar *et al*. 2004).

- A quantitative basis and methodology with which to estimate impacts of different harvest intensites and inter-rotation site management practices on site-nutrient stock.
- The critical importance of conserving nutrients if high production is targeted.
- Harvesting operations must be considered as part of silviculture to achieve long-term sustainability. Current harvesting practices in RAPP, retaining slash and bark and spreading them uniformly before planting using low-pressure track excavators, is influenced by this research and must be encouraged.
- Reliable information about the rate of nutrient uptake in relation to stand development, and relevant information for devising future

fertiliser strategies based on the nutrient budget of the site.

- The need to monitor soil changes in in the longer term, even though there is no indication of any adverse effect that cannot be managed by proper management.
- Removal of slash and litter during site preparation may be warranted to manage root rot incidence. Site-specific management with a compensatory fertilisation regime may be possible.
- Full stocking of plantations is necessary to maximise productivity. Despite improved growth in the second rotation due to better site management and improved genetic material, the magnitude of improvement became marginal due to loss of by root rot, windthrow, and to some extent, lower initial stocking. Further study to improve stocking is necessary.

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References

Bouillet, J.P., Laclau, J.P., Goncalves, J.L.M., Moreira, M.Z., Trivelin, P., Jourdan, C. and Galiana, A. 2008. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 157-172. Center for International Forestry Research, Bogor, Indonesia.

Golani, G.D. 2006. Hardwood plantation development and threats to its sustainability in Indonesia. *In*: Potter, K., Rimbawanto, A. and Beadle, C. (eds.) Heart rot and root rot in tropical *Acacia* plantations, 16-21. ACIAR Proceedings No. 124. Australian Centre for International Agricultural Research, Canberra.

MacDicken, K.G. 1994. Selection and management of nitrogen-fixing trees. Winrock International Institute, Bangkok. 272p.

Mohammed, C.L., Barry, K.M. and Irianto, R.S.B. 2006. Heart rot and root rot in *Acacia mangium*: identification and assessment. *In*: Potter, K., Rimbawanto, A. and Beadle, C. (eds.). Heart rot and root rot in tropical *Acacia* plantations, 26-34. ACIAR Proceedings No. 124. Australian Centre for International Agricultural Research, Canberra.

Mok, C.K., Cheah, L.C. and Chan, Y.K. 2000. Site management and productivity of *Acacia mangium* in humid tropical Sumatra, Indonesia. *In:* Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 87-94. Center for International Forestry Research, Bogor, Indonesia.

Mulawarman, Siregar, S.T.H. and Nurwahyudi. 2006. Tree stand development – Is *Acacia mangium* plantation a viable land use option to increase carbon storage? Poster presented in International Conference on 'Ecosystem Goods and Services from Planted Forests', Bilbao, Spain, 3-7 October 2006.

Noble, A.D. and Randall, P.J. 1998. The impact of trees and fodder shrubs on soil acidification. (http://www.rirdc.gov.au/reports/AFT/csp-4a.pdf).

Nurwahyudi and Tarigan, M. 2004. Logging residue management and productivity in short-rotation *Acacia mangium* plantations in Riau Province, Sumatra, Indonesia. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 107-119. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove, T.S., Mendham, D.S., Corbeels, M., McMurtie, R.F., Shammas, K. and Rance, S.J. 2004. Impacts of inter-rotation site management on nutrient stores and fluxes and growth of eucalypt plantations in southwestern Australia. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 77-91. Center for International Forestry Research, Bogor, Indonesia.

Old, K.M., Lee S.S., Sharma, J.K. and Yuan, Z.Q. 2000. A manual of diseases of tropical acacias in Australia, South-East Asia and India. Center for International Forestry Research, Bogor, Indonesia. 104p.

Rimbawanto, A. 2006. Heart rots in plantation hardwoods: the background to this ACIAR project. *In*: Potter, K., Rimbawanto, A. and Beadle, C. (eds.) Heart rot and root rot in tropical *Acacia* plantations, 22-25. ACIAR Proceedings No. 124. Australian Centre for International Agricultural Research, Canberra.

Simpson, J.A., Smith, T.E., Keay, P.T. and Osborne, D.O. 2004. Impacts of logging residues on soil properties and growth of hybrid pines in Southeast Queensland. Paper presented at the Sixth Workshop on Site Management and Productivity in Tropical Plantation Forests, 22-26 November 2004, Piracicaba, Brazil. 13p.

Siregar, S.T.H., Nurwahyudi and Mulawarman. 2004. Growth and site productivity of a three-year-old *A. mangium* plantation from different harvesting residue management in Riau Indonesia. Paper presented at the Sixth Workshop on Site Management and Productivity in Tropical Plantation Forests, 22-26 November 2004, Piracicaba, Brazil. 17p.

Stone, A.G. Scheuerell, S.J. and Darby, H.M. 2004. Suppression of soil borne diseases in field agricultural systems: organic matter management, cover cropping, and other cultural practices 131-177. (http://oregonstate-edu/dept/hort).

Inter-rotation Site Management, Stand Growth and Soil Properties in *Acacia mangium* Plantations in South Sumatra, Indonesia

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Abstract

This paper presents the results of inter-rotation management on the productivity of a second rotation plantation of *Acacia mangium* in South Sumatra, Indonesia. Slash retention had a positive response on growth. Slash retention also increased soil organic C and N three years after planting. Extractable P tended to decrease over time, but this was not significant. Five years after planting soil pH did not change. High slash addition increased exchangeable Ca and Mg in surface soil. Peak nutrient demand occurred within the first 1-2 years after planting, suggesting the importance of early nutrient inputs. Application of N, K and Ca fertilisers had no effect on tree growth. Phosphorus fertiliser increased tree growth at the early ages but the response diminished with time. The second rotation plantation had higher stem volume production than the first rotation plantation. Overall, the experimental plot grew faster than the operational plantation under a similar silvicultural regime.

Introduction

Acacia mangium was introduced in South Sumatra, Indonesia in 1979 and large-scale plantations have been established since 1990. PT Musi Hutan Persada, a forestry company in South Sumatra now manages 193 500 ha of forest plantations of which 90% consist of *A. mangium*. Harvesting of this crop began in 1999 for the pulp mill with annual capacity of 450 000 t of bleached kraft pulp. All sites are replanted with the same species. Productivity was in the range 20-33 m^3 ha^{-1} yr^{-1} (Arisman and Hardiyanto 2006). Concerns about sustainability of *A. mangium* plantation forest have been raised (e.g. Nykvist 1997, Mackensen and Folters 1999) due to particularly to potential nutrient depletion from sites that have inherently low-medium nutrient status.

Management practices to increase productivity have been implemented by the company through a breeding program and silvicultural practices. Second rotation plantations established with improved genetic stock and appropriate silviculture could potentially increase productivity up to 20-30% over the previous rotation. Optimum spacing, effective weed control, and application of fertilisers at planting are among current management practices.

Inter-rotation site management practices have critical impacts on productivity. Harvesting operations, site preparation and silviculture from planting to canopy closure can have strong influences on the soil and site environment and in turn on productivity of successive plantations (Nambiar and Brown 1997, Mackensen and Folster 1999). This study, initiated in 1999, aimed to address growing concerns about the productivity and sustainability of *A. mangium* plantation over successive rotations. Earlier results from this long-term project have been reported by Hardiyanto *et al.* (2000, 2004). The objectives of this paper are to:

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- assess the impact of slash management on tree growth when the stands have reached 70-85% harvestable age;
- quantify nutrient uptake by fast-growing plantations;
- examine changes in key soil properties over this period; and
- compare the productivity of the second rotation plantation, the first rotation plantation, and operational plantations.

Site, Soil and Stand Description

The company land is located at 103°10'-104°25' E longitude and 3°05'-5°28' S latitude. Altitude ranges from 60 to 200 m above sea level and the terrain is mostly flat to undulating (0-8% slope) with a very minor part of the area having 8-55% slope. The plantation experiences a lowland humid environment with the average daily temperature about 29°C, the average minimum temperature 22°C and the average maximum temperature 32°C. Annual rainfall ranges from 1816 to 3513 mm, falling mainly between October-May with a relatively dry period in June-September. Soil is mainly derived from sedimentary rock of tuff, sandy tuff, sandstone and claystone. Most soils belong to a Red Yellow Podsolic or Ultisol (Soil Survey Staff 1992).

The experiments were established at two sites: Toman and Sodong. Details have been reported in Hardiyanto *et al.* (2000, 2004). Only key features are included here.

Soils in Toman and Sodong have high clay content (64-75%) with medium bulk density (1.22-1.33). Concentrations of C and N in the surface layer range from 2.64 to 3.10% and from 0.23 to 0.24% respectively. Concentrations of extractable P are low (5.77-5.35 mg kg^{-1}). Exchangeable K, Ca and Mg are also low: 0.083-0.086, 0.371-0.570 and 0.257-0.304 cmol kg^{-1} respectively (Hardiyanto *et al.* 2000, 2004).

The first rotation stands of *A. mangium* harvested for the experiments were typical of the region. They were established on alang-alang (*Imperata*) grassland that invaded after clearing native forest. The soil was ploughed twice using a wheeled tractor and harrowed once. Seedlings were from a genetically unselected local seed source. Plant spacing was 4 m x 2 m at Toman and 3 m x 2 m at Sodong. A fertiliser at a rate per tree 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 one month after planting. At harvest, the stand stocking in Toman was 1382 stems ha^{-1} with 19% trees dead. At Sodong the stocking was 1966 stems ha^{-1} with 37% trees dead. Most trees were multistemmed as they were not singled.

Experiment Details

Slash Management Experiment

Details of the experiments at both sites have been reported by Hardiyanto *et al.* (2000, 2004). There are four main slash management treatments:

BL$_0$	All slash, litter and understorey removed after harvesting wood.
BL$_1$	Whole live trees including non-commercial parts were harvested and removed from the site but litter and understorey were retained.
BL$_2$	Only stems of commercial size (diameter > 8 cm over bark) were removed. All non-commercial components (wood, branches, foliage), litter and understorey were distributed evenly.
BL$_3$	The same as BL$_2$ but slash from BL$_1$ plots was brought in and distributed evenly over the slash already present.

An additional set of BL$_2$ plots (BL$_{2B}$) was included for sequential biomass sampling of trees as the stand developed. The experiment was arranged in a randomised complete block design, replicated four times. Plot sizes were: Toman, 40 m x 36 m (128 trees per plot at 4 m x 2 m) and Sodong, 36 m x 36 m (100 trees per plot at 3 m x 3 m). At Toman, seedlings from improved seed (provenance stand of Wipim, Papua New Guinea) were planted in January 2000. At Sodong, seedlings from seed from a seed orchard (Oriomo River, Papua New Guinea provenance) were planted in January 2001.

At both sites, fertilisers were applied at planting with following amounts per tree: 30 g urea (13.8 g N), and 87.5 g superphosphate (14 g P). Trees were singled after 3 months and pruned from the base at 6 months, retaining about 70% of live crown. The site was sprayed with herbicide before planting, manually weeded after 3 months, and herbicide applied at 6 months. At Toman, due to an unforeseen local problem, weed control was carried out from 3 to 12 months. This affected stand growth adversely.

Nutrition Study

At Sodong, two experiments (A and B) with slash retention (BL_2) as the basal treatment were laid out. Study A is a factorial experiment involving three levels of N (0, 13.8 and 27.6 g N tree^{-1}) and P (0, 14.0 and 28.0 g P tree^{-1}). Nitrogen as urea and P as superphosphate fertiliser were applied at planting. Phosphorus fertiliser was reapplied when trees were 26 months old (March 2003) at two rates: 30 and 60 kg P ha^{-1} on treatments which had previously received 14.0 and 28.0 g P tree^{-1} respectively. Phosphorus fertiliser was broadcast evenly in the plot.

Experiment B was designed to test tree growth response to K and Ca. There were four treatments: control (no fertiliser), 150 g KCl (75 g K) tree^{-1}, 825 g hydrated lime (335 g Ca) tree $^{-1}$, and KCl + hydrated lime at above rates. The experiment received a basal fertiliser application: 30 g urea (13.8 g N) tree^{-1} and 87.5 g superphosphate (14.0 g P) tree^{-1}. All fertilisers and lime were applied at planting time. Lime was reapplied at a rate of 580 g hydrated lime (215 g Ca) tree^{-1} when trees were 26 months old (March 2003). Potassium fertiliser at a rate of 462 g KCl (223 g K) tree^{-1} was reapplied in two doses: half of the amount at 26 months and the remaining at 33 months of age (October 2003). Lime and KCl were broadcast evenly in the plot.

At Sodong, four plots (30 m x 30 m with 110 trees per plot) were established in the operational plantation adjacent to the experiment. This plantation was established using site preparation similar to that in BL_2 treatment. It was planted with seedlings from improved seed and according to the prevailing management prescriptions. It was planted two months earlier than the experimental plantation. The objective was to compare tree growth between experimental and operational plantations.

Measurement and Data Analysis

Stand Growth

Tree height and stem diameter at breast height and tree biomass were measured annually (Hardiyanto *et al.* 2004). Sixteen trees representing the range of stem diameter were felled. Biomass components were separated into: stem wood (>5 cm), stem (<5 cm), bark, branches (<1 cm, 1-5 cm, >5 cm) and leaf. Subsamples of each component were oven-dried at 76°C to constant weight. Subsamples were used for chemical analysis. Allometric relationships between stem diameter and biomass components were developed and these regression equations were used to estimate biomass production. Nutrient accumulation was estimated using biomass data and nutrient concentrations in tissues.

Litterfall

At Sodong, litterfall was collected at two-weekly intervals in BL_0 and BL_2 plots. Five litter traps (1 m^2 made of perforated plastic sheet) were placed at random location in each plot. Samples from two successive collection dates were combined and subsamples of these were used for nutrient analyses.

Soil Sampling

At Toman, soil samples were taken just before planting, immediately after marking the plots and then at 4, 5 and 6 years after planting. In Sodong, soil samples were taken initially after marking the plots and every year up to age 5 years. Samples were taken in all slash treatments using a soil corer, five cores per plot at soil depths:0-10, 10-20 and 20-40 cm. Samples were air dried and sieved through a 2 mm sieve and the fraction < 2 mm was used for chemical analyses.

Methods for soil analysis were as follows:

- organic C, by K_2CrO_7 and H_2SO_4 digestion and then by spectrophotometer;
- total N, by H_2SO_4 digestion and Kjeldahl;
- available P, by the Bray No 1 extraction;
- exchangeable K, Ca and Mg, by NH_4Ac extraction at pH 7 and then by Atomic Absorption Spectrometer;
- pH, in 1:2.5 water suspension.

Nutrient Retranslocation in Leaves

We estimated nutrient retranslocation in leaves following the principle described by Nambiar and Fife (1991) and Saur *et al.* (2000). At Sodong, leaf samples at three different stages of life span: live-green, senescent-yellow and dead-brown (retained on the branch) were taken from the same branch of middle crown from BL_0 and BL_3 plots when trees were 39 months old. Ten sets of leaves representing the three stages were taken from each of the four replicate plots. Leaves were dried at 76°C to constant weight for chemical analyses. Nutrient retranslocation was assumed as the difference between nutrient content in the live-green and senescent-yellow leaves. Net retranslocation was expressed as a percentage of the nutrient content in green-leaves.

Results

Tree Growth

There were large differences in productivity between Toman and Sodong site. At Toman at age 5 years the height was 20.8 m, basal area 21.8 m^2 ha^{-1} and mean annual stem volume increment (MAI) was 42.2 m^3 ha^{-1}. At Sodong at age 5 years, the tree height was 24.9 m, basal area 24.7 m^2 ha^{-1} and MAI 53.4 m^3 ha^{-1}. The stand at Toman had a higher proportion of stems in diameter class of 10-15 cm (51%) and 15-20 cm (19%). At Sodong the stem diameter class were 15-20 cm (40%) and 20-25 cm (42%)(Fig. 1). The presence of a higher proportion of trees in the higher diameter classes is partly due to closer initial spacing in Toman (4 m x 2 m, i.e. 1250 trees ha^{-1}, compared to Sodong (3 m x 3 m, i.e. 1111 tree ha^{-1}). The stands at Sodong had higher growth rates than those at the Toman site at the same age.

Effects of slash treatment on tree growth are shown in Table 1. At Toman removal of all slash and litter (BL_0) caused slightly slower height and diameter growth compared to where the slash and litter was retained but effects were not significant. In BL_3 treatment the survival rate of trees was 68%, lower than in other plots (74-80%) due to the high weed growth during the first year. As noted, weed control could not be carried out here during the early months and the first application of herbicide over the slash layer was ineffective

At Sodong there was no difference in height and stem diameter at age 5 years. Stem diameter growth was consistently higher in BL_3 than in BL_0 (Fig. 2) Trees in BL_2 and BL_3 plots were 14.7 and 13.1% respectively higher than those on BL_0 plot (Table 2). These results indicate that loss of litter and slash would be detrimental to production as retention of slash increased stem volume growth.

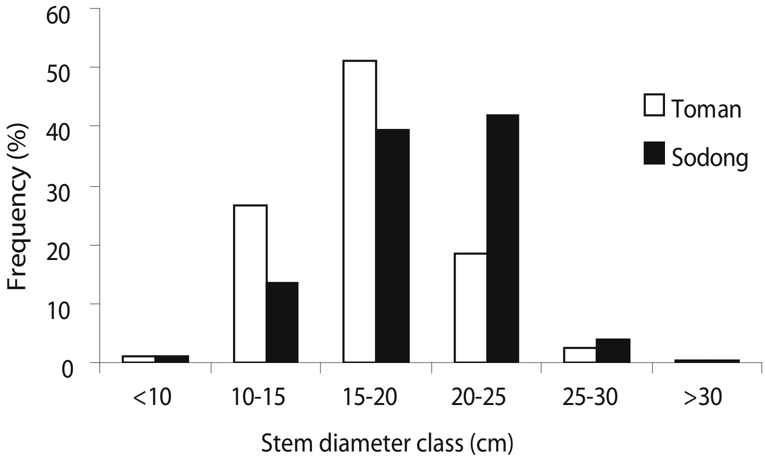

Figure 1. Stem diameter class distribution of *Acacia mangium* at age 5 years

Table 1. The effect of slash treatment on height, stem diameter and stem volume of *A. mangium* at age 6 years (Toman site)

Treatments	Height (cm)	Stem diameter (cm)	Stem volume (m^3 ha^{-1})
BL_0	23.0	17.5	258.9
BL_1	23.4	17.9	257.3
BL_2	23.3	18.2	265.3
BL_3	23.8	19.2	271.8
CV (%)	5.0	5.2	15.4
LSD (p=0.05)	1.9	1.8	70.0

Table 2. Effect of slash treatment on height, stem diameter and stem volume at age 5 years (Sodong site)

Treatments	Height (m)	Stem diameter (cm)	Stem volume (m^3 ha^{-1})
BL_0	24.4	18.7	251.4
BL_1	24.6	19.2	245.2
BL_2	25.2	19.3	288.4
BL_3	25.3	19.7	284.3
CV (%)	3.1	3.4	5.8
LSD (p=0.05)	1.2	1.0	24.9

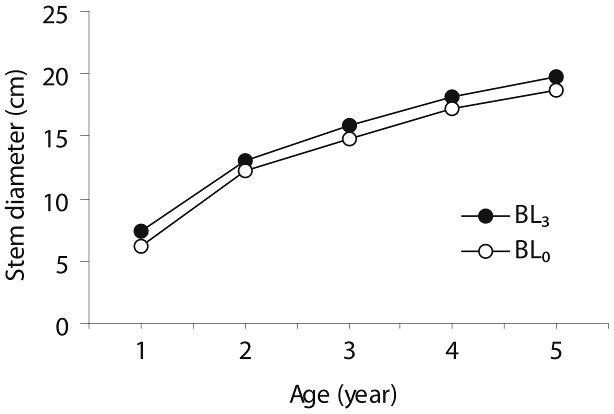

Figure 2. Stem diameter growth of *Acacia mangium* in Sodong

Biomass Development and Nutrient Uptake

Allometric relationships between stem diameter at breast height and biomass components at age 6 years (Toman) and age 5 years (Sodong) are shown in Table 3. Regression with pooled data from both sites gave similar results and there was no significant difference between sites for functions predicting each biomass component. However, the regression of each site was used for predicting biomass component of the respective site. Stem diameter is a reliable predictor of stem wood and bark mass. Regression between stem diameter and branch mass gave a moderate fit. Stem diameter was poorly correlated with leaf mass. Because of this leaf mass was estimated using the mean tree leaf biomass (n=16). For other components the regression equation in Table 3 was used. Estimated total biomass for Toman at age 6 years was 135.2 t ha^{-1}, and at Sodong at age 5 years it was 169.6 t ha^{-1}.

Accumulated amounts of total dry biomass and nutrients at both sites are shown in Fig. 3. The biomass steadily increased with increasing age. The accumulation N peaked at 4 years, while P and K peaked at 3 years. Calcium content continued to accumulate with increasing age, while Mg content increased up to 2-3 years and then fluctuated.

Annual rates of biomass and nutrient accumulation are presented in Fig. 4. At Sodong rates of biomass accumulation increased to age 3 years and then declined at years 4 and 5. At Toman rates increased to age 4 years and then declined sharply at age 5 and 6 years. At both sites, rates of all nutrient accumulation peaked between age 1 to 2 years and then continuously decreased. Thus nutrient accumulation rates for all nutrients, in general, peaked before the biomass accumulation rates reached the maximum rates.

Litterfall

Litterfall data from March 2002 to June 2006 (age from 14 to 66 months) are presented in Fig. 5. Litterfall was collected in BL_0 from March 2002 to April 2004 and this showed no difference between treatments. Litterfall production was high during September and October 2002 (a time of low rainfall) and also in December 2005 (low rainfall). During the first 3 years, litterfall consisted mainly of leaf, however from the year 2005 litterfall also contained branches (21.4%) and reproductive parts (7.5%). The annual litterfall and its nutrient contents are given in Table 4. The annual litterfall production was high, amounting to 10.6 t ha^{-1}.

Nutrient Retranslocation from Leaves

Foliar nutrient concentrations at three stages of life of leaves are shown in Table 5. As the leaves aged from green to senescence, the concentrations of N, P and K decreased, while those of Ca and Mg remained relatively the same. There were no significant differences in the concentrations of N, P, K, Ca and Mg between senesced and dead leaves (fresh litter). Differences in the content of N, P and K between live-green and senesced leaves indicates retranslocation of these elements. Effects due to slash treatments were small except for K and Ca where high slash retention increased the concentrations in live leaves. The percentage of nutrients retranslocated from green to senesced leaves is given in Table 6. Phosphorus was retranslocated in the highest proportion (83.5-86.3%), followed by K (34.8-38.5%) and N (33.0-33.6%).

The effect of slash management on soil organic C, total N and available P from age 1 to 5 years is given Fig. 6 (A,B,C). In general, a high level of slash retention increased soil C (Fig. 6A) and N (Fig. 6B) in the surface soil. Treatments had no effect at 10-20 cm. We found no significant changes in C and N at planting to age 5 years. However, there is a trend that the soil C and N

Table 3. Allometric relationships between stem diameter and biomass component at Toman and Sodong

Site	Regression equation between stem diameter and biomass component			
	Stem wood [(1)]	Bark	Branch[(2)]	Leaf
Toman	$Y = 0.0116\ x^{3.0294}$ $(R^2 = 0.91)$	$Y = 0.0104x^{2.4651}$ $(R^2 = 0.88)$	$Y = 0.0712\ x^{2.21179}$ $(R^2 = 0.65)$	$Y = 2.1195\ x^{0.515}$ $(R^2 = 0.16)$
Sodong	$Y = 0.0009\ x^{3.9677}$ $(R^2 = 0.95)$	$Y = 0.0022x^{2.9229}$ $(R^2 = 0.95)$	$Y = 0.0486\ x^{2.2592}$ $(R^2 = 0.71)$	$Y = 0.1204\ x^{1.448}$ $(R^2 = 0.45)$
Sites combined	$Y = 0.0034x^{3.4847}$ $(R^2 = 0.92)$	$Y = 0.0067x^{2.5571}$ $(R^2 = 0.89)$	$Y = 0.0541\ x^{2.2297}$ $(R^2 = 0.61)$	$Y = 0.4613\ x^{1.003}$ $(R^2 = 0.30)$

Y: dry weight of biomass component, x : stem diameter,

(1) diameter > 5 cm,

(2) including upper stem with diameter < 5 cm.

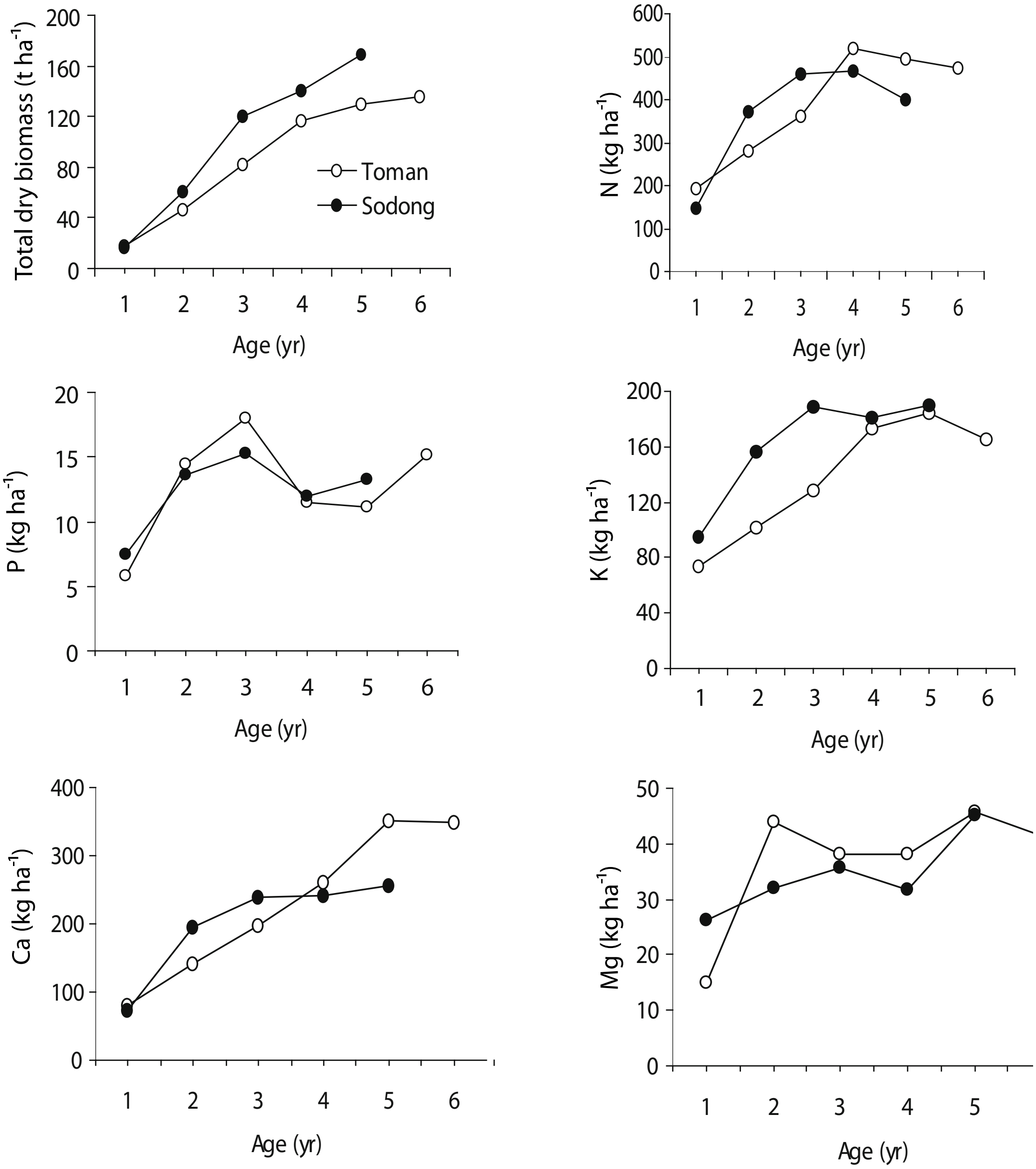

Figure 3. Accumulation of total dry biomass, N, P, K, Ca and Mg content of *Acacia mangium*

after an initial decline to age 3 years is gradually increasing in the surface soil.

There was no a significant effect of slash addition on extractable soil P. However, P in the surface soil decreased with increasing plantation age (Fig. 6C). Extractable P at age 5 years in the surface soil was 63.0-66.2% of what was measured at planting time. Soil P measurements had a high variation and this reduction was statistically not significant for BL_0 and BL_3 treatments.

Results for pH and exchangeable cations in the 0-10 cm soil 5 years after planting are shown in Table 7. Results at age 5 years alone are presented here since there was no clear change in the

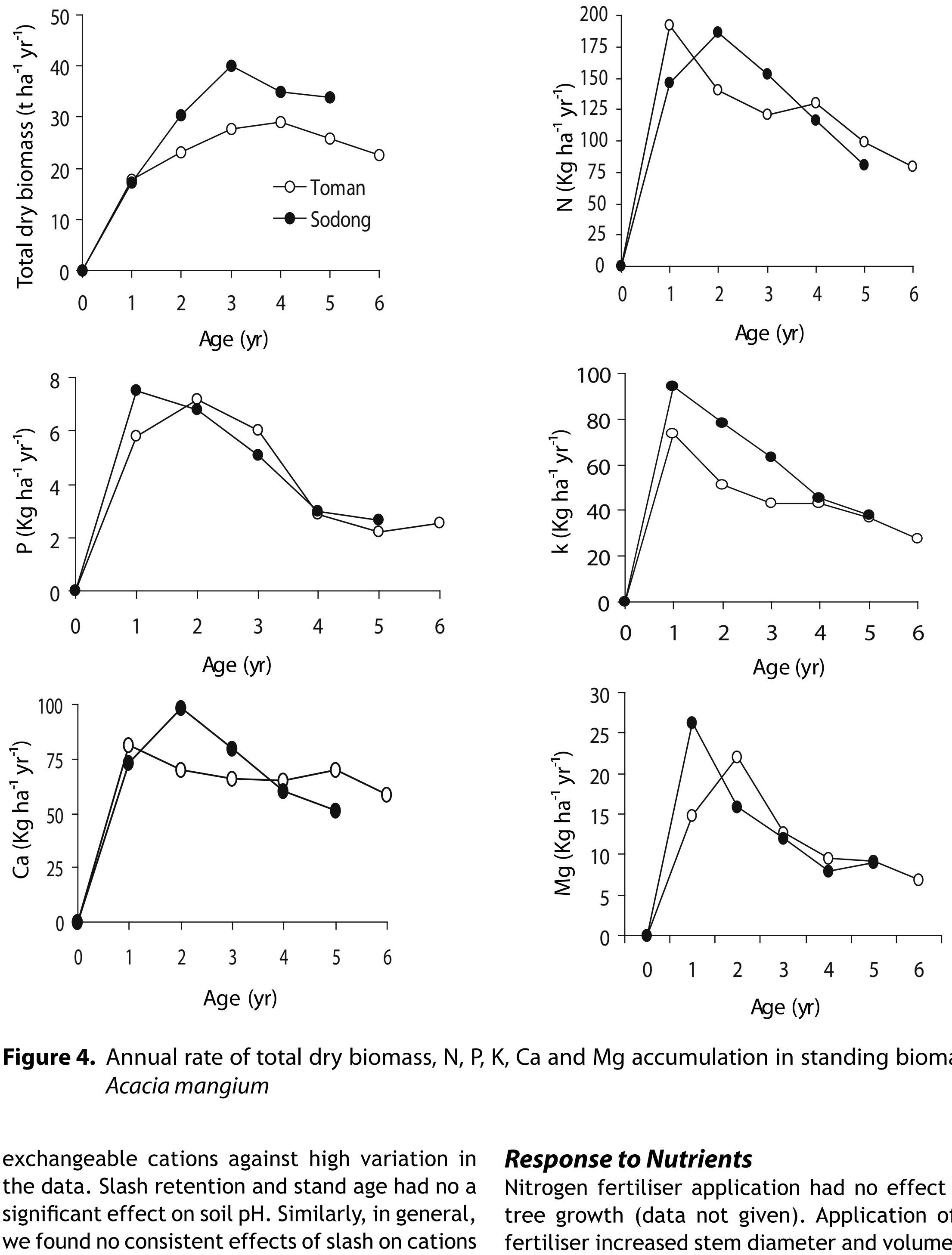

Figure 4. Annual rate of total dry biomass, N, P, K, Ca and Mg accumulation in standing biomass *Acacia mangium*

exchangeable cations against high variation in the data. Slash retention and stand age had no a significant effect on soil pH. Similarly, in general, we found no consistent effects of slash on cations but double slash retention tended to increase exchangeable Ca and Mg in the surface soil.

Response to Nutrients

Nitrogen fertiliser application had no effect on tree growth (data not given). Application of P fertiliser increased stem diameter and volume at age 4 years (significant at this age) and at age 5 years diameter values were 18.4, 18.8 and 18.9 cm for P0, P14 and P28 respectively. Corresponding

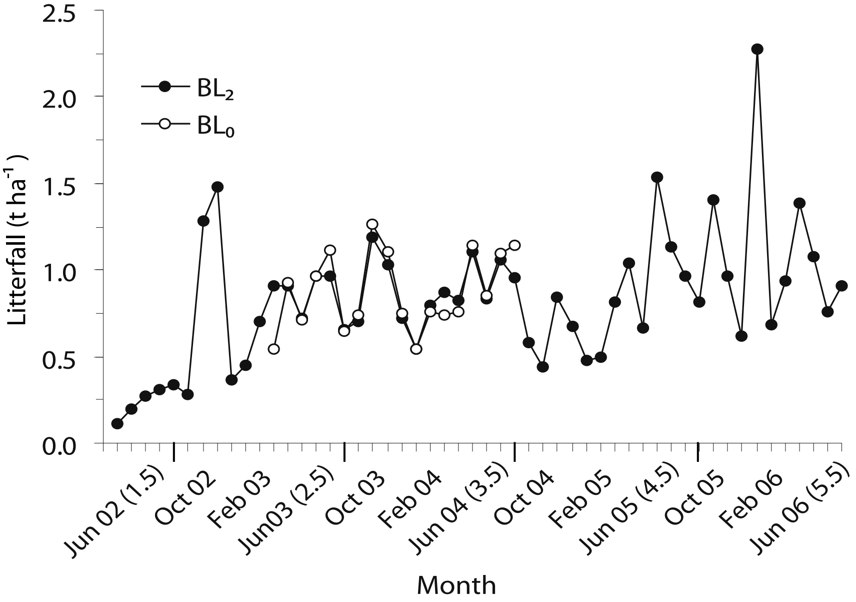

Figure 5. Litterfall production of *Acacia mangium*. The numbers in brackets are tree age in years indicated by long bars in the horizontal axis

Table 4. Annual litterfall mass and nutrient content in litter

Age	Quantity	Nutrient content (kg ha^{-1})				
(yr)	(t ha^{-1})	N	P	K	Ca	Mg
2-3	10.0	145.1	1.6	17.8	91.1	17.1
3-4	9.4	137.3	2.3	22.9	73.6	16.7
4-5	12.5	146.6	3.0	27.3	84.8	18.5
Mean	10.6	143.0	2.3	22.6	83.2	17.4

volumes were 191, 299 and 311 m^3 ha^{-1} However, this response was not statistically significant (Fig. 7). At age 5 years the addition of K and Ca fertilisers had no effect on diameter growth and hence data are not shown.

Discussion

Tree Growth and Nutrient Cycling

Retention of slash and litter accumulated by the previous crop during site preparation for the second crop increased tree growth at both sites, although at Toman the effect was statistically not significant (p=0.37) after 6 years. Nutrients in the slash and litter are shown in Table 8. Wood harvesting removed 7.8-12.2 kg P ha^{-1}, 73-91 kg K ha^{-1} and 267-357 kg Ca ha^{-1} from the site. These amounts are equivalent to 104-207% soil extractable P, 43-63% exchangeable K and 65-82% exchangeable Ca of the nutrient reserves in the soil (0-40 cm depth). Removing the slash from the site will further deplete high amounts of nutrients (5.0-13.3 kg P ha^{-1}, 118-143 kg K ha^{-1}, and 149-424 kg Ca ha^{-1}). The proportion of N loss due to removal of commercial wood was low, i.e. 4% of the nutrient content of soil in 0-40 cm (264-371 kg N ha^{-1}). Slash removal will cause a low proportion of N loss compared to the capacity of *A. mangium* to fix atmospheric N (Bouillet *et al.* 2008). In general, improvement and increase in the volume of wood harvested will lead to higher removal of nutrients from site. This needs to be recognised and managed.

Slash and litter of *A. mangium* decomposes relatively fast, within one year 55% of litter and 39% of twig were decomposed (Hardiyanto *et al.* 2004). This potentially releases 533-557 kg N ha^{-1}, 7.5-12.3 kg P ha^{-1}and 127-148 kg K ha^{-1}, 272-275 kg Ca ha^{-1}and 41-46 kg Mg ha^{-1}, depending on the site (Table 9). The high proportion of nutrient uptake can be partly met by the nutrient released from the slash and litter (Table 9). This supply would be augmented by the amounts available from nutrient retranslocation for new growth (Table 6). Current harvesting practice in the company removes wood (upper diameter >7 cm) with bark but retains slash on site. Debarking on site will certainly improve the nutrient reserve in the soil as bark contains high amounts of nutrients: 1390-1870 kg N ha^{-1}, 1.5 -1.8 kg P ha^{-1}, 31-36 kg K ha^{-1} and 164-175 kg Ca ha^{-1} (Table 8).

At the Toman site, the weight of slash excluding litter accounted for 50.7 t ha^{-1}, equivalent to 27% of the standing biomass of the harvested trees (Hardiyanto *et al.* 2000). At Sodong, slash weight was 61 t ha^{-1}, 25% of the standing biomass (Hardiyanto *et al.* 2004). In principle, retaining slash on site should help to conserve organic C in the soil in the long term, although data from this study points out the difficulty of demonstrating such effect (Fig. 6A). Given the short rotation harvesting cycle of *A. mangium* there may not be a net gain in soil carbon under this condition.

The peak nutrient demand by trees occurred between ages 1 and 2 years (Fig. 4). For example, at Sodong, the standing biomass of 1-year-old trees contained N 146.4, P 7.5, K 94.5 and Ca 72.9 kg ha^{-1}. The amount of nutrients in the fast-growing trees, an indicator of their nutrient demand, seemed high during the first three years of growth (Fig. 3). This high nutrient demand has to be met from the soil and decomposing litter, since the young trees (<1 year old) have little capacity to recycle nutrients although this pool becomes significant later.

Increased tree growth due to P fertilisation was maintained up to 4 years of age and less marked at age 5 years (Fig. 7) despite reapplication of P fertiliser at age 26 months (after canopy closure) and the general decline in soil available P with

Table 5. Foliar nutrient concentration of *A. mangium* at different stages of life span of leaves

Treatments	Leaf stage	Leaf mass (g leaf^{-1})	Nutrient concentration (%)				
			N	P	K	Ca	Mg
BL$_0$	Live-green	13.6	1.84 (0.05)	0.050 (0.002)	0.35 (0.03)	0.93 (0.10)	0.22 (0.01)
	Senesced	13.2	1.26 (0.01)	0.007 (0.001)	0.22 (0.03)	0.87 (0.11)	0.20 (0.02)
	Dead	11.3	1.38 (0.10)	0.010 (0.002)	0.15 (0.03)	0.89 (0.09)	0.20 (0.02)
BL$_3$	Live-green	12.1	1.89 (0.04)	0.056 (0.002)	0.55 (0.03)	1.38 (0.11)	0.20 (0.01)
	Senesced	12.4	1.28 (0.03)	0.009 (0.001)	0.35 (0.06)	1.34 (0.05)	0.19 (0.02)
	Dead	10.7	1.34 (0.04)	0.009 (0.001)	0.18 (0.03)	1.33 (0.06)	0.17 (0.02)

Numbers in brackets represents one standard error.

Table 6. Foliar nutrient retranslocation

Treatments	Leaf phase change	Nutrient retranslocation (%)				
		N	P	K	Ca	Mg
BL$_0$	Live to senescent	33.0	86.3	38.5	8.5	11.1
BL$_3$	Live to senescent	30.6	83.5	34.8	0.5	2.6

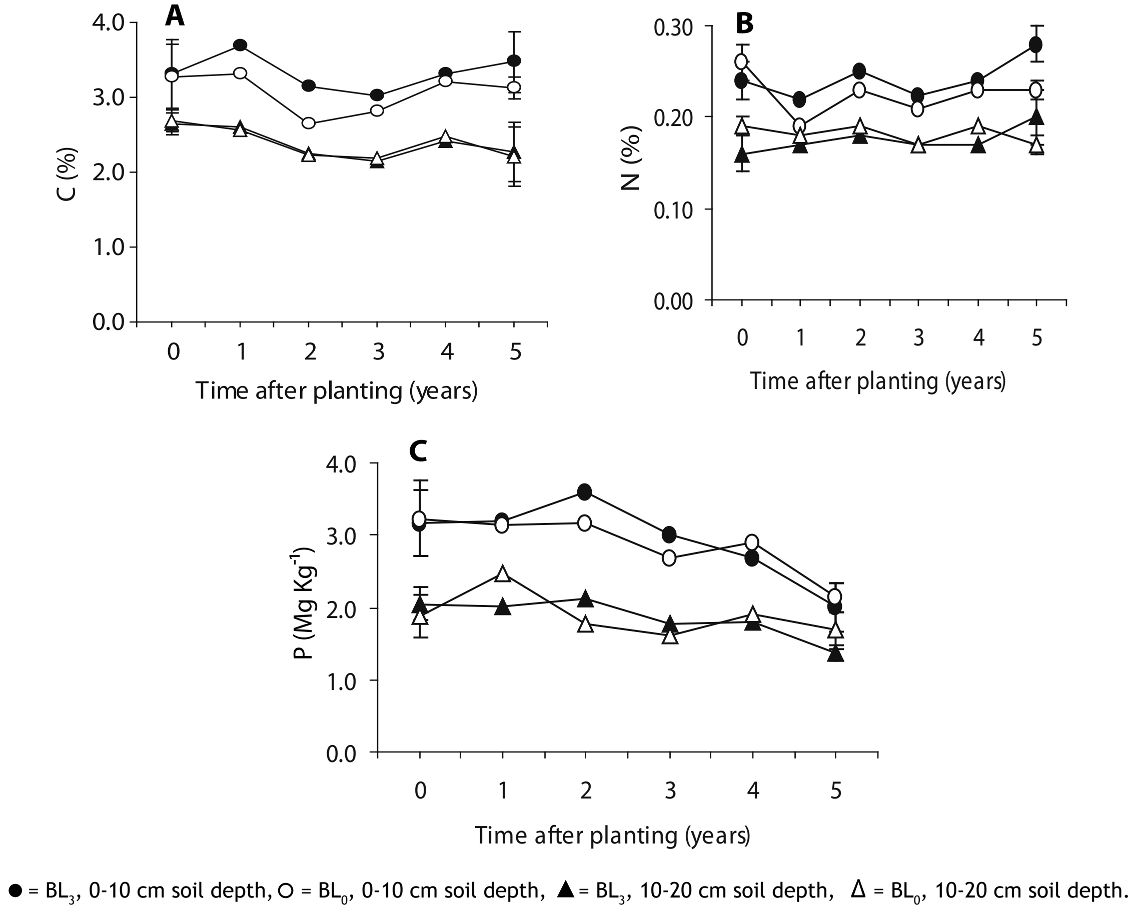

Figure 6. Effect of slash treatment and stand age on soil organic C, N and extractable P in Sodong

Table 7. Soil pH and exchangeable cations in 0-20 cm soil at planting and after 5 years

Soil properties	Year	BL$_0$		BL$_3$	
		0 – 10 cm	10 – 20 cm	0 – 10 cm	10 – 20 cm
pH	0	4.20 (0.04)	4.23 (0.03)	4.33 (0.06)	4.33 (0.09)
	5	4.20 (0.05)	4.30 (0.05)	4.25 (0.06)	4.30 (0.05)
K	0	0.11 (0.017)	0.09 (0.016)	0.13 (0.029)	0.09 (0.017)
	5	0.10 (0.008)	0.04 (0.003)	0.12 (0.004)	0.06 (0.018)
Ca	0	1.55 (0.57)	1.19 (0.49)	1.60 (0.37)	0.85 (0.06)
	5	1.30 (0.19)	0.70 (0.16)	2.27 (0.34)	0.82 (0.18)
Mg	0	0.39 (0.07)	0.31 (0.04)	0.48 (0.06)	0.25 (0.01)
	5	0.47 (0.02)	0.30 (0.03)	0.69 (0.08)	0.37 (0.04)

Numbers in brackets represents one standard error.

stand age (Fig. 6C). There is a possibility that the current rate of P application in operational practice is too low to have a significant effect on growth to the end of a rotation of 7-8 years. Trees would also meet their P demand from decomposing litter and from internal retranslocation, which is high for P (Table 6).

Exchangeable K in the soil (0-40 cm of soil depth) ranged from 116 to 213 kg ha^{-1} (Table 8) and K which could be released from the slash ranged from 143 to 182 kg ha^{-1} (Table 9). The amount of K in the standing biomass at age 5-6 years ranged from 166 to 190 kg ha^{-1} (Table 9) indicating the close link between K availability and uptake. The amounts of exchangeable K in the soil and slash seem to be able to support the K demand during peak growth period (Fig. 2). This observation along with the absence of response to K fertiliser suggests that there is no immediate risk of K deficiency in this environment. However, retention of slash and bark at the site may well be critical for K supply in the long term.

Changes in Soil Properties

At age 5 years, the reduction in extractable P in the surface soil, compared to initial amounts, was 1.2 to 1.3 kg ha^{-1}, while the amount of P accumulated in the tree amounted to 13.2 kg ha^{-1} (Table 10). This indicates that trees did not only take up P from the soil but also from other sources including decomposed slash and litter. The absence of sustained response to added P was also surprising considering the general view about P deficiency in these tropical soils.

A decline in available P over time in the *A. mangium* plantations has also been reported from Riau, Sumatra (Siregar *et al.* 2008) and Sabah, Malaysia (Nykvist 1997). Huong *et al.* (2008) found similar trend in *A. auriculiformis* stand in Vietnam. It is likely that the method of measuring P employed here and in other studies do not adequately represent the available fractions in soil. The addition of P in the form of fertiliser is a common practice in this region to increase plantation productivity. Retention of slash was inadequate to prevent the decline in extractable soil P (Fig. 6C). The response in tree growth to the addition of P underscores the importance of P fertiliser application. Despite the decline in available P and the positive response to P in early ages, the response has diminished with time. More detailed investigations on the dynamics soil P in these soils are warranted (Table 10). Despite the N-fixing ability of *A. mangium* no net increase in soil N has been found so far in this study.

Results on exchangeable cations were somewhat inconclusive partly due to high variation. However, slash retention seemed to increase the exchangeable Ca and Mg particularly in the surface soil similar to that reported in a *Eucalyptus globulus* plantation in south-western Australia (Grove *et al.* 2004).

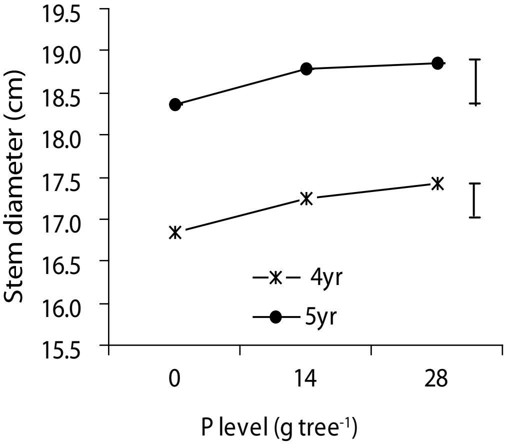

Figure 7. Effect of applied P fertiliser on stem diameter at age 4 and 5 years. Values of LSD 0.05 are shown as bars

Table 8. Nutrient contents in plantation components

Site	Description	Nutrient (kg ha^{-1})$^{(1)}$				
		Total	Extractable	Exchangeable		
		N	P	K	Ca	Mg
Toman	Soil	6600	7.5	116	411	198
	- stem wood (>10 cm)	236 (4)	7.8 (104)	37 (32)	103 (25)	12 (6)
	- bark	1390 (21)	1.5 (20)	36 (31)	164 (40)	6 (3)
	- slash	286 (4)	5.0 (67)	118 (102)	149 (36)	24 (12)
	- litter	271 (4)	2.5 (33)	30 (26)	123 (30)	22 (11)
	- understory	36 (0.5)	1.2 (16)	34 (29)	7 (2)	5 (2)
Sodong	Soil	9265	5.9	213	435	138
	- stem wood (>8 cm)	338 (4)	12.2 (207)	60 (28)	181 (42)	18 (13)
	- bark	1870 (20)	1.8 (30)	31 (14)	175 (40)	8 (6)
	- slash	438 (5)	10.8 (183)	117 (55)	225 (52)	32 (23)
	- litter	95 (1)	1.5 (25)	10 (5)	50 (11)	9 (6)
	- understory	36 (0.4)	1.0 (17)	15 (7)	7(2)	3(2)

Numbers in brackets are the nutrient expressed as percentage of nutrient amounts in the soil to a depth of 40 cm.
(1) Toman site from Hardiyanto *et al*. (2000) and Sodong site from Hardiyanto *et al.* (2004).

Table 9. Nutrient contents in slash and litter of the first rotation stand (1R) and nutrient accumulation by trees growing at the site in the second rotation (2R)

Site	Description	Nutrient (kg ha^{-1})				
		N	P	K	Ca	Mg
Toman	Nutrient in slash and litter (1R)	557	7.5	148	272	46
	Nutrient accumulation age 6 years (2R)	474	15.0	166	349	42
Sodong	Nutrient content in slash and litter (1R)	533	12.3	127	275	41
	Nutrient accumulation age 5 years (2R)	400	13.2	190	257	45

Table 10. The amount of extractable P in the soil surface layer (0-10 cm) and in the tree

Description	Amount of P (kg ha^{-1})
Soil at planting(1)	3.5 - 3.6
Soil 5 years after planting(1)	2.2 - 2.4
Standing tree at age 5 years(2)	13.2

(1) data from BL_0 and BL_3 treatment;
(2) from Fig. 3.

Table 11. Productivity in the first and second rotations of experimental plantations

Site	Rotation	Measured (yr)	Trees (stems) ha^{-1}		Height (m)	Diameter (cm)	Stem volume (m^3 ha^{-1})
			Initial	When measured			
Toman	First	9	1111	1382	22.0	17.7	228 (1)
	Second	6	1250	928	23.4	18.2	233 (2)
Sodong	First	10	1666	1966	24.0	14.1	262 (3)
	Second	5	1111	856	25.2	19.3	253 (4)

(1) Diameter >10cm, not singled (Hardiyanto *et al.* 2000).
(2) Diameter > 7 cm, singled.
(3) Diameter > 8 cm, not singled (Hardiyanto *et al.* 2004).
(4) Diameter > 7 cm, singled.

Table 12. Tree growth in the experimental stand and plantation area in Sodong at age 5 years

Unit	Height (m)		Stem diameter (cm)		Stem volume
	Range	Mean	Range	Mean	(m^3 ha^{-1})
Experiment	21.2 - 28.7	25.2	8.9 - 31.2	19.3	288
Plantation area	14.5 - 25.8	20.5	5.7 - 35.6	17.8	201

Productivity of Successive Crops

Wood yields of the second rotation stands at the experimental sites were higher than those at the first rotation (Table 11). Interpretation of this must be made with caution as it is difficult to make a strict comparison of yield across rotations as many variables which determine productivity change with time. Nevertheless, the productivity of the second rotation plantation at the experimental site is likely to be higher at the end of rotation (7-8 years) than shown in Table 11 as trees continue to grow beyond 5 or 6 years of age (Fig. 2 and 3). This result suggests productivity of second rotation plantations is not declining and in fact is increasing.

