Site Management and Productivity in Tropical Plantation Forests

Proceedings of Workshops in Congo July 2001 and China February 2003

Editors

E.K.S. Nambiar
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CIFOR
CENTER FOR INTERNATIONAL FORESTRY RESEARCH

JAPAN
Official Development Assistance

Published in 2004
Printed by Subur Printing
Cover photos by T. Toma
Design by Kriswanto and Catur Wahyu

ISBN 979-3361-41-7

National Library of Indonesia Cataloging-in-Publication Data

Site Management and Productivity in Tropical Plantation Forests. Proceedings of Workshops in Congo July 2001 and China February 2003./edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma

ISBN 979-3361-41-7
1. Forest Plantations 2. Eucalyptus 3. Acacia 4. Forest Trees 5. Growth 6. Cycling 7. Short Rotation Forestry 8. Silviculture 9. Productivity I. Nambiar, E.K.S. II. Ranger, J. III. Tiarks, A. IV. Toma, T.

Published by
Center for International Forestry Research
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Site Management and Productivity in Tropical Plantation Forests Network

This project has been sponsored and managed by CIFOR since 1995. The leadership of Mr Christian Cossalter (1995-2002) and Dr Takeshi Toma (2003-) has made it possible to operate the project as a network. Scientific advice and support have been provided by Dr Sadanandan Nambiar (CSIRO), Dr Allan Tiarks (USDA Forest Service) and Dr Jacques Ranger (INRA). The network has been supported mainly by contributions from partners, and public and private organisations (their logos appear on the back cover). Additional financial support has been provided by the Official Development Assistance of the Government of Japan as part of the CIFOR/Japan research project 'Rehabilitation of Degraded Tropical Forest Ecosystems'.

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Introduction

E.K.S. Nambiar[1]

Forest plantations in the tropics are becoming increasingly important as a source of wood supply for paper and other wood products. Many countries are now committed to developing plantation forestry and wood-based, value-adding industries as an integral part of their regional and national economic development. An example of a major new development, very relevant to this network, is Vietnam's 'Five Million Hectares Reforestation Program' (5MHRP 1998-2010). Among the strategies for creating sustainable and productive forests are large-scale plantation forests: 1 million ha for pulp, 400 000 ha for plywood, 200 000 ha for solid wood and 200 000 ha for special products (Vu Dinh Huong *et al.* these proceedings). Implementation of this expansion proposes an annual planting rate of 260 000 - 400 000 ha, a formidable task. The reforestation is largely based on exotic species with high growth potential, grown in short-medium rotation crop cycles with a targeted average growth rate of 20 m^3 ha^{-1} yr^{-1}. Industrial scale *Acacia* plantations on degraded land for pulpwood production feature prominently in this scheme. The research required to underpin such a major venture is in its infancy in Vietnam, especially in the area of site and soil management for increased and sustained production. The Forest Science Institute of Vietnam joined the Center for International Forestry Research (CIFOR) partnership project during 2002 to initiate systematic research on this topic.

Sustained productivity of plantation forests is the foundation of successful forestry which can provide diverse benefits. Plantations must be developed with a balance between economic, environmental and social goals. Industrial-scale forest plantations require large capital investments, and expertise in intensive management and environmental care. Their management goals aim at high rates of production and short rotation length. These plantations increase the demands on the soil which may have been degraded by previous land use. Large-scale plantation forestry is a relatively new venture in many areas, and hence the knowledge of ecosystem processes and the management expertise required for increased and sustained production are limited.

CIFOR supports research on sustainable management of planted forests in subtropical and tropical environments. In intensive, short-rotation forestry the greatest impact from management inputs occurs during harvesting, site preparation, planting and early silviculture, including fertilisation and weed control. Recognition of this led to the establishment of an international network research project focused on the impacts of inter-rotation, management practices on processes influencing productivity.

The governing concept, rationale, objectives, research approach and partnership obligations

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have been described in earlier proceedings and will not be repeated here (Nambiar 1999, Tiarks *et al.* 1999, Tiarks and Nambiar 2000). An overview of the project is also included in these proceedings. Since inception, the scope of the project has expanded with increasing numbers of partners. Currently the network includes 16 sites in 8 countries representing forestry in a wide range of biophysical environments, species, productivity potentials and management strategies.