The company is committed to increasing and sustaining productivity of its plantations. Results of this study have provided evidence that the current operational practice of retention of harvest residues and litter (minimum site disturbance) is well founded and should be continued. Retention of bark on site is also desirable and this option is under consideration. This study also provided skills and methods to estimate some key parameters useful for management decisions. These include: (1) assessments of impacts of various harvesting and site management practices on site nutrient capital and depletion in relation to management practices, and (2) estimation of nutrient uptake rates for fast growing stands in relation to targeted growth rates. This information can be used with further work to devise improved fertiliser applications.

Company management has used results of the nutrition study for developing a fertiliser prescription at an operational scale. However, the current prescription is too general for a wide range of sites. The project provided the best evidence so far that productivity of the second rotation plantation is not declining, but can be maintained or even increased providing appropriate management practices are implemented. This is illustrated in Table 12. Productivity in the experimental plot was much higher (23% in height, 8% in stem diameter and 43% in stem volume) than in the plantation areas at the same age. In addition, trees in experiments were more uniform in size than those in general plantations. These results pose challenges to technology transfer and adoption of research outputs on a larger scale.

This project has demonstrated what can be achieved and has been of value for training managers and technical staff, and informing senior managers about the value of investment in sound research as a basis for sustainable forestry.

Conclusions

- Slash retention improved tree growth on the Ultisol soil of the experimental sites and conserved nutrients.
- Debarking on site would increase further the nutrient reserves in the soil.
- High slash retention increased soil organic C and N in the surface soil three years after planting.
- Five years after planting extractable P was lower than at pre-planting.
- Soil pH did not change during the experiment.
- Changes in exchangeable cations were inconclusive due to high variation.
- Highest nutrient demand occurred during the first two years after planting, suggesting the importance of early inputs in the form of fertiliser to achieve high plantation productivity.
- Growth response to P fertiliser application diminished with time despite declining soil available P.
- Application of lime and N and K fertilisers did not have positive response on growth.
- Wood volume growth of the second rotation crop was higher than in the first rotation plantation.

Acknowledgements

We wish to express our sincere gratitude to the management of PT Musi Hutan Persada for their commitment to this site management and productivity study. We also acknowledge the Center for International Forestry Research for arranging and sponsoring the workshop. Our special thanks are extended to Dr. Sadanandan Nambiar of CSIRO Forestry and Forest Products for his valuable advice throughout this project and helpful comments on the manuscript.

References

Arisman, H. and Hardiyanto, E.B. 2006. *Acacia mangium* – a historical perspective of its cultivation. *In*: Potter, K., Rimbawanto, A. and Beadle, C. (eds.) Heart rot and root rot in tropical *Acacia* plantations, 11-15. ACIAR Proceedings No. 124. Australian Centre for International Agriculture Research, Canberra.

Bouillet, J.P., Laclau, J.P., Goncalves, J.L.M., Moreira, M.Z., Trivelin, P., Jourdan, C. and Galiana, A. 2008. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 157-172. Center for International Forestry Research, Bogor, Indonesia.

Grove, T.S., Mendham, D.S., O'Connell, A.M. and Rance, S.J. 2004. Soil nutrient supply and nutrient uptake in *Eucalyptus globulus* plantations in south-western Australia: impacts of inter-rotation site management. Paper presented at the Sixth Workshop on Site Management and Productivity in Tropical Plantation Forests, 22-26 November 2004, Piracicaba, Brazil. 18p.

Hardiyanto, E.B., Ryantoko, A. and Anshori, S. 2000. Effects of site management in *Acacia mangium* plantations at PT. Musi Hutan Persada. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 41-50. Center for International Forestry Research, Bogor, Indonesia.

Hardiyanto, E.B., Anshori, S. and Sulistyono, D. 2004. Early results of site management in *Acacia mangium* plantations at PT. Musi Hutan Persada, South Sumatra, Indonesia. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 93-108. Center for International Forestry Research, Bogor, Indonesia.

Huong, V.D., Quang, L.T., Binh, N.T. and Dung, P.T. 2008. Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 123-138. Center for International Forestry Research, Bogor, Indonesia.

Mackensen, J. and Folster. H. 1999. Study on sustainable nutrient supply in fast growing plantations. Ecological and economic implications in East Kalimantan, Indonesia. Deutsche Gesellscafft fur Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany. 62p.

Nambiar, E.K.S. and Brown, A.G. 1997. Towards sustained productivity of tropical plantations: Science and Practice. *In:* Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests, 527-557. ACIAR Monograph No. 43. Australian Centre for International Agriculture Research, Canberra.

Nambiar, E.K.S. and Fife, D.N. 1991. Nutrient retranslocation in temperate conifers. Tree Physiology 9:185-207.

Nykvist, N. 1997. Uptake nutrients in a plantation of *Acacia mangium* in relation to decrease in soil amounts. Journal of Sustainable Forestry 4:131-139.

Saur, E., Nambiar, E.K.S. and Fife, D.N. 2000. Foliar nutrient retranslocation in *Eucalyptus globulus*. Tree Physiology 20:1105-1112.

Siregar, S.T.H., Nurwahyudi and Mulawarman. 2008. Effects of inter-rotation management on site productivity of *Acacia mangium* in Riau, Sumatra, Indonesia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 93-106. Center for International Forestry Research, Bogor, Indonesia.

Soil Survey Staff. 1992. Keys to soil taxonomy. SMSS Technical Monograph No. 19. 5th ed. Pocahontas Press, Blacksburg, Virginia, USA. 541p.

Site Management and Productivity of *Acacia auriculiformis* Plantations in South Vietnam

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Abstract

This paper describes the effects of slash management on stand productivity and soil properties up to age four years in *Acacia auriculiformis*. Results of additional studies on vegetation and nutrient management on tree growth are also reported. Retention of slash improved volume growth by 7-10% depending on the amount of slash retained. Slash retention and stand growth increased nitrogen and organic carbon in the surface soil. However, Bray-1 extractable phosphorus declined progressively up to at age three years regardless of the nature of slash management. There were no significant changes in pH. Exchangeable potassium, calcium and magnesium declined after three years. Vegetation control improved plantation productivity significantly. Strip weed control increased volume by 52%, compared to no vegetation control. Greater intensity of vegetation control did not further increase growth. Addition of phosphorus increased stem diameter growth by more than 8%. Overall productivity of the second rotation crop was substantially higher compared to the first rotation stand. Retention of harvesting slash, vegetation management and nutrient addition will be recommended for planting practices to ensure sustainable productivity of *A. auriculiformis* plantations in South Vietnam.

Introduction

The Government of Vietnam has embarked upon a five million hectare afforestation program to increase forest cover of the country by 2010. According to this program (1998-2010), there will be 1 920 000 ha of protection forest, and 3 million ha for productive plantations requiring the forest sector to plant 260 000-400 000 ha annually (Nguyen Duong Tai 2002). Fast-growing trees were selected for this program, and *Acacia auriculiformis* A. Cunn. ex Benth. has become an important plantation species because of high potential yields, especially in southern provinces. Areas under *Acacia* plantations will be increased by 10 000-15 000 ha yr^{-1} (Nguyen Hoang Nghia and Le Dinh Kha 1998). Currently, *Acacia* and *Eucalyptus* plantations account for at least 576 000 ha (General Statistic Office 2005) and represent about 46% of tree plantations (Nguyen Huy Son and Dang Thinh Trieu 2004).

Productivity of *Acacia* species in northern Vietnam is lower than that in the southern regions (Nguyen Hoang Nghia and Le Dinh Kha 1998). Plantations of *A. mangium* in the north have a mean annual height increment (MAI) of 2 m yr^{-1} and diameter increment of 2.5 cm yr^{-1}, in the south the corresponding rates are 2.5 m yr^{-1} for height and more than 3.0 cm yr^{-1} for diameter. *Acacia auriculiformis* has good growth potential in commercial plantation in the south with 2.4-2.8 m yr^{-1} for height and 2.5-2.8 cm yr^{-1} for diameter. Growth rates of this species are slow on dry and poor sites, such as in parts of Vinh Phu, Quang Tri and Binh Thuan provinces (Do Dinh Sam 2001).

Productivity of intensively managed plantations of *Acacia* hybrid at age 7-8 years is dependent on soil types (Nguyen Huy Son 2006). Mean annual increments on Orthic Acrisols in Bau Bang (Binh

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Duong Province) is 36-40 m^3 $ha^{-1}yr^{-1}$, on Orthic Ferralsols in Konch'ro (Gia Lai Province) 25 m^3 $ha^{-1}yr^{-1}$, on Rhodic Ferralsols soil in Dong Ha (Quang Tri Province) and Dong Hy (Thai Nguyen Province) were 32 m^3 $ha^{-1}yr^{-1}$ and 25-30 m^3 $ha^{-1}yr^{-1}$ respectively.

Plantation productivity varies considerably depending on the characteristics of site including soil fertility, slope, terrain, soil depth, vegetation, climate and management. Research for industrial plantation establishment has so far been concentrated on tree improvement to identify highly productive species and provenances. Much less effort has been directed to studies on soil productivity and site management. High and sustainable productivity is essential for economically viable plantations that meet private and public sector needs.

Inter-rotation site management, such as soil preparation, weeding, and water and nutrient supply, can influence forest plantation productivity (e.g. Nambiar and Brown 1997, Hardiyanto *et al.* 2004). Productivity increases have been achieved by matching genotypes to site quality together with optimal soil cultivation, harvest residue management, fertiliser application and weed control (Goncalves *et al.* 2004).

Few studies have been carried out in Vietnam to understand and manage sustainable productivity of *A. auriculiformis* plantations, although the scale of planting is increasing rapidly. There is little local research capacity so international cooperation and assistance to obtain information is important for Vietnam's forestry sector. The Forest Science Sub-Institute of South Vietnam has implemented this long-term research on *A. auriculiformis* as a part of an international network project 'Site Management and Productivity in Tropical Plantation Forests' coordinated by the Center for International Forestry Research (CIFOR).

Experimental details and the overall experimental approach have been reported by Vu Dinh Huong *et al.* (2004). Some details are repeated here to provide context for this paper that focuses on tree growth, soil changes and nutrient cycling after four years.

Objectives

Overall objectives and approach of the CIFOR network project have been described by Tiarks *et al.* (1998) and Nambiar (1999).

In this project we aim to develop management practices for increased and sustained production of *A. auriculiformis* plantations in South Vietnam. Focus is on key variables that come in to play during inter-rotation management. They include impacts of harvesting and site management practices on soil and productivity of the next crop; and the effect on tree growth of vegetation management and fertiliser application during early establishment.

A specific goal is to develop an information system for *A. auriculiformis* plantations grown and harvested with different slash and litter management practices. Research aims to provide information on:

- amount of biomass and nutrient store at the site;
- nutrient pools in the soil and the nature of their availability;
- nutrient (nitrogen (N), carbon (C), phosphorus (P), potassium (K), calcium (C) and magnesium (Mg) content in biomass and soil so that impact of harvest and site management on site nutrient capital can be estimated; and
- site conditions and climatic factors.

Results will be used to determine: (1) changes of forest productivity and site conditions under different soil and organic matter conservation treatments, (2) optimum vegetation (weed) management regimes for maximum tree production, and (3) response to fertiliser application at planting. Based on these and other results, we plan to prepare guidelines and options for site management of *A. auriculiformis* plantations and communicate them to forest managers through reports and field demonstrations.

Experimental Details

Study Site

The site is located at Phu Binh Experimental Station of the Forest Science Sub-Institute of South Vietnam, Vinh Hoa Commune, Phu Giao District, Binh Duong Province, (latitude 11°18'87"N, longitude 106°52'68"E, and altitude about 80 m.

Climate

The region has a mean annual temperature of 27°C. Humidity is commonly above 60% with small seasonal variations. Mean annual rainfall is about 2500 mm (range 2250-2750 mm), and annual evaporation is more than 900 mm. Rainy months are May to November, and the dry months are December to April.

Soil

Vu Dinh Huong *et al.* (2004) described the soil type in detail. Site geomorphology is common to that in the south-eastern South Vietnam. The experimental area is relatively flat with slopes of 1-3° and a southerly aspect. Soil type is a Chromic Acrisol derived from common schist parent material.

Soil profile in the slash management study area is:

A horizon (0-19 cm) of greyish brown yellow (10 yr6/2) sandy clay loam;
BA horizon (19-45 cm) of greyish brown yellow (10 yr6/2), sandy clay;
B horizon (45-120 cm) of dull yellowish brown (10 yr5/4), sandy clay.

Soil profile in the vegetation management and nutrient management study area is:

A horizon (0-16 cm) of brownish grey (10 yr4/1), sandy clay;
BA horizon (16-38 cm) of grey yellow brown (10 yr4/2), sandy clay;
Bt horizon (38-54 cm) greyish yellow brown (10 yr5/2), sandy clay, gravel 1- 2%, colour boundary between layers changes slightly,
B horizon (54-120 cm) with dull yellowish brown (10 yr5/3), clay, sandy, high laterite occupied 60-70%.

First Rotation Stand

Degraded native remnant vegetation on the site was cut and burnt, and the site ploughed before establishing the first rotation plantation of *A. auriculiformis* in 1995. Tree spacing was 3 m x 4 m (833 trees ha^{-1}). The stand was weeded by hand and ploughed periodically between rows to control vegetation and reduce fire risk.

The understorey vegetation was high, dense and dominated by *Bauhinia cardinale, Cratoxylon formosum, Imperata cylindrica, Memecylon* sp. and *Panicum maximum*. Litter and understorey components totalled 8.1 t ha^{-1}including understorey (37.3%), branches (21.5%), leaves (17%), wood (16.1%) and pods (8.1%). Growth details of the stand are described in Vu Dinh Huong *et al.* (2004).

Experiments and Design

The second rotation *A. auriculiformis* plantation was established in July 2002 with seedlings raised from seed collected in a seed orchard in Dong Nai province. Trees were planted manually at a spacing of 3 m x 2 m (1666 trees ha^{-1}) and fertiliser applied at planting. Weeds were controlled in the first two years by spraying herbicides as required.

Slash Management

These are basically the same as for CIFOR network project (Tiarks *et al.* 1998) and described by Vu Dinh Huong *et al.* (2003). The experimental design was a randomised complete block with three treatments and five replications. Each of the 15 plots was 1152 m^2 (12 rows x 16 trees/row) comprising a measured area of 8 rows x 12 trees/row and a buffer area. The treatments are:

BL$_0$ All aboveground biomass including the crop trees, understorey and litter removed.
BL$_2$ Single slash. Stem wood with bark harvested, all other slash residue left in plots with minimum disturbance.
BL$_3$ Double slash. The same as BL$_2$ but slash from BL$_0$ plots was brought in and distributed evenly over the slash already present.
Biomass Plot (BP): An additional area of consisting 1250 trees was set up for sequential biomass harvest. This area was treated as in BL$_2$.

Vegetation Management

This experimental area was managed as in BL_2 treatment. Experimental design is a randomised complete block with four treatments and four replicates. Each of the 16 plots is 780 m^2 (10 rows x 13 trees/row) consisting of measured area of 324 m^2 (6 rows x 9 trees/row) and buffer area. The treatments are:

Control (C_1) Pre-planting herbicide applied once.

Strip weed control (C_2) Pre-planting herbicide plus post-planting application, 1.5 m wide spray (spanning 0.75 m on both sides of tree rows), twice per year to age 3 years of the stand.

Complete – 1 (C_3) Pre-planting herbicide plus post-planting application sprayed in full plot area once per year.

Complete – 2 (C_4) Pre-planting herbicide plus post-planting application, sprayed in full plot area, twice per year.

Nutrient Management

This experimental area was managed as in BL_2. Each plot is 432 m^2 (8 rows x 9 trees/row) consisting of measured area of 252 m^2 (6 rows x 7 trees/row) and buffer area. The design was a randomised complete block with five treatments and four replications. The treatments are:

Nil	No fertiliser applied.
C	A fertiliser mixture (N16-P16- K8) at 50 g $tree^{-1}$ to give 8 g N, 8 g P, 4 g K. (current practice).
P_1	Current practice plus superphosphate (7.2% P) at 100 g fertiliser $tree^{-1}$ to give 7.2 g P.
P_2	Current practice plus superphosphate (7.2% P) at 200 g fertiliser $tree^{-1}$ to give 14.4 g P at planting. Two years after planting a second application of superphosphate (7.2% P) at 300 g fertiliser $tree^{-1}$, applied in a circle, radius 50 cm, around the base of the tree.
Ca	Current practice plus calcium 500 kg $Ca(OH)_2$ ha^{-1} (270 kg Ca) broadcast on soil surface.

Phosphorus fertiliser was placed in the planting hole, while NPK fertiliser was placed in a furrow about 10 cm away from the seedling.

Methods

Tree Growth

Tree height and diameter were measured every six months. Height of all trees in the plots was measured up to age 3 years, and subsequently the height (to the top of crown) of 25 trees selected at random per plot. Analysis of height data at age 3 years showed that this method gave similar mean plot height compared to the measurement all trees. At age 4 years, stem volume over bark to 3 cm diameter top end was calculated by using the equation:

$$V= 0.0006X^{2.0024} \quad (R=0.94)$$

Stem volume underbark to 3 cm diameter top end was calculated by using the equation:

$$V= 0.0004X^{2.0763} \quad (R=0.96)$$

where V is stem volume and X is diameter at breast height.

Biomass Development and Nutrient Uptake

Trees were harvested annually (30 trees at age 1 year and 15 trees from age 2 years onwards) for biomass sampling. They were selected to represent the range of diameter classes.

After felling the trees, stem diameter at breast height and tree length up to the top-end diameter of 3 cm were measured. Each tree was divided into three equal length sections; stem wood and bark in each section were weighed and samples were taken for dry mass determination. Fresh weight of branch and foliage were determined and subsamples were dried and weighed. Samples were oven-dried at 76°C to a constant weight. Allometric relationships between stem diameter and biomass components were developed using the model: $Y= a X^b$ where Y is dry weight biomass and X is stem diameter, a and b are coefficients. The regression equations for each biomass component were then used to estimate biomass. The biomass components of six trees were used for nutrient analysis. Nutrient concentrations in the sample were multiplied by the estimated biomass to calculate nutrient uptake by the stand.

Litterfall

Litterfall in the *A. auriculiformis* plantation was collected in litter traps located in the five BL_2 plots in the slash management study. Litter traps were made of plastic pipe frames (1 m^2 suspended with nylon-net 30 cm above the soil surface. There were five traps per plot. Litter was collected every 2 weeks for 3 years (November 2003 to November 2006). Collections were dried at 76°C for 24 hours, and separated into leaf, twigs and other components. Dry weight of each component was determined separately. The litterfall per ha was calculated from this data.

Seasonal Growth of Stem Diameter

In each BL_2 plot, 15 trees were selected representing the range of diameter classes. Diameter of these trees was measured every 2 weeks for 18 months (April 2004 to November 2006).

Plant Analysis

Biomass components (see above) were dried at 70°C, ground and used for analysis. Samples were digested with concentrated sulphuric acid and 30% hydrogen peroxide (Lowther 1980) and all nutrients were measured in the same digest. Nutrients were measured using following methods: N– Kjeldahl; P- spectrophotometer; K- flame photometer; and Ca and Mg- atomic absorption spectrometer.

Soil Sampling and Analysis

Soil sampling

Soil samples were collected in July 2002 before treatment application and at the same time in subsequent years. Soil cores were taken from five points in each plot from four soil depths: 0-10 cm, 10-20 cm, 20-30 cm and 30-50 cm. Samples of the same depth were bulked to obtain composite samples, one for each soil depth. From each composite sample, two subsamples of 1.0 kg were air-dried for about seven days and stored for analysis.

Soil analysis

Chemical analysis was carried out on soil fraction less than 2 mm. Methods used were (van Reewijk 1995*)*:

- organic carbon, Walkley- Black procedure;
- total N, by sulphuric acid- selenium mixture digestion and hydrogen peroxide 30% and Kjeldahl;
- pH in 1:2.5 water suspension;
- bulk density was determined using undisturbed soil cores of known volume obtained from one point in each plot at 0-10, 10-20, 20-30 and 30-50 cm depths. Samples were oven dried at 105°C to obtain oven-dry weight;
- available P- Bray No. 1 (NH_4 1M and HCl 0.5M); and
- CEC - percolation with NH_4Cl 1M solution.

Results

Tree Growth in Response to Slash Management

At age four years, the tree survival was high with no effect of treatments (Table 1). Slash management had no effect on height growth: mean heights were 3.8 m, 8.2 m, 11.3 m and 14.1 m for ages 1, 2, 3 and 4 years, respectively. Residue retention increased tree diameter one year after planting and the difference between slash and no slash treatments increased to age 4 years (Table 1). Slash retention (BL_3) increased under bark stem volume by 9%.

Table 1. Effects of slash treatments on stand growth at age 4 years

Treatments	Height	Diameter	Volume (m^3 ha^{-1})		Survival
	(m)	(cm)	Over bark	Under bark	(%)
BL_0	13.9	11.1	116.0	92.8	95.4
BL_2	14.2	11.4	124.1	99.4	94.2
BL_3	14.3	11.6	127.3	102.1	96.0
p-value	0.45	0.01	0.02	0.03	0.63
LSD (*p*=0.05)	0.7	0.3	7.6	6.3	4.4

Tree Growth Response to Vegetation Management

Vegetation management affected tree survival and stand growth (Table 2). Lowest survival rate (83%) was in the control and the highest (96 %) under full weed control with spraying herbicide once per year (C_3). Lowest height growth was also in the control (11.9 m) and the highest (13.9 m) under full weed control by spraying herbicide twice per year (C_4). Vegetation control increased stem diameter growth from planting to age 4 years (Fig. 1).There was no additional growth response to herbicide application beyond the 1.5 m strips spanning the tree rows (Table 2).

Although vegetation control improved growth rate, it also increased the number of double leaders at age 3.5 years (Table 2). The percentage of trees with double leaders was 2.3% in the control compared to16.2% in full weed control.

A dense understorey of herbaceous and woody plants developed and reached nearly 2 m in height if vegetation was not controlled after planting. Dense, herbaceous vegetation developed in the middle 1.5 m area of the strip control plot. An understorey consisting mostly of grasses developed after three years in full control plots.

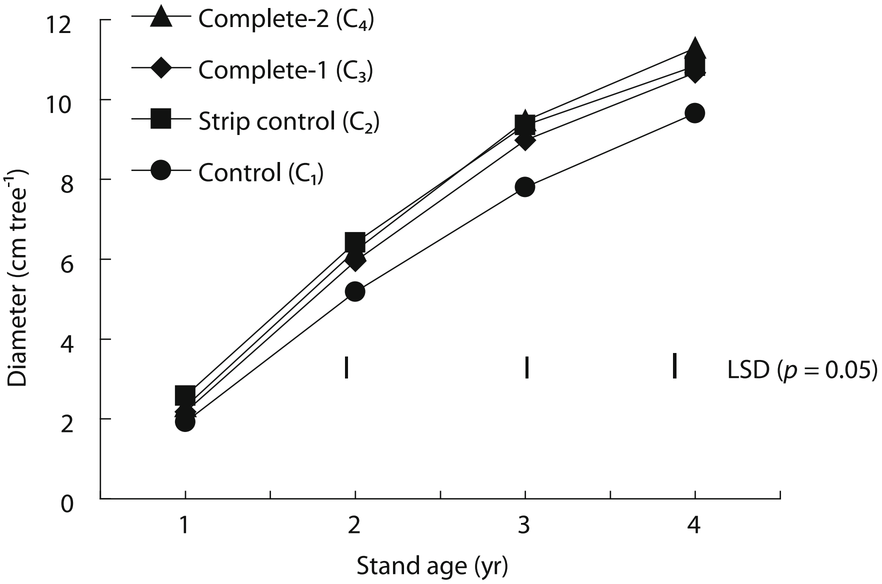

Figure 1. Effects of vegetation management on stem diameter (DBH) growth of trees from planting to age 4 years

Table 2. Effects of vegetation management on stand growth at age 4 years and stem form at age 3.5 years

Treatments	Height	Diameter	Volume (m^3 ha^{-1})		Double leader trees	Survival
	(m)	(cm)	Over bark	Under bark	(%)	(%)
Control (C_1)	11.9	9.7	78.4	62.2	2.3	83.3
Strip control (C_2)	13.6	10.8	119.7	95.9	9.7	93.5
Complete-1 (C_3)	13.5	10.7	113.4	90.7	12.9	95.8
Complete-2 (C_4)	13.9	11.3	127.2	102.1	16.2	94.9
p-value	0.003	0.03	<0.001	<0.001	<0.001	0.002
LSD (*p*=0.05)	0.9	0.66	11.5	9.5	6.2	5.7

Tree Growth in Response to Nutrient Management

Effects on height growth of adding P and Ca were small. Mean tree heights were 3.3 m, 6.9 m, 10.2 m and 13.7 m for ages 1, 2, 3 and 4 years respectively. Adding additional phosphorus (P_2) increased stem diameter by 8% and volume by 14% compared to nil treatment at age 4 years (Table 3).

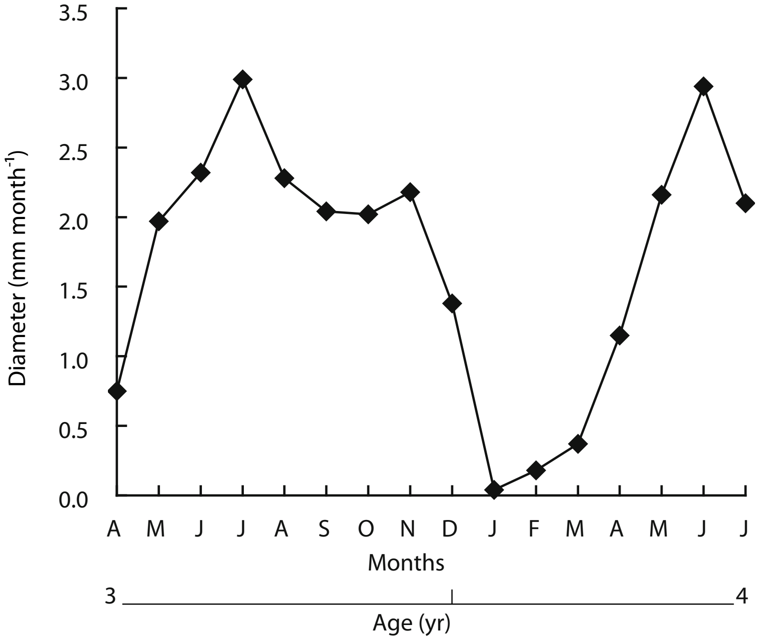

Figure 2. Seasonal variation in diameter growth of *A. auriculiformis* plantation between age 3 and 4 years

Table 3. Effects of nutrient management on tree growth, survival and stand volume at age 4 years

Treatments	Tree height	Diameter	Volume (m^3 ha^{-1})		Survival
	(m)	(cm)	Over bark	Under bark	(%)
Nil	13.2	11.2	121.6	97.4	96.9
Current practice	13.7	11.5	126.7	101.6	91.7
P_1	13.9	11.8	139.5	111.9	97.6
P_2	14.2	12.1	141.7	114.0	97.6
Ca	13.6	11.6	125.6	100.7	94.4
P-value	0.53	0.02	0.11	0.10	0.30
LSD (*p*=0.05)	1.2	0.5	18.0	14.7	7.1

Table 4. Nutrient content in litterfall from age 2 to 4 years

Age (yr)	Litterfall	Nutrient (kg ha^{-1} yr^{-1})				
	(t ha^{-1} yr^{-1})	N	P	K	Ca	Mg
2 - 3	6.7	85.8	2.2	30.4	5.6	4.8
3 - 4	6.2	80.3	2.1	28.4	5.2	4.5

Seasonal Variation in Stem Diameter Growth

Stem diameter growth of trees was highly seasonal. Diameter increments were highest during rainy months (e.g. 3 mm per month in July) and decreased in the dry season with almost no growth during January.

Litterfall

There was a strong seasonal pattern in litterfall (Fig. 3). It was minimum during June and July, coinciding with the rainy season, and maximum during the dry months of January and February. This pattern was opposite to that observed for stem diameter growth. The annual amounts of nutrients in litterfall for two consecutive years between the ages 2 and 4 years are shown in Table 4.

Biomass and Nutrient Uptake

- Allometric relationships between stem diameter at breast height (DBH) and biomass components were established from age 1 to 4 years. At age 4 years, DBH had good correlation with stem wood ($Y = 0.2085X^{2.0919}$, R = 0.90) and stem with bark ($Y = 0.2669X^{2.3066}$, R = 0.88). These equations were used to predict the biomass components. However, regression between DBH and branches and DBH and leaves was moderate with R = 0.64 and R = 0.79, respectively. Because of this, branches and leaf mass were estimated by using the mean tree biomass (n=15) and scaling up to plot data.

Net accumulation of biomass in tree components from age 1 to 4 years is shown in Fig. 4. After 4 years, total biomass was 86.1 (t ha^{-1}) in which stem wood contributed 76%, branches 17% and leaves 7%. Total annual rates of nutrient uptake from planting to age 3 years are presented in Table 5. Results show that the highest rates of uptake for all nutrients were between 1-2 years. The rates declined substantially for all elements, except K, during the next year (age 2-3 years) although the rates of biomass accumulation were about the same for the two periods (Table 5). In general these results point to the need for high nutrient supply to the tree to achieve fast growth rates. However, it should be noted that rates in Table 3 are estimated using the biomass and nutrients

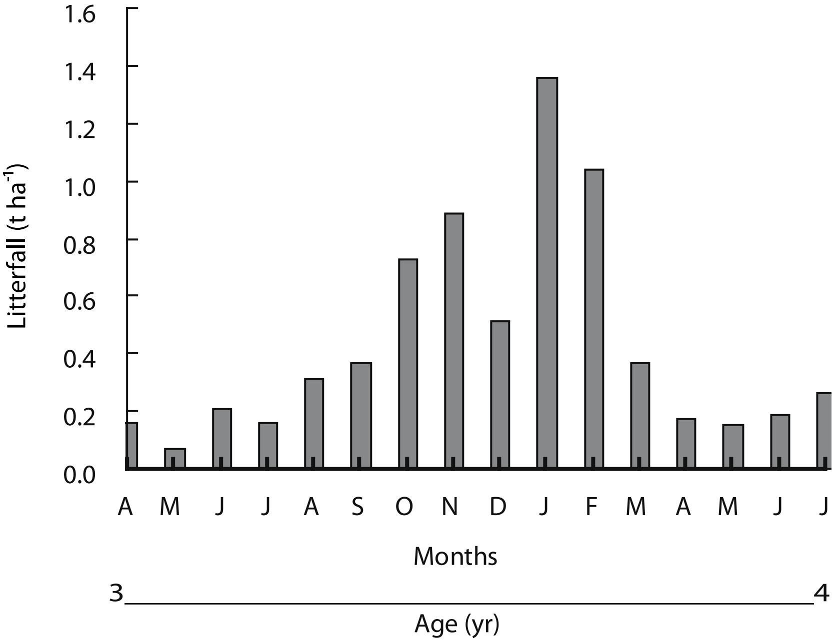

Figure 3. Litterfall production of *A. auriculiformis* plantation from age 3 to 4 years

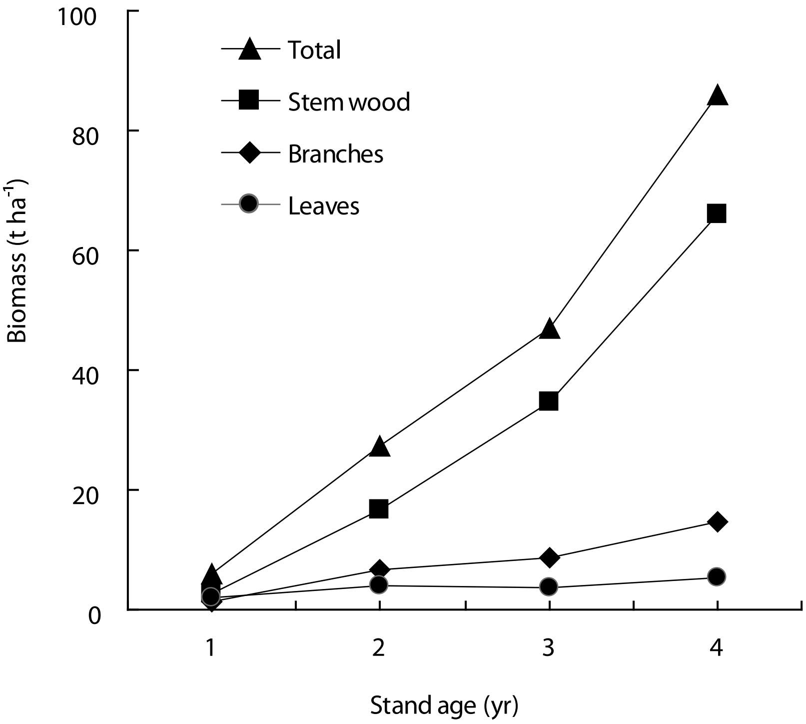

Figure 4. Net accumulation of biomass in tree components from age 1 to 4 years

in standing trees and amounts of nutrients in the litterfall during the period were not taken into consideration.

Soil Properties

As noted in the experimental details, soil samples were collected to 50 cm depth every year but analyses for soil organic C, N, and extractable P have only been completed for the 0-10 cm layer.

Soil pH

Soil pH values did not change significantly from before the establishment of the experiment to four years after planting (Table 6). Soil pH was 4.3 to 4.5 in all treatments with little variation at the depths sampled.

Organic carbon

In all treatments organic C in surface soil (0-10 cm) 1 year after planting was lower (1.55±0.02) compared to first rotation of plantation (1.67±0.03). However, organic C in soil increased gradually as the trees grew and at age 4 years values were higher than initial values in all treatments. Retention of slash and litter improved organic carbon levels significantly (Fig. 5a).

Nitrogen

Changes in total N were similar to those of organic C. One year after planting, total N declined in BL_0 but remained steady in slash-retained treatments. Subsequently, N levels increased gradually in all treatments including BL_0 until 4 years of age. Slash residue treatments significantly affected total N in the soil surface (0–10 cm) from age 1 to 4 years. Double slash increased total N by 45% at age 4 years compared to preharvest values (Fig. 5b). Phosphorus

In contrast to total N and organic C, available P changed little by the end of the first year after planting, then decreased steadily to age 3 years before stabilising (Fig. 5c). Unlike C and N, there was no significant change in available P between different treatments and decline in

Table 5. Annual biomass and nutrient uptake in standing trees of *A. auriculiformis* plantation up to age 3 years

Stand age (yr)	Biomass (t ha^{-1})	Nutrient (kg ha^{-1} yr^{-1})				
		N	P	K	Ca	Mg
0-1	6.0	79.3	4.3	37.0	6.1	2.0
1-2	21.2	147.1	24.9	57.1	24.6	11.7
2-3	19.9	68.3	8.1	48.9	2.1	5.7

Table 6. Effects of slash treatments on soil pH

Parameter	Year:	2002	2006		
	Soil depth (cm)	Initial	BL$_0$	BL$_2$	BL$_3$
pH (H$_2$0)	0 - 10	4.5	4.4	4.5	4.5
	10 - 20	4.6	4.4	4.5	4.4
	20 - 30	4.6	4.4	4.4	4.4
	30 - 50	4.5	4.3	4.4	4.4
pH (KCl)	0 - 10	4.0	3.9	4.0	4.0
	10 - 20	4.0	3.9	4.0	4.0
	20 - 30	4.0	3.9	4.0	4.0
	30 - 50	4.0	3.9	4.0	3.9

available P occurred regardless of treatment. This decline was 39% by age 4 years (mean across treatments).

Exchangeable cations

Although exchangeable cations were measured in samples collected every year, the variation in data was large compared to that for C, and P so the results did not to allow meaningful interpretation of annual changes. The trend was clearer between pre-planting and age 3 years (Table 7). All exchangeable cations decreased 3 years after planting in both no slash and slash retention treatments. Slash treatments had no significant effect on exchangeable Ca, K and Mg at this stage.

Bulk Density

Four years after planting, the treatments had little effect on soil bulk density (Table 8). Averaged across all treatments, the soil bulk density increased with depth, averaging 1.38 g cm^{-3} at the 0-10 cm depth to 1.42 g cm^{-3} at the 10-20cm depth.

Discussion

The effects of slash management on tree growth was consistent throughout the study and confirmed that removal of slash would have an adverse effect on productivity. Huong *et al*. (2004) estimated that removing slash and litter would remove 169 kg ha^{-1} N, 4.9 kg ha^{-1} P and 62.5 kg ha^{-1} K from the site**.** These amounts are less than removing *A. mangium* slash and litter which were estimated at 533-557 kg ha^{-1} N, 7.5-12.3 kg ha^{-1} P and 128-148 kg ha^{-1} K (Hardiyanto and Wicaksono 2008).

Slash retention improved soil organic C and N concentrations in soil (Fig. 5). This suggests slash and litter management will improve productivity. The increase in soil C and N and the decrease in P are not due on the changes in bulk density which were small and tended to become lower with time (Table 8). The change in soil organic C and N is influenced by both slash management and possibly by atmospheric N- fixation of the trees (Fig. 6). There has been little change in the C/N ratio. The initial (2002) C/N ratio across the site was 14.8. Four years after planting, C/N ratios

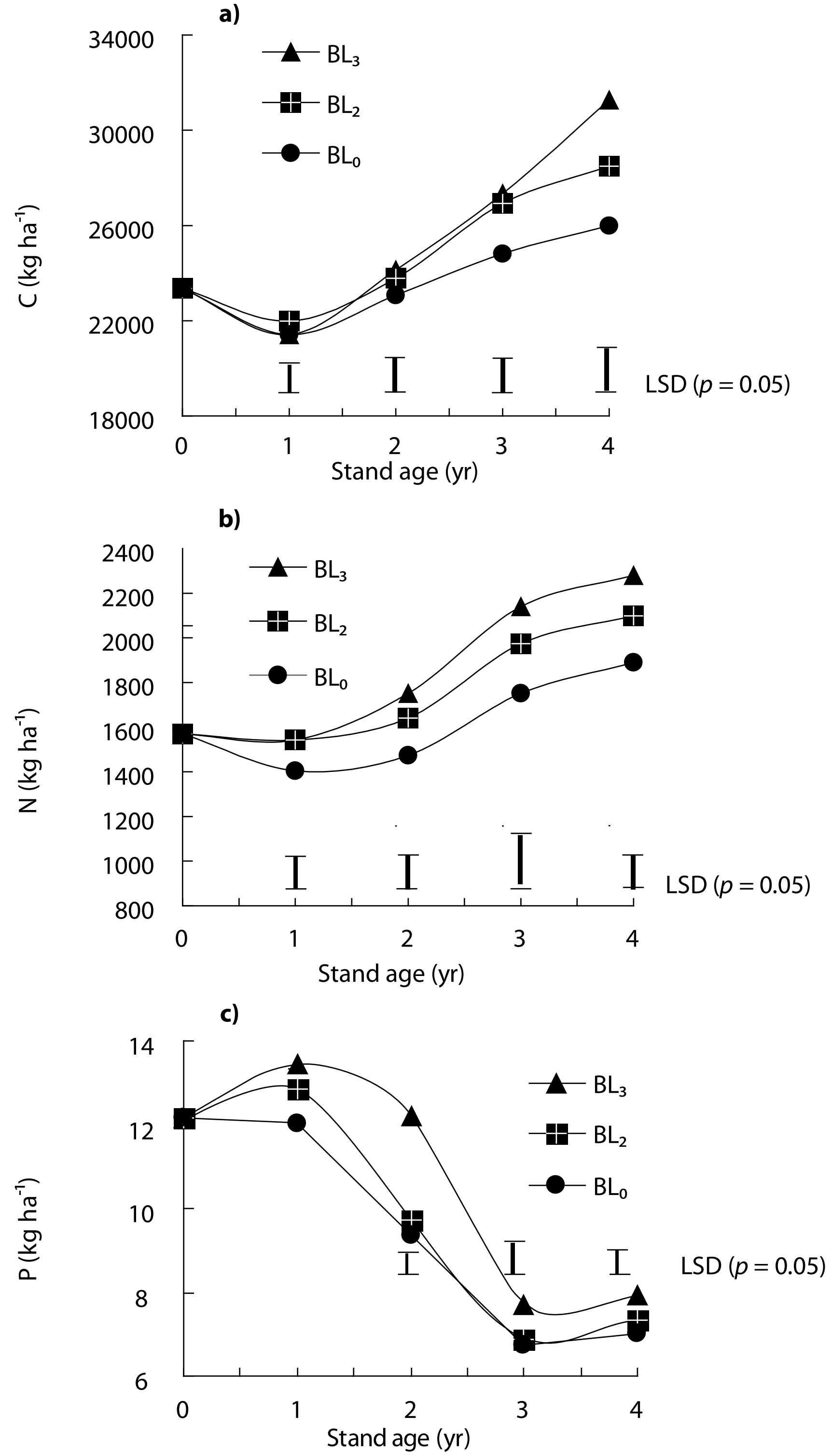

Figure 5. Change in soil (a) organic carbon, (b) nitrogen and (c) available phosphorus in 0 -10cm soil from pre-treatment to age 4 years of stand

Table 7. Change in cations in 0-10cm soil layer before treatment and 4 years after planting

Year of planting	Treatments	Cations (Cmol$_c$kg^{-1})		
		Ca	K	Mg
2002	Initial	0.12 ± 0.02	0.09 ± 0.005	0.23 ± 0.03
2005[1]	BL$_0$	0.06 ± 0.002	0.05 ± 0.002	0.15 ± 0.04
	BL$_{2\&3}$	0.06 ± 0.001	0.07± 0.003	0.14 ± 0.04

[1] BL$_0$ based on 5 replications; BL$_2$ and BL$_3$ data are pooled to see the general effects of slash treatments.

Table 8. Effects of slash treatments on soil bulk density after planting 4 years

Soil depth (cm)	Bulk density (g cm^{-3})			
	Initial	2006		
	2002	BL$_0$	BL$_2$	BL$_3$
0 - 10	1.46 ± 0.05	1.41 ± 0.01	1.39 ± 0.004	1.36 ± 0.03
10 - 20	1.51 ± 0.06	1.42 ± 0.03	1.42 ± 0.01	1.40 ± 0.03

were 13.8, 13.6, and 13.4 for BL$_0$, BL$_2$ and BL$_3$ respectively.

Herbicides are used commonly to control weeds in plantation forestry in many countries. Weed control commonly results in better growth of eucalypts (e.g. Sankaran *et al.* 2004). Herbicide application to control weeds is not a common practice in Vietnam but in our study it significantly improved productivity in *A. auriculiformis*. Applying herbicide in strips 1.5m wide along tree rows increased the volume by 52% at age 4 years. There was no additional growth response to more intensive herbicide application (Table 2). Similar results have been reported for *Pinus radiata* in South Australia (Woods *et al.* 1990). In conditions comparable to our experiment, strip weed control may optimise production at a lower cost. Retention of vegetation on more than 50% of the area would allow understorey regeneration and improve biodiversity on the site. However, these results need to be tested on more sites before general recommendations are made to the growers.

Nutrient application is an important practice to sustain and increase the productivity of plantation on poor sites. This has been reported at many sites, including *Eucalyptus grandis* in Brazil, South Africa and India (du Toit *et al.* 2004, Goncalves *et al.* 2004, Sankaran *et al.* 2004), *E. urophylla* in China (Xu *et al.* 2004) and *A. mangium* in Indonesia (Hardiyanto *et al.* 2004).

Our study showed that in response to phosphorus fertiliser tree growth increased after 2 years after planting and was maintained up to 4 years (Table 3). The level of growth response is small given the large and consistent reduction soil P values.

Available P in the soil (0-10cm) decreased from 12.8 kg ha^{-1} to 9.73 kg ha^{-1} to 6.9 kg ha^{-1} at ages 1, 2 and 3 years respectively, while the amount of P taken up in the trees was 4.3 kg ha^{-1}, 29.2 kg ha^{-1} and 37.4 kg ha^{-1} at ages 1, 2 and 3 years respectively (Fig. 7). This indicates that trees took up P from soil and also from other sources, such as decomposing slash and litter. The practice of fertilising with P can improve productivity (Table 3).

Productivity of the first rotation plantation at harvest age 7 years (Vu Dinh Huong *et al.* 2004) has been compared with that of the second crop at age 4 years (Table 9). The second crop at age 4 years had a MAI of 25.2 m^3 ha^{-1} yr^{-1} compared to 18.6 m^3 ha^{-1} yr^{-1} in the first rotation at 7 years. The higher volume production in the second rotation was partly due to a higher planting density.

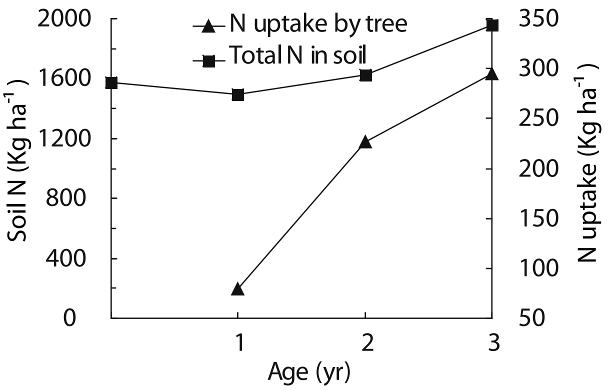

Figure 6. Nitrogen in surface soil (0 – 10cm) and uptake of nitrogen by *A. auriculiformis* plantation from age 1 to 3 years

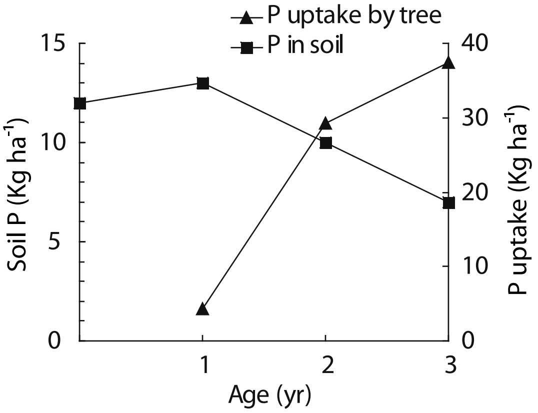

Figure 7. Extractable phosphorus in surface soil (0 – 10cm) and uptake by *A. auriculiformis* plantation from age 1 to 3

Table 9. Productivity of the first rotation plantation at harvest age 7 years and compared with the second crop at age 4 years

Items	First rotation	Second rotation
Age (yr)	7	4
Trees at planting (tree ha^{-1})	833	1666
Tree at harvest (tree ha^{-1})	660	1580
Total standing volume (m^3 ha^{-1})	130	100.6
MAI (m^3 ha^{-1} yr^{-1})	18.6	25.2
Live biomass (t ha^{-1})	51.2	86.1
Litter (t ha^{-1})	5.1(a)	16.1(b)

(a) Litter on forest floor at clear felling.
(b) Litterfall from age 2.25 to 4 years.

Overall results establish the importance of conserving slash and litter at the site and suggest that a substantial increase in productivity is achievable by improved management practices at this site and at many other sites in Vietnam.

Conclusions

- Slash and litter retention increased tree volume at age 4 years, and improved levels of organic carbon and nitrogen in the soil.
- Strip weed control increased volume growth substantially compared with no vegetation control. Using herbicide for vegetation control in plantations has potential to increase productivity and further research is warranted to develop management prescriptions.
- Nutrient additions are necessary for increasing productivity of *A. auriculiformis* but more research is needed to understand the factors determining response to nutrients, especially P, because of the observed reduction in extractable P in soil with stand growth.

Overall productivity of the second rotation crop was substantially higher compared with the first rotation stand. Retention of harvesting slash, vegetation management and nutrient additions will be recommended for planting practices to ensure sustainable productivity of *A. auriculiformis* plantations in South Vietnam.

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References

Do Dinh Sam. 2001. Scientific bases adding silviculture techniques to increase productivity of natural forest after harvesting and industrial plantation. *In*: Research results on forest science and technology, 1996-2000. FSIV-APAFRI-TREELINK. Agriculture Publishing House, Hanoi.

Du Toit, B., Dovey, S.D., Fuller, G.M. and Job, R.A. 2004. Effects of harvesting and site management on nutrient pools and stand growth in a South African eucalypt plantation. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 31-43. Center for International Forestry Research, Bogor, Indonesia.

General Statistic Office (2005). Statistical Yearbook 2004. Statistic Publishing House, Hanoi.

Goncalves J.L.M., Gava J.L. and Wichert M.C.P. 2004. Sustainability of wood production in Eucalyptus plantation of Brazil. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 3-14. Center for International Forestry Research, Bogor, Indonesia.

Hardiyanto, E.B., Anshori, S. and Sulistyono, D. 2004. Early results of site management in *Acacia mangium* plantations at PT. Musi Hutan Persada, South Sumatra, Indonesia. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 93-108. Center for International Forestry Research, Bogor, Indonesia.

Hardiyanto, E.B. and Wicaksono, A. 2008. Inter-rotation site management, stand growth and soil properties in *Acacia mangium* plantations in South Sumatra, Indonesia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 107-122. Center for International Forestry Research, Bogor, Indonesia.

Reewijk, L.P. van. (ed.) 1995. Procedures for soil analysis. Technical Paper No 9. International Soil Reference and Information Centre, Wageningen, The Netherlands.

Lowther, J.R. 1980. Use of a single sulphuric acid-hydrogen peroxide digest for analysis of *Pinus* *radiata* needles. Communications in Soil Science and Plant Analysis 11:175-88.

Nambiar, E.K.S. 1999. Introduction. *In:* Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Pietermaritzburg, South Africa, 16-20 February 1998, 1-3. Center for International Forestry Research, Bogor, Indonesia.

Nambiar, E.K.S. and Brown, A.G. 1997. Towards sustained productivity of tropical plantations: science and practice. *In:* Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests, 527-557. Monograph No. 43, Australian Centre for International Agriculture Research, Canberra.

Nguyen Duong Tai. 2002. Seedling production for five reforestation programmes. MARD special subject on forest breeding. DANIDA-Ministry of Agriculture and Rural Development (MARD), Hanoi.

Nguyen Hoang Nghia and Le Dinh Kha. 1998. *Acacia* species and provenance selection for large-scale planting in Vietnam. *In*: Results of scientific research on silviculture in Vietnam. Agriculture Publishing House, Hanoi.

Nguyen Huy Son. 2006. Research on technology and science solutions to develop wood raw materials for exporting (National Project 2001-2005, Code: KC.06.05.NN). *In*: Results of research technology and science in forestry period 2001-2005, 24-42. Agriculture Publishing House, Hanoi.

Nguyen Huy Son and Dang Thinh Trieu, 2004. *Acacia* and *Eucalyptus* plantations in Vietnam: problems and solutions. Journal of Information on Forest Science and Technology, Forest Science Institute of Vietnam 2:13-18.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kumaraswamy, S., O'Connell, A.M., Grove, T.S. and Mendham, D.S. 2004. Improved productivity of eucalypt plantations through site management practices in the monsoonal tropics: Kerala, India. *In:* Nambiar, E.K.S., Ranger, J. Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 61-76. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A., Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical forest plantations. Occasional Paper No. 16. Center for International Forestry Research, Bogor, Indonesia.

Vu Dinh Huong, Pham Viet Tung, Pham The Dung, Ho Van Phuc, Nguyen Thanh Binh, Ha Minh Duc, and Nguyen Thi Tron, 2004. Site management and productivity of *Acacia auriculiformis* in South Vietnam. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 121-137. Center for International Forestry Research, Bogor, Indonesia.

Xu, D.P., Yang, Z.J. and Zhang, N.N. 2004. Effects of site management on tree growth and soil properties of a second rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Woods, P.V., Nambiar, E.K.S. and Smethurst, P.J. 1990. Effect of annual weeds on water and nitrogen availability to *Pinus radiata* trees in a young plantation. Forest Ecology and Management 48: 145-163.

Pines plantations, New Caledonia (Photo: Christian Cossalter)

Inter-rotation Management Impacts on Growth and Soil Properties in Hybrid Pine Plantations on Sandy Soils in Subtropical Australia

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Abstract

A 29.4-year-old *Pinus elliottii* stand on a low-fertility soil was harvested and slash management, weed control and legume treatments applied to examine impacts of inter-rotation management on tree growth and soil properties of the second rotation hybrid pines (*P. elliottii* var. *elliottii* × *P. caribaea* var. *hondurensis*). Logs harvested from the first rotation stand contained 189.1 kg ha^{-1} N, 10.8 kg ha^{-1} P, 63.2 kg ha^{-1} K, 170.3 kg ha^{-1} Ca and 64.6 kg ha^{-1} Mg. Slash (harvesting residues and litter) contained 64.1 kg ha^{-1} N, 5.0 kg ha^{-1} P, 21.1 kg ha^{-1} K, 76.0 kg ha^{-1} Ca and 21.5 kg ha^{-1} Mg. Average mean annual increment of the second rotation at 10.3 years was slightly higher than that of the first rotation. Slash retention increased stem volume and strongly influenced soil chemical properties. Stem volumes in double slash (BL_3) treatment were 11% and 18% higher than the litter and slash retained (BL_2) and all slash and litter removed (BL_0) treatments, respectively. Tree growth in the BL_2 with the inclusion of legumes (BL_2 + L) and BL_2 minus phosphorus (BL_2 - P) treatments were not significantly different from the BL_2 treatment. Slash retention and weed control (BL_2 + W) increased stem volume by 37.8 m^3 ha^{-1} at age 10.3 years compared to the BL_2 treatment. Treatments influenced soil properties. Increase in the amount of slash resulted in enhanced organic C, total N and effective cation exchange capacity (eCEC) concentrations in the 0-5 cm soil layer at 8.2 years. There was a strong positive correlation between soil organic C and other soil properties: total N, exchangeable K, exchangeable Mg and eCEC. Results have been valuable in quantifying impacts of harvesting and management options on tree growth and nutrient cycling and have improved management.

Introduction

Harvesting and inter-rotation management practices can alter organic matter and nutrient dynamics at a site and impact on plantation productivity (Nambiar 1996, McLaughlin and Phillips 2006). Productivity decline in *Pinus* plantations over successive rotations has been of concern. Declines of 140-280 m^3 ha^{-1} between first and second rotations of *P. radiata* Don. plantations in south-eastern South Australia have been reported (Keeves 1966). Woods (1990) found productivity declines of 25-40% between rotations due to loss of organic matter, in these plantations. Subsequent research and applications of results at an operational level have reversed productivity decline in second and third rotations and substantially higher productivity is currently achieved than was possible in the 1960s and 70s (Boardman 1988, Nambiar 1996, 1999, 2003, Carlyle and Nambiar 2001). Similarly in Queensland, there was a 17% increase in stem volume in *P. elliottii* Engelm. var. *elliottii* at age 9 years in the second rotation stand where organic matter was left undisturbed, compared to the first rotation (Bevege and Simpson 1980). A common factor highlighted by a number of studies

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that retention of organic matter on site was a significant factor for sustaining productivity.

Organic matter plays a major role in nutrient supply and retention in coarse-textured, low-fertility soils. Negative charges arising from the dissociation of carboxyl groups in organic matter provide adsorption sites for cations in soil (Parfitt *et al.* 1995). Clay and silt particles also provide sites for cation adsorption (McAleese and Mitchell 1958, Russell 1977) and can be the dominant fractions contributing to cation exchange capacity (CEC) of fine textured soils (Asadu *et al.* 1997). However, in coarse textured soils, such as those in Queensland used for exotic pine plantations, maintaining an adequate organic matter content becomes more critical for sustaining CEC due to their lower clay contents.

Annual planting rate of second rotation plantations in the south-eastern Queensland ranges from 4000 to 5500 ha (Last personal communication). The plantations cover 129 310 ha and provide 45% of sawlog timber harvested in Queensland (Anon. 2005). Harvesting systems vary in their impact on organic matter and distribution. Whole-tree harvesting and roadside processing is increasingly common. This involves felling and transport of the entire tree with the crown to roadside for processing. Using skidders to remove trees and dragging their canopies behind the skidder results in extraction tracks being swept clean of slash. Docking tops and removing branches produce areas of residue accumulation. This creates areas without slash along extraction tracks, normal slash loads between tracks and high slash loads in processing areas.

Impacts of inter-rotation management, including slash management, on sustainable production of these plantations on acidic, quartzose sandstone-based, coarse-textured soils were investigated in the coastal lowlands of south-eastern Queensland. The objectives were to assess the effects of slash treatments, with and without legumes, weed control and fertiliser additions, on tree growth and soil properties of the second rotation stand. Detailed results of this research have been reported at various stages (Simpson *et al.* 1999, 2000, 2004). This paper highlights some of the major findings of operational significance and synthesises the results to age 10 years.

Methods and Materials

Site Details – First Rotation

Simpson *et al.* (1999) reported details of the experimental site. Some key information is reproduced here.

The trial site is at Toolara in Queensland, Australia (26°00´S, 152°49´E and 61 m altitude). The area has a humid subtropical climate, with a mean annual rainfall of 1354 mm, 56% falling during December to March. The site, which originally carried dry sclerophyll native forest, was cleared in 1959 for plantation establishment. Soils are derived from Mesozoic sandstones, and are acidic, deep and sandy, and classified as Grey Kandosols (Isbell 1996) or Gleyic Acrisols (FAO 1974). They are well drained in the upper horizons but can become waterlogged for short periods during the wet season when the watertable rises to within 50 cm of the soil surface.

The first rotation stand of slash pine was planted in 1966 at 1235 stems ha^{-1}. Fertiliser, 310 kg ha^{-1} Nauru rock phosphate (16.1% P) to supply 50 kg ha^{-1} P, was broadcast at planting and triple superphosphate (44 kg ha^{-1} P) was applied aerially in 1980 when the stand age was 14 years. 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, derived as average height (m) of the 50 tallest stems ha^{-1} at age 25 years, was 23.7, compared with a district average of 23.4 for the species. Total merchantable volume production to a 7 cm top end diameter was 386.9 m^3 ha^{-1} and the mean annual increment (MAI) was 13.2 m^3 ha^{-1} yr^{-1}.

Allometric relationships were established from trees harvested at age 29.4 years and stand biomass nutrient pools were estimated. Litter, belowground biomass and soil nutrient pools were also estimated. Root biomass was determined on two sets of stumps (four trees) of average diameter and located 3.8 m between centres (representing a stocking of 679 stems ha^{-1}). Small roots were sampled from five vertical sections 0.4

m wide × 0.2 m long x 1.1 m deep, cut into the side of open trenches dug between stumps. Vertical sections 1 and 5 were located at stump, 3 in the centre, and 2 and 4 at one third and two-thirds the distance of the trench between stumps. Roots were sieved from the soil, sorted into diameter size classes (<5 mm, 5-10 mm, 10-50 mm, 50-100 mm), weighed and subsampled for chemical analysis. Soil samples were collected to a depth of 120 cm, air-dried and analysed for N, P, K, Ca and Mg as in Collins (2000).

At the end of the first rotation, soil properties (0-10 cm) were as follows: organic C 1.43%; total N 0.037%; total P 41.4 mg kg^{-1}; exchangeable K 0.08 cmol kg^{-1}; exchangeable Ca 0.42 cmol kg^{-1}; exchangeable Mg 0.23 cmol kg^{-1}; Zn 0.296 mg kg^{-1}; and Cu 0.288 mg kg^{-1}.

Slash Management Trial – Second Rotation

Experimental design and treatments

The first rotation stand was harvested in 1995 and treatments were applied in February 1996 (three months after clear felling).

The experiment consisted of six treatments in a randomised complete block with four replications. Gross plots were 12 rows by 12 trees at 3 m x 3 m spacing (0.13 ha) with two rows buffer and net plots of 8 rows by 8 trees (0.058 ha). Simpson *et al.* (1999, 2000, 2004) give additional details of the experimental design and treatments. Treatments were:

BL$_0$	Litter plus logging residue (slash) removed + 50 kg P ha^{-1} added.
BL$_2$	Litter and slash retained + 50 kg P ha^{-1} added.
BL$_3$	Double quantities of slash + 50 kg P ha^{-1} added.
BL$_2$+L	BL$_2$ + leguminous cover crops established at replanting.
BL$_2$+W	BL$_2$ + complete weed control from planting.
BL$_2$-P	BL$_2$ without P fertiliser.

In BL$_0$ it was impossible to remove all litter and slash and about 9 t ha^{-1} of fine material remained on site. The BL$_2$ treatment had 60 t ha^{-1} dry matter of which approximately 40% was forest floor litter. The BL$_3$ treatment (140 t ha^{-1}) widened the possible treatment effects on tree growth and soil processes. This treatment also simulates the windrowing of logging residues that occurs after some logging operations. Phosphorus was applied as a basal treatment at planting on five of the six treatments due to low levels of soil P concentrations and significant tree growth responses to P applications on similar sites.

Stand establishment

In the experimental plots the seedlings were planted in May 1996 in the centre of cultivated spots at 3 x 3 m spacing (1111 stems ha^{-1}). The container-grown seedlings were F$_1$ hybrid of *P. elliottii* var. *elliottii* and *P. caribaea* var. *hondurensis* Barr. et Golf. Seeds from six seed orchards were used and the identity of seed origin was retained as rows in plots. Each net plot had the same genetic composition. Results reported in this paper refer to average data of trees from the six seed sources.

Pre- and post-planting herbicides were applied in the first year along the planting rows. Triple superphosphate was applied to supply 45 g P/seedling (50 ka P ha^{-1}) in all treatments except for BL$_2$-P. A mixture of legume seeds containing Lotononis (*Lotononis bainesii*), Wynns cassia (*Chamaecrista rotundifolia* cv Wynn) and Maku lotus (*Lotus pedunculatus* cv Maku) was sown on three occasions in the BL$_2$+L treatment. The legumes grew slowly and in 2001 covered less than 50% of the area of plots. The stand was thinned at age 3.2 years to a stocking of 694 stems ha^{-1}.

Measurements

Tree height and diameter were measured annually or biennially.

Slash and litter samples were collected before clear felling, at the establishment of treatment and at age 30 months (November 1998) by taking at random, five 1 m^2 samples per plot. At age 39 months (August 1999) only two similar samples per plot were taken. Material was sorted into size classes, dried and prepared for chemical analysis.

Soil samples were collected in January 1996 (after clear felling but 3 months before planting), May 1998 (age 2.1 years), and June 2004 (age 8.2 years). In each plot, samples were collected from five systematically located 1 m^2 quadrats. Five samples were taken from each quadrat. These were bulked for each quadrat and processed for analysis. Samples were collected from depths of 0-5, 5-10, 10-20 and 20-30 cm soil in 1998, but only the 0-5 and 5-10 cm layers were sampled in 2004. Organic carbon was determined using the Walkley-Black method, total N and P were determined by the Kjeldahl method, exchangeable base cations was determined by neutral ammonium acetate extraction, exchangeable acidity were determined by KCl extraction and Cu and Zn were determined by the DTPA extraction (Collins 2000).

Foliar samples were collected in winter (June 2002) at tree age 6.2 years from the recently formed fully expanded needles on the northern side of the tree from the basal spring whorl formed in the season before sampling. They were oven dried at 60°C for 24 hours then analysed for N, P, K, Ca, Mg, Na, Cu, Zn, and B using methods detailed in Collins (2000).

Results

Biomass and Nutrient Distribution at the End of First Rotation

At clearfelling, the stand had a predominant height of 25.2 m, basal area of 39.6 m^2 ha^{-1} and stem volume (679 stems ha^{-1}) to a 7 cm top end diameter of 325.4 m^3 ha^{-1}. Eighty percent of the biomass was aboveground. Merchantable stem (wood plus bark) contained the greatest proportion of biomass (65%) and biomass macronutrients: N 39%, P 40%, K 54%, Ca 40% and Mg 46% (Table 1). Simpson *et al.* (1999) discuss biomass and nutrient distribution.

The quantity of aboveground biomass contained in the foliage, branches and litter (46 t ha^{-1}) was lower than that removed in logs (wood + bark) (206 t ha^{-1}). However, foliage, branches and litter had higher concentrations of N, P, Ca, and Mg (Simpson *et al.* 1999) resulting in nutrient amounts similar to that in logs. An exception was K, as logs contained 2.4 times more K than foliage, branches and litter combined (Table 1).

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

Component	Biomass	N	P	K	Ca	Mg
			(kg ha^{-1})			
Foliage	2038	16.0	1.3	4.1	7.8	4.0
Branches plus stem top	24180	48.1	3.7	17.0	68.2	17.5
Stem wood, bark (> 7cm)	205742	189.1	10.8	63.2	170.3	64.6
Litter	19800	98.2	4.3	4.7	83.4	20.3
Stump	33000	38.3	2.1	11.1	20.7	10.7
Roots	30943	95.7	5.1	16.4	71.6	22.2
Total biomass	315703	485.4	27.3	116.5	422.0	139.3
Soil (to 120 cm)		1991	288	37(1)	1045(1)	1148(1)
Total	315703	2476	315	-	-	-

(1) Exchangeable cations.

Slash Management Trial

Stand development

Stand growth at age 10.3 years is described in Table 2. Site index was 27.7 compared to 23.7 in the first rotation. Stand growth was improved significantly by high slash retention (BL_3). Compared to the BL_0, BL_3 increased tree: height by 0.6 m (4%); diameter 1.5 cm (7%); basal area 3.4 m^2 ha^{-1} (14%); and stem volume 25.8 m^3 ha^{-1} (18%). Response to the BL_2 treatment was intermediate between the BL_0 and BL_3 treatments. BL_2+L and BL_2-P treatments did not differ from each other or from the BL_2. Treatment BL_2+W gave the highest growth with a significant increase over the BL_2 treatment: height by 0.3 m (2%); diameter by 1.7 cm (8%); basal area by 4.2 m^2 ha^{-1} (16%) and stem volume by 28.8 m^3 ha^{-1} (19%). Average MAI (total volume) was 15.3 m^3 ha^{-1} yr^{-1} for the hybrid pine in the second rotation.

Change in slash and litter

Slash and litter had declined to 46% by 2.5 years and 28% by 3.2 years, when compared to original amounts (Table 3).

Rapid decline in biomass by age 2.5 years, due to decomposition, occurred in the BL_3 and BL_2+L treatments. Treatment differences in biomass were not significant at 5.1 years (mean 15.9 t ha^{-1}) and at 6.4 years (mean 17.0 t ha^{-1}). Litterfall (including litter from weeds) may explain the increase in mean biomass levels between years 5.1 and 6.4. The half-life of the first rotation residue (including wood) was about 2.5 years.

There was considerable variation in the biomass results at 3.2 years, possibly due to the reduction from five to two samples bulked per plot for this assessment compared to previous years. However despite the variation, the results demonstrate major changes in biomass (Table 3).

Table 2. Effect of slash treatments on development at age 10.3 years of hybrid pines at Toolara

Treatments	Mean height (m)	DBH (cm)	Basal area (m^2 ha^{-1})	Stem volume (m^3 ha^{-1})
BL_0	15.4	21.4	24.9	141.5
BL_2	15.7	22.0	26.2	150.5
BL_3	16.0	22.9	28.3	167.3
BL_2 + L	15.7	22.4	27.2	157.0
BL_2 + W	16.0	23.7	30.4	179.3
BL_2 – P	15.7	21.6	25.3	145.7
Mean	15.8	22.3	27.1	156.9
LSD $p = 0.05$	N.S.	0.70	1.7	11.5

Table 3. Biomass on soil surface under pines at Toolara

Treatments	Residue (including fresh litter) (t ha^{-1})		
Age (yr)	0	2.5	3.2
BL_0	9.0	4.4	2.8
BL_2	50.8	30.6	13.9
BL_3	141.4	44.8	24.9
BL_2 + L	56.4	18.0	12.3
BL_2 + W	58.0	45.1	21.2
BL_2 – P	73.9	37.6	34.0
Mean	64.9	30.1	18.2
LSD $p = 0.05$	39.5	24.1	15.9

Soil chemical properties

At 8.2 years (1996-2004) there were significant changes in mean (across treatments) values of pH, N, organic C, electrical conductivity, exch. K, exch. Mg and effective cation exchange capacity (eCEC) in the surface 0-5 cm of soil (Table 4). Retention of residue increased organic C, electrical conductivity, total N, eCEC, exch. Mg and decreased pH. Exchangeable K increased temporarily at 2.1 years with slash retention but this effect had dissipated by 8.2 years. Soil concentrations at age 8.2 years were 34, 51 and 58% of the initial concentrations (1998) for K, Ca and Mg, respectively. No significant treatment effects were detected in soil layers below 10 cm at ages 2.1 (1998) or 4.2 years (2000) and data is not reported.

Significantly higher concentrations of organic C (0-5 cm) were found in BL_3 treatment when compared with BL_0 and BL_2 treatments at 8.2 years. There was a consistent trend for BL_2+W to have lower concentrations of organic C than BL_2, BL_2+L and BL_2-P treatments did not differ from BL_2. Total N concentrations followed a similar pattern to organic C concentrations.

At 8.2 years, there were significant correlations between organic C and other properties in the 0-5 cm layer: eCEC (R^2 = 0.97), exch. K (R^2 = 0.81), exch. Mg (R^2 = 0.91), and total N (R^2 = 0.89). Relationships with exch. Ca (R^2 = 0.50) and exch. Na (R^2 = 0.20) were much weaker.

The treatments have had significant effects on cation exchange and exchangeable base cations (*viz.* K and Mg). The eCEC (0-5 cm) was low in the BL_0 treatment and significantly increased with slash retention by 8.2 years.

Table 4. Effect of treatments on chemical properties of the surface 0-5 cm layer of soil at ages 2.1 and 8.2 years

Parameter	Age	Treatments						Mean	LSD p=0.05
		BL_0	BL_2	BL_3	BL_2+L	BL_2+W	BL_2-P		
pH	2.1	5.03	4.99	5.02	5.09	5.24	4.99	5.06	NS
	8.2	5.53	5.35	5.18	5.36	5.50	5.32	5.37	NS
EC_{25} (dS m^{-1})	2.1	0.027	0.026	0.032	0.026	0.026	0.029	0.028	NS
	8.2	0.027	0.028	0.038	0.034	0.026	0.030	0.031	0.007
Org C (%)	2.1	1.97	1.99	2.32	1.72	1.85	2.39	2.04	NS
	8.2	1.53	2.03	2.67	2.13	1.88	2.11	2.06	0.50
Total N (%)	2.1	0.059	0.063	0.071	0.060	0.058	0.070	0.064	NS
	8.2	0.047	0.060	0.071	0.066	0.052	0.061	0.059	0.011
eCEC (cmol kg^{-1})	2.1	2.693	2.827	3.222	2.649	2.669	2.950	2.835	NS
	8.2	1.572	2.042	2.461	1.994	1.764	2.020	1.976	0.444
Exch K (cmol kg^{-1})	2.1	0.056	0.050	0.070	0.053	0.039	0.051	0.053	0.016
	8.2	0.030	0.035	0.043	0.034	0.029	0.038	0.035	NS
Exch Ca (cmol kg^{-1})	2.1	0.941	1.014	1.219	1.006	1.121	1.106	1.068	NS
	8.2	0.375	0.504	0.600	0.511	0.606	0.537	0.522	NS
Exch Mg (cmol kg^{-1})	2.1	0.535	0.558	0.804	0.593	0.618	0.656	0.627	0.165
	8.2	0.204	0.256	0.325	0.286	0.255	0.251	0.263	NS
Exch Na (cmol kg^{-1})	2.1	0.073	0.056	0.067	0.053	0.051	0.056	0.059	NS
	8.2	0.060	0.057	0.065	0.069	0.054	0.057	0.060	NS

Table 5. Effect of treatments on foliar nutrient concentrations at 6.2 years of F1 hybrid pine at Toolara

Treatments	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	Cu (mg kg^{-1})	Zn (mg kg^{-1})	B (mg kg^{-1})
BL_0	0.726	0.086	0.266	0.125	0.122	0.097	2.23	11.6	13.9
BL_2	0.777	0.087	0.343	0.118	0.124	0.079	2.28	15.9	14.4
BL_3	0.800	0.085	0.458	0.114	0.122	0.048	2.47	22.3	16.3
BL_2 + L	0.823	0.084	0.358	0.136	0.133	0.069	2.29	18.2	14.0
BL_2+ W	0.784	0.080	0.296	0.181	0.151	0.075	2.21	16.4	17.4
BL_2 – P	0.779	0.079	0.399	0.130	0.114	0.068	2.21	16.0	12.9
Mean	0.782	0.084	0.353	0.134	0.128	0.073	2.28	16.7	14.8
LSD $p = 0.05$	NS	NS	0.107	0.038	0.021	0.026	NS	4.7	2.5

Foliar nutrients

Slash retention had no significant effects at 6.2 years on foliar N, P and Cu but increased foliar K and Zn concentrations and conversely decreased Na concentrations (Table 5). Foliar N concentrations were regarded as low to marginal for the healthy growth of hybrid pines. Foliar P concentrations were above what is regarded as the critical concentration and not significantly affected by treatments. Weed control resulted in higher foliar Ca, Mg, and B concentrations at 6.2 years, but the effects were not significant in all years.

Discussion

Powers *et al.* (1990) suggested removal of organic matter and soil compaction in forest management may have negative impacts on site productivity. Our results show that removal of organic matter has negative impacts on tree growth and soil properties. Retaining slash improved stem volume at age 10.3 years by 9 m^3 ha^{-1} compared to the slash removal treatment. Addition of legumes or omission of P did not significantly affect tree growth. However, with slash retention and weed control, stem volume increased significantly by 37.8 m^3 ha^{-1} at age 10.3 years. Thus management regimes that retain slash and adopt effective weed management are likely to maintain or improve site productivity.

The mean MAI of 15.3 m^3 yr^{-1} ha^{-1} for the hybrid pine stand in the second rotation was greater than the MAI of 13.2 m^3 ha^{-1} yr^{-1} in the first rotation *P. elliottii* var. *elliottii* stand. However, this result should be treated with caution as the productivity would have been influenced by age, taxa and silviculture and climate.

Slash and litter decomposed rapidly with an estimated half-life of 2.5 years. The concomitant soil inputs of organic C and nutrients improved soil N and cation status of the surface soil with significant changes evident at 8.2 years.

Our work confirms that soil organic matter plays an important role in supply/retention of soil cations. Foliar K and Zn at 6.2 years increased with increasing slash application. At 8.2 years there were strong relationships between organic C and exch. K, exch. Mg, total N and eCEC. These findings concur with results of a land-use change study on the coastal lowlands of Southeast Queensland which showed a positive regression between increases in soil organic matter (SOM) levels and increased soil eCEC (Carlyle *et al.* 2002). In the current study, the positive relationship between organic C and eCEC was also strong. Thus the removal or redistribution of organic matter from the system is likely to have direct impacts on nutrient supply/retention in these course-textured soils.

Nutrient removal by wood harvesting highlights the need for nutrient conservation (retaining slash) and possible supplementary fertiliser to maintain fertility levels. Of most concern was K, with logs containing 2.4 times the amount of K than that in foliage, branches and litter combined. Plantation soils of the coastal lowlands derived from quartzose sandstones have low exchangeable K compared to a suggested ‘critical concentration’ of >2 cmol kg^{-1} (Baker and Eldershaw 1993). In this experiment exchangeable K in the 0-5 cm soil layer decreased from 0.053 cmol kg^{-1} to 0.035 cmol kg^{-1} in an 8-year period. A similar decline in K (from 0.064 to 0.040 cmol kg^{-1}) in 0-7.5 cm soil in plantations of this region was also found in a comprehensive study that compared soils from under pine plantations and adjacent native forests (Carlyle *et al*. 2002). The fact that K deficiency of exotic pines has been identified on several poorly drained soil types in the region and wide scale addition of potassic fertiliser has been carried out to remedy this situation (Simpson and Grant 1991), highlights concern over this nutrient. While exchangeable Ca and Mg concentrations are also well below critical concentrations (>2 cmol kg^{-1}) there has been no report of growth responses in these plantations to additions of these elements in the first rotation, however monitoring the sufficiency status these nutrients may be warranted in the second rotation.

Plantation forestry aims for uniform tree growth across compartments to provide operational efficiencies. Extensive use of clonal planting stock, as opposed to seedling stock, has provided greater uniformity of plantations. However, tree harvesting systems that accentuate nutrient depletion and dislocation are likely to introduce greater variability in tree growth across plantations. Efficiencies in harvesting and establishment operations may need to be balanced against potential site impacts on productivity and variability of successive rotations.

Sustainable management of high productivity plantation systems on soils with low nutrient reserves is challenging. There is no simple route to sustainable plantation forestry and scientists have an obligation to provide balanced information and communicate it in the wider context of sustainability (Nambiar 1996, 1999).

Conclusions and Impacts of Research on Local Management

Retention of first rotation clearfall slash on-site increased tree growth in the second rotation stand. Further increases were achieved with weed control. Slash retention also increased surface soil nutrients and eCEC in soils which inherently have low available nutrients.

This work had significant impacts on the inter-rotation management strategies currently practised in south-east Queensland pine plantations. It is management policy not to burn slash, and slash retention along with appropriate weed control and fertiliser applications are part of routine prescriptions. The data developed has been valuable in quantifying impacts of harvesting and management options on tree growth and nutrient balances. There is now greater recognition of the link between management practices and long-term impacts on soils.

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References

Anon. 2005. DPI forestry pocket facts 2005. Department of Primary Industries Forestry, Brisbane, Australia. 10p.

Asadu, C.L.A., Diels, J. and Vanlauwe, B. 1997. A comparison of the contributions of clay, silt, and organic matter to the effective CEC of soils of sub-Saharan Africa. Soil Science 162:785-794.

Baker, D.E. and Eldershaw, V.J. 1993. Interpreting soil analyses – for agricultural land use in Queensland. Project Report Series QO93014. Department of Primary Industries, Brisbane, Queensland, Australia. 105p.

Bevege, D.I. and Simpson, J.A. 1980. Second rotation investigations in plantation conifers - slash pine. Australian Forestry Research Newsletter 6:177-178.

Boardman, R. 1988. Living on the edge: the development of silviculture in South Australian pine plantations. Australian Forestry 51:135–156.

Carlyle, J.C. and Nambiar, E.K.S. 2001. Relationships between net nitrogen mineralization, properties of the forest floor and mineral soil, and wood production in *Pinus radiata* plantations. Canadian Journal of Forest Research 31:889-898.

Carlyle, J.C., Snowdon, P., Polglase, P.J., Nambiar, E.K.S., Smith, T.E., Simpson, J.A. and Bubb, K.A. 2002. Soil based information for sustainable plantation forestry in Australia. Report for FWPRDC projects PN98.801 and PN97.601. Forestry and Wood Products Research and Development Committee, Melbourne, Victoria, Australia. 93p.

Collins, P. (ed.) 2000. Soil analysis methods. Queensland Forestry Research Institute, Technical Note 17. Queensland Department of Primary Industry, Brisbane, Australia. 44p.

FAO. 1974. FAO - UNESCO soils map of the world 1:5 000 000. Vol. 1, Legend. UNESCO, Paris. 59p.

Isbell, R. 1996. The Australian soil classification. CSIRO, Melbourne, Australia. 143p.

Keeves, A. 1966. Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. Australian Forestry 30:51-63.

McAleese, D.M. and Mitchell, W.A. 1958. Studies on basaltic soils of Northern Ireland V. Cation exchange capacities and mineralogy of silt separates. Journal of Soil Science. 9:81-88.

McLaughlin, J.W. and Phillips, S.A. 2006. Soil carbon, nitrogen, and base cation cycling 17 years after whole-tree harvesting in a low-elevation red spruce (*Picea rubens*)-balsam fir (*Abies balsamea*) forested watershed in central Maine, USA. Forest Ecology and Management 222:234-253.

Nambiar, E.K.S. 1996. Sustained productivity of forests is a continuing challenge to soil science. Soil Science Society of America Journal 60:1629-1642.

Nambiar, E.K.S. 1999. Pursuit of sustainable plantation forestry. South African Forestry Journal 184:45-62.

Nambiar, E.K.S. 2003. Science and technology for sustainable development of plantation forests. Australian Forestry 66:43-50.

Parfitt, R.L., Giltrap, D.J. and Whitton J.S. 1995. Contribution of organic matter and clay minerals to cation exchange capacity of soils. Communications in Soil Science and Plant Analysis 26:1343-1355.

Powers, R.F. *et al*. 1990. Sustaining site productivity in North American forests: problems and prospects. *In*: Gessel, S.P. *et al*. (eds.) Sustained productivity of forest soils. Proceedings of the 7th North American forest soils conference, 49-79. University of British Columbia, Vancouver, Canada.

Russell, E.W. 1977. Soil conditions and plant growth, 10th ed. Longmans, London.

Simpson, J.A. and Grant, M.J. 1991. Exotic pine fertiliser practice and its development in Queensland. Technical Paper No 49. Queensland Forest Service, Brisbane, Australia. 19p.

Simpson, J.A., Osborne, D.O. and Xu, Z.H. 1999. Pine plantations on the coastal lowlands of subtropical Queensland, Australia. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa, 61-67. Center for International Forestry Research, Bogor, Indonesia.

Simpson, J.A., Smith, T.E., Keay, P.T., Osborne, D.O., Xu, Z.H. and Podberscek, M.I. 2004. Impacts of inter-rotation site management on tree growth and soil properties in the first 6.4 years of a hybrid pine plantation in subtropical Australia. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 139-149. Center for International Forestry Research, Bogor, Indonesia.

Simpson, J.A., Xu, Z.H., Smith, T., Keay, P., Osborne, D.O. and Podberscek, M. 2000. Effects of site management in pine plantations on the coastal lowlands of subtropical Queensland, Australia. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 73-82. Center for International Forestry Research, Bogor, Indonesia.

Woods, R.V. 1990. Second rotation decline in *Pinus radiata* plantations in South Australia has been corrected. Water, Air and Soil Pollution 54:607-619.

Slash distribution of *E. globulus* in West Australia. (Photo: Daniel Mendham)

Effects of Site Management on Growth of a Second-rotation Chinese Fir (*Cunninghamia lanceolata*) Plantation

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Abstract

The study aimed to measure the influence of various site management treatments on productivity of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) plantations over a rotation. After clearcutting a first-rotation stand, a second-rotation plantation of the same species was established using five site preparation treatments. Nine years after planting there were no significant differences in tree growth due to treatments. However, trees on the plots retaining a high amount of slash grew the best and those in the slash-burnt plots had the poorest growth. Soil bulk density in the 0-10 cm layer across all the plots decreased slightly initially and then returned to preharvest levels at 2 and 3 years after treatment respectively. Soil pH value, organic C and total N in 0-10 and 10-20 cm layers from before harvesting to 9 years after planting showed significant difference, and a decreasing trend over time. Slash and litter of *C. lanceolata* decomposed fastest in the early stages and the rate of decomposition slowed with time. Leaf residues decomposed most rapidly while the branches decomposed slowly. After 22 months, 50% of the combined residue was decomposed and only 5% remained after 97 months. Burning or removing slash litter can cause productivity decline, probably due to nutrient loss and soil erosion. While the differences in tree growth were not significant at this stage, management practices which conserve organic matter and nutrients at the site are recommended for sustaining long-term productivity.

Introduction

Cunninghamia lanceolata (Lamb.) Hook. is one of the most important tree species producing timber in south China, and it plays a crucial role in forestry in the region. As the area of *C. lanceolata* plantations enlarges, there is more replanting on sites where one or more rotations have been harvested. Concern about the potential of site degradation is rising. The authors have used time series and spatial series methods to investigate management that may prevent site degradation by successive plantations. This study has been reported in other papers (Fan *et al*. 2000, 2001, Fan and Ma 2001, Ma *et al*. 2000a, b).

Long-term research was initiated to study the influence of retaining different levels of slash (harvest residues) and litter on the growth of a second-rotation plantation and the effect on soil properties. The objectives were to examine the potential of site degradation, and propose the optimal management measures to maintain or increase the productivity of second-rotation plantations and sustain soil productivity. Site and experimental details, and results up to age 6 years were reported by Fan *et al*. (1998, 1999a, b, 2004).

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Location and Site Description

The experiment is located in Fujian Province, southeastern China (Xiayang Forest Farm, Nanping), at latitude 26°48' N and longitude 117°59' E. The altitude is 230 m. This is in the middle subtropical zone where mean annual precipitation is 1817 mm, mean annual temperature is 19.4°C, average temperatures in January and July are 9.1°C and 28.4°C respectively, and extreme temperatures range from -5.8°C to 41°C. Annual sunshine is 1709 hours. The soil is an unidentified red soil with a depth of over 1 m. It is acidic and very fertile, making it suitable for growing *C. lanceolata*. The study was established after clearfelling a 29-year-old *C. lanceolata* plantation (Fan *et al.* 1998).

Methods

A randomised complete block design of five plots in each of four blocks was established on a clearfelled area. Each plot is 600 m^2 in area and was planted with 150 *C. lanceolata* seedlings. There were five treatments.

BL$_0$	All aboveground organic matter 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
SB	Stem and bark harvest + burning. Same as BL$_2$ except the residue was burnt.

Planting holes, 50 cm x 50 cm x 40 cm, were hand dug at planting spots. Seedlings were planted in February 1997 and mixed fertiliser (content of N, P, and K were unknown) at a rate of 100 g per seedling was applied in May 1997. Because of poor initial survival caused by weed competition, dead trees were replaced in December 1997. The plots were hand cultivated twice a year in 1997, 1998 and 1999, and once in 2000. Annual measurements of growth included height, diameter at breast-height and survival rate.

Soil samples were collected in October 1996 before harvesting trees. After planting samples were collected in January 2000, January 2003 and December 2005 (3, 6 and 9 years after planting). At each sampling time, soil samples from five random points per plot were collected from three layers, 0-10,10-20 and 20-40 cm, and mixed within depths. Samples were collected from 25-35 cm depth in the 20-40 cm soil layer. The samples were air-dried for chemical analysis. Soil samples for bulk density analyses were collected once a year.

Methods for soil analysis were:
- total N, by $K_2Cr_2O_7$ and H_2SO_4 digestion and H_3BO_3 absorption;
- organic C, by $K_2Cr_2O_7$ and H_2SO_4 digestion; and
- pH, in 1:2.5 water solution.

Decomposition of slash was evaluated in two phases using a nylon mesh bag technique. In the first phase, harvest residue was collected just after the trees were harvested. Each bag (1 mm mesh and 25 cm × 25 cm in size) contained 250 g of fresh leaf and branch residue (111 g dry weight). Twenty-two mesh bags were placed in the BL$_2$ plots in each block. Three bags in each plot were collected 2, 4, 6, 11, 16, 23 and 32 months after harvesting. These samples were used to determine the remaining weight of samples. A portion of each sample was dry ashed at 500°C to express biomass on ash-free basis. The second phase began 32 months after harvesting. Decomposing slash and litter were collected randomly from the BL$_2$ plots in each block. The residue (mainly medium- and large-sized branches) was air-dried and placed into bags and remaining biomass on an ash-free basis was determined 36, 44, 56, 72, 84, and 96 months after harvesting.

Results and Discussion

Tree Growth Response

A landslide heavily disturbed one of the replications and this block was excluded from the trial. As noted earlier, because of mortality during the first year some plots required some re-planting. Preliminary analyses showed that growth differences and

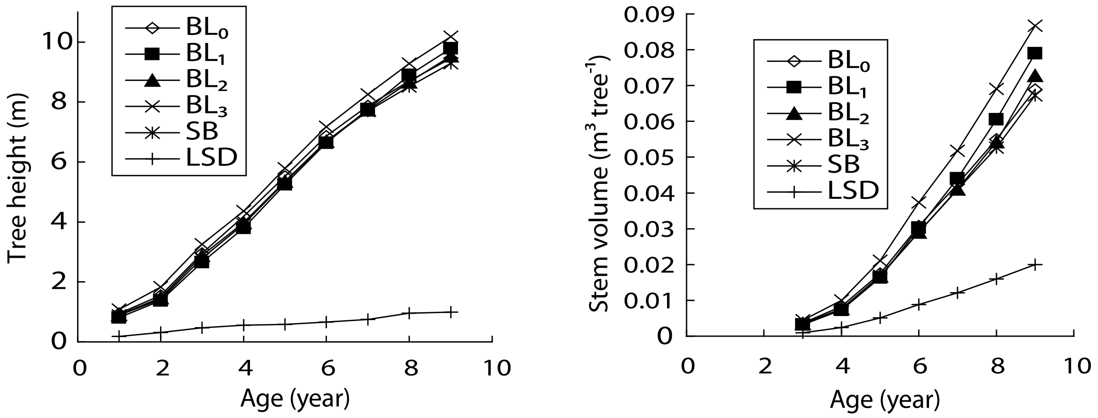

Figure 1. Effect of slash management on tree growth from age 1 to 9-years

Table 1. Number of stems, diameter at breast-height (DBH), height (Ht) and stem volume at age 9 years

Treatments	No. stems (ha^{-1})	DBH (cm)	Height (m)	Volume (m^3 ha^{-1})
BL_0	2 077	13.8	9.4	141.8
BL_1	1 949	14.6	9.8	154.8
BL_2	2 132	14.2	9.5	154.1
BL_3	1 901	15.1	10.2	165.4
SB	1 902	13.8	9.3	128.4
LSD p=0.05	420	1.5	1.0	50.1

treatment effects were not affected by the size of replanted trees, so growth results are calculated using data for all trees.

Slash treatments had significant effects on the growth from 1 to 4 years of age (Fan *et al.* 1999b, 2004) but from ages 5 years onwards, treatments had no significant effect on tree growth as seen from results at age 9 years (Fig. 1, Table 1). While not statistically significant, trees on the plots with double slash (BL_3) consistently grew at faster rates, followed by trees in BL_1 treatment and the lowest growth was found in cases where slash was burnt (SB). Initially trees on the no slash treatment (BL_0) grew better due to less weed competition but this growth rate was not maintained later. Slash burning treatment (SB) did not stimulate tree growth in this study (Fan *et al.* 1998, 1999a, b) (Table 1), although it improved early tree growth in other studies of this network project, e.g. in Brazil (Gonçalves *et al.* 2000), Congo (Bouillet *et al.* 2000) and South Africa (du Toit *et al.* 2000). The main reason for this discrepancy is probably the influence of higher soil fertility at the Chinese site.

Soil Properties

Table 2 summarises the results of soil analysis in relation to time after planting. Since the effects of treatments were small (Table 3), we have summarised the results in Table 2 as mean of all treatments to examine the main effects. Soil bulk density in the 0-10 cm layer across all the plots decreased slightly initially and then returned to preharvest levels at 2 and 3 years respectively after treatment (Fan *et al.* 2004). Bulk density of the soil at this site is lower than most other sites in the CIFOR network (see this volume). Bulk density increased gradually with depth, which is a common observation but was not affected by stand age. Soil pH in 0-10 cm and 10-20 cm layers decreased significantly from before harvesting to age 9 years. There were similar trends in soil organic C and total N. Whether the trends in soil C and total N were indicative of any significant shifts in process are not clear and may have been influenced by the relatively low sampling intensity or shift in laboratory analysis. Clearer conclusions may be possible with long-term data collection.

As described in the experimental methods we sampled and analysed soil to 40 cm depth. In general the effects of treatments on soil properties were small and inconsistent and so only data for the surface soils are reported in Table 3. Also we have presented data only for the start of the experiment and at age 9 years to show the main trend, if any. Results in Table 3 confirm that in general there are no significant and consistent changes in bulk density with the growth of the plantations. However, there was a marked reduction in soil pH, C and N at age 9 years regardless of treatments. When changes in bulk density and organic C are considered, the amount of organic C in the top 0-40 cm of soil decreased from 90.8 t ha^{-1} before harvest to 83.2 t ha^{-1} for 9 years after planting (Tables 2 and 3). The difference was statistically significant.

Organic C and total N are important indexes of soil fertility. Though they were not significantly affected by different treatments, the changes of different treatments before planting, and 9 years after planting are worth considering for further careful measurement and analysis.

Decomposition Rate of Slash and Litter

Cunninghamia lanceolata slash consists mainly of branches and leaves, in proportions of 67.4% and 32.6% of the total dry weight respectively. The branches are mainly 1-2 cm in diameter making up 42.6% of the total dry weight of the branches and 28.7% of the total residue (Table 4).

The measured and modelled decomposition rates of the slash are shown in Fig. 2. The decomposition followed the exponential model proposed by Olson (1963). Calculated with this model, leaves decomposed faster than branches. It took 9

Table 2. Soil properties before harvesting and 9 years after planting (mean values for all treatments)

Property	Soil depth (cm)	Sample (years after planting)		Mean	LSD p=0.05
		0	9		
Bulk density	0-10	0.94	0.93	0.93	0.04
(g cm^{-3})	10-20	1.00	1.03	1.02	0.04
	20-40	1.08	1.10	1.09	0.04
pH	00-10	5.07	4.80	4.94	0.11
	10-20	4.91	4.66	4.78	0.08
	20-40	4.89	4.63	4.76	0.05
Organic C	0-10	31.04	27.70	29.37	2.47
(g kg^{-1})	10-20	24.79	21.96	23.37	1.92
	20-40	17.24	15.86	16.55	1.50
Total N	0-10	1.58	1.41	1.49	0.13
(g kg^{-1})	10-20	1.24	1.14	1.19	0.08
	20-40	0.93	0.89	0.91	0.09
Organic C (t ha^{-1})	0-40	90.84	83.18	87.01	5.32

Table 3. Effects of treatments on soil bulk density, pH, organic C and total N in 0-10 cm layer and organic C in 0-40 cm layer at ages 0 and 9 years

Property	Age (yr)	Soil depth (cm)	Treatments					Mean	LSD
			BL_0	BL_1	BL_2	BL_3	SB		
Bulk density	0	0-10	0.93	0.93	0.93	0.93	0.97	0.94	0.14
(g cm^{-3})	9	0-10	0.93	0.95	0.93	0.89	0.96	0.93	0.05
pH	0	0-10	5.03	5.08	5.08	5.04	5.14	5.07	0.27
	9	0-10	4.63	4.81	4.86	4.87	4.86	4.80	0.25
Organic C	0	0-10	31.19	31.86	28.22	32.54	31.37	31.04	7.28
(g kg^{-1})	9	0-10	26.50	27.13	28.74	29.59	26.51	27.70	4.61
Total N	0	0-10	1.474	1.862	1.470	1.533	1.558	1.579	0.380
(g kg^{-1})	9	0-10	1.368	1.393	1.426	1.488	1.377	1.410	0.158
Organic C	0	0-40	91.57	89.30	89.29	96.28	87.73	90.84	15.69
(t ha^{-1})	9	0-40	79.66	82.29	85.16	84.59	84.18	83.18	10.63

Table 4. Diameter distribution and dry weight of branches in slash

Branch diameter (cm)	Proportion of the branch weight (%)	Proportion of the total slash weight (%)
< 1	14.6	9.8
1-2	42.6	28.7
2-3	37.4	25.2
≥3	5.4	3.7

Table 5. Decomposition rates of slash biomass components

Components	Half-decomposition time (month)	95% decomposition time (month)	98% decomposition time (month)	99% decomposition time (month)
Leaf+branch	22	97	127	149
Leaf	9	17	17	18
Branch	28	121	159	187

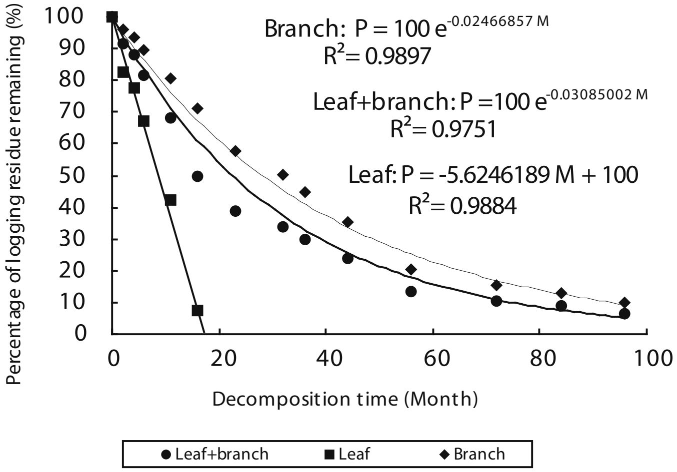

Figure 2. Weight loss from mesh bags during decomposition of logging residue fractions for 96 months

months and 17 months for leaves to decompose to 50% and 5% of the original weight. Branches lost 50% and 95% of their weight in 28 and 121 months respectively (Table 5).

The nature and pattern of decomposition described reflect the rate at which nutrients would be released from slash to the soil. This is characterised by an early rapid release, especially from nutrient-rich leaves, when nutrient uptake by the new stand would also be high.

Conclusions and Management Implications

Management of a site in Nanping with a range of slash and litter management practices had no significant effect on growth of Chinese fir at age 9 years, but there was a trend suggesting that tree growth benefited from a high level of slash retention. This is partly because these soils have relatively high soil fertility.

Soil properties, including bulk density, pH, organic C and total N, also showed no consistent (apart from some small transient changes) effects in relation to slash treatment. There was however a reduction in soil pH, C and N at age 9 years regardless of treatments.

Slash and litter are major store of organic matter and nutrients in these sites (Fan *et al*. 1998 and 1999b) and they decompose gradually to release nutrients to soil. Since Chinese fir plantations are usually on relatively steep sloping land and the soil is erodible, exposure of site after clearfelling by slash and litter removal by local community or the traditional burning practices will have negative consequence on sustainable production. Declining productivity is of concern. Based on these considerations and the results from this study, Nanping Forestry Committee has stopped slash burning at all the state forest farms since 2001, although this practice adds to management costs.

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References

Bouillet, J.P., Nzila, J.D., Laclau, J.P. and Ranger, J. 2000. Effects of site management on *Eucalyptus* plantations in the equatorial zone, on the coastal plains of the Congo. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 7-11 December 1999, Kerala, India, 11-20. Center for International Forestry Research, Bogor, Indonesia.

du Toit, B., Esprey, L.J., Job, R.A., Fuller, G.F. and Dovey S.D. 2000. Effects of site management in *Eucalyptus grandis* plantations in South Africa. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 7-11 December 1999, Kerala, India, 21-30. Center for International Forestry Research, Bogor, Indonesia.

Fan, S., Liao, Z. and Peng, L. 2004. Effects of site management on the growth of a second-rotation Chinese fir (*Cunninghamia lanceolata*) plantation three to six years after planting. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings in Congo July 2001 and China February 2003, 163-170. Center for International Forestry Research, Bogor, Indonesia.

Fan, S., Lin, G. and He, Z. 1999a. Impact of site management on productivity of second generation 1-year-old plantation of Chinese fir. Scientia Silvae Sinicae 35:120-126. (in Chinese)

Fan, S. and Ma, X. 2001. Studies on cultivation nutrition of Chinese fir plantations with multi-generation management. Proceedings of a Silviculture workshop, 2001, 120-131. Chinese Environmental Science Press, Beijing. (in Chinese)

Fan, S., Ma, X. and Chen, S. 2000. Comparative study on growth and development of different generation plantations of Chinese fir. Scientia Silvae Sinicae 36:9-15. (in Chinese)

Fan, S., Ma, X. and Fu, R. 2001. Comparative study on underground vegetation development of different generation plantations of Chinese fir. Forest Research 14: 8-16. (in Chinese)

Fan, S., Yang, C. and Lin, S. 1998. Chinese fir plantation in Fujian Province, China. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa, 69-72. Center for International Forestry Research, Bogor, Indonesia.

Fan, S., Yang, C. and He, Z. 1999b. Effects of site management in Chinese fir (*Cunninghamia lanceolata*) plantations in Fujian Province, China. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 7-11 December 1999, Kerala, India, 83-86. Center for International Forestry Research, Bogor, Indonesia.

Gonçalves, J.L.M., Serrano, M.I.P., Mendes, K.C.F.S. and Gava, J.L. 2000. Effects of site management in a *Eucalyptus grandis* plantation in the humid tropics: São Paulo, Brazil. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 7-11 December 1999, Kerala, India, 3-9. Center for International Forestry Research, Bogor, Indonesia.

Ma, X., Fan, S. and Liu, A. 2000a. A comparison on soil fertilities of Chinese fir plantations of different generations. Forest Research 13:577-582. (in Chinese)

Ma, X., Liu, A. and Ma, Z. 2000b. A comparative study on nutrient accumulation and distribution of different generations of Chinese fir plantations. Chinese Journal of Applied Ecology 11:501-506. (in Chinese)

Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44:322-331.

Discussion of research results (CIFOR Network) with stakeholders, forest engineers and students of the course of forest engineering of ESALQ by the root system of six years old *E. grandis*. Brazil. (Photo: Leonardo Goncalves)

Mixed-species Plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil

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Abstract

Sustainable production from plantation forests depends on conserving organic matter and availability of soil nutrients, especially in short rotation stands on low fertility sites. The introduction of nitrogen-fixing trees may be an option to manage nitrogen and organic matter in those plantations where nitrogen may limit growth. This paper explores the effect of *Eucalyptus grandis* and *Acacia mangium* mixtures on tree growth, biomass allocation, net primary production, and estimation of the atmospheric nitrogen fixation. The acacia understorey in mixed-species stands did not influence biomass production and partitioning in the eucalypt overstorey, resulting in 10% higher total biomass accumulation in the mixture with *A. mangium* at 50% of the *E. grandis* density (50A:100E) than in the pure eucalypt stand (0A:100E), from age 9 months onwards. Total net primary production amounted to 31 t ha^{-1} and 49 t ha^{-1} from 18 to 30 months of age in pure acacia (100A:0E) and pure eucalypt (0A:100E) stands, respectively. Acacia net primary production in 50A:100E was only 3 t ha^{-1} throughout the same period due to high interspecific competition. At age 30 months, the amount of nitrogen fixed was estimated at about 30 kg N ha^{-1} for *A. mangium* planted in 50A:100E by the ^{15}N dilution method, and about 65 kg N ha^{-1} for 100A:0E by the ^{15}N natural abundance method.

Introduction

Eucalyptus and *Acacia* are among the most widely planted tree genera in the tropics (FAO 2001). Empirical observations, as well as biogeochemical cycle studies and modelling approaches, show a general trend for increased N fertiliser requirement over successive rotations in commercial eucalypt plantations (Gonçalves *et al.* 2004, Laclau *et al.* 2005). Inputs of N fertiliser are a significant cost of silviculture in Brazil and little information is available about potential risks of leaching of nitrates in tropical forest soils (Fisher and Binkley 2000). Tropical multi-species plantations are likely to generate greater productivity (Binkley *et al.* 2003, Forrester *et al.* 2006). Planting N-fixing species in commercial eucalypt plantations may be an attractive option to improve the soil N status, since these species are expected to be quickly suppressed by eucalypts and may lead to more complete use of site resources from greater access to above- and below-ground resources (Forrester *et al.* 2006, Kelty 2006).