Five workshops sponsored by CIFOR have been critical for the strategic development and scientific strength of the network, and also for building partnerships This proceedings brings together the papers and ideas discussed at the last two workshops: in Pointe-Noire, Congo in July 2001 and in Guangzhou and Haikou, China in February 2003. After reviewing the papers presented at Pointe-Noire we concluded that while the time intervals between workshops were appropriate for discussions and sharing of ideas, they may be insufficient to warrant a publication on each occasion. Postponing the publication until after the meeting in China allowed greater time for building the database and interpretation. This decision enabled partners to revise their papers with more results and take the science and application to a higher level. All papers have been peer reviewed by the network's Scientific Advisory Group.

This project is a work in progress with varying achievements by individual partners. It will be some years before firm interpretation based on the data across the sites and general conclusions can be drawn. However, the set of experiments at each site was designed to be self-contained and robust enough to provide scientifically valid results on its own merit. Results from individual sites are expected to make significant contributions for improving sustainable management practices in their region. Several papers in these proceedings have identified how results from individual sites are making positive impacts on local plantation management

The forest plantations areas within which the project sites are located are owned by either private or public enterprises with diverse business goals ranging from large-scale export to small-scale domestic consumption. The ultimate test of success of this project will be the effectiveness with which the knowledge gained from each site and from the network has been continually applied in operational forestry. The value of this project is in providing ecosystem and site-specific information, demonstrating impacts and providing solutions as best bet options.

Recently CIFOR recognised this project (in '*Forests and people: Research that makes a difference*') among the 'highlight achievements' in its first decade. Such recognition is a gratifying and encouraging outcome for the network partners.

References

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 16-20 February 1998, Pietermaritzburg, South Africa, 1-3. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A. and Nambiar, E.K.S. 2000. Summary of the third workshop in Kerala, India. *In*: Nambiar, E.K.S., Cossalter, C., Tiarks, A. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: a progress report: workshop proceedings 7-11 December 1999, Kerala, India, 105-108. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A., Nambiar, E.K.S., Cossalter, C. and Ranger, J. 1999. A progress report. *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, 73-76. Center for International Forestry Research, Bogor, Indonesia.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Sustainability of Wood Production in Eucalypt Plantations of Brazil

J.L.M. Gonçalves[1], J.L. Gava[2] and M.C.P. Wichert[3]

Abstract

The main objective of this paper is to provide a critical appraisal of the research results and practical implications arising from the Brazilian part of CIFOR Network project 'Site management and productivity in tropical plantation forests' to the network as a whole. The Brazilian project was set up in Itatinga district, São Paulo State, Brazil in 1995 with the objective of evaluating the effect of site management practices (ranging in intensity from minimum to intensive management regimes) on soil fertility, nutrient cycling, nutrition and productivity of a stand of *Eucalyptus grandis*. We have shown that minimum cultivation and retention of the logging residues and forest-floor on the soil have important effects on water, nutrient content and Carbon store, promoting better use of natural resources of the ecosystem and increasing forest productivity. We also conclude that a high level of wood production can be maintained over successive rotations, but this will require continuous improvements in management decisions. Research results obtained in the CIFOR Network trial and in other regional experiences are assisting judicious management practices to maintain or to increase productivity in Brazil. These studies have also been of much value for research training and for on-site demonstrations for managers.

Introduction

Productivity of large parts of the Brazilian forest plantation estate is below their biological potential, and can be increased on a large scale. Productivity increases have been achieved with appropriate matching of genotypes to site quality together with correct practices of soil cultivation, harvest residue management, fertiliser application and weed control. The challenge is in establishing the balance among strategies designed to increase production in the short economic sense or increase the productivity in the long-term with little or no negative impacts on the environment.

In some sites, especially in those with sandy and medium texture soils, low in fertility, the decline of wood production with successive rotations has

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occurred with the same species (Gonçalves *et al.* 2000b). Usually, a decline of soil fertility is caused by management practices that do not conserve soil and site resources, damage soil physical and chemical characteristics, and include insufficient or unbalanced fertiliser application. The problem is more serious when fast-growing genotypes are planted, which have a high nutrient demand and uptake capacity, and therefore high nutrient output through harvesting. Special attention is required if they are to sustain high rates of productivity in the long-term. Clonal forests have been fundamental on sites with larger water and nutrient restrictions, where they out perform those established from traditional seed-based planting stock. When environmental limitations are small the productivity of plantations based on clones or seeds appears to be similar.