Research on mixed-species plantations began in the 1980s (Kelty 2006) with studies in annual legume cover crops (Nambiar and Nethercott 1987, Little *et al.* 2002) and perennial species (Gadgil *et al.* 1986, Watt *et al.* 2003). Experiments showed mixed-species plantations of *Eucalyptus* with nitrogen-fixing trees have the potential to increase productivity compared to eucalypt monocultures (Khanna 1997, Forrester *et al.*

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2006). However, the success of mixed-species plantations depends greatly on the selection of N-fixing species according to site attributes (Forrester *et al.* 2006). Most of the monospecific eucalypt stands used as controls in previous studies were quite different from the commercial eucalypt plantations in Brazil. A literature review showed mean annual increment (MAI) of eucalypt stands used as controls in all except in four studies of mixed-species ranged from 3 to 17 t ha^{-1} yr^{-1} (Forrester *et al.* 2006). The MAI of commercial plantations ranges from 20 to 30 t ha^{-1} yr^{-1} in Brazil, even on lower fertility soil (Gonçalves *et al.* 2004). Several decades of genetic improvement of eucalypts in Brazil, associated with high levels of fertiliser inputs and complete weed control, have made Brazilian commercial eucalypt plantations much more productive than typical N-fixing tree species. Therefore, competition between these eucalypts and N-fixing species is likely to differ significantly from patterns observed in less productive eucalypt plantations.

Several approaches have been used in mixed-species experiments but the two most common ones are replacement and additive designs (Forrester *et al.* 2006). In replacement designs, the density of monospecific and mixed treatments is constant and the proportions of the two component species are varied. Replacement series designs have been used in mixed-species experiments of *Eucalyptus* and N-fixing species to investigate species interactions and stand-level productivity. Competition and facilitation between *Eucalyptus* and N-fixing species in such designs need to be studied with spatially explicit models of individual tree growth (Boyden *et al.* 2005) since interspecific interactions at the plot level are confounded with changes in spacing between trees of each species. In additive series designs, the density of the commercial species remains constant while that of the other varies. Additive series make it possible to assess the effects of the density of one species on the development of the other species. A combination of these two designs was tested in the present study, comparing monospecific stands of *Eucalyptus grandis* (Hill ex Maid.) and *Acacia mangium* (Wild.) with mixed plantations at 1:1 proportions, and other stands with different densities of acacia for the same density of eucalypts. The experiment was designed to lead to a fine-grained mixture with a stratified canopy in which the lower canopy species is the N-fixer (Kelty 2006).

The aim of this study was to examine the effect of mixtures of *E. grandis* and *A. mangium* on stand growth, biomass allocation, net primary productivity and biological N_2 fixation.

Materials and Methods

Site Characteristics

The study was carried out at the Itatinga experimental station of the São Paulo University (23°02'S, 48°38'W). Maximum altitude is 863 m, mean annual rainfall is 1360 mm with a cold season from June to September, and mean annual temperature is 19°C. The experiment was located on the top of a hill (slope < 3%). Soils are Ferralsols (FAO classification) developed on cretaceous sandstone, Marília formation, Bauru group. Textural homogeneity is high (clay content around 12% in the A1 horizon and ranging from 20% to 25% between the depths of 1 m and 6 m). The soil pH is acidic and amounts of bioavailable nutrients are low (<0.2 $cmol_c$ kg^{-1} exchangeable bases below 5 cm depth).

The experiment was installed in an ex-*E. saligna* (Sm.) plantation which had regrown from coppice without fertiliser application from 1940 to 1997. This was harvested and the stumps were killed. *Eucalyptus grandis* seedlings were planted in 1998 with a fertiliser (300 kg ha^{-1} NPK 10:20:10). A large response to N fertiliser was expected due to the high levels of nutrient exported at harvest (in the boles) and lack of fertilisation since 1940.

Experiment

The *E. grandis* stand was harvested in December 2002. Only the boles were removed from the plot and slash was spread evenly across the experimental plots. A complete randomised block design was installed in May 2003, with seven treatments (100 trees per plot) in four blocks:

T_1 *A. mangium* planted at a stocking density of 1111 trees ha^{-1} (3 m x 3 m spacing), (100A:0E);

T_2	*E. grandis* planted at a stocking density of 1111 trees ha^{-1} (3 m x 3 m spacing), without N fertilisation (0A:100E);
T_3	*E. grandis* planted at a stocking density of 1111 trees ha^{-1} (3 m x 3 m spacing), with N fertilisation (0A:100E+N);
T_4	T_2 + *A. mangium* planted in mixture at a density of 25% of the eucalypt density (25A:100E);
T_5	T_2 + *A. mangium* planted in mixture at a density of 50% of the eucalypt density (50A:100E);
T_6	T_2 + *A. mangium* planted in mixture at a density of 100% of the eucalypt density (100A:100E);
T_7	Mixture at 1:1 proportion between *E. grandis* and *A. mangium* (555 trees ha^{-1} of each species), without N fertilisation (50A:50E).

Eucalypt seedlings were planted in the interrow after subsoil cultivation to 40 cm depth. Acacia seedlings were inoculated with rhizobium strains selected by EMBRAPA (Rio de Janeiro) for their N_2 fixation capacity, and high level of nodulation in the nursery. They were planted at mid distance between eucalypts in T_4 to T_6, in the same planting rows, to allow access in the stand. Fertiliser inputs were typical of the local commercial silviculture in this area. Two tons per hectare of dolomite were applied at planting and 202 g plant^{-1} of superphosphate (45% P_2O_5) were buried at 20 cm from the plants, with 30 g plant^{-1} of KCl (60% K_2O), 27 g plant^{-1} of FTE BR12 (micronutrients), and 27 g plant^{-1} of Borogran (B). In T_3, 30 kg N ha^{-1} were applied (ammonium nitrate form) at planting. Three additional fertilisations were applied, with 80 kg ha^{-1} of KCl (60% K_2O) at ages 6, 12 and 18 months in all the treatments, as well as 30 kg N ha^{-1} (ammonium nitrate form) only in T_3 at the same ages (total application of 120 kg N ha^{-1}).

The treatments selected for biomass estimation were also established in about 10 buffer rows on the two sides of each block, in order to perform sequential destructive samplings without disturbing stand growth inside the trial. However, the number of acacias in T_5 was not sufficient in the buffer rows and several trees were sampled from age 18 months in the T_5 plot of block 4 (B_4T_5).

Biomass and N Accumulation

Aboveground tree components

Circumference at breast height (CBH) and height were measured on each tree in the inner measurement plot (36 to 72 trees per plot measured) at ages 4, 9, 12, 17, 24, 29 and 37 months. Crown diameter was measured at 9 and 12 months of age for each tree in two perpendicular directions. Most of the acacias were multistemmed trees and the circumference of all the stems with a diameter at breast height (D) > 2 cm was measured at each inventory. For multistemmed trees, the basal area at breast height of all the stems was accumulated for each tree and an 'equivalent diameter' 'calculated from the sum of the total basal area of the tree.

Aboveground biomass was estimated by sampling six trees distributed throughout the range of height in T_1 and T_2 at age 6 months. At ages 12, 18 and 30 months, 6, 8 and 10 trees of each species were sampled throughout the range of basal areas, respectively, in three treatments (T_1, T_2 and T_5). The trees were separated into components: leaves, living branches, dead branches, stemwood and stembark. Diameters, lengths and weight were measured in the field. Tree foliage was divided into thirds according to tree height at 18 and 30 months. Subsamples were taken from all the components, dried at 65°C to constant weight, and ground for determination of total N concentration. Biomass and N content tables were established for each component from age 6 months to age 30 months, as polynomial relationships to CBH and age. At 6 months, the relationships derived from trees in pure stands (T_1 and T_2) were applied to trees in the mixture (T_5), as competition had not influenced tree growth at that age.

Belowground tree components

Stumps and coarse roots (diameter > 1 cm) were excavated at 18 months for all the trees sampled aboveground. At 30 months, stumps and coarse roots were excavated for five eucalypt trees covering the range of basal areas (among the 10 trees sampled aboveground), and all the acacia trees sampled aboveground in T_1, T_2 and T_5 (total of 10 eucalypts and 30 acacias). Medium-sized roots (diameter between 3 and 10 mm) were sampled in four pits for each treatment T_1, T_2 and T_5, at ages 18 and 30 months. After carefully removing the adherent soil by hand, stumps and roots were weighed and sampled. The samples of each component were dried at 65°C until constant weight and ground for chemical analysis. Fine root biomass was quantified at ages 6, 12, 18 and 30 months in T_1, T_2 and T_5. Fine roots were sampled at 5-12 distances from selected trees with a root auger in twelve plots (3 treatments x 4 blocks) down to a depth of 1 m at ages 6 and 12 months and down to a depth of 2 m at 18 and 30 months. Composite samples of each root size were heated at 450°C for 4 hours and belowground biomasses were corrected to reach an ash content of 3% corresponding to the mean value found for the aerial components, uncontaminated by soil particles.

Return of N to soil

Litterfall. Litterfall was collected every four weeks in nine plots (T_1, T_2 and T_5 in 3 blocks) up to age 36 months. Leaves, flowers and fruits were collected from five litter-traps (52 cm x 52 cm) systematically situated in the stands to sample representatively different distances from the trees (15 traps per treatment). Bark and branches were collected in a 9 m^2 area delimited in each plot between four trees. The samples of each component were dried at 65°C until constant weight and ground for chemical analysis.

Root mortality. Fine root mortality was not measured in this experiment and quantitative studies on this are scarce for tropical forest plantations. Measurements in eucalypt stands in Congo found fine root turnover to be related to leaf turnover at age 2 years and the same trend was observed in an experiment with contrasting N inputs in the Itatinga experimental station (Unpublished data, Jourdan and Silva). The ratio between fine root mortality and mean fine root biomass throughout each development stage was then considered identical to that measured for leaf litter fall and leaf standing biomass. Fine root biomass was estimated by summing the increment in fine root biomass throughout each period with values of mortality measured for leaves: from 0.0 to 0.2 according to the treatment until age 12 months, from 0.2 to 0.6 between 12 and 18 months and from 1.0 to 1.9 between 18 and 30 months. N content was calculated thereafter according to the nutrient concentration of fine roots.

Estimation of N_2 Fixation

Fixation of atmospheric N_2 by *A. mangium* was estimated by two methods.

^{15}N natural abundance

Nitrogen contents and $\delta^{15}N$ within aerial tree components (leaves, branches, stem wood, stem bark) were determined in T_1, T_2 and T_5, for 4 trees per species at 18 months and 10 trees per species 30 months after planting. Additional leaf samples were collected at 18 months on 4 trees of each species. Belowground parts (stump, coarse roots, medium roots, and fine roots) were sampled on 3 trees at 18 months and 4 trees at 30 months. Trees covering the range of basal areas in each treatment were chosen among the trees sampled for biomass estimation. For a given tree component the percentage of N derived from atmospheric N_2 (Ndfa%) was calculated according to the equation (Shearer and Kohl 1986):

$$Ndfa\% = 100\ (\delta^{15}N_{REF} - \delta^{15}N_F)\ /\ (\delta^{15}N_{REF} - B) \quad (1)$$

where $\delta^{15}N_{species} = [(^{15}N/^{14}N)_{species} - (^{15}N/^{14}N)_{air}]\ /\ (^{15}N/^{14}N)_{air}$, $\delta^{15}N_{REF}$ was the relative natural isotopic abundance of eucalypts in T_2 and T_5, chosen as the reference non-fixing tree, $\delta^{15}N_F$ the relative isotopic abundance of *A. mangium*, and *B* the relative isotopic abundance of *A. mangium* growing on N-free medium. The mean *B* value of -0.3‰ measured by Galiana *et al.* (2002) for *A. mangium* was used for Ndfa% calculations in the present study.

$\delta^{15}N$ values were not significantly correlated with tree size, whatever the component and the species. Mean values of $\delta^{15}N$ for the trees sampled at each age were then used to estimate the %Ndfa in the tree components.

No significant differences in $\delta^{15}N$ of tree components were observed between *E. grandis* growing in pure stands (ET_2) and in mixture (ET_5). Moreover as there was no trend of lower $\delta^{15}N$ values for ET_2 or ET_5, the relative natural isotopic abundances of *E. grandis* were calculated as the means of the $\delta^{15}N$

measured for the eucalypt trees sampled both in T_2 and T_5. As the *A. mangium* litterfall essentially comprised leaves over the study period, the Ndfa% of leaves and litterfall were considered as equals. It was also supposed that the Ndfa% of living and dead fine roots were equals.

The amount of N derived from N_2 fixation (N_{fixed}) was estimated as follows:

$$N_{fixed} = \%Ndfa_{leaves} * N_{leaves} + \%Ndfa_{branches} * N_{branches} + \%Ndfa_{stem} * N_{stem} + \%Ndfa_{stump} * N_{stump} + \%Ndfa_{coarse\ roots} * N_{coarse\ roots} + \%Ndfa_{medium\ roots} * N_{medium\ roots} + \%Ndfa_{fine\ roots} * N_{fine\ roots} + \%Ndfa_{litterfall} * N_{litterfall} + \%Ndfa_{deadfine\ roots} * N_{deadfineroots} \tag{2}$$

where $N_{component}$ was the N content of the tree component estimated at the stand level by applying N tables to stand inventory, except for medium-sized and fine roots (hectare-basis-mean of the N contents of roots estimated by auger sampling and excavation in T_1, T_2 and T_5). Stembark and stemwood were analysed separately at 30 months but not at 18 months. A weighted average of the relative isotopic abundance of the stem was therefore calculated at 30 months according the following equation (Guinto *et al.* 2000).

$$\delta^{15}N_{stem} = (\delta^{15}N_{stemwood}\ N_{stemwood} + \delta^{15}N_{bark}\ N_{bark}) / (N_{stemwood} + N_{bark}) \tag{3}$$

15N dilution

The study was conducted in a 0.20 ha area planted with the T_5 design and separated from block 4 by five buffer rows. Ammonium sulphate (0.5 atom% ^{15}N) was applied 18 months after planting, at a rate of 20 kg N ha^{-1}. The fertiliser was dissolved in water and spread uniformly on the soil using a watering can.

Four *A. mangium* and four *E. grandis* trees covering the range of basal areas were sampled at 30 months in the inner plot. Representative samples of the different biomass components (leaves, branches, stemwood, stembark, stump and coarse roots) were collected for each tree. For a given tree component %Ndfa was calculated from the equation (Fried and Middelboe 1977):

$$\%Ndfa = 100\ [1 - (AE_{F30}) / AE_{REF30})] \tag{4}$$

where $AE = {}^{15}N*100/({}^{15}N + {}^{14}N) - 0.003663$, AE_{F30} was the per cent atom excess of *A. mangium* at 30 months and AE_{REF30} was the per cent atom excess of *E. grandis* at 30 months. Results of the natural abundance study were used to estimate %Ndfa of medium and fine roots. The amount of N derived from N_2 fixation was estimated from equation (2). The rate of N_2 fixation was considered unchanged before and after soil labelling.

Chemical and Isotopic Analysis

Total N was analysed for all tree components sampled at each age, by titration after Kjeldahl digestion. ^{15}N natural abundance was measured using a mass spectrophotometer (Delta Plus, Thermo Electron, Bremen, Germany) coupled to an elemental analyser (Carlo Erba NA 1110 CHNS, CE Instruments, Rodano, Italy). The precision of the measure was 0.5 ‰. Isotopic analyses were performed for the ^{15}N dilution experiment using a mass spectrometer with automatic N analysis, model ANCA-SL, from PDZ Europe, Crewe, United Kingdom (Barrie and Prosser 1996). The analytical precision was ±0.001 atom % ^{15}N.

Statistical Analysis

Pearson correlation coefficients were calculated in SAS using the PROC COR procedure. Homogeneity of variances was tested at each age by Levene's test and original values were log transformed when variances were unequal. Differences between treatments were tested in SAS using one-way or two-way ANOVA (SAS 1998). The probability threshold used to determine significance was $p < 0.05$. When the ANOVA indicated significant effects, the means were compared with Newman Keuls' multiple comparison tests, until age 18 months. From this age onwards, the plot B_4T_5 was excluded from the analysis and the PDIFF statement of PROC GLM was used.

Results

Stand Growth

N fertilisation significantly increased *E. grandis* height at 4 and 12 months after planting. While this response was not maintained at later measurements, the N-fertilised trees grew about

0.6 m taller than non-N-fertilised trees up until at age 36 months. Nitrogen application tended to increase eucalypt basal area ranging from 5 to 9 cm^2 tree^{-1}, from 12 to 36 months of age (Fig. 1) but this effect was not significant.

Productivity of eucalypt and acacia mixtures was influenced by treatment. Increasing acacia density in the eucalypt stands increased acacia height at age 12 months (100A:0E < 25A: 100E < 50A:100E < 100A:100E). A similar trend was observed in the eucalypt stands at this age, although differences were not significant. Competition for light started very early in the additive series, as mean crown diameter at age 9 months ranged from 1.0 to 1.3 m and 2.3 to 2.5 m for *A. mangium* and *E. grandis*, respectively, according to the planting design. The distance of 1.5 m between eucalypts

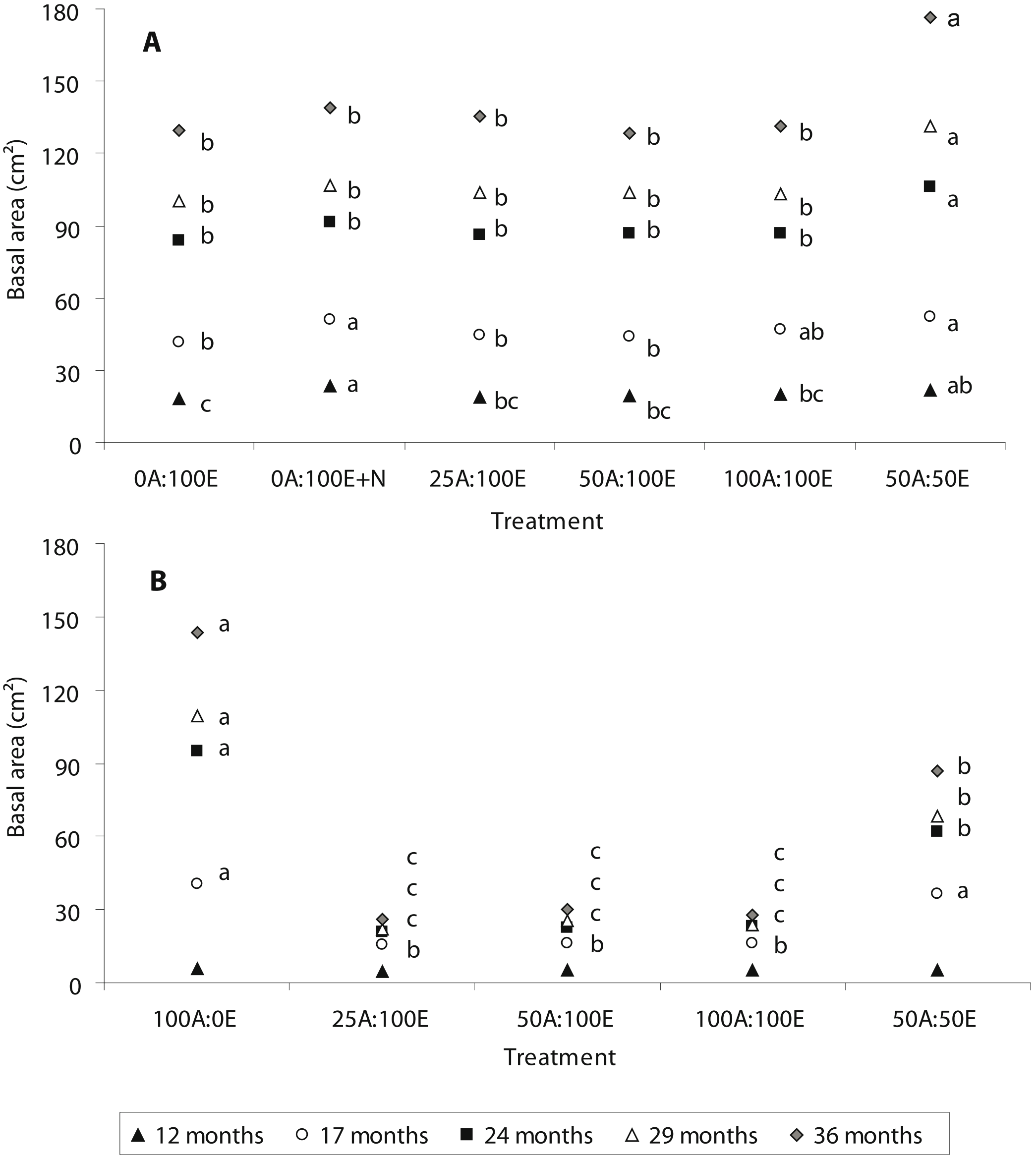

Figure 1. Mean basal area per tree of *E. grandis* (A) and *A. mangium* (B), from age 12 months to age 36 months. Different letters indicate significant differences ($p < 0.05$) among treatments at a given age.

and acacias in the planting row in 25A:100E, 50A:100E and 100A:100E was already occupied by *A. mangium* and *E. grandis* crowns at age 9 months. Interspecific competition led to a stratified canopy, with a significant suppression in acacia height growth between 17 and 24 months after planting. Effects of interspecific competition appeared earlier for basal area increment and significant differences were already observed at age 17 months. Moreover, the influence of competition with eucalypts on acacia growth was much more pronounced for basal area than height.

Spacing between acacias and eucalypts modified the architectural development of trees. Whereas eucalypt height was similar in all treatments, mean individual basal area of eucalypts was significantly higher in 50A:50E from age 2 years onwards. Height to diameter at breast height ratios (H/D) were not significantly different among treatments for eucalypts at age 12 months, but were significantly higher for acacia trees in 100A:100E than in 100A:0E. The influence of the planting design on H/D ratios increased from 12 to 36 months for the two species. Lower H/D ratios for eucalypts in 50E:50A showed that stems were more tapered when they grew in conditions of low interspecific competition. When interspecific competition was high for *A. mangium* (25A:100E, 50A:100E, 100A:100E), H/D ratios were significantly higher than in mono-specific stands. Moreover, interspecific competition led to a sharp decrease in number of stems per tree for acacias, from age 12 months onwards, leading to low basal area increments per acacia tree in 25A:100E, 50A:100E and 100A:100E. The mean number of stems per acacia tree at age 36 months was significantly higher in 100A:0E (3.7), than in 50A:50E (2.7) and in the additive series 25A:100E, 50A:100E, 100A:100E (between 1.6 and 1.8).

Biomass Production and Partition within Trees

Dynamics of biomass accumulation were influenced by planting design for the two species, regardless of tree component. A marked reduction in biomass accumulation for acacias was observed from the onset of competition for light with eucalypts. Biomass of acacia leaves and living branches were 2.5 and 2.7 times lower in 50A:100E than in 100A:0E at age 9 months, and 3.3 and 3.5 times lower at age 12 months, respectively. From age 12 months onwards, the biomass of all tree components remained approximately stable for acacias planted in the eucalypt stand (50A:100E). In monospecific stands, acacia grew slower than eucalypts, regardless of tree component. Leaf, living branch and stem biomass in 100A:0E were only 65%, 34%, and 28% of the amounts accumulated in 0A:100E, at age 12 months. However, a huge development of acacia crown in monospecific stands occurred from age 12 to age 18 months since acacia leaf biomass in 100A:0E was 1.4 times higher than eucalypt leaf biomass in 0A:100E at age 18 months.

Acacias did not influence biomass accumulation in eucalypts, regardless of component (Fig. 2). The lack of depressive effect of acacias on eucalypt growth led to a total biomass accumulation in 50A:100E about 10% higher than in 0A:100E from age 12 months onwards. However, differences between 50A:100E and 0A:100E were not significant ($p < 0.05$) until age 30 months.

Net Primary Production

Litterfall began 10 months after planting and amounted to about 8845, 13535, 1145, 12185 kg ha^{-1} of dry matter until age 3 years in 100A:0E, 0A:100E, 50A:100E (acacia litterfall) and 50A:100E (eucalypt litter fall), respectively. The great influence of interspecific competition on acacia growth led to a production of acacia litter eight times higher in monospecific stands than in 50A:100E, whereas the acacia stocking density was only double.

A sharp increment in total NPP of eucalypts was observed throughout the early growth of the stands since eucalypt NPP increment was four times higher from age 18 to 30 months than from 0 to 12 months in 0A:100E and in 50A:100E (Table 1). By contrast, acacia NPP was strongly influenced by interspecific competition, from the first year after planting. While the acacia stocking density in 50A:100E was 50% of that in 100A:0E, the total acacia NPP was three times lower in 50A:100E throughout the first year of growth. The influence of the interspecific competition on acacia biomass

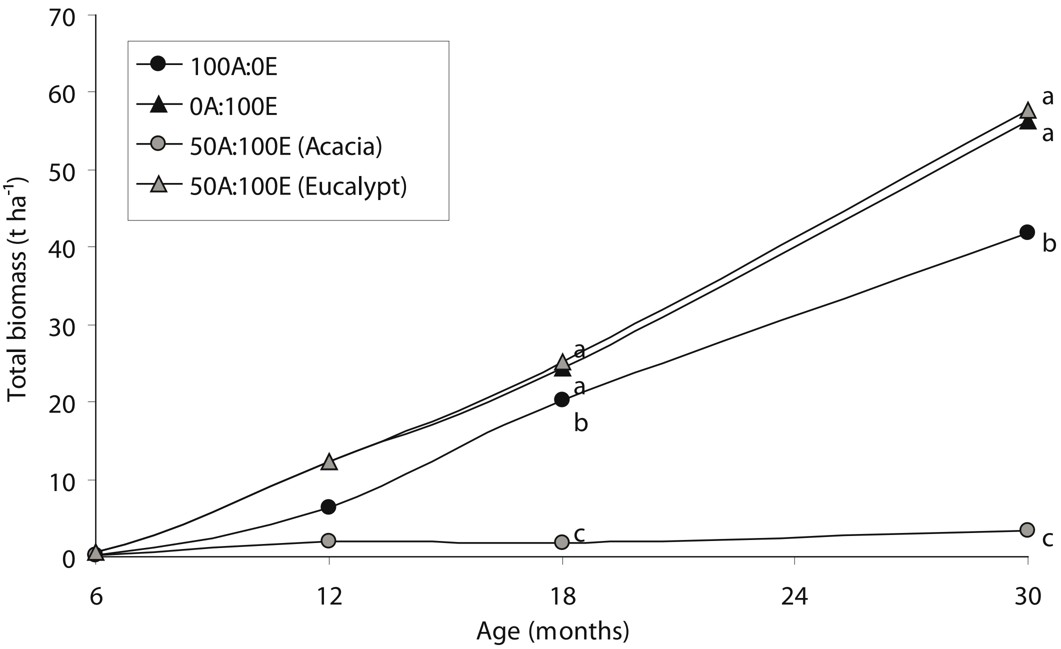

Figure 2. Dynamics of biomass accumulation in the stands 100A:0E, 0A:100E, and 50A:100E. The biomass of the aboveground and belowground components was cumulated at each age. Different letters at each age indicate significant differences in dry matter amount ($p< 0.05$).

production increased sharply with stand age since total acacia NPP was 12 times lower in 50A:100E than in 100A:0E between 18 and 30 months of age. NPP from 18 to 30 months after planting amounted to 31 t ha^{-1} and 49 t ha^{-1} in 100A:0E and 0E:100A, respectively. Fine root mortality estimations represented from 10% to 19% of total NPP between 18 and 30 months of age, according to the species. Aboveground NPP (ANPP) was 60% of total NPP the first year of growth for the two species, and the proportion of ANPP increased to about 80% of total NPP from 12 to 18 months after planting.

Nitrogen Concentration in Trees

At 30 months *A. mangium* in 50A:100E (AM) exhibited N higher concentrations than *E. grandis* growing both in 0A:100E (EP) and 50A:100E (EM). The differences were statistically significant except for medium roots (Table 2). A similar trend was observed for *A. mangium* in 100A:0E (AP), with significantly higher N concentrations than in *E. grandis*. In these cases AP showed lower N concentrations than *E. grandis* but the differences were not significant between the two species. No significant difference in N concentration was observed between EP and EM. Moreover, there was no general trend for higher N concentrations in eucalypts growing in mixture than in pure stands. Nitrogen concentration among components decreased in the following order: leaves > bark > fine roots > branches > stump/medium roots/coarse roots > stemwood. Nitrogen concentrations decreased from 18 months to 30 months after planting, higher for AM than for AP, irrespective of tree components and treatments, except for leaves of AP (data not shown).

Nitrogen Accumulation

Nitrogen content in the aboveground parts was significantly higher in the mixed-species stand (50A:100E) than in monospecific stands up to 12 months after planting (Fig. 3). Thereafter, N accumulation was higher in the pure acacia stand (100A:0E) than in 50A:100E, despite a lower overall stocking density. N accumulation in the

Table 1. Biomass increment, litterfall, fine root production and net primary production (NPP) from age 18 to 30 months (expressed in kg ha^{-1})

	T1 (100A:0E)	T2 (0A:100E)	T5 (50A:100E)		
	Acacia	Eucalypt	Acacia	Eucalypt	Total
Aboveground biomass increment	19114	27444	1385	27558	28943
Litterfall	6058	9406	690	8653	9343
Aboveground NPP	25172	36850	2075	36211	38286
Belowground biomass increment	2416	4562	25	4961	4986
Fine root mortality estimation	3233	7976	499	5844	6343
Belowground NPP	5649	12538	524	10805	11329
Total NPP	30821	49388	2599	47016	49615

Table 2. N concentration (g kg^{-1}) in the tree components at 30 months, and nitrogen content (kg N ha^{-1}) accumulated at 30 months after planting in the stands and total uptake from planting, including the returns to soil with litterfall and fine root mortality in 100A:0E, 0A:100E, and 50A:100E

Components	100A:0E	0A:100E	50A:100E		100A:0E	0A:100E	50A:100E	
	Acacia	Eucalypt	Acacia	Eucalypt	Acacia	Eucalypt	Acacia	Eucalypt
	N concentration				N content			
Leaves	21.5b	17.7c	24.7a	18.3c	123.6a	89.9b	11.8c	101.3b
Stem	3.8b	1.9c	4.8a	2.0c	77.0a	52.2b	6.6c	61.6b
Branches	5.3b	3.3c	6.7a	3.3c	43.9a	22.7b	3.8c	20.0b
Stump + coarse roots	4.9a	2.8b	4.4a	2.5b	15.1b	24.1a	1.4c	24.7a
Medium-sized roots	9.1a	3.2b	5.6b	2.8b	5.2a	2.5b	0.1c	1.7b
Fine roots	13.7a	6.1c	9.0b	5.3c	38.8a	19.4b	2.3c	15.2b
Total N in standing biomass					303.6a	210.8b	27.2c	223.5b
Litterfall					90.0b	105.0a	15.8c	95.0b
Fine root mortality(1)					51.8	59.7	9.5	39.7
Total N uptake from planting (1)					445.4	375.5	52.5	358.2

Different letters indicate significant differences ($p < 0.05$) among species for a given age and tree component.

(1) Root mortality estimation prevented from performing statistical analysis.

leaves 30 months after planting was 90, 113 and 124 kg ha^{-1} in 0A:100E, in 50A:100E and 100A:0E, respectively, representing from 40-45% of the amount of nitrogen in the standing biomass (Table 2). The N content of the stump and the roots ranged from 45 kg N ha^{-1} (0A:100E and 50A:100E) to 59 kg N ha^{-1} (100A:0E), representing about 20% of the total accumulation of N in the stands. The total amount of nitrogen involved in the biological cycle over 30 months after planting in 100A:0E, 0A:100E and 50A:100E was about 445, 375 and 410 kg N ha^{-1}, respectively. Litterfall and fine root mortality were two major fluxes of the N cycle, with a total input to the soil throughout the 30 months period estimated at about 140 kg N ha^{-1} for 100A:0E, 165kg N ha^{-1} for 0A:100E and 160 kg N ha^{-1} for 50A:100E. These fluxes represented around 45%, 80% and 65% of N contents within the standing biomass for 100A:0E, 0A:100E, and 50A:100E, respectively. The flux of N provided by fine root mortality over this period was estimated at about 17% and 35% of the amount of N accumulated in the standing biomass of AP and AM respectively, at age 30 months.

Estimation of N_2 Fixation

^{15}N natural abundance

Comparisons of δ^{15}N values in composite samples of leaves collected at 18 and 30 months after planting in 100A:0E, 0A:100E, and 50A:100E showed that the inter-block variability was non-significant, irrespective of species or sampling age. Moreover, δ^{15}N values in all the components of *E. grandis* trees were not significantly different in 0A:100E and 50A:100E, irrespective of sampling age. Mean δ^{15}N values were low, ranging mainly from 0.5 to 3%, and declining from 18 to 30 months after planting.

At age 18 months the higher δ^{15}N values of *A. mangium* than *E. grandis* observed in 0A:100E and 50A:100E prevented reliable estimations of %Ndfa. By contrast, even if most of the differences between the two species were not significant in the 30-month-old stands, the %Ndfa was estimated since δ^{15}N values in all the components of *A. mangium* were lower than those in *E. grandis*. Large differences of %Ndfa were observed among

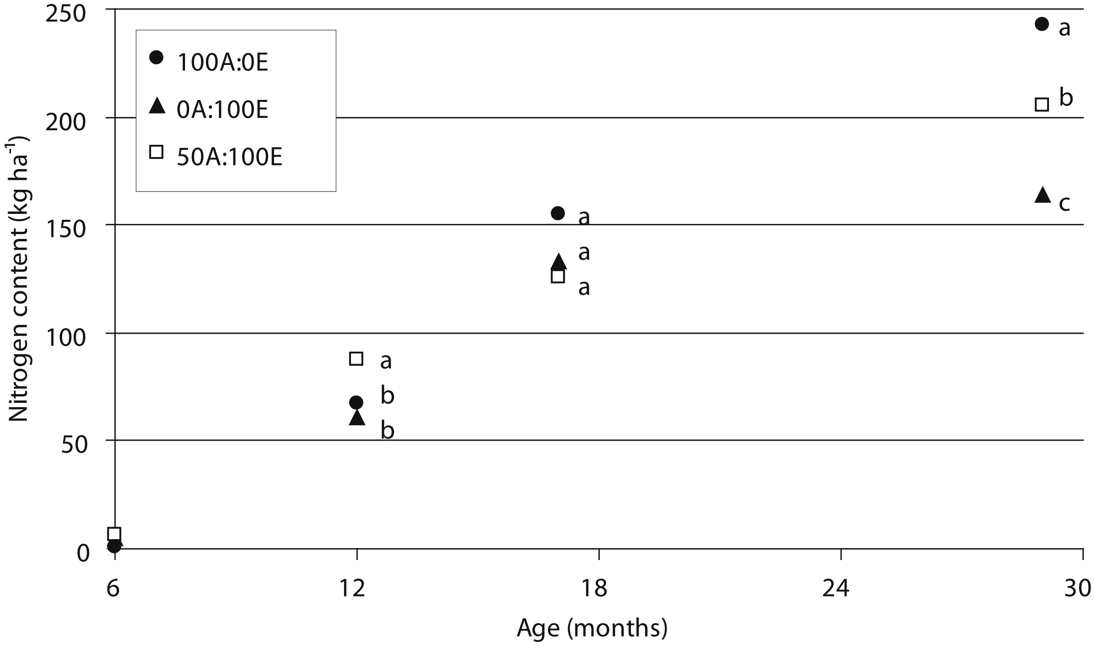

Figure 3. Change in N content of the aboveground components for treatments 100A:0E, 0A:100E and 50A:100E. Different letters indicate significant differences ($p < 0.05$) among treatments.

tree components for a given treatment. Leaves exhibited very low %Ndfa values (3 %) for both AP and AM. The %Ndfa of branches ranged from 20 to 75%, and that of medium and fine roots from 30 to 50%, except in AP (2%). The amounts of N derived from atmospheric fixation in the standing biomass and cumulated over 30 months of growth were much higher for AP (respectively 62.3 and 65.8 kg N ha^{-1}) than for AM (*resp.* 2.8 and 7.1 kg N ha^{-1}) (Table 3). The amount of N fixed accounted for 10 to 20% of the amount of N accumulated in the 30-month-old stands.

^{15}N dilution

The mean values of AE ranged from 0.0015 to 0.0091%, with a marked variability among tree components. *E. grandis* exhibited significantly higher AE values than *A. mangium*, irrespective of tree components.

%Ndfa estimated from ^{15}N dilution showed higher percentages of N_2 fixation, especially for leaves and stem, and much lower within-tree variability than with the ^{15}N natural abundance method. The amount of nitrogen derived from atmospheric N_2 was estimated at 16.0 kg N ha^{-1} in the standing biomass and 30.6 kg N ha^{-1} including N returns to the soil from planting with litterfall and fine root mortality (Table 3). The corresponding %Ndfa amounted to about 60%. The N fixed was found mainly in leaves, litterfall and dead fine roots that contained respectively 26, 35% and 13% of the total N fixed from planting.

Discussion

Influence of Acacia Stocking Density on Eucalypt Growth

We established this experiment on a site considered likely to be responsive to N fertiliser because of its 60 year history of cultivation under eucalypts without fertiliser amendment, and relatively poor soils. However, the NPP of eucalypts without N inputs (0A:100E) was higher than expected and differences in height and basal area between 0A:100E and 0A:100E+N were not significant beyond 2 years. This shows that it is important to understand the plantation response to N fertiliser when interpreting the response in a species mixture. However, a quantitative

Table 3. Estimation of N_2 fixation in the different components of *Acacia mangium* in 100A:0E (AP) and 50A:100E (AM), at 30 months after planting. Values (kg N ha^{-1}) of N derived from atmospheric N_2 in the standing biomass and in the total amount of N accumulated from planting are indicated. The ^{15}N natural abundance and ^{15}N dilution methods were used.

Tree components	AP	AM	AM
	^{15}N natural abundance		^{15}N dilution
Leaves	3.2	0.3	8.0
Stem	17.3	0.3	3.5
Branches	33.5	0.9	2.5
Stump + coarse roots	5.8	0.2	0.9
Medium-sized roots	1.7	0.1	0.1$^{(3)}$
Fine roots	0.8	1.0	1.0^{c}
Total N derived from atmospheric N_2 in standing biomass	62.3	2.8	16.0
Litterfall$^{(1)}$	2.4	0.4	10.7
Dead fine roots$^{(2)}$	1.1	3.9	3.9
Total N fixed from planting	65.8	7.1	30.6

$^{(1)}$ %Ndfa litterfall = %Ndfa leaves; $^{(2)}$ %Ndfa dead fine roots = %Ndfa fine roots; $^{(3)}$ estimated by ^{15}N natural abundance method.

assessment of tree response to N inputs is lacking in most of the studies of mixed-species plantations of eucalypts with nitrogen-fixing trees in the literature. Treatments to quantify stand response to N input should be implemented in future experiments dealing with N-fixing trees in mixed-species plantations. Such information is important to assess the potential of N-fixing trees to increase the productivity of non-N-fixing trees through improving N availability.

The complementary resource use of the two species made it possible to increase the overall biomass production, as observed in other studies with eucalypts and N-fixing trees (*A. auriculiformis*, *A. crassicarpa, A. dealbata*, *A. mearnsii*, *A. melanoxylon*, *Falcataria moluccana*, *Leucaena leucocephala*…) (Binkley *et al.* 2003, Forrester *et al.* 2006). This pattern might be different in pedo-climatic conditions leading to higher interspecific competition for water or nutrients (Rothe and Binkley 2001, Forrester *et al.* 2004). Moreover, it will be only possible to draw a definitive conclusion on an interaction between the two species at the end of stand rotation, as the increase in total biomass observed at age 30 months might be a result of the higher stocking density in the additive series. Experiments in this area have shown that maximum stemwood production of *E. grandis* plantations is obtained with stocking densities ranging from 1000 to 1500 trees ha^{-1} (Gonçalves *et al.* 2004). The stocking of 1111 trees ha^{-1} used for eucalypts in the additive series should then lead to a complete use of available resources in monospecific stands by age 7 years. When an increase in biomass production is observed in mixed species plantations at the end of stand rotation, this feature should be attributed to complementary resource use between the two species.

Biomass Production and Allocation

A large influence of interspecific competition on *A. mangium* development was observed. While *A. mangium* height was little affected by the planting design until age 2 years, the number of stems per stump was significantly reduced in mixed plantations. Height to diameter ratio (H/D) has been used to indicate the level of competition in even-aged forests. The H/D of acacias was highly dependent on their distance from eucalypts. The dynamics of biomass accumulation suggests that a higher competition for light than for belowground resources led to an adjustment of *A. mangium* structure: trees allocated more assimilates to height than to basal area and root increment to maintain as long as possible their crown in the upper part of the canopy. The same pattern was observed in mixed species plantations of *E. globulus* and *A. mearnsii* (Forrester *et al.* 2004). A significantly lower H/D ratio in 50A:50E than in 0A:100E at age 30 months suggests less competition for light in *E. grandis* when they grow farther from other *E. grandis* trees. Even if *A. mangium* was strongly suppressed from age 1 year in the additive series and did not show adaptation to low-light subcanopy environments, trees survived well under *E. grandis*, as observed for other N-fixing species considered to be shade intolerant (Binkley *et al.* 2003, Forrester *et al.* 2004, Hunt *et al.* 2006).

N Concentration and N Transfer from A. mangium to E. grandis Trees

The higher N concentration in *A. mangium* than in *E. grandis* globally observed in 100A:0E and 50A:100E might be a result of N_2 fixation. The same trend was observed in other mixed-species plantations, e.g. *A. mangium* vs *E. urophylla* (Blake) (Galiana *et al.* 2002); *Inga edulis* (Mart.) vs *Terminalia amazonia* (Gmel.) (Nichols and Carpenter 2006); *Casuarina equisetifolia* (L.) vs *E. robusta* (Sm.) (Parrotta *et al.* 1994). However, the higher N concentrations in AM than in AP might be partly explained by the lower growth of AM that might lead to a higher proportion of living tissues. The decrease in N concentration observed between 18 and 30 months both for *A. mangium* and *E. grandis* might be a dilution effect in the biomass of the trees, reflecting internal translocation of this element from older to younger tissues (Nambiar and Fife 1987, Laclau 2001). Whereas Khanna (1997) observed that N concentrations in *E. globulus* fine roots at 33 months after planting were higher when this species was planted in mixture with *A. mearnsii* than in monospecific stands, N concentrations in *E. grandis* trees were not influenced by the mixture with *A. mangium* until age 30 months in the present study. The lack of N transfer from N-fixing trees to the non-fixing ones in 50A:100E was likely to be confirmed by the similar values of $\delta^{15}N$ natural abundance for *E. grandis* trees in 0A:100E and 50A:100E. A large increment in soil N availability through N_2 fixation in mixed-species plantations requires: (1) N_2 fixation by the bacteria in symbiosis with the legume species, (2) N accumulation in the living tissues of the nitrogen-fixing tree, (3) returns to the soil of organic matter enriched in N, and (4) a mineralisation of legume-derived organic N. Even in fast-growing tropical plantations, such a process requires time.

Estimation of N_2 Fixation

Low values of $\delta^{15}N_{REF}$, as observed in the present study, prevent an efficient application of the ^{15}N natural abundance method (Dommergues *et al.* 1999, Unkovich and Pate 2001). Low ^{15}N natural abundance values measured in *E. grandis* and the limited number of trees sampled at each age (5 to 10) might explain inconsistent findings as $\delta^{15}N$ values at age 18 months higher in *A. mangium* than in *E. grandis* for several tree components. Further investigations would be necessary to assess the factors controlling the ^{15}N natural abundance values in each species. Studies should be also carried out to quantify the effect of the afforestation of the native savanna (cerrado) that contains legume species, on the time course of soil $\delta^{15}N$. In the present conditions the dilution method was likely to give the best estimation of N_2 fixation. Values of %Ndfa varied from 40 to 70% according to tree components with a weighted average of 60% both for standing biomass and total N uptake from planting. These results are consistent with those of Galiana *et al.* (2002) who estimated, using ^{15}N natural abundance, %Ndfa of about 50% for 2-year-old-stands of *A. mangium* in Ivory Coast.

Several limitations appeared in the present study to using ^{15}N natural abundance and ^{15}N dilution methods to estimate N_2 fixation by *A. mangium*:

- We have not quantified the possible difference in the N uptake pattern of the reference species and nitrogen-fixing tree as Danso *et al.* (1993*)* did. Variations in nitrate and ammonium availability might occur with soil depth, leading to differences in $\delta^{15}N$ of the mineral nitrogen taken up by the two species, as NH_4^+ is less depleted in ^{15}N than NO_3^- (Boddey *et al.* 2000).
- We observed that both *E. grandis* and *A. mangium* growing in monocultures (100A:0E and 0A:100E) developed a dense root system in the top soil (data not shown). In the mixture, however, *E. grandis* exhibited a much higher biomass of fine roots than *A. mangium* in the surface soil layer and this difference in root exploration might bias the estimation of N_2 fixation. Variations in nitrate and ammonium availability might occur with soil depth, leading to differences in $\delta^{15}N$ of the nitrogen taken up by the two species, as NH_4^+ is less depleted in ^{15}N than NO_3^- (Boddey *et al.* 2000).
- *Acacia mangium* fine root mortality was a major pathway for incorporation of N in the soil in both 100A:0E and 50A:100E. But two factors led to great uncertainties in the estimation of N_2 fixed in this component: (1) fine root mortality was estimated from observations made on leaf turn-over, and (2) only 4 bulk samples for each treatment were analysed to assess the relative isotopic abundance of this component. This sampling could have caused a poor estimation of the $\delta^{15}N_{fineroots}$ and therefore an overestimation of the differences in %Ndfa between AP (2%) and AM (41%). Two conditions must be then fulfilled to get an accurate estimate of the quantity of atmospheric N_2 fixed by acacia: (1) a reliable quantification of fine root mortality, and (2) an intensive sampling of fine roots for $\delta^{15}N$ analysis. Moreover, the potential translocation of N to living roots occurring during the root senescence was not taken into account and could have led to an overestimation of the N_2 fixation. However, previous studies have suggested that N translocation in fine roots is limited (Gordon and Jackson 2000).

Management Impacts

This study does not provide definitive results on the potential of mixed-species plantations of *A. mangium* and *E. grandis* in Brazil. However, at 3 years of age a total biomass accumulation in 50A:100E about 10% higher than in pure eucalypt stands, such mixed-species plantations might represent a good opportunity to increase stand production. They may also lead to a diversification of forest products (firewood, round wood, pulpwood), as well as a higher biodiversity (birds, insects, fungi, etc.). They are also likely to increase significantly N soil availability. The N input we have measured in the mixed stand is not negligible in such N depleted soil since *A. mangium* survives under the *E. grandis* canopy and may continue to fix N until the end of the rotation.

It must be stressed that the ecological conditions in the Itatinga region (low temperatures during winter) are not optimal for *A. mangium* growth and N_2 fixation. The same design has been duplicated at five sites in Brazil to assess the potential of this legume tree to increase the productivity of eucalypt plantations. Other experiments will be set up in Brazil to test other legume species, as well as various arrangements of both *E. grandis* and *A. mangium* trees, to contribute to an overall assessment of the potential of mixed-species plantations.

Forest managers will also have to balance the benefits and the additional-costs of the mixed species plantations in comparison with pure eucalypt stands. We stress that the design used in the present study does not impede mechanised operations. The additional costs are for seedling production, planting and the initial fertilisation of the acacias. Stand management may also need special attention depending on management goals.

Conclusions

Planting *A. mangium* as an understorey in *E. grandis* led to a biomass accumulation in the 50A:100E mixture about 10% higher than in monospecific stands from age 12 months. Net primary production increment of eucalypts was estimated to be about 49 t ha^{-1} from 18 to 30 months after planting. Acacia NPP was strongly influenced by interspecific competition, and was 31 t ha^{-1} and 3 t ha^{-1} throughout the same period in 100A:0E and 50A:100E, respectively. Under the experimental conditions described here ^{15}N dilution gave more reliable estimates of N_2 fixation than ^{15}N natural abundance. At age 30 months, the amount of nitrogen fixed was estimated to be about 30 kg N ha^{-1} for *A. mangium* in 50A:100E by ^{15}N natural abundance method, and about 65 kg N ha^{-1} in 100A:0E by the ^{15}N natural abundance method.

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References

Barrie, A. and Prosser, S.J. 1996. Automated analysis of light-element stable isotopes by isotope ratio mass spectrometry. *In*: Boutton, T. W. and Yamsahi, S. (eds.) Mass spectrometry of soils. 1-46. Marcel Dekker, New York, USA.

Binkley, D., Senock, R., Bird, S. and Cole, T.G. 2003. Twenty years of stand development in pure and mixed stands of *Eucalyptus saligna* and nitrogen-fixing *Facaltaria moluccana*. Forest Ecology and Management 182:93-102.

Boddey, R.M., Peoples, M.B., Palmer, B. and Dart, P.J. 2000. Use of ^{15}N natural abundance technique to quantify biological nitrogen fixation by woody perennials. Nutrient Cycling in Agroecosystems 57:235-270.

Boyden, S., Binkley, D. and Senock, R. 2005. Competition and facilitation between *Eucalyptus* and nitrogen-fixing *Falcataria* in relation to soil fertility. Ecology 86: 992-1001.

Danso, S.K.A., Hardarson, G. and Zapata, F. 1993. Misconceptions and practical problems in the use of ^{15}N soil enrichment techniques for estimating N_2 fixation. Plant and Soil 152:25-52.

Dommergues, Y.R., Duhoux, E. and Diem, H.G. 1999. Les arbres fixateurs d'azote. Caractéristiques fondamentales et rôle dans l'aménagement des écosystèmes méditerranéens et tropicaux. Cirad Editions Espaces 34. Montpellier, France, Food and Agriculture Organization of the United Nations, Rome and IRD, Paris. 500p.

FAO. 2001. Global forest resource assessment. 2000. Main report. FAO Forestry Paper 140. Food and Agriculture Organization of the United Nations, Rome. 479p.

Fisher, R.F. and Binkley, D. 2000. Ecology and management of forest soils. 3rd ed. John Wiley, NewYork, USA. 489p.

Forrester, D.I., Bauhus, J. and Khanna, P.K. 2004. Growth dynamics in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. Forest Ecology and Management 193:81-95.

Forrester, D.I., Bauhus, J., Cowie, A.L. and Vanclay, J.K. 2006. Mixed plantations of *Eucalyptus* with nitrogen fixing trees: a review. Forest Ecology and Management 233:211-230.

Fried, M. and Middelboe, V. 1977. Measurement of amount of nitrogen fixed by legume crop. Plant and Soil 43:713-715.

Gadgil, R.L., Charlton, J.F.L., Sandberg, A.M. and Allen, P.J. 1986. Relative growth and persistence of planted legumes in a mid-rotation radiata pine plantation. Forest Ecology and Management 14:113-124.

Galiana, A., Balle, P., N'Guessan Kanga, A. and Domenach, A.M. 2002. Nitrogen fixation estimated by the ^{15}N natural abundance method in *Acacia mangium* Willd. inoculated with *Bradyrhizobium* sp. and grown in silvicultural conditions. Soil Biology and Biochemistry 34:251-262.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Smethurst, P. and Gava, J.L. 2004. Silvicultural effects on the productivity and wood quality of eucalypt plantations. Forest Ecology and Management 193:45-61.

Gordon, W.S. and Jackson, R.B. 2000. Nutrient concentrations in fine roots. Ecology 81:275-280.

Guinto, D.F., Xu, Z., House, A.P.N. and Saffigna, P.G. 2000. Assessment of N_2 fixation by understorey acacias in recurrently burnt eucalypt forest of subtropical Australia using ^{15}N isotope dilution techniques. Canadian Journal of Forestry Research 30:112-121.

Hunt, M.A., Battaglia, M., Davidson, N.J. and Unwin, G.L. 2006. Competition between plantation *Eucalyptus nitens* and *Acacia dealbata* weeds in northeastern Tasmania. Forest Ecology and Management 233:260-274.

Kelty, M.J. 2006. The role of species mixtures in plantation forestry. Forest Ecology and Management 233:195-204.

Khanna, P.K. 1997. Comparison of growth and nutrition of young monocultures and mixed stands of *Eucalyptus globulus* and *Acacia mearnsii*. Forest Ecology and Management 94:105-113.

Laclau, J.P. 2001. Dynamique du fonctionnement minéral d'une plantation d'eucalyptus. Effet du reboisement sur un sol de savane du littoral congolais; conséquences pour la gestion des plantations industrielles. Thèse de Doctorat, INA-PG, Paris. 146p.

Laclau, J.P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-André, L., Marlet, S. and Bouillet, J.P. 2005. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo. 3. Input-output budgets and consequences for the sustainability of the plantations. Forest Ecology and Management 210:375-391.

Little, K.M., Schumann, A.W. and Noble, A.D. 2002. Performance of a *Eucalyptus grandis x Eucalyptus camaldulensis* hybrid clone as influenced by a cowpea cover-crop. Forest Ecology and Management 168:43-52.

Nambiar, E.K.S. and Fife, D.N. 1987. Growth and nutrient translocation in needles of radiata pine in relation to nitrogen supply. Annals of Botany 60:147-156.

Nambiar, E.K.S. and Nethercott, K.H. 1987. Nutrient and water availability to and growth of young radiata pine plantation intercropped with lupins. New Forests 1:117-134.

Nichols, J.D. and Carpenter, F.L. 2006. Interplanting *Inga edulis* yields nitrogen benefits to *Terminalia amazonia*. Forest Ecology and Management 233:344-351.

Parrotta, J.A., Baker, D.D. and Fried, M. 1994. Application of ^{15}N enrichment methodologies to estimate nitrogen fixation in *Casuarina equisetifolia*. Canadian Journal of Forestry Research 24:201-207.

Rothe, A. and Binkley, D. 2001. Nutritional interactions in mixed species forests: a synthesis. Canadian Journal of Forestry Research 31:1855-1870.

SAS 1998. SAS/STAT User's guide. Release 6.03 Edition. SAS Institute, Cary, North Carolina, USA. 2018p.

Shearer, G. and Kohl, D.H. 1986. N_2 fixation in field settings: estimations based on natural ^{15}N abundance. Australian Journal of Plant Physiology 13:699-756.

Unkovich, M. and Pate, J.S. 2001. Assessing N_2 fixation in annual legumes using ^{15}N natural abundance. *In*: Unkovich, M., Pate, J., Mc Neill, A. and Gibbs, D. J. (eds.) Stable isotope techniques in the study of biological processes and functioning of ecosystems. 103-118. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Watt, M.S., Clinton, P.W., Whitehead, D., Richardson, B., Mason, E.G. and Leckie, A.C. 2003. Above-ground biomass accumulation and nitrogen fixation of broom (*Cytisus scoparius* L) growing with juvenile *Pinus radiata* on a dryland site. Forest Ecology and Management 184:93-104.

Slash and Litter Management Effects on *Eucalyptus* Productivity: a Synthesis Using a Growth and Yield Modelling Approach

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Abstract

Within the context of sustainable management of forest ecosystems, a network was started by the Center for International Forestry Research in 1995 to evaluate the impacts of slash management practices on the productivity of eucalypt, acacia and pine plantations. This network has now reached one full rotation for the ten eucalypt sites in Australia, Brazil, China, Congo, India and South Africa. This paper reports an overall synthesis of tree and stand growth. Using a growth and yield modelling approach, we investigated the effects of slash management on site index defined as the asymptotic dominant height, basal area growth and stand structure. There were significant effects of slash and litter management treatments on two processes that drive tree and stand growth: site index and ability of trees to capture the site potential. These impacts were strongly site dependent. As expected, the soil organic carbon concentration could not be used alone to predict the intensity of stand response. Conversely, a ratio between nitrogen content in slash and litter prior to planting and the nitrogen concentration within the 0-10 cm soil layer, was a good predictor of the differences in stand productivity across treatments.

Introduction

To promote sustainable management of forests, a research network was established by the Center for International Forestry Research (CIFOR), Bogor, Indonesia in the 1990s to evaluate the impact of slash and litter management practices. These practices can play an important role in maintaining soil fertility, and ultimately on the productivity of tropical plantations (see Tiarks *et al*. 1998 for the rationale of the project, and Tiarks *et al*. 2004 for a summary of progress). Among the 16 sites of this network, ten sites planted with eucalypts have been (or are about to be) harvested in six countries (Australia, Brazil, China, Congo, India and South Africa). Using these data, growth responses to slash and litter management treatments can be assessed from growth curves that span the whole of the rotation, offering greater analysis power than the usual year-by-year analysis of variance approach.

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Two main methods of modelling the impact of silvicultural practices such as fertilisation, burning, or site preparation on tree and stand growth have been explored. The first is a process-based approach where a conceptual model is built up and tested against data in order to identify the main driving factors of the management effect on biomass production (e.g. CenW – Kirschbaum 1999, 3PG – Esprey *et al.* 2004, CABALA - Battaglia *et al.* 2004, G'Day - Corbeels *et al.* 2005a, TRIPLEX –Zhou *et al.* 2005). The second uses the growth and yield approach where empirical models are fitted to data in order to identify both stand and individual growth responses to the management practices (among others, Snowdon and Waring 1990, Dhôte 1994, 1996, Pienaar and Rheney 1995 and Snowdon 2002). Both approaches have strengths and limitations. The process-based method links process to outcome but these have a greater demand for data and increased complexity. The growth and yield method is more concerned with capturing the emergent stand growth properties and linking these to generalised site characters or indices. The advantage of this is that models are largely mensuration data driven and usually require little and easily collected data; the disadvantage is at the same scale as output data somewhat reducing the capacity to explain the causes of growth differences if equations are too empirical.

The mensurational, rather than physiological, emphasis on data collection from the CIFOR experiments has led us to adopt the growth and yield method although the process-based method was applied where the input data were available (Australian sites and G'day model, Corbeels *et al.* 2005b). The chosen approach is inspired by two studies Snowdon and Waring (1984) (in Snowdon 2002) and Pienaar and Rheney (1995) which respectively introduced a typology of growth responses to silvicultural practices (positive benefits of fertilisation for site and/or for trees) and the concept of decomposition of growth processes to track how these management practices impact tree and stand growth. In this study, we will use a growth model proposed by Dhôte (1990, 1994, and 1996) and adapted by Saint-André *et al.* (2002) to *Eucalyptus* plantations. This model is based upon phenomenological processes and is summarised by three principles: site index (or fertility, including soil properties and local climate) is given by the dominant height growth; the overall stand production is solely function of the dominant height growth after canopy closure, known as Eichorn's Law (Assmann 1970); and the tree and stand levels are totally compatible in the sense of Clutter (1963). This model allows decomposing growth processes into simple elements such as site index, ability of trees to capture the site potential, mortality, between tree competition, and allocation between height and diameter.

The objective of this paper is to provide a synthesis for all the eucalypt sites of the network on the effects of slash and litter management treatments on the two first elementary processes. We also tested the sensitivity of results to (1) the chosen equation for the dominant height growth and (2) the input data set when the growth curve was only partly known.

Material and Methods

Site Description and Treatment Design

Site characteristics and data are widely documented in du Toit *et al.* (2004), Gonçalves *et al.* (2004), Nzila *et al.* (2004), O'Connell *et al.* (2004), Sankaran *et al.* (2004), Xu *et al.* (2004) and are not repeated in this paper. Nonetheless, because there are some variations between countries, treatment designations are relabelled for this synthesis and correspondences are given in Table 1. SMT_0 (all slash removed) is the only treatment applied at all sites. SMT_0, SMT_1 and SMT_2, are fully comparable across countries. Treatment SMT_3 differs slightly between the group of Congo, China and India, on the one hand, where stem wood and bark were removed and the group of South Africa and Australia on the other hand where only stem wood was removed. However, the main idea was to add a double supply of slash to the top soil. We decided to keep a single designation for these two options. The same discrepancy was observed between India and the group of Australia, South Africa, Brazil and Congo for SMT_4 treatment but we also decided to keep a single treatment designation for slash burnt. For all sites, the same amount of fertilisers was applied in all treatments.

Table 1. Treatment designation. SMT_0 – all material removed; SMT_1 – stem wood + bark removed, the rest of the material is left on the soil; SMT_2 – stem wood removed; SMT3 stem wood removed + additional slash disposed on the soil; SMT_4 – similar to SMT_2 except that the remaining slash was burnt. Correspondences are given in O'Connell *et al.* 2004 (Australia), Gonçalves *et al.* 2004 (Brazil), Nzila *et al.* 2004 (Congo), du Toit *et al.* 2004 (South Africa), Xu *et al.* 2004 (China), and Sankaran *et al.* 2004 (India)

	Designation in the published studies					
	South Africa	Congo	Brazil	China	India	Australia
SMT_0	BL_0	BL_0	BL_0	BL_0	BL_0	BL_0
SMT_1		BL_2	BL_2	BL_2	L	BL_2
SMT_2	BL_2	BL_4	BL_1			
SMT_3	BL_3	BL_3		BL_3	BL_3	BL_3
SMT_4	BS	BL_5	SLb		BS	B

	Slash management at harvesting			
	Commercial trees			Non commercial trees +
	Stemwood	Bark	Crown	litter on the soil + understorey
SMT_0			Removed	
SMT_1	Removed			Retained
SMT_2	Removed			Retained
SMT_3	Removed	Retained/Removed(1)		Retained + slash added
SMT_4	Removed	Retained/Removed(2)		Burnt

(1)Removed in Congo, China and India; retained elsewhere.
(2)Removed in India; retained elsewhere.

Data Collection

Tree height and stem circumference were measured regularly at the ten sites. Stand dominant values, height or circumference at breast height, were calculated as the mean height (or circumference) of the *n* largest trees in circumference within a *n**100 sq. m plot and then averaged among replicates for a given treatment. With the exception of South Africa, stand basal area was calculated, first, for each plot as the sum of the individual tree basal area divided by the plot area and, then, averaged among replicates. For practical aspects in the South African experiment, the stand basal area was calculated from the average circumference, the initial stand density and the survival rate. When the distributions deviated from normality (using a test of normality d'Agostino *et al.* 1990), we have used the median circumference value instead of the average. A statistical procedure based upon the dominant height growth (noted hereafter H_o) and a Richard's model was applied to test whether a given replicate should be considered as an outlier or not. When the observed F-value (Brown and Rothery 1993) was higher than the tabulated one (meaning that the replicates are significantly different), the plot that contributed mostly to the sum of square errors (SSE) was removed and the equations were refitted. The procedure was stopped when the observed F-value was below or close to the tabulated one. This resulted in the removal of 1 to 6 data sets per site, each treatment having at least 2 to 4 valid replicates. Sometimes, it was easy to understand why local growth conditions led to such discrepancy of growth: for example, in Australia-Busselton, BL_0 in block 1 was unfortunately planted on a former sheep shelter, leading to a very fertile local site. In Congo, a similar case occurred (also for BL_0 in block 1, there was a more fertile small zone) but the cause was not clear.

Some sites have been thinned during the experiment: India-Vattavada and India-Surianelli when stands were 24 months old and Australia-Manjimup when the stand was 84 months old. The year just after thinning was removed for stand basal area growth analyses.

Lastly, a severe running fire occurred in Congo just before stand felling. Tree and stand growth were not affected between 72 and 84 months, but mortality increased considerably in replicates 1 and 2. So the stand basal area at 84 months was obtained only from replicates 3 and 4.

Description of the Growth and Yield Approach

A complete description of the chain of models can be found in Saint-André *et al.* (2002). The four main relationships are shown in Fig. 1. In this study, we focused on dominant height growth and the stand basal area growth which both drive overall stand production.

Dominant height is modelled as a function of stand age. Dominant height is widely used by foresters to assess the 'Site Index' which includes the soil chemical and physical properties, the topography and the average climate of the plot. The use of the dominant height for this purpose is based upon the fact that the growth of dominant trees is less responsive to forest management so that it better reflects site growing conditions than mean height or stand basal area growth. 'Site Index' was defined in this study by the maximum dominant height reached by the stand (asymptote of the curve). Figure 2 shows the four main possible effects of slash and litter management on this relationship. In the first case, there are no treatment effects. In the second case, the stage of stand development is advanced but the inherent productivity of the site is not changed (type 1 responses, as defined by Snowdon 2002). The third case indicates a long-term change in site productivity induced by treatments (type 2 responses, as defined by Snowdon 2002). In the fourth case, both stand development is advanced and site productivity is changed by treatments. The time required to achieve this maximum response (U) and the temporal magnitude of stage advancement (M, only for type 1 responses) are obtained from procedures of Pienaar and Rheney 1995 and Snowdon 2002. The use of the asymptotic dominant height avoids the complications of polymorphic curves but necessitates having a large part of the rotation length for its evaluation.

Stand basal area increment was modelled as a function of the dominant height increment. Such relationship is known as the Eichhorn law (Assmann 1970) which assumes that for even-aged and pure stands, wood production is solely dependant on dominant height growth. This relationship has been verified for a large span of thinning regimes (provided that canopy closure is reached rapidly). In our study, it allowed us to explore the possibility of using the dominant height growth as a vehicle of stand fertility and slash and litter management effects. The main idea (as suggested by Pienaar and Rheney 1995) is to test whether an additional effect of treatments has to be modelled for the basal area growth or not. The slope of this relationship is furthermore an indicator of the species' ability to capture the site potential (notion of efficiency): the higher is the slope, the higher is the amount of wood produced by trees for a given potential (dHo).

The two equations were fitted treatment by treatment. A close look at the parameter values in combination with an F-test based on the SSE (Brown and Rothery 1993) permitted identification of which parameters were varying across treatments and which parameters were constant. In all cases, when parameters were non-significantly different from zero, they were removed and equations were fitted again (see Saint-André *et al.* 2004 for details).

Dominant Height Growth: Sensitivity to the Chosen Equations

There are many well-known equations suitable to describe the stand dominant height growth (among others: Gompertz, logistic, Bertalanffy, Chapman-Richard, and Korf) In fact, this diversity is only valid for integral forms: Zeide (1993) showed that all these equations can be reduced to two main differential forms that combine a growth expansion (tree size raised to a power p positive) and a growth decline associated with age (PD- power decline form or ED- exponential decline form). These two basic differential equations are given by:

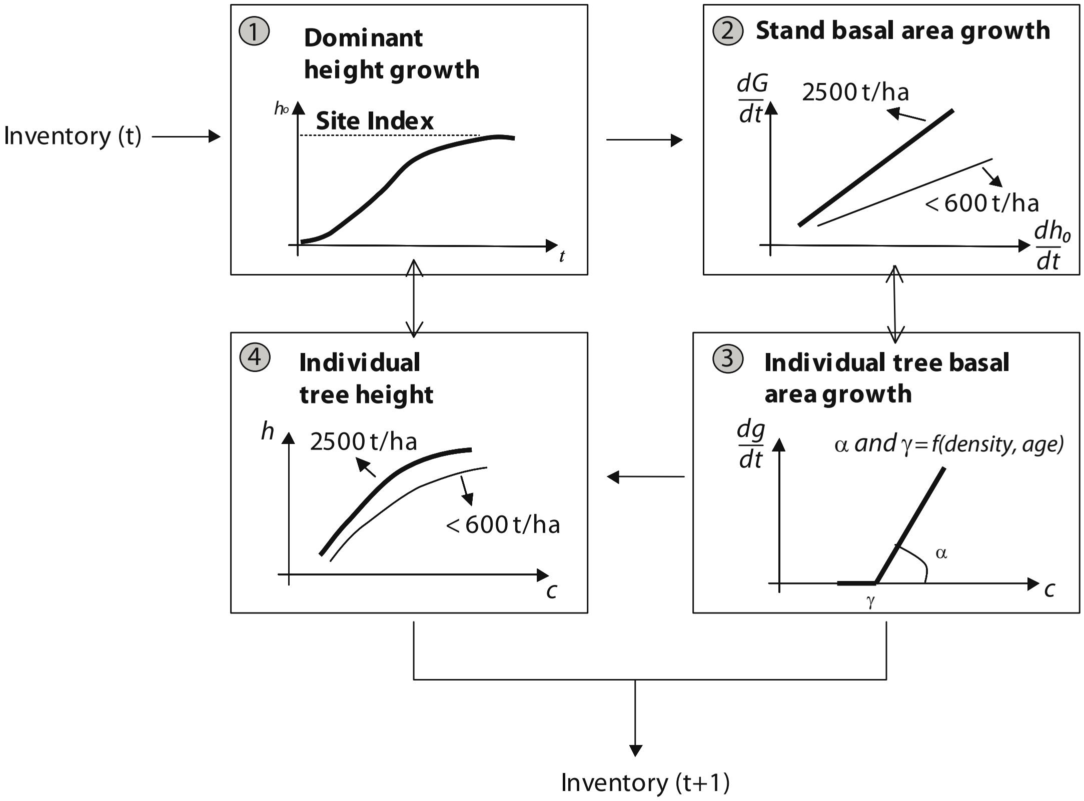


Figure 1. Overall description of Eucalypt-Dendro's growth module (Saint-André *et al.* 2002). Four equations are used: 1) dominant height growth as a function of stand age and site index; 2) Stand basal area increment as a function of dominant height increment and stand density; 3) Individual tree basal area growth as a function of tree circumference, stand density and indirectly stand age; 4) Individual tree height as a function of tree circumference, stand density and dominant heigh

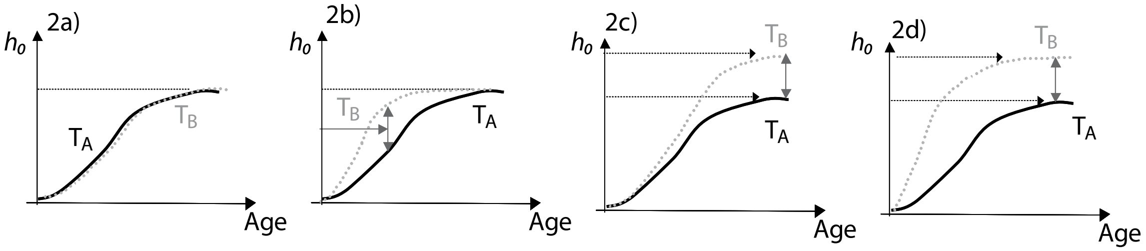


Figure 2. Potential effects of slash management on the dominant height growth: 2a) no effect; 2b) the stage of stand development is advanced but site index remains unchanged; 2c) site index only is modified; 2d) both site index and development are affected

$$ED : \frac{dy}{dt} = k y^p e^{qt} \quad (1)$$

$$PD : \frac{dy}{dt} = k y^p t^q \quad (2)$$

where $\frac{dy}{dt}$ is the tree size increment, k, p and q are parameters to be estimated, and t is the stand age. According to the values of p and q, Shvets and Zeide (1996) identified six types of integral form that are suitable to describe tree growth (i.e. giving asymptotic or quasi asymptotic growth).

For our application, we decided to test one equation of each group (Table 2 – with the exception of group no.4 which has not yet been explored for growth equations). We focused only on three-parameters' growth equations (*a* is the asymptote, *b* is the rate at which the asymptote is obtained and *c* is a curve-shape parameter). The Chapman-Richard equation was considered as the reference model. The four other equations, namely Gompertz, Logistic, Korf and Hossfeld IV were fitted treatment by treatment. Model's performance was assessed using the Sum of Square Errors (SSE), the Mean Error (ME), the Mean Absolute Error (MAE) and the modelling efficiency (MEF, defined by Mayer and Butler 1993). Parameter variations among treatments were only assessed for the best and worst models. This sensitivity analysis was undertaken for sites in the Congo, Brazil and South Africa that were representative of the observed responses to slash management.

Results

Dominant Height Growth: Sensitivity to the Chosen Equation?

Among the tested equations, the most suitable model to describe the dominant height growth for the three selected sites (Congo, South Africa and Brazil) was the Korf's equation, ranking first for 9 out of 12 criteria (3 sites x 4 criteria of model performance, see Material and Methods section). The worst was the logistic equation (data not shown). Across the ED- (exponential decline) group, the Chapman-Richard equation was definitely the most efficient. Lack of efficiency of the two other ED-models can be explained by a discrepancy between the parameter values imposed by the structure of the model (*p*=1 for Gompertz's equation and *p*=2 for the logistic) and the actual parameter value (average *p* was about 0.5, 0.3 and 0.1 respectively for the South African, Congolese, and Brazilian sites). When assessing slash and litter management effects on dominant height growth, Chapman-Richard and Korf equations were strictly equivalent. In both cases, dominant height growth response is of type 1 for the South African and the Brazilian sites (Figs. 2b, 3), whereas a significant effect was observed on site index for SMT_0 in Congo (Figs. 2c, 3). The worst-fitting model (logistic equation) however gave similar results. The only difference lay in the treatment ranking for the Congolese site ($SMT_3>SMT_2=SMT_1=SMT_4>SMT_0$ for the logistic model whereas it was $SMT_3>SMT_2>SMT_1=SMT_4>SMT_0$ for both Korf and Chapman-Richard models). For the rest of the paper, we used the Korf's equation to describe the dominant height growth at all sites.

Dominant Height Growth: is there a Modification of Site Index?

There was a significant effect of treatments on dominant height growth for five of the ten sites studied (Congo, Brazil, South Africa, India-Kayampoovam and Australia-Busselton (Fig. 3). Congo and Australia-Busselton are the only sites where site index was significantly modified (Fig. 2c). For Brazil, South Africa, India-Kayampoovam sites, the stage of stand development was advanced but site index remained unchanged (Fig. 2b). We did not find any site where both site index and stage of development were affected. SMT_0 was the least productive treatment in Congo, South Africa and Brazil but, for India-Kayapoovam and Australia-Busselton, SMT_4 (burnt) was the lowest. In contrast, SMT_3 (double-slash) was the most productive treatment in Congo, India-Kayapoovam and Australia-Busselton but, for South Africa and Brazil, SMT_4 was the highest. Slash and litter management effects affected all species studied (hybrid *Eucalyptus* in Congo, *E. grandis* in Brazil and South Africa, *E. tereticornis* in India-Kayampoovam and *E. globulus* in Australia-Busselton) and the magnitude of the response was not species dependant. For example, India-Surianelli and India-Vattavada sites were also planted with *E. grandis* in which there was no response of dominant height growth to slash management.

Table 2. Main types of growth equations (from Shvets and Zeide 1996). The chosen equations for our study are bolded

Basic form	Range of the parameter value (basic form)	Well known equation that belongs to the group	Integral representation	Relationship between parameters
ED	$p<1$ and $q<0$	**Chapman-Richard**	$y=a(1-e^{-bt})c$	$p=1-1/c$, $q=-b$ $k=a^{1/c}bc$
ED	$p=1$ and $q<0$	**Gompertz**	$y=a[e^{-b\exp(-ct)}]$	$p=1$, $q=-c$ $k=bc$
ED	$p>1$ and $q<0$	**logistic**	$y=a/(1+ce^{-bt})$	$p=2$, $q=-b$ $k=bc/a$
PD	$p<1$ and $q<-1$	None		
PD	$p=1$ and $q<-1$	**Korf**	$y=a[e^{-bt^{-c}}]$	$p=1$, $q=-(1+c)$ $k=bc$
PD	$p<1$ and $q<-1$	**Hossfeld IV**	$y=t^c/(b+t^c/a)$	$p=2$, $q=-(1+c)$ $k=bc$

Table 3. Summary of processes affected by slash management treatments in the 10 sites studied

	Dominant height growth	Stand basal area growth	Impact on stand basal area
Congo	**Modification of site index**	**Alteration of tree ability to capture the site potential**	≠ 6.3m^2.ha^{-1}; 73%; Max = SMT$_3$; Min = SMT$_0$
Brazil	**Stage of development advanced**	**No response**	**≠ 7.7m^2.ha^{-1}; 41%; Max = SMT$_4$; Min = SMT$_0$**
South Africa	**Stage of development advanced**	**Differences between treatments but non -significant**	**≠ 5.1m^2.ha^{-1}; 35%; Max = SMT$_3$; Min = SMT$_0$**
India-Kayampoovam	Stage of development advanced	Differences between treatments but non -significant	≠ 3.4m^2.ha^{-1}; 22%; Max = SMT$_3$; Min = SMT$_4$
China	**No response**	**No response**	**≠ 1.6m^2.ha^{-1} ;18%; Max = SMT$_3$; Min = SMT$_1$**
India-Vattavada	No response	No response	≠ 5.6m^2.ha^{-1} ;14%; Max = SMT$_0$; Min = SMT$_4$
India-Surianelli	No response	No response	≠ 4.3m^2.ha^{-1}; 20%; Max = SMT$_3$; Min = SMT$_4$
India-Punnala	No response	No response	≠ 1.8m^2.ha^{-1}; 13%; Max = SMT$_4$; Min = SMT$_0$
Australia-Busselton	**Modification of site index**	**Differences between treatments but non -significant**	**≠ 6.6m^2.ha^{-1}; 55%; Max = SMT$_3$; Min = SMT$_4$**
Australia-Manjimup	No response	No response	≠ 4m^2.ha^{-1}; 16%; Max = SMT$_1$; Min = SMT$_4$

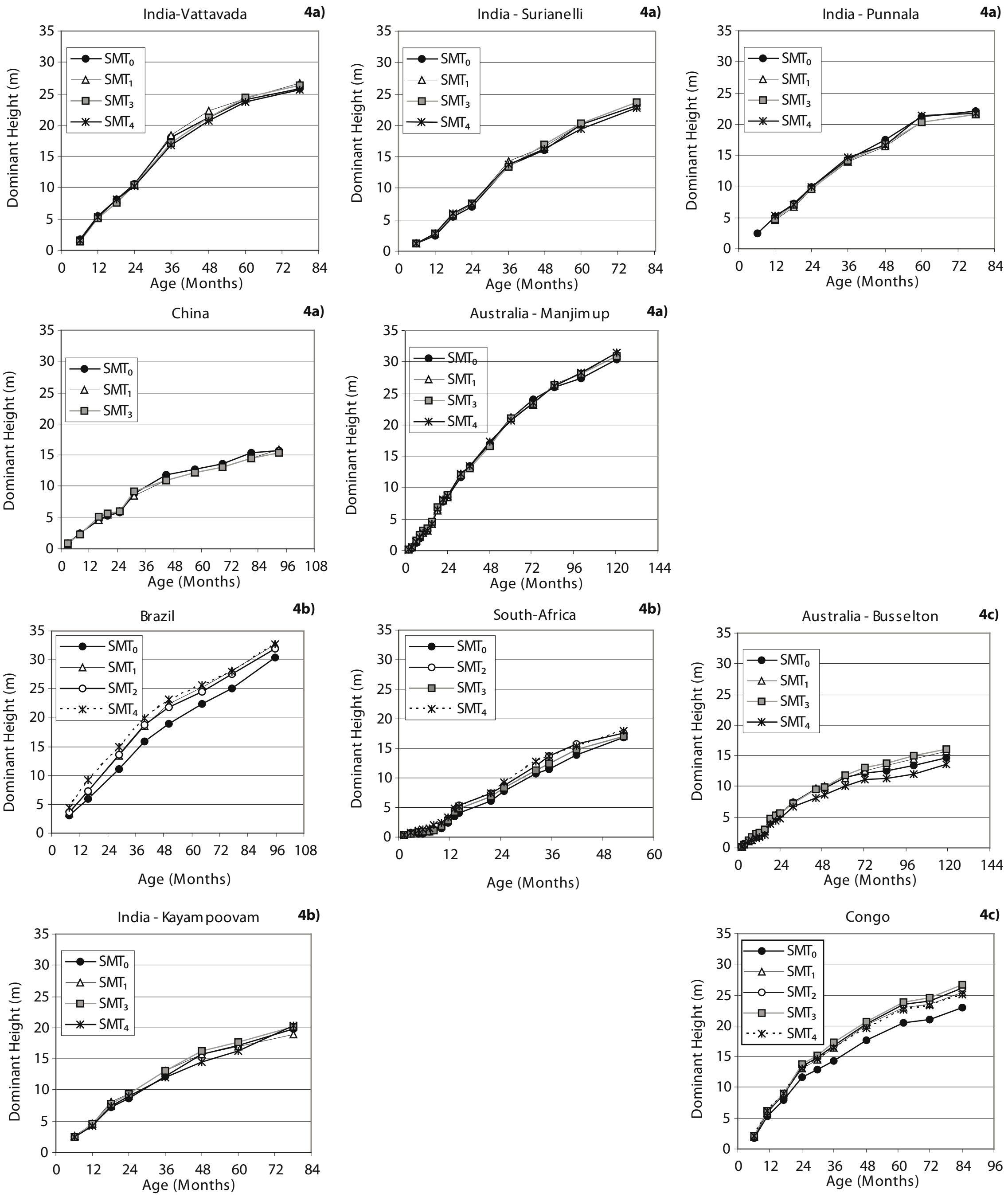


Figure 3. Effects of slash management treatment on the dominant height growth: 4a) no effect for 5 sites; 4b) the stage of stand development is significantly advanced but the inherent productivity of the site is not changed (type 1 response, as defined by Snowdon 2002) for Brazil, South Africa, India-Kayapoovam; 4c) there is a long term change in site productivity induced by treatments (type 2 response, as defined by Snowdon 2002) for Congo and Australian-Busselton

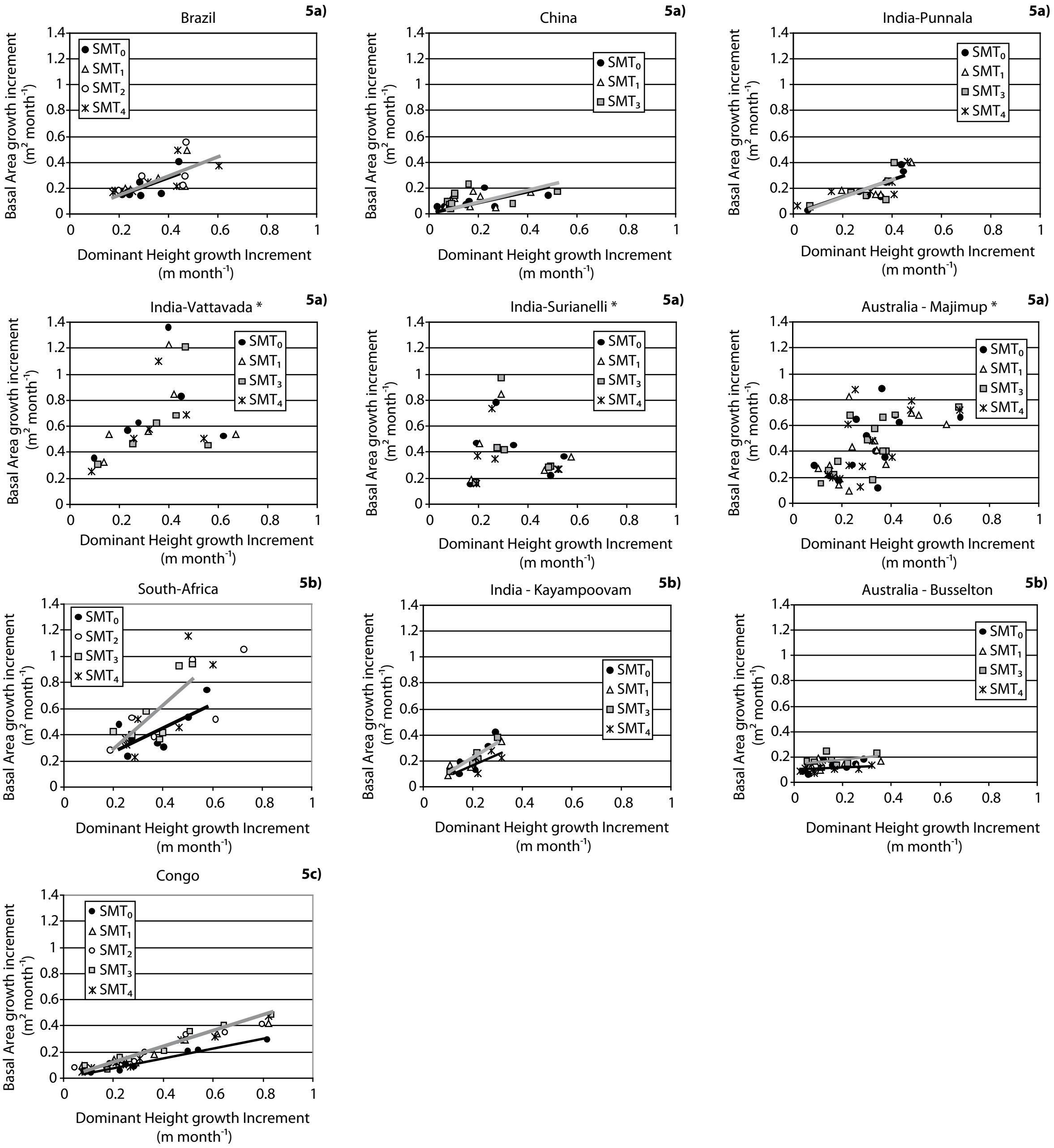
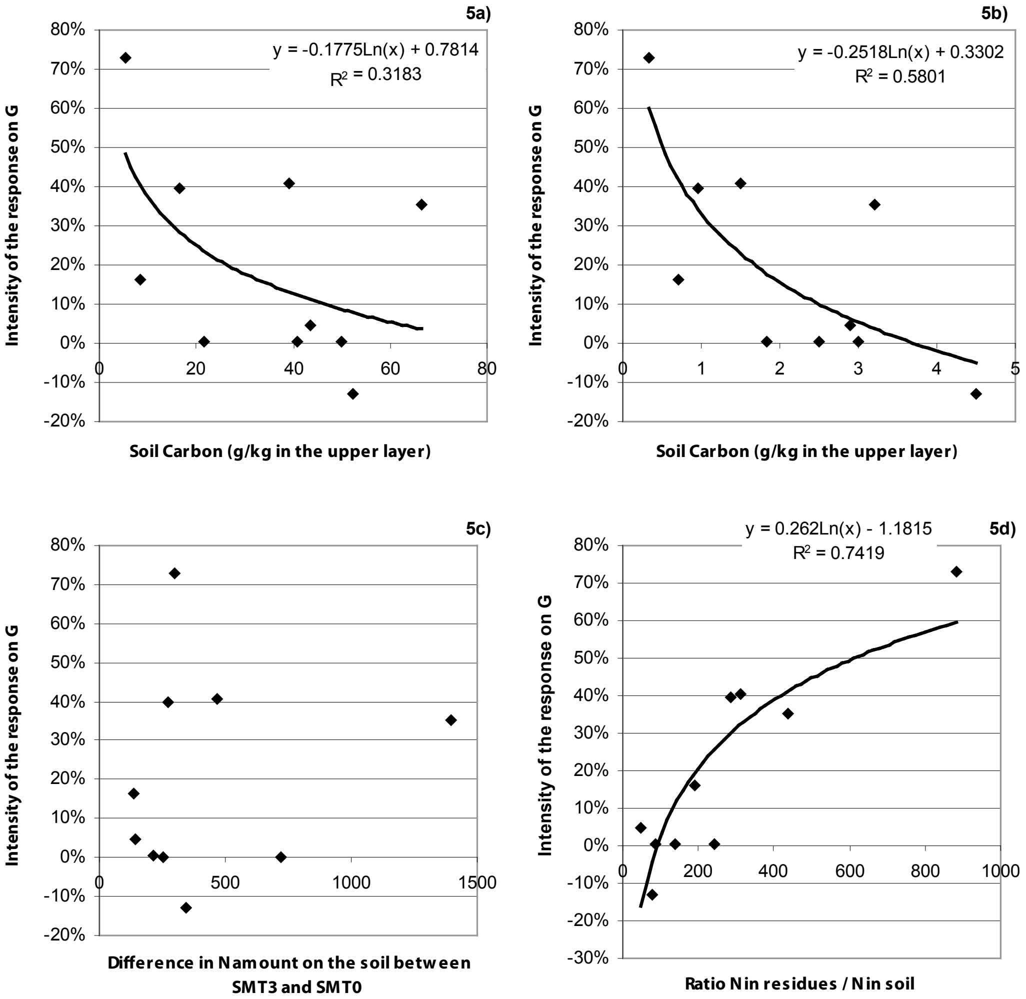


Figure 4. Effects of slash management treatment on the stand basal area growth: 5a) no effect for 6 sites; 5b) a non significant trend for South Africa, India-Kayapoovam and Australian-Busselton; 5c) a significant effect on the slope of the relationship for Congo. Stars indicate that these sites have been thinned during the experiment

Figure 5. Relative difference between SMT$_0$ and SMT$_3$ in basal area at the end of the rotation related to: 5a) soil carbon concentration in the upper soil layer (0-10 cm), 5b) soil nitrogen concentration in the upper soil layer (0-10 cm), 5c) difference in N supply between SMT$_3$ and SMT$_0$ (slash, litter and fertilisation were summed up in each treatment before calculating the difference), 8c) an index of nitrogen loading (N supply divided by the nitrogen concentration in the 0-10cm soil layer)



The time required to achieve the maximum dominant height growth response was about 37 months for the South African site, 42 months for the Brazilian site, 48 months for India-Kayampoovam (type 1 response), 105 months for the Congolese site and 134 months for the Australian site (type 2 response). Maximum growth response (compared to SMT$_0$) ranged from 0.6 m for SMT$_1$ in India-Kayampoovam to 4.0 m for SMT$_3$ in Congo. For type-1-response sites, the temporal magnitude of stage advancement ranged from 3 months (SMT$_1$ in India-Kayampoovam) to 15 months (SMT$_4$ in Brazil).

Basal Area Growth: is there a Modification of the Eichhorn Law?

Figure 4 presents the relationship between stand basal area growth (dG) and dominant height growth (dHo) for all sites studied. In all cases, the relationship was rather good, except for India-Surianelli, India-Vattavada and Australia-Manjimup because these three sites had been thinned (reduced from 2500 to 1666 stems ha^{-1}). This pattern illustrates that the Eichhorn law can be affected by silvicultural operations, such as thinning, if the canopy closure is not reached rapidly after treatments. Congo was the only site where there was a significant effect of slash and litter management treatments on the relationship between dG and dHo. Trends were also identified for South African, India-Kayampoovam and Australia-Busselton sites but differences between treatments were not significant. As a result, for the Brazilian, South African, Indian-Kayampoovam and Australia-Busselton sites, effects of slash and litter management treatments on stand productivity (basal area) were mainly driven by the changes in site index curves. The ability of trees to capture the site potential was not (or little) altered by the removal of slash and litter in the SMT$_0$ treatment.

Conversely, for the Congolese site, the Eichhorn law was modified meaning that the ability of trees to capture the site potential was changed and this effect came in addition to the modification of the site index curve. This cannot be attributed to a lower stocking rate because in Congo there was no impact of slash management on tree mortality.

Discussion and Conclusions

Methodology

The main advantage of the methodology used here is that it requires few data. A simple recording of tree diameter and tree height over the rotation permitted decomposition of the influence of slash management on most processes that drive tree and stand growth. The methodology allows exploration of a large number of sites and identification of general and generic patterns. Processing data this way is often criticised on the basis that equations used for this purpose are merely statistical description with no mechanistic basis and that usually good fits are simply obtained by adjusting parameters and no attempt is made to understand the values of the parameters or the functions in the equations from any underlying theory of growth (West *et al*. 2004). That can be true if the growth equation is too integrative (for example, plant mass as a direct function of time) and if parameter values are not discussed. In our case, the growth pattern is decomposed in elementary phenomenological processes supported by the dendrometric theory of growth (Assman 1970, Dhôte 1996). By analysing parameter variations of each basic equation, we were then able to provide insights into slash and litter management effects on stand growth (Table 3).

However, this approach is indeed statistical and care should be taken in both experiment design and data analysis. For example, the methodology cannot be used when plots are too small to be considered as representative of a normal stand (i.e. with no side effects). In our study, the minimum number of trees per plot unit was 16 in South Africa and 18 in Australia. These figures are probably too small for a correct assessment of dominant height (assessed on three trees). This probably caused mismatches for a clear relationship between stand basal area growth and dominant height growth and explained why the observed differences between slash management treatments on this relationship were non-significant for these sites. On the contrary, the maximum number of trees per replicate and per treatment was 120 in Congo which was very large but allowed a clear distinction between treatments.

Concerning the data analysis, we stress that:

- missing data in the late stages of the stand growth have a great influence on the results and this, whatever the chosen method (not shown here, but the approach failed in detecting the type 2 response for the dominant height growth at the Congolese site when only the 6- to 40- months data were used). From a practical point of view, it is absolutely necessary to get, at least, two measured points in the declining part of the stand height growth for an accurate evaluation of long-term slash management effects;

- the chosen equation has little influence on the assessment of slash management effects, provided that this equation is suitable to describe the stand dominant height growth. The only difference observed between the best and poorest fitting models was in their ability to detect fine differences between treatments (group composition); and
- the two methods tested in this study (Pienaar and Rheney 1995 and Snowdon 2002) were found to be equivalent in assessing slash and litter management effects. They were complementary and provided useful information for the forest manager (type of the growth response, maximum gain in basal area, time required to achieve the maximum response, temporal magnitude of slash and litter management effects). Some improvement of the Pienaar and Rheney submodel could be made to better reflect type 2 responses. This was noticed by Snowdon (2002) who proposed an alternative quadratic function. We did not try to find other formulations.

A limitation of our approach was shown for the Chinese site which exhibited significant differences on average values despite no statistical response on the two main processes (dominant height growth and stand basal area growth). A close look at the dataset showed that there was a small difference between SMT_3 and SMT_0 on the stand basal area increment. But this difference was low compared to the variability of stand basal area increment (probably induced by inter-annual climatic variations) and it could not be detected by our methodology. In such cases, the basis for growth increment analysis should be made on a two-year (rather than yearly) basis so as to increase the growth rate and reduce the influence of climate on the relationship.

Was the Intensity of the Response Across Sites Predictable?

Results obtained for the ten eucalypt sites studied and the consequences of slash management on stand basal area are summarised in Table 3. Sites in bold characters showed significant differences between SMT_0 and SMT_3. The response intensity depends on the number of processes affected by treatments, the Congolese and Australian-Busselton sites being the only ones where almost all relationships were modified. Besides, for these two sites, differences between treatments on stand basal area growth were the highest: respectively 73% and 55% at the end of the rotation. To investigate if the variety of responses across sites could be predictable, we tried to relate the relative difference between SMT_0 and SMT_3 in basal area to soil properties and the intensity of material loading (quantities of nutrient brought to and removed from the soil). For the soil properties, we used the values given in the soil synthesis of Tiarks and Ranger (2008). We focused only on the physical and the chemical characteristics that were fully comparable among sites. As a first result, there was no evidence that the soil C (Fig. 5a) or soil N (Fig. 5b), or the amount of nutrient brought to the soil (Fig. 5c) could explain solely the observed variability in growth response. But, if we used an index of nutrient loading intensity such as ‘nitrogen brought to the soil’ divided by ‘nitrogen concentration within the 0-10 cm soil layer’, the relationship is much stronger (Fig. 5d). This index explains 74% of the observed variability in growth responses. If we use a linear model with the N concentration in the soil (in log-form) and the N supply (in log-form), the explained variability increases to 80%. After a graphical check, the amount of Ca brought to the soil was the most correlated variable to the residuals of this first relationship. A multiple linear regression including the total amount of Ca brought to the soil increased the r^2 up to 0.90 and the third variable (total amount of Ca) was significant ($t = -2.5$, $p > t = 0.047$). Calcium and Mg amounts in harvest residues are highly correlated and the introduction of Mg in the equation improved also the relationship but to a lesser extent than Ca (r^2 increased to 0.82; $t = -0.66$; $p > t = 0.533$ for Mg). Indexes of nutrient loading intensity calculated for Ca and P (the two other elements that were fully comparable across sites in the soil analysis) were less correlated to the growth response than the N index: r^2 was respectively 0.59 and 0.03 for Ca and P.

Management implications

The data set in the network covers a wide range of environmental conditions and genetic material representative of the diversity of eucalypt commercial plantations in tropical and subtropical areas worldwide. Large differences in growth patterns were observed across sites and specific studies on N mineralisation (Nzila *et al.* 2002, O'Connell *et al.* 2004, Gonçalves *et al.* 2004a), slash and litter decay (Nambiar *et al.* 2004) and changes in soil chemical properties over stand rotation (Mendham *et al.* 2003, Deleporte *et al.* 2008, Gonçalves *et al.* 2008) made it possible to gain insight in the processes responsible for the response of trees in each site to slash and litter management practices. The modelling approach presented here provides complementary information on the influence of environmental conditions on tree growth.

Current silvicultural practices in eucalypt plantations are quite different across the countries of the network. In China harvest intensity is high and litter is frequently removed by local people, whereas in Australia, South Africa, Congo and Brazil the norm is litter retention, sometimes combined with burning. The perception of the results of the residue management treatments by forest managers is therefore different among sites. However, the overall synthesis on tree and stand growth in the present paper demonstrates for forest managers the impacts that a modification of the current practices of harvest residue management might have on the productivity of eucalypt plantations. We then focused on the differences between SMT0 and SMT3, the two most contrasting treatments, to understand what was changed in the growth process.

The main finding of this work is the strong relationship between stand response to harvest residue management treatments and an index representing the input of N contained in harvest residues as a function of N availability in the top soil. Low N availability commonly limits the growth of *E. nitens* plantations in Tasmania (Smethurst *et al.* 2004) and a strong response to N fertilisation is observed on low-N sites in Congo (Laclau *et al.* 2005) and Brazil (Gonçalves *et al.* 2004b). Tree response to N fertiliser application is generally higher in the first years after planting because there is a high demand for N to establish foliage and fine roots (Laclau *et al.* 2003, Smethurst *et al.* 2003). However, plantations are likely to experience N deficiency after canopy closure or not at all, according to the fit between N supply from the soil and stand demand (Smethurst *et al.* 2004). Appropriate timing of N fertilisation is therefore required to maximise growth of eucalypt plantations. The index proposed in this study can account for tree response to residue management practices for a large range of site fertility: on a fertile site (e.g. with 4% of N in the 0- 10 cm soil layer), 750 kg ha-1 of added N would induce a small response (less than 20%) whereas on a poor site (0.3% of N), the response would be very large (87%); similarly, the sites in the network that exhibited little or no response can be split into those that would not respond whatever the amount of N added to the soil (e.g. India-Vattavada) and those where we can expect a response (e.g. China) provided that the amount of N added is sufficient. This index enabled accounting for sites where the removal of material was so important that it induced a growth response (e.g. South Africa). It is then a good indicator for the growth response. But the model formulation is not completely satisfactory since one could expect a plateau to large fertiliser inputs (Smethurst *et al.* 2004). Furthermore this index is only valuable to assess changes in growth when the baseline is the current silvicultural practice. The reliability of the system was not tested in this study and this index cannot be used to forecast what would occur if we have a succession of SMT0 or if one put SMT0 and SMT3 alternately.

The amount of N in harvest residues is highly correlated with amounts of other nutrients, and the amount of N in the top soil is also highly correlated with CEC and availability of exchangeable base cations for tree nutrition. Therefore, the predictive quality across sites of the index proposed might be a result of its ability to represent the load of nutrients in harvest residues relative to their availability in the soil. In Congo, for example, N is the first nutritional limiting factor of tree growth and the index probably accounts for the effect of N availability on stand growth (Deleporte *et al*. 2008). However, we can hypothesise that this index accounts for tree response to other nutrients more limiting than N for tree growth that are retained in harvest residues on other sites. The weakest relationship obtained with Ca- and P-indexes across sites might be a result of the lowest response of trees to the availability of theses elements in harvest residues, but a higher contribution of the availability of these nutrients in deep soil layers (not considered in the index) cannot be excluded.

Even if slash and litter management treatments are likely to modify soil bulk density in the upper layer (Mendham *et al*. 2003), evaporation up to litter accumulation of the new stand after planting (Matthews 2005), and soil runoff, such effects should be limited in time and are unable to account for the large differences in growth patterns observed throughout the whole rotation at the various sites. Dominant height growth responses suggest a modification of soil functioning which was temporary for Brazil, South Africa and India-Kayampoovam and permanent for Congo and Australia-Busselton. This modification of soil properties may have induced a change in leaf area index (LAI) (due to a modification of leaf biomass such as observed at age three years in Congo, Nzila *et al*. 2004) and then a higher stand production in double slash treatments (see du Toit and Dovey 2005 for South Africa). Moreover, modification of the relationship between stand basal area growth and dominant height growth (SMT_0 in Congo and to a lesser extent in South Africa) suggests that the ability of trees to capture the site potential was also altered at these sites, and that the overall response can partly come from the trees themselves and not only from the modification of soil properties. Growth efficiency (GE), calculated as the increment of aboveground biomass per unit of LAI at the South African site, was lower in SMT_0 and SMT_4 than in SMT_3 but differences between treatments were not significant (du Toit and Dovey 2005). This is consistent with our study where a trend was observed in South Africa for the relationship between stand basal area growth and dominant height growth but differences between treatments were not significant. For Congo and South Africa, we hypothesise that the photosynthetic properties were changed in SMT_0 treatment, and this, combined with the nutrient availability on LAI would have enhanced the magnitude of the response at these sites.

The present data set does not make it possible to draw conclusions on the ability of trees to use resources but, for the second rotation, it would be very useful to investigate what are the physiological processes modified in $SMT_{0,}$ for example, photosynthetic properties, and/or allocation patterns between shoots and roots (Haynes and Gower 1995) that lead to a large modification in carbohydrate allocation among aboveground tree components. Impacts of slash management practices on these physiological processes may also differ between young and old trees (Cordell *et al*. 2001) and this supports the need to study the whole rotation.

The study showed large differences in the sensitivity of eucalypt growth to management practices. Even in soils with relatively high nutrient availability, as in South Africa, removal of the upper soil layer during site preparation led to a significant effect of slash and harvest residue management on dominant height growth which was not expected in that soil type. The results of the present synthesis across sites strongly support the conclusions of most studies at each site that minimum soil preparation techniques without burning, so retaining harvest residues on site, are required for a sustainable management of these fast-growing plantations (Nambiar and Kallio 2008).

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References

Assmann, E. 1970. The principles of forest yield studies. Pergamon Press, Oxford, UK. 503p.

Battaglia, M., Sands, P., White, D. and Mummery, D. 2004. CABALA: a linked carbon, water and nitrogen model forest growth for silvicultural decision support. Forest Ecology and Management 193:251-282.

Brown, D. and Rothery, P. 1993. Models in biology: mathematics, statistics and computing. Wiley, Chichester, UK. 688p.

Corbeels, M., McMurtrie, R.E., Pepper, D.A. and O'Connell, A.M. 2005a. A process-based model of nitrogen cycling in forest plantations. Part II. Simulating growth and nitrogen mineralisation of *Eucalyptus globulus* plantations in south-western Australia. Ecological Modelling 187:449-474.

Corbeels, M., McMurtrie, R.E., Pepper, D.A., Mendham, D.S., Grove, T.S. and O'Connell, A.M. 2005b. Long-term changes in productivity of eucalypt plantations under different harvest residue and nitrogen management practices: A modelling analysis. Forest Ecology and Management 217:1-18.

Cordell, S., Goldstein, G., Meinzer, F.C. and Vitousek, P.M. 2001. Morphological and physiological adjustment to N and P fertilisation in nutrient-limited *Metrosideros polymorpha* canopy trees in Hawaii. Tree Physiology 21:43-50.

Clutter, J.L. 1963. Compatible growth and yield models for loblolly pine. Forest Science 9:354-371.

Deleporte, P., Laclau, J.P., Nzila, J.D., Kazotti, J.g., Marien, J.N., Bouillet, J.P., Szwarc, M., D'Annunzio, R. and Ranger, J. 2008. Effects of slash and litter management practices on soil chemical properties and growth of second rotation eucalypts in Congo. *In:* Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 5-22. Center for International Forestry Research, Bogor, Indonesia.