When forest plantations started in Brazil in the late 1960s, eucalypt yield was about 12 m^3 ha^{-1} yr^{-1}. Now, as a result of investments in research and technology average productivity varies from 20 to 60 m^3 ha^{-1} yr^{-1} depending on site quality (Schumann 1992, Eldridge *et al.* 1994, Santana *et al.* 2000, Stape *et al.* 2001). Productivity restrictions relate to the following environmental factors in order of importance: water deficits > nutrient deficiency > soil depth and strength.

Over the last 15 years, practices of soil and harvest residue management have been referred to as ‘minimum cultivation’. Several questions related to the effect of soil cultivation and residue management on soil fertility, forest nutrition and sustainability of wood production in short and long terms have been addressed by research institutions and forest companies. Main issues addressed are: effects of minimum cultivation on soil conservation; fertility and biological activities; importance of residues for maintenance of soil properties; nutrient release in residues to trees; relationship or synchronisation between nutrient release and nutritional stage or growth of trees; and effects of these factors on productivity.

These activities provided the framework in which CIFOR project ‘Site management and productivity in tropical plantation forests’ was conducted. In this paper we provide a synthesis of the overall knowledge experience in the Brazilian context. The details of the experimental work and parts of the results have been reported (Gonçalves *et al.* 1999, Gonçalves *et al.* 2000a) Gonçalves *et al.* 2000b).

Environmental Description

The area of natural vegetation of ‘cerrado’ (Brazilian savanna), where most of the *Eucalyptus* and *Pinus* stands are established, occupies 1.8 million km^2 or about 20% of the Brazilian territory. It extends mainly through the Centre-West region, with smaller areas in the North, Northeast and Southeast regions, (latitude 5-21°S and longitude 43-63°W). Altitudes vary up to about 500-800 m.

Climate

The climate is predominantly of the Aw type (humid tropical climate, dry winter, classification of Köppen). Mean annual temperature varies between 20°C and 26°C. Mean annual rainfall and its distribution throughout the year varies greatly. Most areas have a rainy season (November-April), when 80% of the rain falls, and a dry season (May-October). About 65% of Brazilian savanna areas receive between 1200 and 1800 mm annual rainfall. The period of water deficit varies between 4 and 7 months (Adámoli *et al.* 1986).

Edaphic Conditions

The great majority of soils in the Brazilian Southeast region (tropical and subtropical climate) is derived from sedimentary rocks and are in an advanced stage of weathering. The common clay minerals are kaolinite, Fe and Al oxides and amorphous materials. In general, the primary mineral content is low, CEC is low to medium, P-fixing capacity is medium to high and drainage is high, which gives the soils high leaching potential (Gonçalves *et al.* 1997a). Under these circumstances, the soils are prone to degradation and loss of available nutrients if proper management practices are not applied.

Most soils have favourable physical and relief characteristics. For example, they have excellent structure (aggregation). In general, the soils do not have natural physical impediments for rooting and landscape relief varies from flat to gently undulating, and is easy for mechanisation. Because these favourable conditions reduce the cost of forest operations, larger investments have been made with the intention of correcting chemical limitations of the soils through fertiliser application.

Study Area

Our study is conducted in a commercial plantation of *Eucalyptus grandis* Hill ex Maiden, Itatinga district, São Paulo state, Brazil. It is located at latitude 23°00’S, longitude 48°52’W and altitude 750 m. The site was originally occupied by ‘cerrado’, vegetation typical of the area. The climate of the area is the Cwa type, according to the classification of Köppen, i.e. mesothermic, dry winter, with mean temperatures in the coldest month (July) below 18°C, and in the hottest month (January) above 22°C. The mean annual rainfall at the experimental site is about 1600 mm, 57% of this occurring during December to March. However, there is no pronounced period of water deficit over winter, despite the prolonged rainless period, when the temperature and evapotranspiration are relatively low.