Dhôte, J.F. 1990. Modèles de la dynamique des peuplements forestiers: articulation entre les niveaux de l'arbre et du peuplement. Applications à la sylviculture des hêtraies. Ph.D. Thesis, Université Claude Bernard – Lyon 1 – No. 131-90, France. 256p.

Dhôte, J.F. 1994. Hypotheses about competition for light and water in even-aged common beech (*Fagus sylvatica* L.). Forest Ecology and Management 69:219-232.

Dhôte, J.F. 1996. A model of even-aged beech stands productivity with process-based interpretations. Annals of Forest Science 53:1-20.

d'Agostino, R.B., Belanger, A. and d'Agostino, R.B.jr. 1990. A suggestion for using powerful and informative tests of normality. The American Statistician 44:316-321.

du Toit, B. and Dovey, S.B. 2005. Effect of site management on leaf area, early biomass development, and stand growth efficiency of a *Eucalyptus grandis* plantation in South Africa. Canadian Journal of Forest Research 35:891-900.

du Toit, B., Dovey, S.B., Fuller, G.M. and Job, R.A. 2004. Effects of harvesting and site management on nutrient pools and stand growth in a South African eucalypt plantation. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 31-44. Center for International Forestry Research, Bogor, Indonesia.

Esprey, L.J., Sands, P.J. and Smith, C.W. 2004. Understanding 3-PG using a sensitivity analysis. Forest Ecology and Management 173:235-250.

Gonçalves, J.L.M., Gava, J.L. and Wichert, M.C.P. 2004a. Sustainability of wood production in eucalypt plantations of Brazil. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A., Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 3-14. Center for International Forestry Research, Bogor, Indonesia.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Smethurst, P. and Gava, J.L. 2004b. Silvicultural effects on the productivity and wood quality of eucalypt plantations. Forest Ecology and Management 193:45-61.

Gonçalves, J.L.M., Wichert, M.C.P., Gava, J.L. and Serrano, M.I.P. 2008. Soil fertility and growth of *Eucalyptus grandis* in Brazil under different residue management practices. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 51-62. Center for International Forestry Research, Bogor, Indonesia.

Haynes, B.E. and Gower S.T. 1995. Belowground carbon allocation in unfertilized and fertilized red pine plantations in northern Wisconsin. Tree

Physiology 15:317-325.

Kirschbaum, M.U.F. 1999. CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. Ecological Modelling 118:17-59.

Laclau, J.P., Deleporte, P., Ranger, J., Bouillet, J.P. and Kazotti, G. 2003. Nutrient dynamics throughout the rotation of *Eucalyptus* clonal stands in Congo. Annals of Botany 91:879-892.

Laclau, J.P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-André, L., Marlet, S. and Bouillet, J.P. 2005. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo. 3. Input–output budgets and consequences for the sustainability of the plantations. Forest Ecology and Management 210:375–391.

Matthews, S. 2005. The water vapour conductance of *Eucalyptus* litter layers. Agricultural and Forest Meteorology 135:73-81.

Mayer, D.G. and Butler, D.G. 1993. Statistical validation. Ecological Modelling 68:21-32.

Mendham, D.S., O'Connell, A.M., Grove, T.S. and Rance, S.J. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management 181:357-372.

Nambiar, E.K.S. and Kallio, M. 2008 Increasing and sustaining productivity in tropical forest plantations: making a difference through cooperative research and partnerships. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 205-228. Center for International Forestry Research, Bogor, Indonesia.

Nzila, J.D., Bouillet, J.P., Laclau J.P. and Ranger, J. 2002. The effects of slash management on nutrient cycling and tree growth in *Eucalyptus* plantations in the Congo. Forest Ecology and Management 171:209-221.

Nzila, J.D., Bouillet, J.P., Laclau, J.P. and Ranger, J. 2004. Effects of slash management on tree growth and nutrient cycling in second-rotation *Eucalyptus* replanted sites in the Congo. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 15-30. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove, T.S., Mendham D.S., Corbeels, M., McMurtie, R.F., Shammas, K. and Rance, S.J. 2004. Impacts of inter-rotation site management on nutrient stores and fluxes and growth of eucalypt plantations in south-western Australia. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 77-92. Center for International Forestry Research, Bogor, Indonesia.

Pienaar, L.V. and Rheney, J.W. 1995. Modeling stand level growth and yield response to silvicultural treatments. Forest Science 41:629-638.

Saint-André, L., Laclau, J.P., Bouillet, J.P., Deleporte, P., Miabala, A., Ognouabi, N., Baillères, H. and Nouvellon, Y. 2002. Integrative modelling approach to assess the sustainability of the *Eucalyptus* plantations in Congo. Paper to Fourth workshop, IUFRO Working Party S5.01.04, Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software, Harrison Hot Springs, British Columbia, Canada, 8-15 September 2002. 10p.

Saint-André, L., Nouvellon Y., Laclau, J.P., Ranger, J., Bouillet, J.P., Nzila, J.D., Deleporte P. and Gonçalves, J.L.M. 2004. Modelling nutrient cycling and integrating nutrient cycling into growth models. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 171-84. Center for International Forestry Research, Bogor, Indonesia.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kumaraswamy, S., O'Connell, A.M., Grove, T.S. and Mendham, D.S. 2004. Improved productivity of eucalypt plantations through site management practices in the monsoonal tropics: Kerala, India. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Shvets, V. and Zeide, B. 1996. Investigating parameters of growth equations. Canadian Journal of Forest Research 26:1980-1990.

Smethurst, P., Baillie, C., Cherrie, M. and Holz, G. 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. Forest Ecology and Management 176:531-542.

Smethurst, P., Holz, G., Moroni, M. and Baillie, C. 2004. Nitrogen management in *Eucalyptus nitens* plantations. Forest Ecology and Management 193:63-80.

Snowdon, P. 2002. Modeling Type 1 and Type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. Forest Ecology and Management 163:229-244.

Snowdon, P. and Waring, H.D. 1984. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and the consequences for management. Proceedings of IUFRO symposium on site productivity and fast-growing plantations. Vol. 2, 701-711. South African Forest Research Institute, Pretoria, South Africa.

Snowdon, P. and Waring, H.D.1990. Growth response of *Pinus radiata* to combinations of superphosphate, urea and thinning type. Forest Ecology and Management 30:313–325.

Tiarks, A. Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical plantations. CIFOR Occasional Paper No. 16. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A., Nambiar, E.K.S., Ranger, J. and Toma, T. 2004. Summary of progress. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 185-193. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A. and Ranger, J. 2008. Soil properties in tropical plantation forests: evaluation and effects of site management: a summary. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 191-204. Center for International Forestry Research, Bogor, Indonesia.

West, G.B., Brown, J.H. and Enquist, B.J. 2004. Growth models based on first principles or phenomenology? Functional Ecology 18:188-196.

Xu, D.P., Yang, Z.J., and Zhang, N.N. 2004. Effects of site management on tree growth and soil properties of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Zeide, B. 1993. Analysis of growth equations. Forest Science 39:594-616.

Zhou, X., Peng, C., Dang, Q., Chen, J. and Parton, S. 2005. Predicting forest growth and yield in northeastern Ontario using the process-based model of TRIPLEX 1.0. Canadian Journal of Forest Research 35:2268-2280.

Eucalyptus plantation on savanna soil, Congo. (Photo: Takeshi Toma)

Soil Properties in Tropical Plantation Forests: Evaluation and Effects of Site Management:

a Summary

A. Tiarks[1] and J. Ranger[2]

Abstract

Effects of slash management and other practices on soil carbon and nutrients were measured in a network of 16 sites where forest plantations were harvested and replanted. The sites are located in the tropics and subtropics planted with the species appropriate for each site. The species used were in the genera *Acacia*, *Cunninghamia*, *Eucalyptus* and *Pinus*. Soil properties were measured at time of harvesting the previous rotation and at several times during the experimental rotation. After harvesting, core treatments applied to each site included removing all aboveground slash, retaining all slash, and in some cases applying a double slash treatment. Changes in soil carbon and nutrient levels were minor at all sites and soil degradation was not indicated. Removing slash did not affect soil organic carbon levels at seven sites and reduced it at only one site. Retaining slash increased the soil organic carbon above initial levels at five sites, and none showed a loss of soil organic carbon when slash was left. Soil nitrogen followed a pattern similar to soil organic carbon confirming the linkage between these soil properties. Soil acidification, measured as pH, did not occur at any site. A reduction in exchangeable K, Ca or Mg in the surface 0-10cm soil was measured at seven sites but in all cases this could be replaced by fertiliser at levels applied commonly on an operational basis. It is possible that these cations are retained in the lower soil horizon and may be available to the tree later. Appropriate management practices, including retention of slash on site, fertilisation, and genetically improved planting stock will increase tree growth and maintain soil productivity.

Introduction

Climate and soils are the only environmental factors that are fixed at a site. Species and their genetic make up, and silvicultural practices can be changed by management. Climate may vary or change, but it is beyond the control of local management. While many soil parameters such as texture, horizonation and topographical features are fixed, some factors which directly affect productivity can be influenced by management. It is these parameters, for example P availability, base status, organic matter level (OM) or N retention that need to be addressed by scientific study and analysis. The effects of management may be negative, such as loss of nutrients during harvest of short rotations or positive such as fertiliser application or retaining slash on site. Soil properties important to plantation productivity as well as properties that may be affected by plantation forestry management are the focus of the soil studies.

In geological time scale, soils are constantly adjusting to long-term changes in climate, vegetation, and other soil-forming processes, but in the time scale relevant to land use, soils are in equilibrium with the native vegetation

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and climate. The chemistry of soils is complex so changes in one property, such as pH, may affect another property, such as the availability of a nutrient, in unexpected ways. Tree growth and a broad range of soil properties must be measured to understand the effects forest management on soil productivity. Soils will remain productive with proper management, and production can be increased, if appropriate scientific knowledge is available and utilised. In the case of short-rotation forest plantations on tropical soils, the greatest potential for loss of productivity is loss of organic matter, decline in soil nutrients or acidification.

The objective of studying soil changes in the productivity network is to ensure productivity is not declining, that any changes in nutrient levels are understood and any decline is measured so remedial practices can be applied if needed.

The CIFOR partnership evaluating site management of tropical plantation forests is a network of independent sites using a common template of treatments rather than a unified study conducted by a single organisation. Thus a definitive comparison of changes in soils is not yet possible for the following reasons.

- The experimental sites were established over a period of several years and have rotation lengths ranging from 7 to 30 years. The harvest of the first experimental rotation (which is at least the second crop rotation) has been completed at several sites including Australia (Western Australia), Brazil, China (Guangdong), Congo and India (Kerala), while the sites planted with acacias in Vietnam and Indonesia (Sumatra) are only approaching the end of the first experimental rotation.
- The intensity of the soil sampling and measurements varies between sites due to differences in research resources available to the partners. These constraints have limited data collection at some sites in the latest sampling periods.
- It was not possible to analyse standard soil samples at each of the laboratories, limiting the confidence of direct comparisons between sites.
- The sites have a wide range of soil characteristics which makes comparisons between some soil properties difficult. A small loss of a nutrient may be important if the original level was deficient, but of no consequence if the original level was high.

As a rigorous comparison of changes in the soils between sites is not possible, this summary paper makes a general evaluation of the trends in soil chemistry with special emphasis on those properties which may affect forest productivity. While this analysis will not allow statistical comparisons that may detect small changes, sufficient information is available to assess the probable effect of the productivity of future plantations.

Soil Organic Carbon and Nitrogen

Soil organic matter, measured and expressed as organic carbon (OC), is an important indicator of the productivity of a soil. Much of the influence of OC on productivity is through effects on physical properties such as aggregation, water holding capacity and hydraulic conductivity, but OC also an important nutrient store. Decomposing organic matter can be a major source of nutrients required for plant growth, especially in many of the soils represented in the network where there may be few weatherable minerals. In the case of nutrients that are easily leached, slowly decomposing OC is the dominant source of nutrients for trees. Nitrogen is the dominant nutrient derived from OC, but others such as boron and sulphur may be derived from this source. Because of the importance of N mineralised from soil organic matter, OC and N cycles are tightly linked. This linkage is confirmed by consistent C:N ratios at many of the sites. Processes and management activities that affect one usually have a corresponding effect on the other.

At the 16 sites included in the productivity network, the OC values in the surface soil range from 5.4 g kg^{-1} in the Congo to 66.5 g kg^{-1} in South Africa with a mean value of 29.4 g kg^{-1} (Table 1). These are the expected levels for soils under planted forests in the tropics. Total N concentrations in the surface soil range from 0.34 g kg^{-1} in the Congo to 4.5 g kg^{-1} in India (Vattavada). In contrast to the stable C:N ratios found within sites, the ratios varied between sites, ranging from a low of 9.3 in

Vietnam to 38.6 in Australia (Queensland). The C:N ratios were not related to mean temperatures or rainfall. However, the C:N ratios of sites in the tropics (< 23.5 degrees from the equator) are all lower than 16.5 while the subtropical sites have C:N ratios > 19.5. Lower C:N ratios generally indicate a more intense decomposition which would occur in the warm, humid tropical climates. The relatively high rate of decomposition in the tropics compared to the cooler climates also indicates that sequestering significant amounts of carbon in tropical soils is unlikely.

The direction of change in OC and N from initiation of the study to the latest measurement for each of the sites is shown in Table 2. The interval between initial measurements and last measurements varied between sites, from 4 years in Vietnam to 10 years at the two sites in Western Australia, because experiments were established at different times and the rotation length varies between sites (Nambiar and Kellio 2008). If the slash retention treatments had a significant effect, the plots where all slash was removed (BL_0) was used to determine the trend in Table 2. Of the 11 sites reporting OC levels after treatment establishment, seven showed no change, three showed an increase and one a decrease. At the South African eucalypt site, the OC increased rapidly from 66 g kg^{-1} at time 0 to about 75 g kg^{-1} 2 years later, but there was little additional change from age 2 to 7 years (du Toit *et al.* 2008). This large initial change may have been caused by surface litter being mixed into the soil or by a difference in sampling methods. A different pattern was reported in *Acacia auriculiformis* in Vietnam where the OC changed little in the first 2 years and then increased in the following 2 years (Vu Dinh Huong *et al.* 2008). The same pattern of little initial change followed by an increase occurred at the eucalypt site in China (Guangdong) (Xu *et al.* 2004). At the Chinese fir site in subtropical China (Fujian), the OC decreased from 31.0 to 27.7 g kg^{-1} after 9 years (Fan *et al.* 2008). The small decrease may have resulted from multiple cultivations used for weed control or because of variability in soils. Changes in total soil N followed the same pattern as OC excepting the China (Guangdong) site where total N decreased even though the OC increased. However, the amount of available N increased at both 2 and 4 years after planting while the total N dropped only in the period from time of planting to the next measurement at age 2 years (Xu *et al.* 2004). Such inconsistencies are common when measurements of OC and N are made over several time periods. After measuring OC and N in a watershed in southern USA, it was concluded that OC and N fluctuate over time as well as being highly variable in space (Johnson *et al.* 2007). Only large changes with time can be reliably detected. Most of the sites in the tropical plantation network showed no differences and at the sites that had some change, the differences were small. We conclude that the harvesting and replanting of tropical forest plantations did not affect soil OC and N to a degree that will affect productivity.

Retaining slash on the soil surface did not affect OC at six sites and nor total soil N at seven sites (Table 3). Slash retention increased OC at five sites and N at four sites. None of the sites reported a decrease in OC or N on the slash retention plots. At the site in Brazil, slash retention increased the OC and soil N consistently in the surface 5 cm for all the measurement periods (Goncalves *et al.* 2008). However, little or no differences in the OC or N were found in the 5-10 cm layer. In South Africa after 7 years, the double slash retention increased OC in the surface 10 cm to 89 g kg^{-1} compared to 79 g kg^{-1} for the burn treatment (du Toit *et al.* 2008). In Indonesia (Sodong), slash retention increased both OC and soil N significantly 5 years after planting (Hardiyanto and Wicaksono 2008). In Vietnam, a similar pattern was observed 4 years after planting (Vu Dinh Huong *et al.* 2008).

Variability of OC and soil N make measuring the effect of retaining slash challenging. For example, in pines in Australia (Queensland), the minimum difference needed to differentiate between residue treatments was 6.7 g kg^{-1} at the sampling 4.2 years after the initiation of the experiment (Simpson *et al.* 2004). Since the mean OC content was about 24 g kg^{-1}, a 25% difference was required for statistical significance. While there were statistically significant differences at 4.2 years, slash treatments did not have a statistically significant effect at 6.4 years even though the same trends were apparent (Simpson *et al.* 2004). By age 8.2 years, the effect of retaining slash was again significant with a LSD of 5.0 g kg^{-1} (Smith *et al.* 2008).

Quantities of OC and N in the soil are large compared to the amounts added in the residue treatments. In acacias in Indonesia (Riau, Sumatra), the total N in the soil at time of planting was 8394 kg ha^{-1} while the N in the slash in the double slash treatment (BL_3) was 1131 kg ha^{-1} so the soil contained 88% of the total (Siregar *et al.* 2008). So, only relatively large changes in the soil N can be detected because of the large background of total N. In this case, the effect for C was somewhat less with the soil containing 56% of the carbon. Also, the 51 200 kg ha^{-1} of carbon in the slash is in forms that are easily decomposed and will be respired as CO_2 while the soil carbon is highly resistant to decomposition processes. Using sampling depths in increments of less than 10 cm probably would not affect the results as the decomposition of slash seems to occur on the soil surface. In Mexico, removing or leaving crop residue on the surface did not affect soil OC if the mean annual temperature was above 20°C (Potter *et al.* 2007).

The effect of slash treatment on soil OC is also confounded with the effect of the organic matter on soil physical properties and the mulching effect on decomposition rates. In southwestern Australia, the slash treatments significantly increased the concentration of OC in the surface 5 cm of soil 3 years after harvest. The increase was from about 50 g kg^{-1} for BL_0 to 58 g kg^{-1} for BL_2 and 75 g kg^{-1} for BL_3 (O'Connell *et al.* 2004). However, the treatments also decreased the soil bulk density, presumably because of increased soil fauna activity causing higher porosity. Thus when expressed as the amount rather than concentration, the level of OC in the surface 5 cm was not affected by the residue treatments. The mulching effect occurs because the slash shades the soil surface. Soil temperature fluctuations are moderated and soil water contents may be more favourable to decomposition. In South Africa the total available soil water was generally higher in the plots where slash was retained (BL_2) compared to plots where the slash was removed ($BL_{0)}$, exposing bare soil (du Toit *et al.* 2008). While this mulching effect is difficult to document, it is probably a factor in limiting the final effect of the slash on soil OC.

To date, the effects of clear cutting and replanting and the effects of slash management on soil OC and N have been minor with the trend of no change or a small increase. None of the sites showed a loss of OC or soil N that could be expected to affect future production. However, at many sites, slash retention and other management practices such as fertilisation have increased the productivity of the latest rotation compared to the previous rotation. As fine root growth may have a greater direct effect on OC and soil N than retaining slash (Russell *et al.* 2007), increased plantation productivity should increase the soil OC and N in later rotations. At lower productivity sites, the effect of retaining slash may last for years while at the higher productivity sites any initial effect will tend to disappear more quickly. This was clearly shown by models comparing the short and long term effects of treatments on low and high fertility soils (Saint-André *et al.* 2008). In Western Australia, the slash treatments at the low fertility Busselton site are showing an effect at age 10 years while the slash treatments on the fertile Manjimup site never showed a significant difference (Mendham *et al.* 2008).

Soil Phosphorus

Several methods have been used for determining the amount of 'available P' in agricultural soils. Methods vary in the type and strength of the extractant in attempts to estimate the amount of P available to a specific crop in soils with a specific mineralogy. In the network, methods of determining 'available' P include Bray1, Bray2, Mehlich1, citric acid and total P. At each site the method was chosen as being most appropriate for the soils and laboratory capability, but the use of multiple methods makes a comparison between sites difficult. The available P measured at the initiation of the study ranged from 0.8 mg kg^{-1} at the site in China (Guangdong) to 62.6 mg kg^{-1} at the site in Western Australia (Manjimup) (Table 1). When these two extremes are excluded, the average of the remaining sites is 6.4 mg kg^{-1}. For many tree species, this level of available P is probably sufficient, but site-specific fertiliser studies are required to determine the need for P fertiliser to achieve high growth rates.

Of the eight sites reporting extractable P levels, four reported no change from the time of planting to the latest measurement (Table 2). At three of the sites where acacias were planted, extractable P levels declined with the largest reduction at the Indonesia (Riau) site where the P declined from 3.4 mg kg^{-1} to about 1 mg kg^{-1} at age 5 years (Siregar *et al*. 2008). The other two sites showed about a 35% decline in available P (Vu Dinh Huong *et al*. 2008, Hardiyanto and Wicaksono 2008). Even though different extraction methods were used at these three sites, all showed a consistent decline in P. Despite this, there was little tree growth response to added P. In Brazil, the resin extracted P declined from 6.0 to 4.0 mg kg^{-1} after 7 years with the change occurring gradually after planting.

The only site where slash retention had any effect on soil P levels was in China (Guangdong) (Table 3). There the P in the surface 10 cm increased from 0.7 mg kg^{-1} in the BL_0 treatment to 1.5 mg kg^{-1} in the BL_3 treatment (Xu *et al*. 2004). At the other sites, lack of effect of the slash treatments on soil P is not surprising because of the relatively small amount of P in the slash. For example, at the Indonesia (Riau) site, the understorey contained only 9 kg ha^{-1} and the slash contained another 9 kg ha^{-1} (Siregar *et al*. 2008). The results in this tropical plantation study are similar to results in a similar slash management study in the southern USA. At four sites, removal of loblolly pine slash and understorey reduced the available P at only one site (Scott *et al*. 2004).

At the sites where P fertiliser was added, tree growth increases have been small and somewhat transient. At the four sites in India where eucalypts were planted P fertiliser increased growth only at Punnala and the gain was no longer significant after 4 years (Sankaran *et al*. 2008). Young trees with a small root system may respond to P fertiliser, but with time, the roots occupy more soil volume and the apparent P requirement declines. More studies are needed to find the amount of P fertiliser that is economically optimal and to relate the P requirements to the soil tests at these sites. Unfortunately, based on the experience of predicting P requirements for agricultural crops, improving the reliability of P soil tests will require a series of P fertiliser trials at many of the sites. Using a common extractant such as Mehlich 3 in these trials would increase the potential of comparing information between sites and perhaps between species.

Soil pH

Soil pH is easy to measure, relatively consistent between laboratories, and is a good indicator of soil base status. So pH is useful to compare chemistries of widely differing soils with only minor concerns of method differences between laboratories. Soil pH does not give any indication of the amount of exchange capacity but it is related to the base cation saturation. If the pH becomes lower, i.e. more acidic, some ions such as Al or Mn may reach levels that are toxic to tree growth. However, the relationship is mechanistic for a specific soil, as soil organic matter and soil mineralogy of each soil affect the ion exchange relationships. Also, in a given soil pH may be buffered at different levels so changes in pH from treatment effects are difficult to compare between sites. Thus pH is an index that can be used to identify changes in base status from treatments or harvesting.

All sites in the network reported the pH of the surface soil at the initiation of the trials using soil-water solutions except the Brazil which used a $CaCl_2$ solution (Table 1). The pH of the surface soils ranged from 3.6 at the acacia site in Indonesia (Riau) (Nurwahyudi and Tarigan 2004) to 6.0 at a eucalypt site in Western Australia (Manjimup) (Mendham *et al*. 2008). The pH values are in the normal range for the highly weathered tropical soils included in the network. The difference between pH in water and pH in KCl or delta pH has been reported for five sites. The delta pH ranges from 0.16 at the Indonesia (Sodong) site (Hardiyanto *et al*. 2004) to 0.8 in Vietnam (Binh Duong) (Vu Dinh Huong *et al*. 2004). The delta pHs give more information on the activity of the soil exchange complex.

Several sites have reported soil pH at different depths and in all cases the change in pH with depth was minor. At the Vietnam (Binh Duong) site, the pH_{water} declined from 4.8 in the surface to 4.5 at the 30-50 cm depth (Vu Dinh Huong *et al.* 2004). At the Indonesia (Sodong) site, pH increased from 4.08 in the surface 10 cm to 4.24 at the 20-40 cm depth (Hardiyanto *et al.* 2004). These small changes indicate that the soil chemistry in the soils included in the network does not change dramatically within the profile to the depths measured. No information of soil properties is available for the depths beyond 1 m any of the sites Because of the rooting depth of the trees and the indicator value of pH, some exploratory sampling and pH measurement to depths of 2-3 m could be used to evaluate the need to measure other soil properties below 1 m.

Of the sites reporting pH at the initiation of the experiment and at later sampling times, six reported no change, two recorded a slight decline and one showed an increase (Table 2). At the Chinese fir site in China (Fujian), the pH declined from 5.1 at planting to 4.6 at 9 years (Fan *et al.* 2008). At the acacia site in Vietnam (Binh Duong), the pH of the BL_0 plots declined from 4.5 by only 0.1 pH unit (Vu Dinh Huong *et al.* 2008). In contrast, 5 years after harvest, the pH of the slash removal plots at the Indonesia (Riau) site under *Acacia mangium* increased from 3.6 to 4.2. At some sites the pH changed in intermediate measurement periods but had returned to the initial level by the latest measurement. For instance, in South Africa, the pH_{water} was 4.2 at planting, increased to 5.1 after 2 years and by the seventh year had returned to 4.4. The temporary rise was attributed increased decomposition, even on the slash removal plots.

Of the nine sites reporting the effect of slash retention on soil pH, five sites found no change, three measured an increase and one a decrease (Table 3). At the Brazil and Vietnam sites, the increase was only 0.1 pH units after 7 years and 4 years respectively (Goncalves *et al.* 2008, Vu Dinh Huong *et al.* 2008). At the South African site, retaining slash increased the pH from 4.4 to 4.6 (du Toit *et al.* 2008). While these differences are statistically different, they may be too small to indicate a change in soil chemistry. The trend for the pH to increase as more slash is retained is probably because of 'bases' such as K and Ca released from the decaying litter. (Ca and K are usually called 'base cations'. They are not bases but they act by saturating sites and replacing H). Conversely, at the pine site in Australia (Queensland) the pH_{water} declined from 5.5 in the BL_0 treatment to 5.2 in the BL_3 (double slash) 8.2 years after stand establishment (Smith *et al.* 2008).

In summary, the soil pH is acidic at all the sites and is relatively constant with depth, time and treatment. The sites planted to *Acacia* sp. showed the same general response to pH as the sites with *Eucalyptus* sp. indicating that the nitrogen-fixing species did not cause further acidification because of leaching of cations from the soil. The small differences in soil pH indicate the harvesting and replanting of the tropical forest plantations did not have a serious effect on soil chemistry.

Exchangeable bases (K, Ca, Mg)

Exchangeable K

Exchangeable K in the surface 10 cm ranged from 0.02 $cmol_c\ kg^{-1}$ at the China (Guangdong) site to 2.5 $cmol_c\ kg^{-1}$ at the China (Fujian) site (Table 1). As expected for tropical soils that have not been heavily fertilised, exchangeable K at 13 of the 16 sites is 0.51 $cmol_c\ kg^{-1}$ or below.

Of the 14 sites reporting on exchangeable K in the surface 10 cm from time of planting to the latest measurement, six reported no change, two reported a decrease and six reported an increase (Table 2). At sites reporting no change between the study initiation and the latest measurement, the K concentrations sometimes fluctuated in the intermediate periods, but returned to near original levels. For example, in South Africa the exchangeable K rose slightly in the first two years, but then returned to the original levels by age 8 years (du Toit *et al.* 2008). In Congo, the K concentration in the BL_0 plots decreased from 0.042 $cmol_c\ kg^{-1}$ at time 0 to 0.021 $cmol_c\ kg^{-1}$ in the first year (Deleporte *et al.* 2008). By age 8 years the K levels had returned to the original levels. Because K leaches readily from slash and to some

Table 1. Soil chemistry values in surface 10 cm at planting

	Country-site	Species	O.C. (g kg^{-1})	Total N (g kg^{-1})	C/N ratio	Extr. P (mg kg^{-1})	pH(1)	Exch. K ($\text{cmol}_c\ \text{kg}^{-1}$)	Exch. Ca ($\text{cmol}_c\ \text{kg}^{-1}$)	Exch. Mg ($\text{cmol}_c\ \text{kg}^{-1}$)
1	Congo: Pointe-Noire	Eucalyptus hybrid	5.4	0.34	15.9	NR	4.4	0.03	0.08	0.05
	India: Kerala									
2	Punalla	*E. tereticornis*	43.6	2.89	15.1	NR	5.1	0.35	2.08	1.52
3	Surianelli	*E.grandis*	40.9	2.49	16.4	NR	4.5	0.51	3.21	2.58
4	Vattavada	*E.grandis*	52.3	4.50	11.6	NR	5.3	1.13	24.30	7.13
5	Kayampoovam	*E. tereticornis*	21.5	1.83	11.7	NR	5.3	0.47	9.83	2.51
6	China: Guangdong	*E. urophylla*	8.3	0.7	11.9	0.8	4.4	0.02	0.21	0.41
7	Brazil: Itatinga	*E. grandis*	15.2	1.8	8.4	6.0	3.5	0.04	0.17	0.15
8	South Africa: KZ-Natal	*E. grandis*	66.5	3.2	20.8	2.7	4.2	0.16	0.43	0.64
	Western Australia:									
9	Busselton	*E. globulus*	27.7	1.4	19.8	13.9	4.9	0.06	1.91	0.59
10	Manjimup	*E. globulus*	49.8	2.3	21.7	62.6	6.0	0.19	3.17	0.61
	Indonesia: Sumatra									
11	Riau	*A. mangium*	24.9	2.6	9.5	3.4	3.6	0.35	1.03	0.81
12	Toman	*A. mangium*	26.4	2.3	11.5	5.8	4.3	0.08	0.74	1.04
13	Sodong	*A. mangium*	31.0	2.4	12.9	5.3	4.2	0.11	1.55	0.39
14	Vietnam: Binh Duong	*A. auriculiformis*	11.2	1.2	9.3	10.8	4.5	0.09	0.12	0.23
15	Australia: Queensland	*P. elliottii* x *P. caribaea*	14.3	0.37	38.6	NR	5.7	0.08	0.42	0.23
16	China: Fujian	*C. lanceolata*	31.0	1.58	19.7	3.1	5.1	2.50	10.70	5.5

NR= not reported.

(1) All pH was measured in water except in Brazil where $CaCl_2$ solution was used.

extent in the soils, the short-term changes may be caused by K movement associated with the harvest and replanting. As the stand develops, K is rapidly taken up and recycling of K is soon re-established by leaching from the live crown and from litter. The sites in China and Brazil showed an increase in exchangeable K from harvest to the most recent reporting date. At the eucalypt site in China (Guangdong), the magnitude of change in exchangeable K was highly variable, but consistent, with all of the treatments and depths showing an increase (Xu *et al*. 2004). Fertiliser K had been applied at planting, but the amount applied was not sufficient to account for the increase in soil K. The exchangeable K increased from the year of harvesting to age 7 years in Brazil (Goncalves *et al*. 2008). As in China, the levels fluctuated greatly with time and treatment indicating the changes may be due to soil variability. At the two sites in Western Australia, the decline in exchangeable K was marked in the first 3-4 years but then stabilised at the new, lower levels. At the grey sand site (Busselton) the amount of exchangeable K in the

Table 2. Change in soil chemistry values in the surface 10 cm from time of planting to latest measurement reported

	Country-site	Species	O.C. (g kg^{-1})	Total N (g kg^{-1})	Extr. P (mg kg^{-1})	pH	Exch. K (cmol$_c$ kg^{-1})	Exch. Ca (cmol$_c$ kg^{-1})	Exch. Mg (cmol$_c$ kg^{-1})
1	Congo: Pointe-Noire	Eucalyptus hybrid	↔	↔	NR	NR	↔	↓	↔
	India: Kerala								
2	Punalla	*E. tereticornis*	NR	NR	NR	NR	↓	↔	↔
3	Surianelli	*E.grandis*	NR	NR	NR	NR	↔	↔	↔
4	Vattavada	*E.grandis*	NR	NR	NR	NR	↔	↔	↔
5	Kayampoovam	*E. tereticornis*	NR	NR	NR	NR	↔	↔	↔
6	China: Guangdong	*E. urophylla*	↑	↓	↔	NR	↑	↑	↔
7	Brazil: Itatinga	*E. grandis*	↔	↔	↓	↔	↑	↔	↑
8	South Africa: KZ-Natal	*E. grandis*	↑	↑	↔	↔	↔	↔	↔
	Western Australia:								
9	Busselton	*E. globulus*	↔	↔	↔	↔	↓	↔	↔
10	Manjimup	*E. globulus*	↔	↔	↔	↔	↓	↔	↔
	Indonesia: Sumatra								
11	Riau	*A. mangium*	↔	↔	↓	↑	↓	↓	↓
12	Toman	*A. mangium*	NR	NR	NR	NR	NR	NR	NR
13	Sodong	*A. mangium*	↔	↔	↓	↔	↔	↔	↔
14	Vietnam: Binh Duong	*A. auriculiformis*	↑	↑	↓	↓	↓	↓	↓
15	Australia: Queensland	*P. elliottii x P. caribaea*	↔	↔	NR	↔	↓	↓	↓
16	China: Fujian	*C. lanceolata*	↓	↔	NR	↓	NR	NR	NR

↑ Concentration increased.
↓ Concentration decreased.
↔ No significant change.
NR data not reported.

surface 10 cm declined from about 55 to 35 kg ha^{-1} (Mendham *et al.* 2008). In Queensland, the decline in K continued though the first 8 years going from 0.08 to 0.03 cmol$_c$ kg^{-1}. In Vietnam, the exchangeable K declined after the first year and had not recovered by the third year (Vu Dinh Huong *et al.* 2008). A similar drop was noted at the Indonesia (Riau) site where a 50% loss in the exchangeable K was measured after 5 years (Siregar *et al.* 2008). However, based on the longer term results from other locations, it is too early to assume the decline at this site will continue.

Retention of slash did not affect the exchangeable K in the surface 10 cm of soil in 13 of the 14 sites reporting data (Table 3). Only at the Brazil site was there a decline in K on the slash retention plots compared to the slash removal plots. However, this was due to the exchangeable K increasing less on the slash retention plots than on the plots where all slash was removed. This may have been caused by an increased uptake of K caused by the faster growth of the stand on the slash retention plots. The faster growth was probably due to availability of N and other nutrients (Goncalves *et al.* 2008).

Exchangeable Ca

At the time of planting, the exchangeable Ca in the surface 10 cm of soil ranged from 0.08 cmol$_c$ kg^{-1} at the Congo site to 24.30 cmol$_c$ kg^{-1} at the India (Vattavada) site (Table 1). Seven of the sites had an exchangeable Ca level below 1.0 $cmol_c$ kg^{-1} which is used as a critical level for some crops. However, at the 10 sites where *Eucalyptus* sp. was harvested, there was no relationship between annual biomass production and the exhangeable Ca in the soil (r^2<0.02). Hence Ca does not seem to be limiting tree growth at these sites.

Of the 14 sites reporting Ca levels, exchangeable Ca in the slash removal plots did not change from time of harvest until the latest soil measurements at nine sites (Table 2). Of these, the Ca was above 1.0 $cmol_c$ kg^{-1} at all except sites in South Africa and Brazil. At the South African site, the Ca increased in the first year after planting, but returned to the original level through age 7 years (du Toit *et al*. 2008). At the Brazil site, Ca increased in the surface 5 cm of soil during the 7-year rotation, but the Ca declined by an equal amount in the 5-10 cm layer (Goncalves *et al*. 2008). At both sites in Western Australia, the exchangeable Ca declined until about age 7 years and then by age 11 years increased to levels that were higher than at time of planting (Mendham *et al*. 2008). The magnitude of change was greater in the surface 0-10 cm but exchangeable Ca in the 10-20 cm depth followed a similar pattern. The only site to report an increase with time in the BL_0 plots was in China (Guangdong) where the exchangeable Ca increased from 0.21 to over 0.60 $cmol_c$ kg^{-1} in the first four years after planting. At the Indonesia (Riau) site (Siregar *et al*. 2008), the site in Vietnam (Vu Dinh Huong *et al*. 2008), and at the Queensland site (Smith *et al*. 2008), the amount of exchangeable Ca declined by 50% or more over the measurements period. The greatest loss occurred at the Congo site where exchangeable Ca in the surface 100 cm of soil in the BL_0 plots declined from 263 kg ha^{-1} to 58 kg ha^{-1} at age 8 years, a loss of 75% of the initial reservoir (Deleporte *et al*. 2008). While this loss of Ca at the Congo site seems dramatic, it could be related to past land use. Before plantations were established, the area was savanna. Grasses are usually more efficient in retaining Ca in the soil. Thus, the loss in Ca may be the soil establishing a new equilibrium after the conversion to trees. Most of the change in Ca occurred in the first 3 years and then stabilised, confirming a new equilibrium has been reached. Retaining slash after harvest, compared to complete removal, had no effect on exchangeable Ca at 10 locations. Four sites reported a significant increase in soil Ca when slash was retained. In South Africa, exchangeable Ca increased proportionately with the amount of slash from about 0.5 $cmol_c$ kg^{-1} for the complete removal treatment to 1.1 $cmol_c$ kg^{-1} for single slash retention to about 1.5 $cmol_c$ kg^{-1} for double slash (du Toit *et al*. 2008). A similar pattern occurred at the two sites in Western Australia with the greatest effect at the more fertile Manjimup site (Mendham *et al*. 2008). Retaining slash increased Ca at the Riau site in Indonesia compared to slash removal plots, but Ca levels in both slash treatments were below the original levels (Siregar *et al*. 2008).

Application of Ca to acacia stands in Vietnam (Vu Dinh Huong *et al*. 2008) and Indonesia (Sodong and Toman) (Hardiyanto and Wicaksono 2008) gave no tree growth response. The lack of response may be attributed to several factors including:

- calcium applied to the soil surface may not be readily available to the existing tree crop, but remains in the top few centimetres of soil; and
- the sites where Ca was applied may not have been below critical levels for tree growth.

Lack of a relationship between productivity of the previous stand and the soil Ca levels indicates the second factor is the most important. Tree harvesting removes relatively high rates of Ca but this can be minimised by retaining slash on the site. Other management options such as retaining bark on site can aid Ca retention. While no deficiencies are apparent at any of these sites, wood harvest removes a large percentage of Ca at some sites. Retaining as much Ca as possible on site is a wise management strategy, especially in low-Ca soils such as those at the Congo site.

Exchangeable Mg

Exchangeable Mg in the soil followed the same pattern as exchangeable Ca at most of the sites. As with Ca, the lowest Mg levels were in at the Congo site and the highest were at the Vattavada site in India (Table 1). Across all sites, the Ca concentration was 2.8 times the Mg concentration with all sites closely following this relationship (Fig. 1).

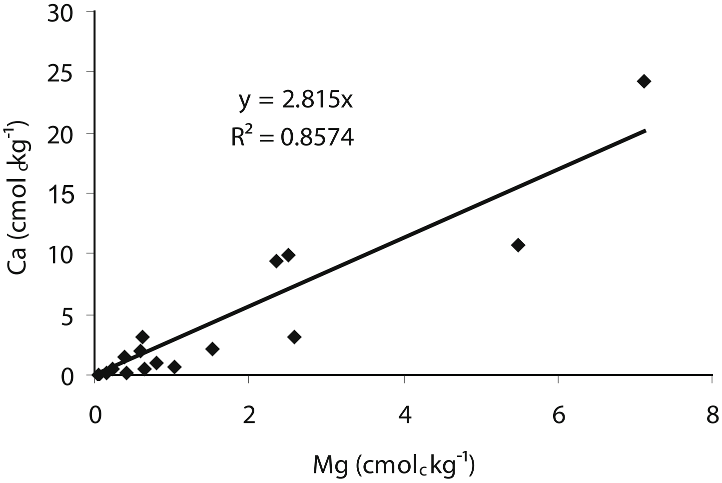

Figure 1. The relationship between exchangeable Mg and Ca in the surface soil of all sites included in the network

Table 3. Effect of slash retention treatments compared to total removal (BL_0) on soil chemistry values in the surface 10 cm at latest measurement reported

	Country-site	Species	O.C. (g kg^{-1})	Total N (g kg^{-1})	Extr. P (mg kg^{-})^{1}	pH	Exch. K (cmol$_c$ kg^{-1})	Exch. Ca (cmol$_c$ kg^{-1})	Exch. Mg (cmol$_c$ kg^{-1})
1	Congo: Pointe-Noire	Eucalyptus hybrid	↔	↔	NR	NR	↔	↔	↑
	India: Kerala								
2	Punalla	*E. tereticornis*	NR	NR	NR	NR	↔	↔	↔
3	Surianelli	*E.grandis*	NR	NR	NR	NR	↔	↔	↔
4	Vattavada	*E.grandis*	NR	NR	NR	NR	↔	↔	↔
5	Kayampoovam	*E. tereticornis*	NR	NR	NR	NR	↔	↔	↔
6	China: Guangdong	*E. urophylla*	↔	↔	↑	NR	↔	↔	↔
7	Brazil: Itatinga	*E. grandis*	↑	↑	↔	↑	↓	↔	↔
8	South Africa: KZ-Natal	*E. grandis*	↑	↔	↔	↑	↔	↑	↑
	W. Australia								
9	Busselton	*E. globulus*	↔	↔	↔	↔	↔	↑	↔
10	Manjimup	*E. globulus*	↔	↔	↔	↔	↔	↑	↑
	Indonesia: Sumatra								
11	Riau	*A. mangium*	↔	↔	↔	↔	↔	↑	↔
12	Toman	*A. mangium*	NR	NR	NR	NR	NR	NR	NR
13	Sodong	*A. mangium*	↑	↑	↔	↔	↔	↔	↔
14	Vietnam: Binh Duong	*A. auriculiformis*	↑	↑	↔	↑	↔	↔	↔
15	Australia: Queensland	*P. elliottii x P. caribaea*	↑	↑	NR	↓	↔	↔	↑
16	China: Fujian	*C. lanceolata*	↔	↔	NR	↔	NR	NR	NR

↑ Concentration increased.
↓ Concentration decreased.
↔ No significant change.
NR data not reported.

Of the 14 sites reporting Mg concentrations over time, 10 had no significant change, one an increase and three a decrease (Table 2). The site in Brazil was the only location where the Mg concentration increased from time of planting to the latest measurement period. Magnesium in the surface 5 cm of soil increased from 0.08 $cmol_c$ kg^{-1}at time of planting to 0.30 $cmol_c$ kg^{-1} after 7 years (Goncalves *et al.* 2008). Unlike the change in Ca at this site, the Mg in the 5-10 cm layer did not change leaving an overall positive effect over the 7 years. At the Riau site in Indonesia, exchangeable Mg in the surface 10 cm of soil declined from 0.81 to about 0.40 $cmol_c$ kg^{-1} in 5 years (Siregar *et al.* 2008). Similar losses occurred in Queensland over an 8.2-year-period and in Vietnam over 4 years (Smith *et al.* 2008, Vu Dinh Huong *et al.* 2008).

Retention of slash had no effect on the Mg concentrations in the surface 10 cm of soil at 10 sites (Table 3). At the Congo site, the double slash treatment was able to maintain the same Mg concentration as was measured at planting, while the level in the total removal (slash and litter) plots was lower (Deleporte *et al.* 2008). At the Queensland site, slash treatments increased the Mg in the soil from 0.20 $cmol_c$ kg^{-1} for the BL_0 treatment to 0.32 $cmol_c$ kg^{-1} for the double slash (BL_3) treatment at age 8.2 years (Smith *et al.* 2008). However, compared to the measurement at 2.1 years, Mg was lower regardless of slash retention. At the Western Australia (Manjimup) and South African sites, the Mg levels were higher in the double slash plots indicating that the additional Mg added to the site was retained (du Toit *et al.* 2008, Mendham *et al.* 2008).

As in the case for Ca, the productivity of the previous rotation was not related to the Mg levels in the soil at the time of harvesting that rotation. Unfortunately, there is little information available on the requirement for Mg by tree crops. In this set of studies, most sites showed no Mg loss and none sites noted Mg deficiency symptoms.

Exchange Capacity

As with 'available' P, the methods used to determine cation exchange capacity (CEC) varies with the site. Because the interpretation of CEC depends on the method used and not all sites reported CEC, no comparisons have been made in this summary paper. However, for the sites that have measured CEC, changes may be important in determining the capacity of the soil to retain nutrients. The difference between pH_{water} and pH_{KCl} indicates that some of the soils have anion exchange capacity (AEC) as well. Occurrence of AEC in tropical soils is of interest because of its potential to prevent some nitrates from leaching.

Conclusions

The period from harvest through replanting is when forest soils are most subject to changes in organic matter and nutrients (Nambiar and Kellio 2008). Soils can lose nutrients though export of nutrients. Nutrients in soil have the potential of being leached during this time especially where there is high rainfall (Nambiar and Kellio 2008). Changes in soil chemistry reported in this project are relatively small and do not indicate leaching from the surface has occurred. However, the potential for loss of nutrients emphasises the benefits of retaining slash and re-establishment of the stand soon after clearcutting. A significant amount of nutrients is released from decomposing slash after the new stand is well established and can utilise the nutrients. The mulching effect of the slash protects the soil from dramatic increases in mineralisation due to changes in physical conditions.

Harvesting removes wood which often represents a large percentage of the surface organic matter on a site. For example, at the Indonesia (Sodong) site, wood comprised 67% of the living, aboveground biomass when the previous crop was harvested. After the harvest, rapid decomposition of the remaining slash further reduces the surface organic matter, but the small changes of OC and soil N show that at these sites loss of surface biomass does not affect soil productivity.

At sites where stores of nutrients are naturally low, nutrient export through wood harvest can be large. In Congo, the surface one metre of soil contained about 260 kg ha^{-1} of exchangeable Ca while the aboveground trees contained an additional 74 kg ha^{-1} including 28 kg ha^{-1} in the wood (Deleporte *et al*. 2008). Therefore, while a total tree harvest will remove about 22% of Ca, retaining slash and debarking on site will remove only 8% of Ca. While the nutrients removed during harvest can be a high portion of available nutrients in the soil, the amounts are in the range that can easily be replaced by fertiliser, as is already done in most agricultural systems.

Fertiliser is added as a standard practice at many sites meaning productivity will probably increase with time. With the information from this network and other sources clarifying the amounts and types needed for economic responses, fertiliser use will probably increase, further enhancing the soil productivity. For example, at the Indonesia (Riau) site, the results indicate that a higher level of P fertiliser will increase economic returns (Siregar *et al*. 2008).

As previously noted, limited resources at some sites prevented a sampling scheme that would allow precise measurements of the effects of the harvest and replanting of these sites. Somewhat different sampling intensities and the use of different laboratory methods limit the comparisons that can be made between sites. Because only one species was grown at each site, comparisons between species are not possible. Despite these limitations, the overall results from all sites show that change in the soils across diverse sites and species are small and there is no indication of any decline in soil properties under these tropical forest plantations. The network has also shown that management practices such as retaining the slash on the site and fertilisation can increase forest productivity as well as protecting and conserving the soil. Data from the soil analyses show little change and demonstrate that tropical plantation forestry is a sustainable system if managed properly. However, most sites of the network have completed only one crop cycle. The study must continue for several rotations to test the validity of this conclusion and allow development of new management practices for wood production while protecting the soil and environment.

References

Deleporte, P., Laclau J.P., Nzila, J.D., Kazotti, J.G., Marien, J.N., Bouillet, J.P., Szwarc, M., D'Annunzio, R. and Ranger, J. 2008. Effects of slash and litter management practices on soil chemical properties and growth of second rotation eucalypts in the Congo. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 5-22. Center for International Forestry Research, Bogor, Indonesia.

du Toit, B., Dovey, S.B. and Smith, C.W. 2008 Effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. *IIn*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 63-78. Center for International Forestry Research, Bogor, Indonesia.

Fan Shaohui, Liao Zuhui, Peng Longfu, Yang Xujing, He Zongming, He Zhiying and Lin Sizu. 2008. Effects of site management on growth of a second-rotation Chinese fir (*Cunninghamia lanceolata*) plantation. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 149-156. Center for International Forestry Research, Bogor, Indonesia.

Gonçalves, J.L.M., Wichert, M.C.P., Gava, J.L. and Serrano, M.I.P. 2008. Soil fertility and growth of *Eucalyptus grandis* in Brazil under different residue management practices. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 51-62. Center for International Forestry Research, Bogor, Indonesia.

Hardiyanto, E.B., Anshori, S. and Sulistyono, D. 2004. Early results of site management in *Acacia mangium* plantations in PT Musi Hutan Persada, South Sumatra, Indonesia. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 94-108. Center for International Forestry Research, Bogor, Indonesia.

Hardiyanto, E.B. and Wicaksono, A. 2008. Inter-rotation site management, stand growth and soil properties in *Acacia mangium* plantations in South Sumatra, Indonesia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 107-122. Center for International Forestry Research, Bogor, Indonesia.

Johnson, D.W., Todd, D.E. Jr., Trettin, C.F. and Sedinger, J.S. 2007. Soil carbon and nitrogen changes in forests of Walker Branch watershed, 1972 to 2004. Soil Science Society of America Journal 71:1639-1646.

Mendham, D.S., Grove, T.S., O'Connell, A.M. and Rance, S.J. 2008. Impacts of inter-rotation site management on soil nutrients and plantation productivity in *Eucalyptus globulus* plantations in south-western Australia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 79-92. Center for International Forestry Research, Bogor, Indonesia.

Nambiar, E.K.S. and Kallio, M. 2008 Increasing and sustaining productivity in tropical forest plantations: making a difference through cooperative research and partnerships. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 205-228. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M., Grove, T.S., Mendham, D.S., Corbeels, M., McMurtrie, R.F., Shammas, K. and Rance, S.J. 2004. Impacts of inter-rotation site management on nutrient stores and fluxes and growth of eucalypt plantations in southwestern Australia. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 77-91. Center for International Forestry Research, Bogor, Indonesia.

Potter, K.N., Velazquez-Garcia, J., Scopel, E. and Torbert, H.A. 2007. Residue removal and climatic effects on soil carbon content of no-till soils. Journal of Soil and Water Conservation 62:110-114.

Russell, A.E., Raich, J.W., Valverde-Barrantes, O.J. and Fisher, R.F. 2007. Tree species effects on soil properties in experimental plantations in tropical moist forests. Soil Science Society of America Journal 71:1389-1397.

Saint-André, L., Laclau, J.P., Deleporte, P., Gava, J. L., Gonçalves, J. L. M., Mendham, D., Nzila, J. D., Smith, C., du Toit, B., Xu, D.P., Sankaran, K.V., Marien, J.N., Nouvellon Y., Bouillet, J.P. and Ranger, J. 2008. Slash and litter management effects on *Eucalyptus* productivity: a synthesis using a growth and yield modelling approach. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 173-188. Center for International Forestry Research, Bogor, Indonesia.

Sankaran, K.V., Mendham, D.S., Chacko, K.C., Pandalai, R.C., Pillai, P.K.C., Grove, T.S. and O'Connell, A.M. 2008. Impact of site management practices on growth of eeucalypt plantations in the monsoonal Tropics in Kerala, India. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 23-38. Center for International Forestry Research, Bogor, Indonesia.

Scott, D.A., Tiarks, A.E., Sanchez, F.G., Elliott-Smith, M. and Stagg, R. 2004. Forest soil productivity on the southern long-term soil productivity sites at age 5 years. *In*: Connor, K.F. (ed.) Proceedings of the 12th biennial southern silvicultural research conference, 372-377. General Technical Report SRS-71, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, North Carolina, USA. 594p.

Simpson, J.A., Smith, T.E., Keay, P.T., Osborne, D.O., Xu, Z.H. and Podberscek, M.I. 2004. Impacts of inter-rotation site management on tree growth and soil properties in the first 6.4 years of a hybrid pine plantation in subtropical Australia. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 139-149. Center for International Forestry Research, Bogor, Indonesia.

Siregar, S.T.H., Nurwahyudi and Mulawarman. 2008. Effects of inter-rotation management on site productivity of *Acacia mangium* in Riau province, Sumatra, Indonesia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 93-106. Center for International Forestry Research, Bogor, Indonesia.

Smith, T.E., Osborne, D.O. and Simpson, J.A. 2008. Inter-rotation management impacts on growth and soil properties in hybrid pine plantations on sandy soils in subtropical Australia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 139-148. Center for International Forestry Research, Bogor, Indonesia.

Vu Dinh Huong, Le Thanh Quang, Nguyen Thanh Binh and Pham The Dung. 2008 Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 123-138. Center for International Forestry Research, Bogor, Indonesia.

Vu Dinh Huong, Pham Viet Tung, Pham The Dung, Ho Van Phuc, Nguyen Thanh Binh, Ha Minh Duc, and Nguyen Thi Tron. 2004. Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam. *In*: Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 121-137. Center for International Forestry Research, Bogor, Indonesia.

Xu, D., Yang, Z.J. and Zhang, N.N. 2004. Effects of site management on tree growth and soil properties of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. *In*: Nambiar, E.K.S, Ranger, J., Tiarks, A. and Toma, T. (eds.) Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003, 45-60. Center for International Forestry Research, Bogor, Indonesia.

Increasing and Sustaining Productivity in Subtropical and Tropical Plantation forests:

Making a Difference through Research Partnership

E.K.S. Nambiar[1] and M.H. Kallio[2]

Abstract

This research project was initiated in 1995 to address some concerns of many people, including scientists, who were questioning the prospects of tropical plantations established in short-rotation forestry as a sustainable natural resource. It is an international partnership of public and private organisations coordinated by the Center for International Forestry Research (CIFOR). It is based on the proposition that productivity is the foundation of successful plantation forestry managed for wood production and/or ecosystem services. The main aim was to examine critically effects of site management on productivity of successive rotations of plantations and on soils. The project has 16 experimental sites (10 eucalypt, 4 acacia and 2 conifers) in Australia, Brazil, Congo, China, India, Indonesia, South Africa and Vietnam. From results gathered for a decade in plantations, with growth rates from 6 to 46 $m^3 ha^{-1} yr^{-1}$ in a range of environments and forest management conditions, we conclude that subtropical and tropical plantations can be managed to increase and sustain productivity. Conserving site resources (organic matter and nutrients) to maintain production is very important. No major risks to soils were identified that cannot be managed by scientifically-based practices. One site had a problem with a fungal pathogen and no insect problems were observed at any site. The capacity of the individuals and organisations to explore new opportunities for sustainable management has been greatly strengthened through capacity building, mutual learning and sharing of information with complete transparency. The project has made significant impacts on forest management in partner organisations and developed options for improving plantation productivity of their plantations. Impacts are extending beyond the boundaries of partners' plantation areas. Questions of long-term sustainable production can not be resolved from experiments of one rotation at a few sites so there is a compelling case to continue and build on this research programme to support plantation forestry in the tropics.

Introduction

In the early 1990s, several major issues focusing on the development of tropical plantation forestry emerged. Some national Governments, especially in Asia and South America, recognised an economic opportunity and supported investments in plantation forestry. As a result, the area of plantation forests expanded rapidly. Controversies on the sustainability of this form of land use and opposition to these ventures also emerged. These controversies were based on a number issues including doubts about sustained biological productivity, impacts of converting native forest to plantations on biodiversity and other environmental values, and impacts on local communities. At the same time, knowledge of the impacts of such large-scale changes in land use was in its infancy.

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This project does not address all these issues. It was conceptualised and planned to provide scientific evidence to address concerns about one critical issue, i.e. the sustained productivity of planted forests. Initially ideas were drawn from a concurrent project which provided a multi-disciplinary synthesis of the state of the knowledge of the critical soil and environmental processes determining productivity and management of tropical plantations (Nambiar and Brown 1997a).

Productivity is a foundation of successful forestry, regardless of whether plantations are managed for wood production or ecosystem services. It is also a central issue whether plantations are managed by large industrial companies or by individual, small-scale growers. Productivity per unit area and growth rates influence the return on investments to all growers. Furthermore, scientifically based site management is an important way to avoid the off-site impacts of forestry practices. These principles were the basis for the partnership of diverse organisations with shared goals in this research project.

Partnership, Objectives and Site Selection

The core objectives of the project were evolved during 1994-95 in consultation with potential partners from several countries. The aim was to understand the impacts of management practices on the productivity of successive rotations of plantations in subtropical and tropical environments and to develop management options for increasing and sustaining productivity. Experimental approach was focused on the management phase between the harvesting of one crop and the establishment of the next because this period of inter-rotation management is a window of considerable risks to the site but also a time of opportunity to correct the mistakes and set the course of sustainable management (Nambiar and Brown 1997b). The rationale, approach, core treatments and details of project development have been described by Tiarks *et al.* (1998) and Nambiar *et al.* (1999).

The major objectives were to:

- evaluate the impacts of soil and site management practices on the productivity of successive rotations of plantations. The impacts to be measured as plantation growth and pertinent changes in soil;
- develop management options for maintaining or increasing productivity in a form which can be applied by local managers and facilitate adoption; and
- strengthen capacity of local institutions in research and application to respond to new problems and opportunities.

All partners were expected to benefit to a greater or lesser degree through mutual learning. To achieve these objectives it was necessary to identify partners with commitment for long-term research on plantation sustainability and who were willing to establish and maintain experimental sites. Criteria for site selection included: availability of a stand growing the most common species planted in the region and representative of the local commercial plantations; degree of certainty for the protection of the site and long-term access, and prospects of active involvement by local managers to foster prompt uptake of results.

A central principle was that while the project had to have a set of common treatments, the programme at each location should be robust enough to provide locally relevant and self-contained scientific outcomes. Two types of treatment structure were designed to achieve this: (1) a set of *core treatments* common to all sites so that the results could be compared and generic relationships explored (Saint-Andre *et al.* 2008). These were based on intensity of harvests and sequential removal of slash and litter, ranging from treatments which removed all aboveground biomass to those in which the amount of slash and litter was doubled (Tiarks *et al* 1998). Additional treatments including burning slash, and organic matter incorporation were applied in some studies. These were applied with uniform rigour to allow the best possible interpretation of results. (2) A set of *optional treatments* focused on local needs. Ideas of local researchers and managers were included in the design. Results from optional treatments gave valuable insights into specific factors influencing productivity in some environments. Examples include vegetation management studies in Vietnam and Kerala (Sankaran *et al.* 2008, Vu Dinh Huong *et al.* 2008), nutrient management studies in Sumatra (Hardiyanto and Wicaksono 2008) and the mixed species plantations research using eucalypts and acacias in Brazil and Congo (Bouillet *et al.* 2008). Combination of results from core and optional treatments provided valuable information on constraints on production and management at a site.

Networking and site selection and began in 1994-95. The first two sites in Western Australia were planted in 1995 and last in 2002 in Vietnam. Currently there are 16 experimental installations of eucalypts, acacias, Chinese fir and pine located in Australia, Brazil, China, Congo, India, Indonesia, South Africa and Vietnam (Fig. 1). They represent a very wide range of growing environments and local management systems with harvesting cycles from 5.5 to 30 years. The ten eucalypt experiments have grown for the full rotation length and have been harvested. Acacia stands are likely to be harvested in 2008. The pine and Chinese fir plantations will continue to their typical rotation age of about 30 years.

Results from individual locations and their application to management for improving productivity are described in 12 papers in these proceedings. They illustrate the value of the research concept which stipulated that each site should aim to produce results which are self-contained and their contributions to science and application should not be dependant on the success or failure of other sites or the network. After a decade of work, the project completed Phase 1 with a workshop in November 2006 in Bogor, Indonesia.

In this paper, we present a general synthesis based on results from all sites. The focus is on results from *core* treatments as they allowed comparison of sites. We have also used results from *optional* treatments to illustrate the effects of management on production. Where relevant, observations made during several site visits by the senior author to all sites are used in the discussions. First, we draw attention to the wide range of productivity in commercial plantations typically grown in the subtropics and tropics. Secondly, we discuss how management practices including harvesting intensity influenced organic matter and nutrient pools and fluxes at the site in relation to wood production across the productivity range. Thirdly, the general trend in productivity changes from the first to the second rotation at the same site is illustrated. Since the impacts of management on soils were an important objective, general comments on trends are included. Key findings on soils are discussed in detail in the proceedings by Tiarks and Ranger (2008). Finally, the scientific out puts, contributions to capacity building and the practical impacts of this research on local management are summarised.

Growing Environments of Experimental Plantations

The experimental sites cover a wide range of geographical zones and environment. Their locations in relation to equator and latitudes are shown in Fig. 1. In general, nine sites are located in the tropics, five in the subtropics and two in a Mediterranean environment. Biophysical variables (Table 1) illustrate the wide range of environmental conditions of sites and species represented in the network. Sites are grouped within the tree genera *Eucalyptus* and *Acacia*, and conifers (*Cunninghamia lanceolata* and a hybrid *Pinus*), and listed in order of their latitudes. Climatic data, including temperature and rainfall, were not collected at the experimental sites. Temperatures are usually long-term means for the region. Rainfall figures for most sites are taken from locations of varying distances from the experimental sites. The number of years for which

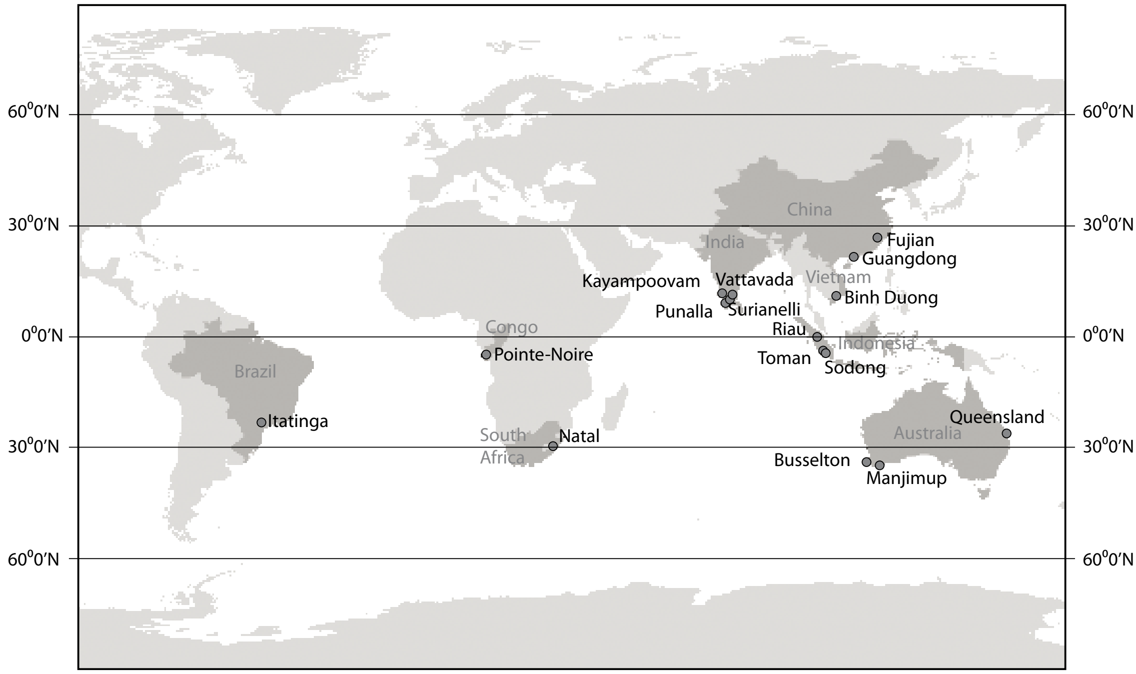

Figure 1. Geographic location of the 16 experimental installations in the network project

these means are estimated is not uniform between sites. Soil types are tabulated as described by the authors, based on classification systems including FAO, USDA or national systems. (e.g. Australia). They represent a wide range of soils with diverse properties (Tiarks and Ranger 2008). In general, climatic data and soil classification should be considered as best available approximations for the local area and not as site specific data. They are useful for understanding the broader biophysical characteristics of sites and may not be precise enough for interpreting process level information across sites.

The sites in the tropics are in a band close to the equator. In contrast, the sites in Western Australia have a Mediterranean environment, characterised by winter rainfall and long periods of relatively hot and dry summer months. Mean annual rainfall varied from 825 to 3000 mm between sites and the average annual temperature varied from 15 to 29°C. Some sites have pronounced monsoonal climate with clear and often prolonged dry periods (e.g. Kerala and Sodong) and in some cases rainfall may be distributed more evenly through the year (e.g. sites in Brazil and Riau, Indonesia). All sites are located in regions where planted forests represent a resource of significant economic importance.

Productivity of First Rotation Stands

Stands that were clearfelled to establish the new set of experiments are called first rotation (1R). They were raised from seedlings except for two *E. tereticornis* sites (Sites 2 and 5 in Table 1) in Kerala which were coppice stands. The range of growing environment, species and rotation lengths as well as the variations in local forest management including stocking gave rise to a large variation in productivity, as measured mean annual increment (MAI) and total aboveground biomass (Table 2).

Variations in productivity were large within species and between sites. The MAI of *A. mangium* in Sumatra varied by three-fold between the three sites and by two-fold between two sites (Sites 12 and 13) located closely and had similar land use history and management (Table 1). Productivity varied considerably within a region, where the experimental programme included more than one site. For example, productivity of four eucalypt sites owned and managed by the same organisation in Kerala, ranged from a MAI of 6.1 m^3 ha^{-1} yr^{-1} to 31.3 m^3 ha^{-1} yr^{-1}. At this location, even within the same species, variation was large (Sankaran *et al*. 2008). Similarly, the growth rates of two *E. globulus* plantations in Western Australia ranged form 12.2 m^3 ha^{-1} yr^{-1} to 48.7 m^3 ha^{-1} yr^{-1}. Amounts of slash after harvest ranged from 6 to 61 t $ha^{-1}$and the litter accumulated by the end of the rotation varied from 5 to 37 t ha^{-1} (Table 2). Such variations in productivity within a region are common in plantation forestry because of variation in soils which influences soil water and nutrient availability. Allocation of biomass to various components by the end of the rotation is highly dependant on site environment, species (including within species variation) and silviculture. In general, the ratio between the weights of stem to slash ranged from 2 to 8 across sites with an exceptionally high ratio of 22 for *E. grandis* at the Brazilian site. There are significant correlations between different components of the biomass. The amounts of biomass harvested, the amounts left at the site, and nutrient contents of these components determine the extent of impacts inter-rotation site management would have on soil and nutrient supply for the next rotation.

Nutrient Conservation, Displacements and Depletion

Harvesting intensity and subsequent site preparation practices for the next crop can lead to outcomes which enable conservation of organic matter and nutrients or cause displacement or depletion of these site resources. Methods of harvesting and processing logs, manually or mechanically lead to uneven distribution of slash and varying levels of disturbance on soil- litter layers. In this project, harvesting and transporting logs out of experimental area were done manually to minimise soil disturbance. Where slash was retained as a treatment, it was re-distributed throughout the plot.

Focus of this study was on the potential impacts of wood and biomass harvesting on organic matter and nutrients in the ecosystem, and subsequently on production. These effects are described in several papers in this and the earlier proceedings. Amounts of nutrients potentially vulnerable to management-induced changes can be estimated from the nutrient contents in biomass components (Table 3). Relationships between biomass and nutrient contents were not as strong as expected, partly because the difference between sites in tree nutrient concentrations. The correlation coefficient between biomass and amounts of nutrients in the biomass are 0.59 for N, 0.28 for P and 0.28 for K. The types of information in Tables 2 and 3 allow managers to estimate the progressive removal of biomass and nutrients from a site in relation to intensity of harvest as wood and biomass.

Figure 2 combines this information as an example to illustrate how increasing intensity of harvests (biomass removal) progressively increases amounts of N, P, K and Ca removed from a site. The information is drawn from two sites, *A. mangium* in Sumatra (Site 13) and *E. grandis* in Brazil (Site 7). In both cases, harvesting of merchantable wood alone (usually stem under 5-10 cm top end diameter) leads to minimum loss compared to whole standing tree biomass harvest. The results show the potential for nutrient removal increasing in steps with the intensity of harvest. They also show that the amounts of such removal are specific to sites and nutrients.

Harvesting intensity ranging from removal of wood alone (after debarking at the site) to total aboveground biomass (industrial wood plus biomass for example for energy production) is practised among our partner countries. It is customary in some countries, including Vietnam, China, India and Indonesia, to allow local communities to collect residual wood including branches from harvest and some times litter for firewood and other needs. Industrial scale harvesting of biomass (in addition to stem) is practised in economically advanced countries such as Finland and Sweden. Pressure for biomass harvesting is likely to increase if bio-fuel production became more feasible and popular.

Table 1. Location, species, climate, previous land use and main soil types of the sites

Site	Country-site	Species	Location	Climate	Temp (°C)	Rainfall (mm yr^{-1})	Previous land use	Soil type
1	Congo: Pointe-Noire	Eucalyptus hybrid	04°48′S, 11°54′E	Tropical	25	1200	Savanna	Sandy, Arcrisol
	India: Kerala							
2	Punalla	*E. tereticornis*	09°06′N, 76°54′E	Tropical	27	2000	Degraded moist dediduos forest	Sandy loam to clay loam, Ferrasol
3	Surianelli	*E. grandis*	10°02′N, 77°10′E	Tropical	27	3000	*Grassland*	Medium clay to sandy loam, Ferrasol
4	Vattavada	*E. grandis*	10°08′N, 77°15′E	Tropical	27	1800	Natural semi-evergreen (Shola forest)	Clay loam to medium clay, Ferrasol
5	Kayampoovam	*E. tereticornis*	10°41″N, 76°23′E	Tropical	27	2700	Degraded moist deciduos forest	Light to medium clay, Ferrasol
6	China: Guangdong	*E. urophylla*	21°43′N, 111°35′E	Subtropical	22	2178	Degraded soil, shrubs and few *Pinus massoriana*	Lateric red soil, Ultisol
7	Brazil: Itatinga	*E. grandis*	23°00′S, 48°52′W	Subtropical	20	1579	Cerrado native vegetation	Red yellow latosol, Oxisol
8	South Africa: KZ-Natal	*E. grandis*	29°24′S, 30°12′E	Subtropical	15	950	Virgin grassland	Clay, Kranskop 1000, Ferrasol
	Australia: W. Australia							
9	Busselton	*E. globulus*	33°45′S, 115°07′E	Mediterranean	17	825	Farmland-pasture	Grey sand over laterite, Haplic Podsol
10	Manjimup	*E. globulus*	34°20′S, 116°00′E	Mediterranean	14	1023	Farmland-pasture	Red earth, Rhodic Ferrasol
	Indonesia: Sumatra							
11	Riau	*A. mangium*	0°20′S, 101°48′E	Tropical	27	2460	Degraded land	Clay loam to clay, Typic Hapludult (fine), Ferric Acrisol
12	Toman	*A. mangium*	04°05′S, 103°45′E	Tropical	29	2610	*Imperata* grassland	Red yellow podsolic, Typic Kandiudult
13	Sodong	*A. mangium*	04°05′S, 103°45′E	Tropical	29	2610	*Imperata* grassland	Red yellow podsolic, Typic Plynthudults
14	Vietnam: Binh Duong	*A. auriculiformis*	11°18′N, 106°52′E	Tropical	27	2500	Native remnant vegetation	Chromic Acrisol
15	Australia: Queensland	*P. elliottii* x *P. caribaea*	26°00′S, 152°49′E	Subtropical	26	1354	Dry sclerophyll forest	Sandy soil, Grey Kandosol
16	China: Fujian	*C. lanceolata*	26°45′N, 118°10′E	Subtropical	19	1817	Forestry farm	Red soil

Table 2. Aboveground tree biomass distribution of first rotation (1R) stands

Site	Species	Age (yr)	MAI ($m^3 ha^{-1} yr^{-1}$)	Total tree	Stem+bark	Slash	Litter
				Biomass ($t ha^{-1}$)			
1	Eucalyptus hybrid	8	17	118	102	15	15
2	*E. tereticornis*	6.5	6	34	24[(a)]	10[(b)]	11
3	*E. grandis*	6.5	9	44	31[(a)]	13[(b)]	11
4	*E. grandis*	6.5	31	142	115[(a)]	27[(b)]	14
5	*E. tereticornis*	6.5	12	63	46[(a)]	17[(b)]	12
6	*E. urophylla*	6	10	44	38	6	5
7	*E. grandis*	7	29	140	134	6	24
8	*E. grandis*	7	21	135	100	34	70
9	*E. globulus*	8	12	98	67	31	17
10	*E. globulus*	9	46	275	194	51	29
11	*Acacia mangium*	7	41	151	119	32	37
12	*A. mangium*	9	25	190	139	51	17
13	*A. mangium*	10	13	241	180	61	7
14	*A. auriculiformis*	7	19	51	40	11	5
15	*Pinus elliottii x P. caribaea*	30	11	232	207	25	20
16	*Cunninghamia lanceolata*	29	18	223	197	26	109[(c)]

(a) India, Kerala: only stemwood without bark.
(b) India, Kerala: total tree - stemwood (includes bark).
(c) China, Fujian: herbs + litter + shrubs.

Burning slash as a site preparation operation aggravates the loss of carbon and other nutrients and causes site degradation (Delaporte *et al.* 2008). Risks are high with N in eucalypts and pine plantations because N will be lost in volatilisation and on some sites through subsequent leaching. Several papers in this and previous proceedings (Nambiar *et al.* 2000, 2004) have estimated the removal of nutrients from the site by harvesting as a proportion of the available pool of nutrients (measured as either extractable or exchangeable) in the soil. It is important to recognise that there is no single relationship applicable to all nutrients between soil and tree in the same sense in which one can examine water relations, because each of the nutrients essential for biological functions has unique soil chemistry, fluxes and pools, plant uptake processes and requirements. Critical limits of nutritional constraints are unique to individual elements and tree species. Nevertheless, good estimates of nutrient budgets and quantitative information on the impacts of inter-rotation management on nutrient cycling, including the fate of fluxes and pools, can be used to guide management practices and to avoid risks (for examples see Siregar *et al.* (2008) and Hardiyanto and Wicaksono (2008).

The risks of not paying serious attention to these issues in short-rotation plantation forestry aimed to produce high rates of growth have been raised by a number of researchers including Nykvist (1997), Mackensen *et al.* (2003) and Gonçalves *et al.* (2004). These reports typically provide estimated potential losses of nutrients as a consequence of different intensities of biomass or wood harvests and site management practices. Values of potential losses are some times expressed as the percentage of the nutrient capital in the various components of the ecosystem (e.g. Mackensen *et al.* 2003). Considerable uncertainties arise when these losses are presented as a percentage of the available site nutrient capital. We do not yet have reliable methods for quantifying the pools of nutrients available over the life of a plantation forests and the depth from which and to which nutrients are cycled in the soil-tree system. Therefore conclusions about the impacts of nutrient losses on production without direct evidence of the relationship between the two remain weak. For example, based on a study of forests in Sabah, Nykvist (2000) concluded based on soil analysis of forest sites that in many parts of Sabah “a sustainable forestry is not possible with the present rotation without compensating for the harvest related loss of calcium”. However, no evidence linking Ca removal and productivity was given. There have been other speculations about timber harvests, nutrient loss and sustainability. In this context, observations from this network are relevant. Firstly, application of Ca has given no growth response so far to any of the second rotation acacia plantations in Sumatra and Vietnam. Secondly, productivity seems to be maintained at sites with low levels of exchangeable cations including Ca in the soil, e.g. at the Brazilian site exchangeable Ca was 0.17 $cmol_c$ kg^{-1} and the best yield was 277 m^3 ha^{-1} and at Congo site exchangeable Ca was 0.08 $cmol_c$ kg^{-1} and the best yield was 161 m^3 ha^{-1}. Thirdly, although significant reduction of exchangeable cation levels can occur during the first 1-3 years after harvest and replanting, levels seem to start recovering from that stage returning to pre-harvest values at most sites, depending on management strategies (Tiarks and Ranger 2008).

Field operations between harvesting of one crop, intensity of that harvest, and site management and preparation for the next crop can have

Table 3. Nutrient content and distribution in aboveground tree biomass of first rotation (1R) stands

Site	Species	Total tree			Stem+bark			Slash			Litter		
		N	P	K	N	P	K (kg ha^{-1})	N	P	K	N	P	K
1	Eucalyptus hybrid	315.8	47.8	118.7	189.2	33.1	80.2	126.6	14.7	38.5	nr	nr	nr
2	*E. tereticornis*	92.0	8.3	85.0	62.9	5.5	57.6	29.1	2.8	27.4	96.0	7.1	nr
3	*E. grandis*	106.0	22.3	89.0	32.5	15.6	56.4	73.5	6.7	32.6	110.0	6.6	nr
4	*E. grandis*	232.0	28.1	271.0	113.7	18.0	176.2	118.3	10.1	94.8	66.0	5.0	nr
5	*E. tereticornis*	178.0	42.1	230.0	107.1	31.5	161.1	70.9	10.6	68.9	117.0	8.1	nr
6	*E. urophylla*	106.0	8.0	48.0	64.0	5.0	29.0	42.0	3.0	19.0	49.0	2.1	8.1
7	*E. grandis*	332.4	38.2	182.7	259.6	30.6	153.7	72.8	7.6	29.0	187.2	9.5	35.5
8	*E. grandis*	311.0	27.0	220.0	132.0	16.0	98.0	179.0	12.0	122.0	nr	nr	nr
9	*E. globulus*	nr	nr	nr	nr	nr	nr	219.0	16.0	57.0	nr	nr	nr
10	*E. globulus*	521.0	55.9	nr	140.0	28.0	nr	347.0	23.0	181.0	nr	nr	nr
11	*A. mangium*	593.0	16.0	357.0	285.0	7.0	171.0	308.0	9.0	186.0	483.0	8.0	60.0
12	*A. mangium*	661.0	14.3	191.2	375.0	9.3	73.0	286.0	5.0	118.2	271.0	2.5	29.5
13	*A. mangium*	962.0	24.3	208.1	525.0	14.0	90.6	437.0	10.3	117.5	95.4	1.5	10.2
14	*A. auriculiformis*	198.5	7.1	144.2	107.7	4.4	115.8	90.8	2.8	28.4	50.6	1.0	17.7
15	*Pinus elliottii x P. caribaea*	253.2	15.8	84.3	190.6	10.8	63.7	62.6	5.0	20.6	98.2	4.3	4.7
16	*Cunninghamia lanceolata*	309.0	55.2	375.0	195.0	39.8	241.0	114.0	15.6	134.0	82.0[a]	6.8[a]	126[a]

nr = not-reported

[a] China, Fujian: nutrient content in herbs + litter + shrubs

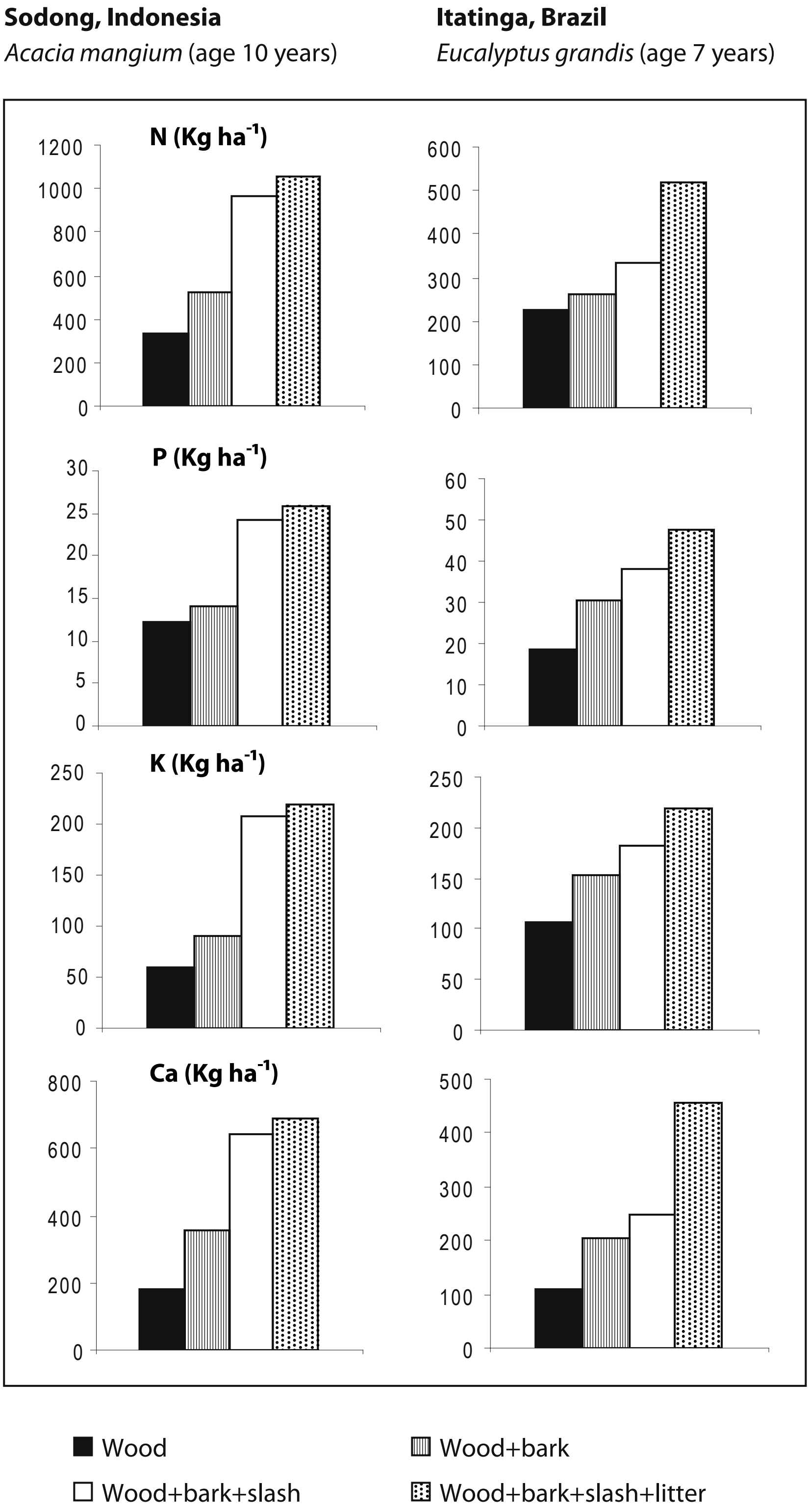

Figure 2. Sequential removal of nutrients in relation to harvesting intensity from two sites representing *Acacia* and *Eucalyptus* species

major effects on soil properties. The types of information generated in this project can be incorporated in simple models and used as tools to inform managers about the consequences of various site management practices.

Harvesting equipment used when soil conditions are vulnerable to damage (e.g. when a soil is wet) may induce soil compaction and erosion. Properly planned and site sensitive mechanical harvesting operations are possible with current technology and operational knowledge. These are not available to all our partners and they currently practice manual harvesting.

Well designed and ecosystem specific impact assessment studies are necessary to understand the effects of management practices on soils and sustained productivity. This invariably means long-term studies as planned for this project and those in progress elsewhere (e.g. Powers *et al.* 2005).

Impacts of Organic Matter and Nutrient Conservation or Depletion on Production

One of the main aims of this research was to establish an experimental base to examine the relationship between conservation or depletion of site resources (organic matter and nutrients) and productivity across a range of environments. Figure 3 shows the comparison between wood volume production in two main treatments: all aboveground biomass including the litter and understorey removed (high intensity harvest) and only stemwood with bark removed (low intensity harvest).The ages at which the stem growth were measured varied between sites (Table 5) since all experiments were not established at the same time. Treatment effects are compared for 12 sites where treatment implementation clearly allowed this comparison. Data is presented in increasing order of growth in the intensive harvest treatment. Improved growth due to slash and litter conservation was evident in all species. Within each species, the degree of response varied considerably from a small but significant (e.g. acacia in Vietnam, pine in Queensland) to substantial (e.g. eucalypt sites in Congo, Brazil). Double litter and slash treatment was applied at a number of sites in this study. At majority of sites, this treatment increased growth over and above that obtained by normal amounts of slash retention. The sites in Kerala are not included in Fig. 3. However, the trend in Fig. 3 was noted in three out of four sites where normal slash retention gave no significant response but doubling the slash improved growth rates (Sankaran personal communication). In the Congo, as the amounts of slash and litter retained increased from 0 to about 48 t ha^{-1} the stem volume at age 7 years of Eucalyptus hybrid increased from 80 m^3 ha^{-1} to about 160 m^3 ha^{-1}; the linear regression between the two variable gave an R^2 value of 0.98 (Fig. 5 in Deleporte *et al.* 2008).

Double slash application is not a practical operation. It was included to create a range of experimental conditions to understand the processes in soil and their effects on production. However, after a normal logging operation, slash distribution is usually uneven depending on the harvesting system. The harvested area consists of patches ranging from highly disturbed areas where all the organic matter is displaced with exposed surface soil (similar to BL$_0$ treatment) to areas where slash remain heaped (resembling BL$_2$ and BL$_3$). In a significant proportion of the land area (typically 25-40%), the amount of slash left may be comparable to that under the double slash treatments. Uneven distribution of slash and litter leads to uneven growth of stands especially on sites low in soil organic matter and nutrients. At two sites double slash application had negative effects (de Toit *et al.* 2008, Siregar *et al.* 2008).

There was no simple relationship, across the sites or within species, between the amounts of slash and litter retained or the nutrients in them and the growth rates of second rotation stands. This is not surprising given the variation in other factors which influence production, but results from Congo and Brazil sites illustrate the significance of minimum tillage practices and the need to conserve site resources to maintain and increase productivity.

Impacts of management are highly site specific. An example is the different productivity of two sites in Western Australia where *E. globulus* was grown under comparable local management regime (Table 4) and Mendham *et al*. (2008). The striking feature is the profound influence of soil type and probably rainfall (Table 1) on production. At the lower quality site (sandy soil with low rainfall) normal slash retention made little difference but doubling the slash increased growth by 63%. In contrast, at the more fertile site (red earth with higher rainfall) slash retention had no significant effect on growth. The effect of burning slash also was also different at the two sites.

Trends in productivity linking all sites are presented in Fig. 4 in which the MAIs in treatments where all slash and litter was retained are plotted against those where it was all removed. Growth rates (MAI) rather than net volumes are used because the age of stands differed between sites (Table 5). The dashed line indicates 1:1 parity between treatments. Results show that 10 of the 16 sites are below the parity line, at some sites significantly so, confirming the importance of conserving site and soil resources for ensuring long-term productivity.

Powers *et al* (2005) summarised the results from a comprehensive network project in USA and Canada. The scope of the USA project is much larger than the CIFOR project but both have a common in approach to research on sustainable production. In a synthesis paper they compared the all slash and litter retained treatment with all slash and litter removed from 26 experiments including three forest types using standing biomass at age 10 years as the measure of productivity. They found that biomass removal during harvesting had no influence on forest growth through 10 years, an important but surprising conclusion. However, this study included forests managed over rotations of 60 to 200 years. In our study, the positive effects of slash and litter retention at the site on growth (measured as stem wood volume) were significant and consistent. A comparative analysis of the factors driving productivity in experiments in USA and Canada and our CIFOR sites is not within the scope of this paper. However, we conclude that the impacts of harvesting and site management on

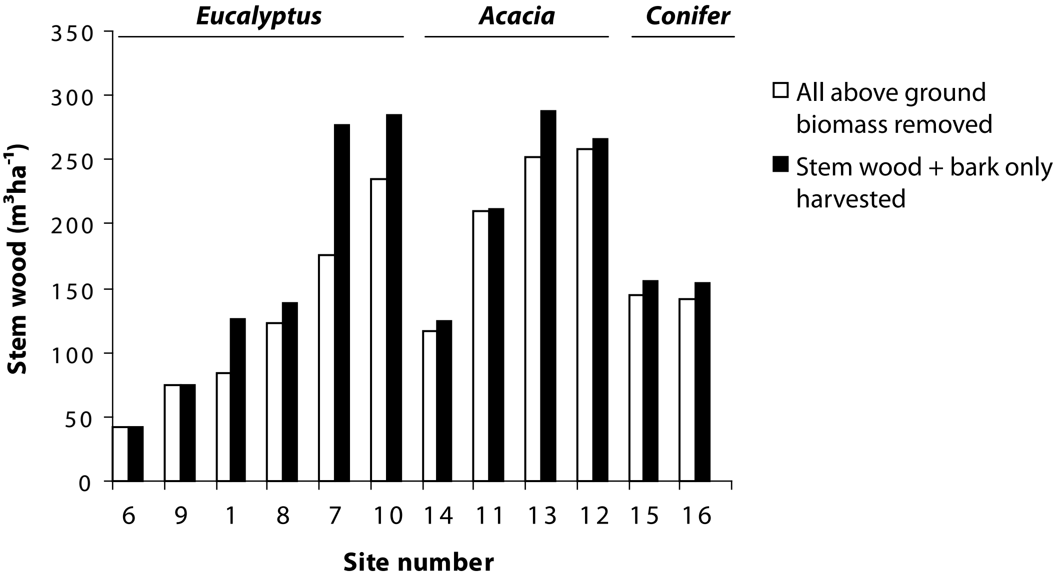

Figure 3. Wood production in the second rotation stand under two treatments: (1) All aboveground biomass removed and (2) Only stemwood + bark harvested

Table 4. Productivity and responses of site management on two *Eucalyptus globulus* stands at age 10 years grown in contrasting soils in Western Australia

Treatments	MAI ($m^3 ha^{-1} yr^{-1}$)	
	Red earth	Grey sand
All above ground biomass removed	45.2	7.5
Stem wood + bark harvested	43.4	7.4
Double slash retained	48.7	12.2
Slash burned	43.8	10.5
LSD $p = 0.05$	ns	2.5

sustainable production are critical in subtropical and tropical soils and environments (Figs. 3 and 4), probably more so than in forest sites in temperate climates. Processes influencing changes in productivity will be intense in short-rotation forestry plantations that are harvested more frequently.

The general positive effects of organic matter retention on growth are not entirely attributable to improved nutrient supply, although those treatments would increase nutrient supply (Gonçalves *et al.* 2008, Tiarks and Ranger 2008, Vu Dinh Huong *et al.* 2008). In clearfelled sites, soil water retention in the surface soil may be improved by the conservation of organic matter and this may be important at sites where soil available water limits growth for varying periods. For example, Vu Dinh Huong *et al.* (2008) showed that in South Vietnam the monthly diameter increments of 4-year-old *A. auriculiformis* decreased from 2.5- 3.0 mm month^{-1} during wet months to 0- 0.5 mm month^{-1} in dry months. Even a relatively small improvement in available water in dry periods may influence growth under such circumstances and such effects could be more important in young trees.

At Riau, Indonesia (Site 11, Table 2) slash retention adversely affected tree health of *A. mangium*. It was observed that the more slash retained the greater the incidence of root rot disease and tree mortality (Siregar *et al.* 2008). Given the potential threat of root rot diseases in that environment, this is an important observation and warrants significant new studies to help management decisions.

Managing to Increase and Maintain Long-term Productivity

Results from this project allow us to examine some key issues of managing productivity in two interrelated aspects. First is to examine the extent to which productivity per unit area can be increased by judicious management during a rotation. Second is to examine how productivity can be maintained, at a desired level, over successive rotations as well as maintaining the productive capacity of the soil base. We discuss the opportunities and risks in this section.

Opportunities for Increasing Production

One of the project's aims was to provide information to assist local plantation managers determine site-specific management options. This was an important reason for including core and optional treatments at all sites. There was a large variation in tree growth within most sites in response to both core and optional treatments. This is summarised in Table 5 as the lowest and the highest volume growth achieved at each site. Treatments that resulted in the lowest and the highest yields were not always common across sites. In general, retention of slash and application of fertiliser gave the best results. Weed management also increased production greatly at sites where it was tested (Kerala, Vietnam and Queensland). Vu Dinh Huong *et al.* (2008) demonstrated the opportunity for minimum application of herbicide allowing both good growth of trees while maintaining floral biodiversity in the plantations. Sankaran *et al.* (2008) showed the potential for a large increase in production by correcting N and P deficiencies on some sites and the opportunities for developing

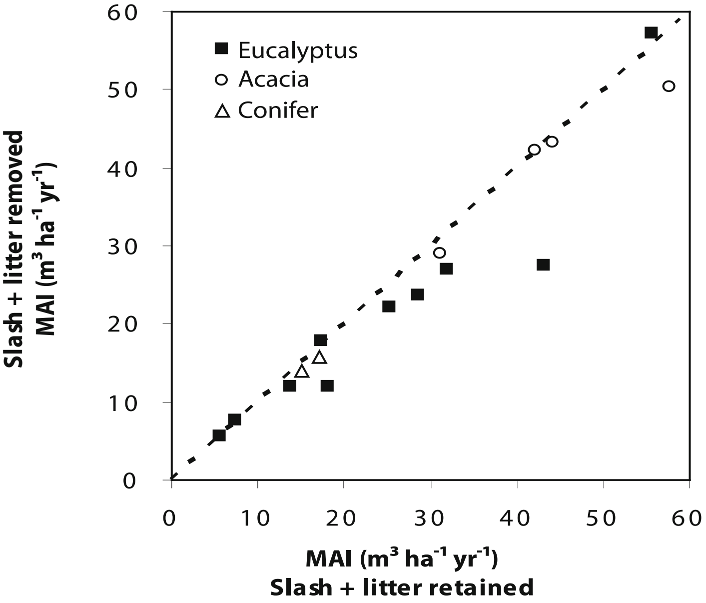

Figure 4. Mean annual increments (MAI) of second rotation stands (2R) as influenced by two treatments: slash and litter retained and slash and litter removed

diagnostic procedures. Xu *et al.* (2008) and Bouillet *et al.* (2008) identified opportunities for using N-fixing trees in eucalypt plantations as a means to improve N supply and tree growth.

Slash burning was applied as a treatment at some of sites. Effects of slash burning on forest production have been a subject of many investigations and varying conclusions and controversies. There is clear evidence now that slash burning will lead to loss of organic matter and nutrients, especially N (Gonçalves *et al.* 2008). Nitrogen loss may be less critical for plantations of N-fixing species although the soil N level in *Acacia* plantations in general is not higher than those at eucalypt or pine sites (Tiarks and Ranger 2008). Slash burning adversely affected growth in Kerala and at the Chinese fir site in China. In Brazil, although slash burning reduced mineral N by more than 50% compared to slash retention, growth under the burning treatment remained relatively high throughout the rotation (Gonçalves *et al.* 2008). Similarly, in at the South African site, which had a high amount of slash and a very high level of litter accumulation (Table 2), slash burning had little adverse effect on growth. In such special circumstance managers may resort to mild burning in order to facilitate reasonable survival and growth of seedlings. On the other hand, slash burning before planting followed by repeated litter burning and/or ploughing between tree rows to minimise the fuel load and fire risk are practised in plantations in South Vietnam. Plantation growth under this management regime appears to be declining in productivity partly due to soil degradation (Nambiar personal observation). A decision to use prescribed burning in a particular ecosystem needs to be made with an appreciation of the relevant processes operating in that ecosystem and the potential effects of repeated loss of organic matter and nutrients that would occur at each burning event. Immediate impacts of burning on productivity may be difficult to demonstrate and this may mislead the managers about the potential long-term negative effects.

Results in Table 5 illustrate the potential for managing production through site-specific management. The gain in production by improved management ranged from 6 to 256% (Table 5). It should be noted that neither the lowest nor

Table 5. The lowest and highest amount of wood produced in response to selected treatments at each site during the second rotation (2R)

	Site	Species	Stand age (years)	Lowest wood volume (m^3 ha^{-1})	Highest wood volume (m^3 ha^{-1})	Gain (%)
1	Pointe-Noire	Eucalyptus hybrid	7.0	84.1	160.9	91
2	Punalla	*E. tereticornis*	6.5	78.2	278.0	256
3	Surianelli	*E. grandis*	6.5	166.7	269.5	62
4	Vattavada	*E. grandis*	6.5	328.4	350.0	7
5	Kayampoovam	*E. tereticornis*	6.5	87.4	140.0	60
6	Guangdong	*E. urophylla*	7.5	38.9	52.5	35
7	Itatinga	*E. grandis*	8.7	176.2	276.7	57
8	KZ-Natal	*E. grandis*	5.5	123.0	146.0	19
9	Busselton	*E. globulus*	10.0	74.0	122.0	65
10	Manjimup	*E. globulus*	10.0	434.0	487.0	12
11	Riau	A. mangium	5.0	187.3	222.9	19
12	Toman	*A. mangium*	6.0	257.3	271.8	6
13	Sodong	*A. mangium*	5.0	245.2	288.4	18
14	Binh Duong	*A. auriculiformis*	4.0	78.4	141.7	81
15	Queensland	*P. elliottii* x *P. caribaea*	10.3	145.0	186.5	29
16	Fujian	*C. lanceolata*	9.0	128.4	165.4	29

the highest growths in Table 5 represent the benchmark in production at the two boundaries. They are indicative and limited by the treatments applied in each case. Further increase in productivity could have been achieved, at most sites, had we tested a wider array of treatments. Planting stock used in all sites can be improved with further tree genetic improvement and access to better quality seedlings. Conversely, further reduction in yield would have occurred if site management caused more losses of organic matter, for example by practices which can trigger soil erosion, planting of poor genotypes, repeated coppicing or by poor vegetation management practices. Studies in Brazil at 14 sites of *E. grandis* (Gonçalves *et al.* 2004) clearly illustrated the difference in production between seedling-raised stands (1R) and coppice stands (2R) is dependant on whether the site was managed to conserve resources or not. Studies exploring the potential productivity of sites through a combination of balanced site management practices would be valuable in the future. Understanding factors controlling productivity and quantitative information on the impacts of management on them will lead to further progress in developing management systems for increasing and sustaining high productivity. The scope for and the potential benefits from such studies is high in the tropics.

Can Productivity of Tropical Plantations be Sustained over Rotations?

This question is being asked by diverse interest groups, but in the absence of a sound experimental evidence on which to base a response, most arguments remain speculative. Figure 5 provides a comparison of MAIs between the first rotation stands which were clearfelled (1R) and those in the experiment (2R). The MAI for each second rotation site is the mean value of all the core treatments so that they are more representative of the productivity of that site and were applied at all sites. For all eucalypt sites, 2R volumes are at the end of on the full rotation, harvested according to local practices. The acacia sites will be harvested during 2008. Histograms in Fig. 5 are arranged in an ascending order of growth rates measured in 1R within each group of species.

There are some constraints in making a direct comparison between 1R and 2R production data. Growth rates in each rotation are influenced by several factors, including variations in climate (especially rainfall) between rotation periods, use of genetically different planting material, stocking, survival and management. Despite these unavoidable factors, the trend in Fig. 5 shows the second rotation stands at 13 of the 16 sites grew at rates faster than the corresponding previous crop. The trend was consistent across all tree species. A small reduction in 2R growth occurred at two eucalypt sites and at the Chinese fir site. The relationship between MAI in 1R and 2R is plotted for all species (Fig. 6a) and for eucalypt stands (Fig. 6b) which have reached full rotation. The dotted lines show the 1:1 parity. The regression between MAIs of 1R and 2R sites shows that all sites fitted within a simple relationship and a general gain in production from 1R to 2R across sites.

There were significant correlations between 1R and 2R volume growth indicating the inherent influence of site factors on growth rate. In seven out of ten eucalypt sites the improvement was significant and substantial, similarly in three of the four acacia sites. It is important to note that such improvements occurred both at low and high yielding sites indicating the potential for improvement across all sites as shown in Table 5.

Despite limitations in comparing MAIs between rotations mentioned earlier, the general trend of results is important in the debates about sustainability of tropical plantations. Research in this network and some associated research in progress among our partners indicate opportunities for increasing production in a sustainable manner. There is no suggestion from a decade of research in the CIFOR network reported in this and previous proceedings that these resources are facing any significant risks to production and maintenance of soil properties. Only the sites at Riau, Indonesia, encountered significant problems with biological pathogens. At Riau root rot fungi caused tree mortality in *A. mangium* plantations (Siregar *et al*. 2008) and this may be a risk in the future. The collective experience of a number of partner countries where plantation forestry has been through one or more rotations (e.g. Australia, Brazil, South Africa) shows that increased and sustained production is achievable (Evans 1999, Powers 1999, Nambiar 2002). However, that would require continuous investments in strategic and adaptive research especially in countries where research on plantation forestry is in its infancy.

Effects of Management on Soils

Productivity is, arguably, the best single integrating measure of the changes that may be taking place in soils as a consequence of repeated harvests and other management interventions. It is also important that the changes in soil properties are studied directly so that the direction and the intensity of changes can be understood correctly to assist revision and application of management practices as necessary. Tiarks and Ranger (2008) have reviewed and summarised the main trends using all measured data from the network on organic carbon, total N, available P, pH and exchangeable cations K, Ca and Mg. Currently information is available for periods of 4 to 8 years after planting. They concluded, based on results from the surface soils (Table

3 in Tiarks and Ranger 2008), where changes are likely to be more measurable, that some short-term changes in soil properties do occur. However, there is no evidence of significant changes in key soil properties, including on soil organic carbon, which indicate potential for adverse effects. Soil pH under the *Acacia* spp. either remained unchanged or increased slightly at all sites. This is important information given concerns about soil acidification under plantation forestry. There were some site-specific changes which are important. For example, extractable P decreased continuously from planting to age 4 years corresponding to the increased uptake of P by the new stand (Vu Dinh Huong *et al*. 2008). This pattern of reduction in extractable P was also observed at other acacia sites. Clearly it would be useful to explore the dynamics of P in these ecosystems because many of these soils are low in extractable P and application of P fertiliser is a common practice.

The difference in surface soil properties between complete organic matter removal and retention was surprisingly small and seldom significant (Tiarks and Ranger 2008). As noted earlier, and in a number papers in this proceedings the amounts of nutrients removed by harvests as a proportion of the soil-available pool can be large depending on the harvesting system. The absence of large changes in soil so far should not lead to complacency and diminish investment in studies on soil impacts. Plantation productivity may be maintained against a gradual decline in soil nutrients reserves until the decline reaches a threshold limit. Impacts on soils may be more measurable in subsequent rotations. Restoring soil fertility from a depleted state is not an easy task. It is therefore critical that the types of studies undertaken so far in this networks are reviewed regularly and continued over a long period. There are lessons to be learned from a number of experiences worldwide. About a decade ago growth response to N fertiliser was not common in Brazilian eucalypt plantations, but now significant and profitable responses to N applications are common. Similarly, the incidence of K deficiency was rarely known in plantation forestry in past decades but it is increasing in eucalypt plantations in Brazil and southern China. These and other experiences highlight the need for forest managers aiming for high yields and shorter harvesting cycles to adopt management practices promoting site resource conservation. Even then,

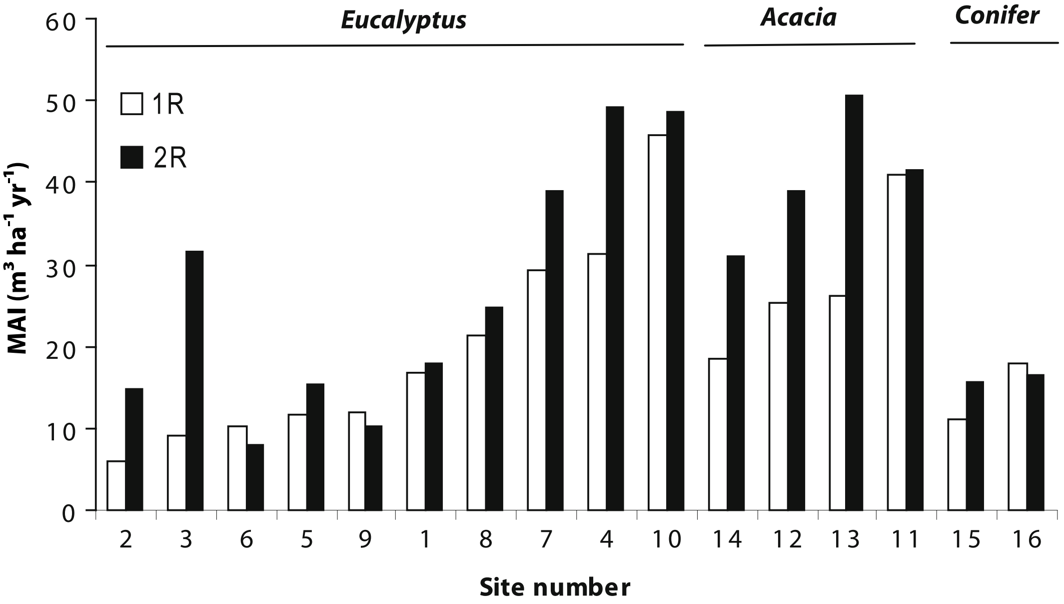

Figure 5. Mean annual increment (MAI) at the first (1R) and the second (2R) rotation stands. Data of 2R experiment are means of all treatments

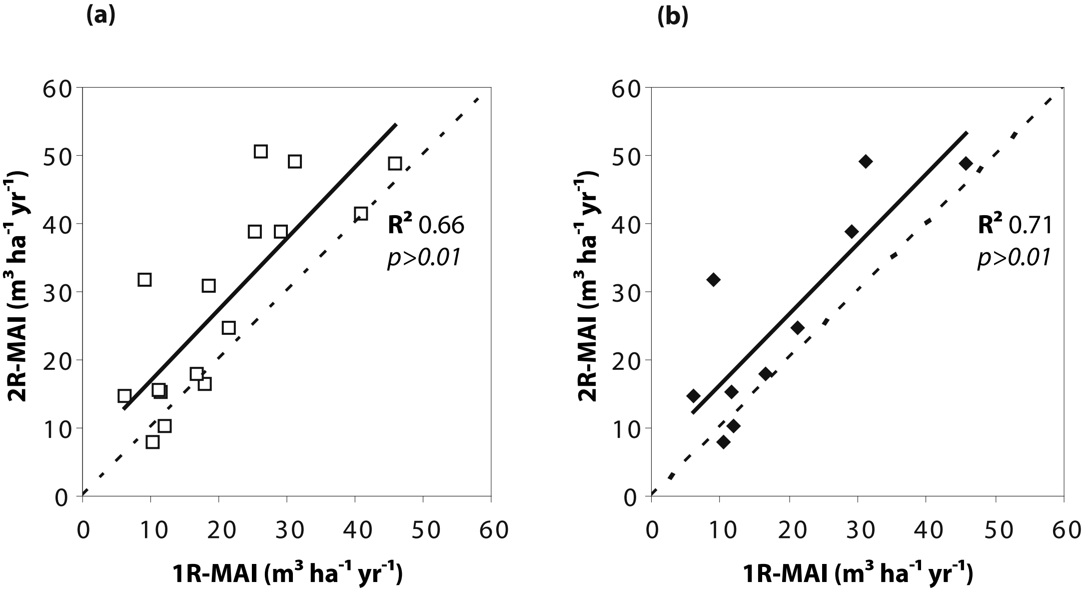

Figure 6. Relationship between growth rates of the first (1R) and the second (2R) rotation plantations. (a) all sites and species (b) eucalypt sites

judicious use of fertilisers may be necessary for increasing productivity in many soils.

Productivity of Subtropical and Tropical Plantation in Context

This network provides productivity data from 16 sites over two rotations. All sites were selected for their representativeness of local/ regional forest estate grown for commercial wood production. Naturally, their productivity under the prevailing conditions spans a wide range. This information along with some relevant data from other sites provides a basis to place the current level of productivity of these plantations in context. This would be useful because it is popular to describe sections of subtropical and tropical forest plantations as '*fast-wood forestry*' (Cossalter and Pye-Smith 2003), '*new generation plantations*'(Dudley and Luis 2008) or other names such as "high yield forestry". There is no consensus on the definition of these terms, however, the common criteria that they use is that such plantations grow at the fast rates. It is also suggested that they draw more criticisms (Dudley and Luis 2008). Cossalter and Pye-Smith (2003) suggested a minimum MAI of 15 $m^3 ha^{-1} yr^{-1}$ as the threshold for *fast-wood* and pointed out that such plantations are relatively limited in extent. The question is how many forestry enterprises in poor or developing tropical countries reach high productivity? Most of them do not have the biophysical environments, silvicultural systems and investment frame works comparable to those developed over three decades in some countries, for example in Brazil.

Stands at several sites in the CIFOR project during the first and second rotations (experimental stands) grew at a MAI less than 10 $m^3 ha^{-1}$; seven or eight of them at 15 or less $m^3 ha^{-1}$ and nine of the 16 sites at less than 20$m^3 ha^{-1}$ (Table 2 and Fig. 5). All of these stands were grown for industrial wood production by large organisations. In reality, planted forests in many tropical countries typically have low growth rates, probably far below their potential capacity because of several site and management constraints (Table 5). We do not have a good understanding of the constraints on production in these environments. Even in countries such as Brazil, where plantation forestry is well developed, site management practices can lead to more than two-fold difference in production, a fact which emphasises the importance of sound management (Gonçalves *et al.* 2008). Similarly the results from Congo (Deleporte *et al.* 2008) show that planting of selected hybrids in itself does not lessen the importance of sound site management in economic production.

Yamada *et al.* (2004) summarised the productivity of 40 industrial short rotation plantations, mainly eucalypts and acacias, from 21 sites located in 11 countries (including the 16 sites in this network). The range in productivity expressed as a standing biomass was 7.8-10.5 t C ha^{-1} $yr^{-1}$for acacias and 3.1-22.9 t C ha^{-1} yr^{-1} for eucalypts. Out of the 40 sites, 29 sites produced less than 10 t C $ha^{-1}yr^{-1}$ and only one site produced more than 20 t C $ha^{-1}yr^{-1}$. Large areas of plantations in some countries, including those where our partners are located, achieve only low growth rates. For example, productivity of *E. tereticornis* plantations in Karnataka state in southern India, ranged between 0.2 and 7.0 m^3 ha^{-1} yr^{-1}` at age 6 years in regions receiving 590 to 880 mm yr^{-1} rainfall (Dury and Majunath 1992). Large areas of such plantations can be seen in seasonally dry or low rainfall tropical environments in several developing countries. A report on global outlook of plantations pointed out that over 60% of the plantations in Asia and Africa have been assessed as unsuitable for commercial wood production as a result of low productivity (ABARE- Jaakko Poyry 1999). This scenario may not have improved significantly even today, although large areas may have been planted since the report. There are many reasons for low production and failure including: poor species selection and inability to manage the site-based constraints on production such as poor management of soils, water, nutrition, pests and diseases, and silviculture. When the plantations are owned and managed by local or other Government agencies, resource development programmes starve for investments. Some management practices which improve productivity are not available to forest growers in many circumstances. For example, while effective use of herbicides is common in Brazil and South Africa, herbicides are seldom used now in operational forestry in Vietnam and India. Repeated cycles of coppicing of stands raised from poor genetic stock leading to very low productivity are common in some countries. Constraints imposed by soil through availability of water and nutrients can be considerable. Vast areas of tropical plantations are neither “fast wood forestry ” nor “new generation forestry”. It is important to recognize the current weak state of large areas of tropical plantation forestry and the need for developing investment, management and policy frame works to improve their productivity with environmental care.

Impacts of this Network Project

Science and Local Capacity Building

The project was guided by a principle that each site should be managed as a self-contained study, capable of providing critical information for local management. It was also envisaged that the results from each site should be robust enough to be acceptable in peer reviewed international journals should the partners choose to publish their work beyond the CIFOR proceedings. This approach enabled research partners to gain support from their local stakeholders and enhance the scientific rewards for scientists.

The core results from this project, the ongoing impacts at each location and the overall progress have been published systematically in 54 papers in four proceedings (Nambiar *et al.* 1999, 2000, 2004 and Nambiar 2008). Each proceedings was preceded by one or two workshops at which all results were reviewed and discussed. In addition, partners have presented or published about 80 papers in national or international meetings, industry technical reports, local journals and other avenues of communication in five languages (Appendix 1, this proceedings). Several partners have produced simple guidelines for improving management in local languages in simple styles. Site-based research has contributed fully or partially to several postgraduate programmes: 9 PhD, 19 MSc and 2 BSc (Honours) degrees. Publications have been written by nearly 80 scientists employed by private companies, public research institutions, local forestry agencies and universities. For several of them, this offered the first significant research experience and the first challenge in writing scientific publication in English. Many more, particularly technical staff, have gained experience valuable to them and to their employers. Improved skills include training in experimental work and long-term data acquisition, retrieval and analysis. Many of these colleagues are effective agents of change in their environment and undoubtedly more contributions will come from this network.

Impacts on Diverse Local Forestry

Practical and large-scale changes towards sustainable management are seldom achieved by a single research programme. This project is no exception. Impacts of silvicultural research are not characterised by breakthroughs and quantum leaps; they promote gradual incremental improvements. There are immediate cost considerations and operational constraints in adopting new research. Results of site management research are not easy to scale up and apply, unlike the products of tree breeding research when genetic gains can be delivered on a large scale through planting stock. Reports from partners provide instances of the way the network's research has influenced local forestry practice. At all sites, retention of slash and litter is now the recommended option and in few cases slash burning has been discontinued completely by partner organisations. Sound relationships between desired growth rates, nutrient uptake rates required to support growth, and fluxes and pools of nutrients in the ecosystem are now available for several plantation sites. These are improving management decisions. In some cases, conclusions from the project have been formulated as the best management practice and implemented across the company or the region. These practices, by improving the quality of site-stand management, will avoid or minimise off-site impacts. The methodology developed can be applied to other sites by organisations which have expanding planting programmes or in cases where targets for productivity need to be revised to meet local needs and environments.

The experiments have been effective as demonstrations of what R&D can do and this in turn has attracted serious attention of senior managers and some policy makers. For example, Hardiyanto and Wicaksono (2008) demonstrated that the overall productivity of the experimental site is significantly higher than the adjacent broad scale plantations, although both the experimental site and the operational forests were established with the same genetically improved seedlings and under similar management regime. Such demonstrations are a powerful means of communication. The Government of Vietnam has decided in 2008 that it will not only continue the current work but also will scale up the study as a national network with new sites in different regions.

Sound forest management recognises that forest operations cannot be implemented in the field exactly as prescribed by research. Trade-offs and compromises between research results, costs and operational issues together result in the management decision. If management has to depart from the 'best protocol', the critical issue is to know the consequences of that action in a quantitative way. All partners are now in a position to provide sound information on the impacts of various harvesting and site management systems on their local resources so that remedial actions if necessary can be implemented in an informed way. This project has made a positive difference to management practices which enable conservation of site resources and improve productivity.

Results from this research can contribute in two ways to improving productivity in plantations of small-scale growers. Firstly, many forest companies now have out-grower programmes to ensure their wood supply and to enhance benefit to local community. In such programmes companies provide support to growers through mechanisms including transfer of better technology, wages in return for labour and small investments. These are also in the interest of the company. Secondly, small-scale growers are diverse in their size and capacity for investments. Some can adopt information on improving productivity readily. Science-based practical information for increasing and sustaining production and caring for the soil resources is important for all growers, small or large, to achieve overall sustainability. However, relevant information and support need to be delivered in special ways to help the small grower.

Future

This project has thrived for more than decade. Despite many constraints faced along the way, we have not lost a site or a partner and the team has shown remarkable cohesion and shared values. This in itself is a major achievement. A perspective and the lessons learned from this unique partnership have been prepared for CIFOR (Nambiar unpublished). This project was initiated at a time when there were many questions about the prospects of sustainable production in tropical plantations. The overall results gathered under a range of environmental and forest management conditions, support the conclusion that tropical plantation forests can be managed to increase and maintain productivity and soil properties.

Large areas of tropical plantation forestry remains in poor condition and grow at rates far below their potential. They receive minimum silviculture with no 'intensive management'. Every year hundreds of thousands of hectares of plantations are established on so-called degraded land and soils about which little is known, and in highly stress-prone environments in developing countries. It is a serious mistake to assume that they will be sustainable. Substantial research, building on known principles, will be required to understand the factors which limit production in stress-prone environments and then to develop and implement management options. This also requires capacity building of both scientists and institutions in some developing countries in the tropics.

The workshop held at Bogor, Indonesia in 2007 and this proceedings mark the summation of the first phase of this programme. The critical questions of site and soil sustainability in short-rotation forestry cannot be confidently understood in one rotation, despite the robustness of the results so far. Value from the project will increase if it is continued to successive rotations. Results from each rotation will add greater insights. All experiments have been designed to allow multiple rotations and the concept of core and optional treatments provides many opportunities for revision and innovation. They could provide an excellent framework to explore new ideas about the impacts of climate change on planted forests and carbon sequestration. Such objectives can be accommodated with out losing focus on providing management options for local growers and supporting partners.

Private companies and public organisations that have contributed to the ideas and carried the full cost of local research have unhesitatingly shared their information. This model of partnership between private and public organisations is central for advancing sustainable forestry in many developing countries. Yet such collaboration is not common in those countries. This should be fostered further for the long-term goals.

The value of long-term partnership research on planted forests, developed in the context of climate change and needs of societies for wood, employment and money, has never been more relevant than it is today. There is a compelling case to continue and build on this project as a contribution for advancing sustainable forestry in the tropics. It will require a greater awareness among international agencies of the value of long-term biophysical research for sustainable forestry and the collective leadership of many partner organisations to take this unique partnership forward.

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References

ABARE-Jaakko Poyry 1999. Global Outlook of Plantations, ABARE Research Report 99.9, Australian Bureau of Agricultural and Resource Economics, Canberra, Australia. 99p.

Bouillet, J.P. Laclau, J.P., Gonçalves, J.L.M., Moreira, M.Z., Trivelin, P., Jourdan, C. and Galiana, A.2008. Mixed-species Plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 157-172. Center for International Forestry Research, Bogor, Indonesia.

Cossalter, C. and Pye-Smith, C. 2003. Fast-wood forestry: myths and realities. Forest Perspectives No. 1. Center for International Forestry Research, Bogor, Indonesia. 50p.

Deleporte, P., Laclau J.P., Nzila, J.D., Kazotti, J.G., Marien, J.N., Bouillet, J.P., Szwarc, M., D'Annunzio, R. and Ranger, J. 2008. Effects of slash and litter management practices on soil chemical properties and growth of second rotation eucalypts in the Congo. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 5-22. Center for International Forestry Research, Bogor, Indonesia.

du Toit, B., Dovey, S.B. and Smith, C.W. 2008 Effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 63-78. Center for International Forestry Research, Bogor, Indonesia.

Dudley, N. and Silva, L.N. 2008. New generation plantations. WWF Background Paper January 2008. WWF International, Gland, Switzerland. 15p.

Dury, S.J. and Majunath, B.E. 1992. The influence of site factors on eucalypts growth in Karnataka. *In*: Calder, I.R., Hall, R.L. and Adlard, P.F. (eds) Growth and water use of forest plantations. Proceedings of International Symposium, February 1991, Bangalore, India. Wiley and Sons, New York. 82-102.

Evans, J. 1999. Sustainability of forest plantations: the evidence. Report The Department of International Development. May 1999. London. 64p.

Gonçalves, J.L.M., Stape, J.L., Benedetti, V., Fessel, V.A.G., Gava, J.L. 2004. An evaluation of minimum and intensive soil preparation regarding fertility and tree nutrition. *In*: Gonçalves, J.L.M. and Benedetti, V. (eds) Forest nutrition and fertilization. Translated by McNabb, K. IPEF, Piracicaba, Brazil. 13-64.

Hardiyanto, E.B. and Wicaksono, A. 2008. Inter-rotation site management, stand growth and soil properties in *Acacia mangium* plantations in South Sumatra, Indonesia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 107-122. Center for International Forestry Research, Bogor, Indonesia.

Mackensen, J. and Folster, H. 2000. Cost-analysis for a sustainable nutrient management of fast growing- tree plantations in East-Kalimantan, Indonesia. Forest Ecology and Management 131: 239-253.

Mackensen, J., Klinge, R., Ruhiyat, D. and Folster, H. 2003. Assessment of management-dependant nutrient losses in tropical industrial tree plantations. Ambio 32:106-112.

Mendham, D.S., Grove, T.S., O'Connell, A.M. and Rance, S.J. 2008. Impacts of inter-rotation site management on soil nutrients and plantation productivity in *Eucalyptus globulus* plantations in south-western Australia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 79-92. Center for International Forestry Research, Bogor, Indonesia.

Nambiar, E. K. S. 2002. Science and technology for sustainable development of plantation forests. Australian Forestry 66: 43-50.

Nambiar, E.K.S. (ed.) 2008. Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004, Piracicaba, Brazil and 6-9 November 2006,Bogor, Indonesia. Center for International Forestry Research, Bogor, Indonesia. Center for International Forestry Research, Bogor, Indonesia.

Nambiar, E.K.S. and Brown, A.G. (eds.) 1997a. Management of soil, nutrients and water in tropical plantation forests, ACIAR Monograph No. 43. Australian Centre for International Agriculture Research, Canberra. 571p.

Nambiar, E.K.S. and Brown, A.G. 1997b. Towards sustained productivity of tropical plantations: science and practice. *In:* Nambiar, E.K.S. and Brown, A.G. (eds). Management of soil, nutrients and water in tropical plantation forests, 527-557. ACIAR Monograph No. 43.

Australian Centre for International Agriculture Research, Canberra.

Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. 1999. Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa. Center for International Forestry Research, Bogor, Indonesia. 76p.

Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. 2000. Site management and productivity in tropical plantation forests: progress report: workshop proceedings 7-11 December 1999, Kerala, India. Center for International Forestry Research, Bogor, Indonesia. 108p.

Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. 2004. Site management and productivity in tropical plantation forests: proceedings of workshops in Congo, July 2001 and China, February 2003. Center for International Forestry Research, Bogor, Indonesia. 226p.

Nykvist, N. 1997. Total distribution of plant nutrients in a tropical rainforest ecosystem, Sabah, Malayasia. Ambio 26:152-157.

Nykvist, N. 2000. Tropical forests can suffer from a serious deficiency of calcium after logging. Ambio: 29:310-313.

Powers, R. F. 1999. On the sustainability of planted forests. New Forests 17: 263-306.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff. J.D. and Stone, D. M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. Forest Ecology and Management 220: 31-50.

Saint-André, L., Laclau, J.P., Deleporte, P., Gava, J.L., Gonçalves, J.L. M., Mendham, D., Nzila, J.D., Smith, C., du Toit, B., Xu, D.P., Sankaran, K.V., Marien, J.N., Nouvellon Y., Bouillet, J.P. and Ranger, J. 2008. Slash and litter management effects on *Eucalyptus* productivity: a synthesis using a growth and yield modelling approach. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 173-188. Center for International Forestry Research, Bogor, Indonesia.

Sankaran, K.V., Mendham, D.S., Chacko, K.C., Pandalai, R.C., Pillai, P.K.C., Grove, T.S. and O'Connell, A.M. 2008. Impact of site management practices on growth of eucalypt plantations in the monsoonal Tropics in Kerala, India. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 23-38. Center for International Forestry Research, Bogor, Indonesia.

Siregar, S.T.H., Nurwahyudi and Mulawarman. 2008. Effects of inter-rotation management on site productivity of *Acacia mangium* in Riau province, Sumatra, Indonesia. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 93-106. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A. and Ranger, J. (2008). Soil properties in tropical plantation forests: evaluation and effects of site management: a summary. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 191-204. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A., Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical forest plantations. CIFOR Occasional Paper 16. Center for International Forestry Research, Bogor, Indonesia. 11p.

Vu Dinh Huong, Le Thanh Quang, Nguyen Thanh Binh and Pham The Dung. 2008 Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 123-138. Center for International Forestry Research, Bogor, Indonesia.

Xu, D.P., Yang, Z.J. and Zhang, N.N. 2008. Effects of Site Management on Tree Growth, Aboveground Biomass Production and Nutrient Accumulation of a Second-rotation Plantation of *Eucalyptus urophylla* in Guangdong Province, China. *In*: Nambiar, E.K.S. (ed.) Site management and productivity in tropical plantation forests: workshop proceedings, 22-26 November 2004 Piracicaba, Brazil, and 6-9 November, Bogor, Indonesia, 39-50. Center for International Forestry Research, Bogor, Indonesia.

Yamada, M., Toma, T., Hiratsuka,M. and Morikawa, Y. 2004. Biomass and nutrient removal by harvesting in short-rotation plantations, 213 –226. *In:* Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. 2004. Site management and productivity in tropical plantation forests: proceedings of workshops in Congo, July 2001 and China, February 2003. Center for International Forestry Research, Bogor, Indonesia. 226p.

Trial stand of Eucalypts plantation for 20 years rotation, Sumatra. (Photo: Takeshi Toma)

Appendix 1. CIFOR Network Project (1995-2008)

Site Management and Productivity in Tropical Plantation Forests

Publications and Postgraduate Theses from Research Associated with the Network Project

CIFOR Publications

Tiarks, A., Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical forest plantations. CIFOR Occasional Paper 16. Center for International Forestry Research, Bogor, Indonesia. 11p.

Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. 1999. Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February 1998, Pietermaritzburg, South Africa. Center for International Forestry Research, Bogor, Indonesia. 76p.

Nambiar, E.K.S., Tiark, A., Cossalter, C. and Ranger, J. 2000. Site management and productivity in tropical plantation forests: progress report: workshop proceedings 7-11 December 1999, Kerala, India. Center for International Forestry Research, Bogor, Indonesia. 108p.

Nambiar, E.K.S., Ranger, J., Tiarks, A. and Toma, T. 2004. Site management and productivity in tropical plantation forests: proceedings of workshops in Congo, July 2001 and China, February 2003. Center for International Forestry Research, Bogor, Indonesia. 226p.

Nambiar, E.K.S. (ed.) 2008. Site management and productivity in tropical plantation forests. Proceedings of workshops in Piracicaba, Brazil, 22-26 November 2004 and Bogor, Indonesia, 6-9 November 2006. Center for International Forestry Research, Bogor, Indonesia.

Other Publications and Postgraduate Theses

Eucalypt Sites

Australia (Western Australia)

Journal papers and international conferences

Corbeels, M., O'Connell, A.M., McMurtrie, R.E., Grove, T.S. and Mendham, D.S. 2002. Modelling long-term changes in nitrogen mineralization following conversion of improved pasture to eucalypt plantation. Agronomie 22: 801-815.

Mathers, N.J., Mendham, D.S., O'Connell, A.M., Grove, T.S., Xu, Z., Saffigna, P.G. 2003. Harvest residue management effects in *Eucalyptus globulus* plantations on soil organic matter composition as determined by solid state ^{13}C NMR spectroscopy. Forest Ecology and Management 179: 253-267.

Mendham, D.S., O'Connell, A.M., Grove, T.S. and Rance, S.J. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management 181: 357-372.

Mendham, D.S., Sankaran, K.V., O'Connell, A.M. and Grove, T.S. 2003. *Eucalyptus globulus* harvest residue management effects on soil carbon and microbial biomass at 1 and 5 years after plantation establishment. Soil Biology and Biochemistry 34: 1903-1912.

O'Connell, A.M., Grove, T.S., Mendham, D.S. and Rance, S.J. 2004. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in south western Australia. Soil Biology and Biochemistry 36: 39-48.

Corbeels, M., McMurtrie, R.E., Pepper, D.A., Mendham, D.S., Grove, T.S. and O'Connell, A.M. 2005. Long-term changes in productivity of eucalypt plantations under different harvest residue and nitrogen management practices: a modelling analysis. Forest Ecology and Management 217: 1-18.

Postgraduate theses

George, S. 2004. PhD. University of Western Australia. Effects of land-use change on phosphorus forms in southwest Australian soils

Shammas, K. 1999. B.Sc (Honours). University of New South Wales, Australia. Decomposition and nutrient content of slash residue in an *Eucalyptus globulus* plantation in south west Australia

Heagney, E. 2001. B.Sc (Honours). University of New South Wales, Australia. Sustaining the productivity of short-rotation eucalypt plantations in south-west Western Australia: using particulate organic matter as an indicator of site fertility and productivity

Brazil

Books, journal papers and international conferences

Gonçalves, J.L.M. and Barros, N.F. 1999. Improvement of site productivity for short-rotation plantations in Brazil. Bosque, Valdivia 20: 89-106.

Gonçalves, J.L.M., Mendes, K.C.F.S. and Sasaki, C.M. 2001. Mineralização de nitrogênio em ecossistemas florestais naturais e implantados do estado de São Paulo. Viçosa, Revista Brasileira de Ciência do Solo 25(3): 601-616.

Gonçalves, J.L.M. and Stape, J.L. (eds) 2002. Conservação e cultivo de solos para plantações florestais. IPEF, Piracicaba, Brazil. 498p.

Gonçalves, J.L.M. 2002. Soil conservation. *In:* Gonçalves, J.L.M. and Stape, J.L. (eds) Soil conservation and tillage for forest plantations, 47-129. IPEF, Piracicaba, Brazil.

Gonçalves, J.L.M., Stape, J.L., Wichert, M.C.P. and Gava, J.L. 2002. Residue management and soil preparation. *In:* Gonçalves, J.L.M. and Stape, J.L. (eds) Soil conservation and tillage for forest plantations, 131-204. IPEF, Piracicaba, Brazil.

Benedetti, V., Gonçalves, J.L.M. and Fessel, V.A.G. 2004. Mechanization of forest fertilization. *In:* Gonçalves, J.L.M., Benedetti, V. (eds) Translated by K. McNabb. Forest nutrition and fertilization, 409-421. IPEF, Piracicaba, Brazil.

Gonçalves, J.L.M., Stape, J.L., Benedetti, V., Fessel, V.A.G. and Gava, J.L. 2004. An evaluation of minimum and intensive soil preparation regarding fertility and tree nutrition. *In:* Gonçalves, J.L.M. and Benedetti, V. (eds) Translated by Ken McNabb. Forest nutrition and fertilization, 13-64. IPEF, Piracicaba, Brazil.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Smethurst, P. and Gava, J.L. 2004. Silvicultural effects on the productivity and wood quality of eucalypt plantations. Forest Ecology and Management 193: 45-61.

Martins, L.F.S., Poggiani, F., Oliveira, R.F., Guedes, M.C. and Gonçalves, J.L.M. 2004. Características do sistema radicular das árvores de *Eucalyptus grandis* em resposta à aplicação de doses crescentes de biossólido. Scientia Forestalis 65: 207-218.

Gonçalves, J.L.M., Wichert, M.C.P., Gava, J.L., Masetto, A.V., Arthur, J.J.C., Serrano, M.I.P. and Mello, S.L.M. 2007. Soil fertility and growth of *Eucalyptus grandis* in Brazil under different residue management practices. Southern Hemisphere Forestry Journal 69(2): 95-102.

Mello, S.L.M., Gonçalves, J.L.M. and Gava, J.L. 2007. Pre- and post-harvest fine root growth in *Eucalyptus grandis* stands installed in sandy and loamy soils. Forest Ecology and Management 246: 186-195.

Sasaki, C.M., Gonçalves, J.L.M. and Silva, A.P. 2007. Ideal subsoiling moisture content of Latosols used in forest plantations. Forest Ecology and Management 243: 75-82.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Bouillet, J.P. and Ranger, J. 2008. Assessing the effects of early silvicultural management on long-term site productivity of fast growing eucalypt plantations: the Brazilian experience. Southern Hemisphere Forestry Journal (Accepted).

Postgraduate theses

Pires Serrano, M.I. 1997. M.Sc. University of São Paulo, Brazil. Organic matter and nitrogen mineralization in *Eucalyptus grandis* plantations under minimum and intensive soil tillage.

de Miranda Mello, S.L. 1997. M.Sc. University of São Paulo, Brazil. Root configuration of eucalypt plantations established by seedlings and cuttings.

Sorbelini Mendes, K.C.F. 1999. M.Sc. University of São Paulo, Brazil. Nitrogen mineralization in natural and established forest ecosystems of the State of São Paulo.

de Lira, A.C.S. 1999. M.Sc. University of São Paulo, Brazil. Soil respiration and mesofauna under eucalypt plantations and savannah vegetation.

Gava, J.L. 2005. M.Sc. University of São Paulo, Brazil. Relationships between soil attributes and wood quality for pulp production of *Eucalyptus grandis* plantations.

Pulito, A.P. M.Sc. (in progress) University of São Paulo, Brazil. Nitrogen potentially available in forest plantations of the State of São Paulo.

Alvarez, C.A. M.Sc. (in progress) University of São Paulo, Brazil. Study of relationships between soil attributes and productivity of eucalypt stands by GPS techniques.

da Silva, E.V. M.Sc. (in progress) University of São Paulo, Brazil. Development of *Eucalyptus grandis* fine roots at mixed plantations of *Eucalyptus grandis* and *Acacia mangium*.

de Miranda Mello, S.L. 2005. PhD. University of São Paulo, Brazil. Dynamics of fine roots and contribution of carbon in the soil under *Eucalyptus grandis* stands in the State of São Paulo.

Teixeira, C.M. 2006. PhD. University of São Paulo, Brazil. Soil carbon dynamic under eucalypt plantation.

da Silva Gomes, S. PhD. (in progress) University of São Paulo, Brazil. Prediction of the nitrogen availability and potential response to fertilizer prescription in eucalypt plantations.

de Almeida, J.C.R. PhD. (in progress) University of São Paulo, Brazil. Efficiency of water use for *Eucalyptus grandis* in response to potassium and sodium fertilization.

Macquère, V. PhD. (in progress) University of São Paulo, Brazil. Processes and modelling of nutrient fluxes after fertilization in *Eucalyptus grandis* stands.

China

Postgraduate thesis

Xu Daping 2001. PhD. Murdoch University, Australia. Managing nutrients to increase productivity of plantation eucalypts in south China.

Congo

Journal papers and international conferences

Nzila, J.D., Laclau, J.P., Ranger, J. and Bouillet, J.P. 2001. Changes in nitrogen mineralization over successive rotations in clonal *Eucalyptus* plantations in Congo. *In:* Developing the Eucalypt of the Future. IUFRO International Symposium, Valdivia, Chile, 10-15 September 2001. 10p.

Nzila, J.D., Laclau, J.P., Bouillet, J.P. and Ranger, J. 2002. Effects of successive rotations of *Eucalyptus* on tree growth and soil nitrogen mineralization in Congo. *In:* Proceedings of the 17th World Congress of Soil Science, 14-21 August 2002, Thailand, 300/1-300/13.

Nzila, J.D., Bouillet, J.P., Laclau, J.P. and Ranger, J. 2002. Slash management effects on the tree growth and nutrient cycling in young *Eucalyptus* replanted sites in the Congo. Forest Ecology and Management 171: 209-221.

Laclau, J.P., Ranger, J., Nzila, J.D., Gelhaye, D., Bouillet, J.P. and Deleporte, P. 2003. *Eucalyptus* et fertilité des sols au Congo. Bois et Forêts des Tropiques 277 (3): 69-84.

Bouillet, J.P., Gonçalves, J.L.M., Ranger, J., Galiana, A., Deleporte, P.and Laclau, J.P. 2004. Potential for legume introduction in short rotation plantation forests as a means to improve productivity and soil fertility? A need of co-ordinated research. IUFRO, Division 1 Conference, June 14-18, 2004, Montpellier, France. 3p.

Ranger, J., Nzila, J.D., Zeller, B., Laclau, J.-P., Bouillet, J.P., Deleporte, P., Moukoumi, J., Jussy, J.H. and Marien, J.N. 2004. Control of the nitrogen mineralizing activity of micro-organisms by vegetation is a key-parameter to be taken into account by managers whatever the ecosystem function considered. *In:* International symposium: Forests Soils under Global and Local Changes: from Research to

Practice. 15-18 September, 2004. Bordeaux, France.

Saint-André, L., Deleporte, P., Gava, J.L., Gonçalves, J. L.M., Laclau, J-P., Nzila, J.D., du Toit, B. and Ranger, J. 2004. Assessing the impact of slash management on the eucalyptus productivity: a modelling approach. 275-282. *In:* Borralho, N.M.G., Pereira, J.S., Marques, C., Coutinho, J., Madeira, M. and Tomé, M. (eds) *Eucalyptus* in a changing world. Proceedings IUFRO Conference, 11-15 October, Aveiro, Portugal. RAIZ, Instituto Investigação da Floresta e Papel, Portugal.

Cucchi, V., de Coligny, F., Cornu, G., Gazull, L., Deleporte, P., Moukini, R. and Saint-André, L. 2006. Development of a spatial decision support tool for the management of eucalypt plantations in Congo. *In:* PMA6 the second international Symposium on Plant Growth Modelling, Simulation, Visualization and Application, 13-17 November 2006, Beijing, P.R. China.

Laclau, J.P., Gonçalves, J.L.M., Bouillet, J.P., Jourdan, C. and Saint-André, L. 2006. Consórcio de *Eucalyptus grandis* x *Acacia mangium* na E.E.C.F. de Itatinga: resultados de três anos de experimentação. Oral Presentation, workshop Plantio Misto de Eucalipto com Leguminosa para Produção de Madeira, 18 October 2006, IPEF, Piracicaba, Brazil.

Saint-André, L., Ranger, J., D'Annunzio, R., Thongo M'Bou, A., Deleporte, Ph., Nouvellon, Y., Laclau, J-P., Jourdan, C. and Bouillet, J-P. 2006. Integrating nutrient cycling into a growth and yield model calibrated for *Eucalyptus* plantations in Congo. *In:* PMA6 the second international Symposium on Plant Growth Modelling, Simulation, Visualization and Application, 13-17 November 2006, Beijing, P.R. China.

Bouillet, J.P., Gonçalves, J.L.M., Gava, J.L., Silva, C.R., Leite, F.P., Deleporte, P., Moreira, M.Z., Bassiloua, B., Galiana, A., Trivelin, P., Jourdan, C. and Laclau, J.P. 2007. Stand growth and soil fertility in mixed-species plantations of *Eucalyptus* and *Acacia* in Brazil and Congo. *In:* Proceedings of Workshop 2.08.03 IUFRO *Eucalyptus* and Biodiversity: Balancing Productivity and Sustainability, 22-26 October 2007, Durban, South Africa. 11p.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Bouillet, J.P. and Ranger, J. 2007. Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. *In:* Proceedings of Workshop 2.08.03 IUFRO *Eucalyptus* and Biodiversity: Balancing Productivity and Sustainability, 22-26 October 2007, Durban, South Africa. 25p.

Bouillet, J.P., Laclau, J.P., Gonçalves, J.L.M., Moreira, M.Z., Trivelin, P., Jourdan, C., Silva, E.V., Piccolo, M.C., Tsai Sui Mui and Galiana, A. 2008. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil. 2. Nitrogen accumulation in the stands and N_2 biological fixation. Forest Ecology and Management (submitted).

D'Annunzio, R., Conche, S., Landais, D., Saint-André, L., Joffre, R. and Barthes, B.G. 2008. Pairwise comparison of soil organic particle size distributions in native savannas and *Eucalyptus* plantations in Congo. Forest Ecology and Management Forest Ecology and Management 255 (3):1050-1056.

Laclau, J.P., Bouillet, J.P., Gonçalves, J.L.M., Silva, E.V., Jourdan, C., Cunha, M.C.S., Moreira, M.R., Saint-André, L., Gonçalves, M.R., Maquère, V., Nouvellon, Y., Ranger, J. 2008. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil. 1. Growth dynamics and net primary production. Forest Ecology and Management (submitted).

Silva, E.V., Gonçalves, J.L.M. and Laclau, J.P. 2008. Interações radiculares entre *Acacia mangium* e *Eucalyptus grandis* em um povoamento misto. Scientia Forestalis (accepted).

Postgraduate theses

Boutet, C, 2004. M.Sc. Systèmes Ecologiques, Bordeaux I, France. Estimation du potentiel fixateur d'azote et caractérisation des rhizobiums associés chez *Acacia mangium* et l'hybride *Acacia mangium* x *Acacia auriculiformis* sur sol de plantation forestière du Congo. 14p.

Bassiloua, J.B. 2006. M.Sc. Université Marien Ngouabi, Congo. Variabilité de la nodulation *d'Acacia mangium* dans une chronoséquence *Eucalyptus-Acacia*. 36p.

Banzouzi, E. 2007. M.Sc. Université Marien Ngouabi, Congo. Etudes des interactions génotype x environnement dans les tests clonaux multi topographiques. 56p.

Mialoundama, R. 2007. M.Sc. University of Nancy, France. Courbes de réponse du modèle E.Dendro à l'apport de fertilisants. 30p.

Silva, E.V. 2007. M.Sc. University of São Paulo, Brazil. Contraste de produção, crescimento e regeneração de raízes finas vivas em povoamentos puros e mistos de *Eucalyptus grandis* e *Acacia mangium*. 54p.

D'Annunzio, R. 2005-2007. M.Sc. Engref, France. Evolution et modélisation de la matière organique sous peuplements forestiers mono spécifiques. Comparaison entre plantation d'*Eucalyptus* au Congo et forêt de hêtre en France.

Bikindou, F. 2006-2009. M.Sc. Université Marien N'Gouabi, Congo. Détermination et caractérisation de facteurs de production dans un massif de plantations clonales d'*Eucalyptus* à Pointe-Noire (Congo).

India

Journal papers and international conferences

Mendham, D.S., Sankaran, K.V., O'Connell, A.M. and Groven, T.S. 2002. *Eucalyptus globulus* harvest residue management effects on soil carbon and microbial biomass at 1 and 5 years after plantation establishment. Soil Biology and Biochemistry 34:1903-1912.

Mendham, D.S., Kumarasway, S., Balasundaran, M., Sankaran, K.V., Corbeels, M., Grove, T.S., O'Connell, A.M. and Rance, S.J. 2004. Legume cover cropping effects on early growth and soil nitrogen supply in eucalypt plantations in south-western India. Biology and Fertility of Soils 39: 375-382.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Balasundaran, M., Grove, T.S., Mendham, D.S. and O'Connell, A.M. 2004. Influence of harvest residue management, weed control, legume cover cropping and trenching on eucalyptus productivity in Kerala, India. Journal of Tropical Forestry 16: 232-247.

Sankaran, K.V., Grove, T.S., Kumaraswamy, S., Manju, V.S., Mendham, D.S. and O'Connell, A.M. 2005. Export of biomass and nutrients following harvest of eucalypt plantations in Kerala, India. Journal of Sustainable Forestry 20: 15-36.

Little, K.M., Willoughby, I., Wagner, R.G., Adams, P., Frochot, H., Gava, J., Lautenschlager, R.A., Orlander, G., Sankaran, K.V. and Wei, R.P. 2006. Towards reduced herbicide use in forest vegetation management. Southern African Forestry Journal 207: 63-79.

Sankaran, K.V., Mendham, D.S., Chacko, K.C., Pandalai, R.C., Grove, T.S. and O'Connell, A.M. 2007. Increasing and sustaining productivity of tropical eucalypt plantations over multiple rotations. Journal of Sustainable Forestry 24: 109-121.

South Africa

Journal papers, international conferences and institute reports

du Toit, B., Job, R.A. and Fuller, G.M. 2000. Effect of six site management operations on the nutrition and productivity of a young eucalypt plantation in South Africa, 85-86. International Symposium: Managing forest soils for sustainable productivity, 18-22 September 2000, Villa Real, Portugal.

Little, K., Arnot, L., du Toit, B. and Maxfield, M. 2000. The killing of *Eucalyptus grandis* multiple-stem cut-stumps in the Karkloof Project: putting recommendations into practice. ICFR Bulletin 03/2000. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 6p.

du Toit, B., Esprey, L.J., Job, R.A., Fuller, G.M. and Dovey, S.B. 2001. Effects of site management in *Eucalyptus grandis* plantation in South Africa; early results of the Karkloof project ICFR Bulletin Series 22/2001. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit, B. and Scholes, M.C. 2002. Nutritional sustainability of *Eucalyptus* plantations: a case study at Karkloof, South Africa. Southern African Forestry Journal 195: 63-72.

du Toit, B. and Dovey, S.B. 2002. Research in eucalypt plantations of the Congo with some ideas that may find application in the South African context: trip report on the 4th workshop in the

CIFOR network entitled 'Site Management and Productivity in Tropical Plantation Forests', 9-12 July 2001, Pointe-Noire, Republic of Congo. ICFR Bulletin 02/2002. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 8p.

du Toit, B. 2003. Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa. Southern African Journal of Forestry 199: 15-25.

Job, R.A., du Toit, B. and Esprey, L.J. 2003. Estimating selected input parameters for 3-PG from an age series of *Eucalyptus grandis*. ICFR Bulletin Series 15/2003, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit, B., Fuller, G., Campion, J., McNamara, L. and du Plessis, M. 2003. Proceedings of workshop: Slash Management and Slash Burning in South African Forests: Issues and Research Needs. ICFR Bulletin 08/2003. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Dovey, S.B. 2005. Simple ratios to estimate biomass components and nutrient contents in mature stands of some important commercial plantation species. ICFR Bulletin 13/2005. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit, B. and Dovey, S.B. 2005. Eucalypt plantation response to changes in soil water and nutrients following intensive site management. ICFR Research Symposium, June 2005, Pietermaritzburg, South Africa.

du Toit, B. and Dovey, S.B. 2005. Effect of site management on leaf area, early biomass development and stand growth efficiency of a *Eucalyptus grandis* plantation in South Africa. Canadian Journal of Forestry 35: 891-900.

Smith, C.W., Little, K.M., Rolando, C. and du Toit, B. 2005. The plantation forestry sustainability initiative: a framework for monitoring and measuring the sustainability of intensively managed southern African forest plantations. ICFR Bulletin 08/2005. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit, B. 2006. Information requirements to fertilize plantations with greater precision in a dry country, 245-260. Proceedings of International Precision Forestry Symposium, 5-10 March 2006, Stellenbosch, South Africa.

Dovey, S.B. and du Toit, B. 2006. A review of nutrient fluxes across South African plantation forestry areas. ICFR Bulletin 11/2006. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Dovey, S.B. and du Toit, B. 2006. Calibration of LAI-2000 canopy analyser with leaf area index in a young eucalypt stand. Trees Structure and Function 20: 273-277.

Esprey L.J. 2006. Assessment of a process-based model to predict the growth and yield of *Eucalyptus grandis* plantations in South Africa. ICFR Bulletin 05/2006. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Dovey, S.B., Smith, C.W. and du Toit, B. 2007. Effects of site management on nutrient accretion of a *Eucalyptus grandis* plantation in South Africa. ICFR Bulletin 02/2007. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit, B. 2008. Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of *Eucalyptus grandis* in South Africa. Forest Ecology and Management, doi:10.1016/j.foreco.2007.12.037. (Accepted).

Postgraduate theses

Mbeko, N. 2002. M.Sc. University of Witwatersrand, South Africa. Some effects of early silvicultural management operations on root turnover in *Eucalyptus grandis* plantations.

du Toit, B. 2006. PhD. University of Witwatersrand, South Africa. Effects of site management on nutrition, sustainability and productivity in a *Eucalyptus grandis* stand in South Africa. 145p.

Acacia Sites

Indonesia

Books, journal papers and international conferences

Hardiyanto, E.B. 2004. Silvikultur dan pemuliaan *Acacia mangium,* 207-282. *In:* Hardiyanto, E.B. and Arisman, H. (eds) Pembangunan hutan tanaman *Acacia mangium* - Pengalaman di PT Musi Hutan Persada, Sumatera Selatan.

National conferences, workshops and institute reports

Anshori, S. 2000. Sumbangan hutan tanaman *Acacia mangium* terhadap sifat-sifat tanah-Studi kasuh di PT. Musi Hutan Persada, 149-154. *In:* Hardiyanto, E.B. (ed.) Prosiding seminar nasional status silvikultur 1999. Fakultas Kehutanan Universitas Gadjah Mada, Yogyakarta, Indonesia.

Hardiyanto, E.B. 2004. Peningkatan produktivitas hutan tanaman dan upaya menjaga kelestariannya, 113-132. *In:* Na'iem, M., Hardiwinoto, S., Sabarnurdin, M.S. and Suhardi (eds) Prosiding seminar nasional dalam rangka 70 tahun Prof. Dr. H. Soekotjo. Fakultas Kehutanan Universitas Gadjah Mada, Yogyakarta, Indonesia.

Hardiyanto, E.B. 2005. Beberapa isu silvikultur dalam pengembangan hutan tanaman (Current silvicultural issues in the development of plantation forests) 121-134. *In:* Hardiyanto, E.B. (ed.) Prosiding Seminar Nasional Peningkatan Produktivitas Hutan. Yogyakarta 26-27 May 2005. ITTO dan Fakultas Kehutanan Universitas Gadjah Mada, Yogyakarta, Indonesia.

Vietnam

Postgraduate theses

Vu Dinh Huong 2007. M.Sc. Nong Lam University of Ho Chi Minh City, Vietnam. Effect of slash retention management on soil properties and productivity of *Acacia auriculiformis* plantation in Binh Duong Province.

Nguyen Thanh Binh M.Sc. (in progress). Nong Lam University of Ho Chi Minh City, Vietnam. Effect of vegetation management on properties and productivity of *Acacia auriculiformis* plantation in Binh Duong Province.

Conifer Sites

Australia (Queensland)

Postgraduate thesis

Shane, S. T. PhD (in progress). Griffith University, Australia. Impacts of inter-rotation management on carbon and nutrient cycling in exotic pine plantations of southeast Queensland.

China

Journal papers and international conferences

Yang Xujing and Ying Jinhua. 1999. The effect of yield and site preparation on the growth of the second rotation young stands of Chinese fir. Journal of Fujian College of Forestry 19: 174-177. (in Chinese)

Fan Shaohui, Lin Guangyao, He Zongming, Lu Shantu and Yang Xujing. 1999. Impact of site management on productivity of second generation 1-year-old plantation of Chinese fir. Scientia Silvae Sinicae 35(3): 120-126. (in Chinese)

Ying Jinhua, He Zongming, Fan Shaohui, Weng Xianquan and Yang Chengdong. 2001. Effects of site management on some soil properties of a second-rotation plantation of Chinese fir. Soil and Environmental Sciences 10(3): 201-203. (in Chinese)

Lin Guangyao, Fan Shaohui, He Zongming, Yang Xujing, Ying Jinhua and Lu Shantu. 2001. A study on the influence of site management measures on the growth of 3-year-old *Cunninghamia lanceolata* plantation of second-generation. Forest Research 14(4): 403-407. (in Chinese)

Weng Xianquan, Su Huiqin, Lian Huasen, Fan Shaohui, Yang Chengdong and He Zongming. 2001. Research on soil properties of a first-rotation Chinese fir plantation of 29-year-old. Journal of Fujian College of Forestry 21(4): 367-370. (in Chinese)

Ying Jinhua, He Zongming, Fan Shaohui, Su Huiqin and Lian Huasen. 2001. Research on biomass and its distribution of a 29-year-old, first

rotation Chinese fir plantation. Journal of Fujian College of Forestry 21(4): 339-342. (in Chinese)

He Zongming, Fan Shaohui, Lin Guangyao, Yang Xujing and Ying Jinhua. 2002. Effects of site management treatments on growth of 2-year-old, second-rotation Chinese fir plantations. Journal of Fujian College of Forestry 22(1): 1-3. (in Chinese)

Fan Shaohui, Liao Zuhui, Ying Jinhua, Yang Xujing, He Zongming and Lin Guangyao. 2002. A study on the influence of site management measures on the growth of four-year-old Chinese fir plantation of second-generation. Forest Research 15(2): 169-174. (in Chinese)

He Zongming, Chen Qingshan, Fan Shaohui, Yang Xujing and Ying Jinhua. 2003. Effects of site management measures on growth of 4-year-old, second-rotation Chinese fir plantations. Scientia Silvae Sinicae 39(4): 54-58. (in Chinese)

Chen Qingshan, Zhang Haiyan, Wu Qingmin, Pan Ruimin and Yang Xujing. 2004. Impacts of stand density of first-rotation Chinese fir on growth of 4-year-old, second-rotation Chinese fir plantations. Journal of Fujian College of Forestry 24(3): 202-205. (in Chinese)

Lian Huasen. 2005. Effect of management factors on the growth of 3-year-old, second-rotation Chinese fir plantations. Journal of Northeast Forestry University 33(2): 4-5, 17. (in Chinese)

Fan Shaohui, He Zongming, Lu Jingming, Pan Ruimin and Yang Xujing. 2006. Effects of site management treatments on growth of 5-year-old, second-rotation Chinese fir plantations. Forest Research 19(1): 27-31. (in Chinese)

Chen Qingshan, He Zongming, Fan Shaohui, Lin Sizu and Yang Xujing. 2006. Long-term decomposition rate of logging slash of a 29-year-old Chinese fir plantation. Journal of Fujian College of Forestry 26(3): 202-205. (in Chinese)

He Zongming, Fan Shaohui, Lu Jingming, Yang Xujing and Weng Xianquan. 2006. Effects of site management treatments on growth of 6-year-old, second rotation Chinese fir plantations. Scientia Silvae Sinicae 42(11): 47-51. (in Chinese)

He Zongming, Fan Shaohui, Lu Jingming, Yang Xujing and Weng Xianquan. 2007. Effects of site management treatments on growth of six-year-old, second rotation Chinese fir (*Cunninghamia lanceolata*) plantations. Frontiers of Forestry in China 2(4): 396-400.

Postgraduate thesis

Zhong Yingxi. 2005. M.Sc. Fujian Agriculture and Forestry University, China. Effects of slash management treatments on the productivity of a second-rotation Chinese fir (*Cunninghamia lanceolata*) plantation. (in Chinese)

Donors

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CIFOR is a leading international forestry research organization established in 1993 in response to global concerns about the social, environmental, and economic consequences of forest loss and degradation. CIFOR advances human well-being, environmental conservation, and equity by conducting research to inform policies and practices that affect forests in developing countries. CIFOR is one of 15 centres within the Consultative Group on International Agricultural Research (CGIAR). CIFOR's headquarters are in Bogor, Indonesia. It also has offices in Brazil, Bolivia, Burkina Faso, Cameroon, Ethiopia, Vietnam, Zambia and Zimbabwe, and works in over 30 other countries around the world.

These proceedings present results from research done for a decade in the CIFOR project Site Management and Productivity in Tropical Plantations. They include papers presented at a workshop in Brazil in November 2004 and then updated at a workshop in November 2006 at Bogor, Indonesia. These papers complement the proceedings in the series published by CIFOR in 2004, 2000, and 1999. Currently the research network includes 16 sites in 8 countries representing a range of biophysical environments, species, productivity potentials and management strategies. Research is focused on inter-rotation site management. Good management of this phase, between harvesting and tree establishment in the next rotation, is critical for the future outcome of plantations. During this phase, there is potential for soil degradation, but also opportunities to introduce sound new technologies to improve long-term productivity and soil properties. Although the species, the site, and soil problems vary according to local conditions, all experiments are designed to provide knowledge that will benefit all plantation growers and our understanding of the underlying processes which enable us to increase and sustain plantation productivity with environmental care.

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