The specific soil type of the experimental area is characterised as a Red-Yellow Latosol (Oxisol), medium texture (200 g kg^{-1} clay, 30 g kg^{-1} silt and 770 g kg^{-1} sand), dystrophic (pH in CaCl$_2$ 0.01 mol L^{-1} = 3.7, total C = 12.2 g dm^{-3}, total N = 1.0 g dm^{-3}, P-resin = 4.2 g dm^{-3}, exchangeable K = 0.04 cmol$_c$ dm^{-3}; bulk density of A horizon = 1.4 g dm^{-3}), depth > 2 m, site relief (< 5% slope).

Forestry System

Forestry management in the study region is based on the coppice system. Eucalypt plantations are usually grown for seven years before the first clearcut which is followed by a coppice rotation (one or two sprouts per stump) of seven years. On low quality sites, no more than two clearcuts are taken but on high quality sites (usually more clayey and fertile) three or four clearcuts are possible. Small diameter wood is used, in order of volume consumed, for energy (power and charcoal), pulp and building purposes.

Experimental Description

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

BL$_0$	All aboveground biomass, including the crop trees, understorey, slash and forest-floor were removed.
BL$_1$	All stemwood harvested. All bark, understorey, slash and forest-floor were retained with minimum disturbance to site (Note that in BL$_1$ treatment as per the CIFOR Protocol, aboveground parts including bark of the commercial-sized crop stems are removed). This treatment is described as ‘minimum cultivation’ in Brazil.
BL$_2$	Stemwood with bark harvested. All slash, understorey and forest-floor retained with minimum soil disturbance.
SC	Standing crop left intact.
SL$_p$	Harvest stemwood. All residue (bark, slash, forest-floor and understorey) incorporated in the soil with a heavy harrow.
SL$_b$	Harvest stemwood. All residue distributed on the soil and burnt.
CP	Clearcut the stand and harvest stemwood. All residue retained on the soil. Cut stumps allowed to coppice and thinned to one stem after 18 months.

The experiment was laid out in a randomised complete block design, with 7 treatments and 4 replicates. Each plot consisted of 121 trees (11 x 11) and the total area occupied 1.75 ha.

The stand was clearcut in July 1995 and treatments were applied by August 1995. In treatments BL$_0$, BL$_1$, BL$_2$, SL$_p$ and SL$_b$ seedlings for the new plantations were planted in September 1995 at a spacing of 3 m x 2 m. *Eucalyptus grandis* of Coffs Harbour provenance was used. Seedlings were planted in furrows and fertilised at planting with 15, 13 and 12 kg ha^{-1} of N, P and K, respectively, and a basal dressing of 250 kg ha^{-1} of KCl was applied in May 1996. Weeds were controlled manually. Treatment CP, coppice, received the same fertilisation as a basal dressing in split dose: 15, 13 and 12 kg ha^{-1} of N, P and K, respectively, applied 2 months after clearcut followed by 250 kg ha^{-1} of KCl in May 1996.

Effect of Site Management on Productivity

The different soil preparation and residue management treatments resulted in pronounced effects on the growth of *E. grandis* stands (Fig. 1). The treatment where all residues were retained on soil, (BL_1), and in the treatment where the residues were incorporated (SL_p) or burned (SL_b) showed similar growth at 6.4 years of age. The poorest growth was where all residues were removed (BL_0). Removal of the bark and slash caused a productivity reduction of 40 m^3 ha^{-1} (14.5%) of stem volume compared to the treatment where all residues were retained (contrast BL_1 - BL_2) and, the removal of all residues, a reduction of 101 m^3 ha^{-1} (36.5%) (contrast BL_1 - BL_0). The importance of the residues on the productivity of soils with low fertility is very clear. Results from other network sites where soils are low in fertility in Australia (O'Connell *et al.* 2000, Simpson *et al.* 2000), and Congo (Bouillet *et al.* 2000) also show similar trends. Besides the nutrient store contained in residues (Table 1), which are rapidly mineralised, the residues created a favourable microclimate (soil temperature and moisture) for initial growth of the plants. Gonçalves *et al.* (1999) found that in BL_1 and BL_2 the temperature and water fluctuations in the soil were lower, mean water content of soil was higher and the surface temperature of soil was lower than in the treatments where the residues were burned or removed. These effects influenced positively the N mineralisation (Table 2). Similar effects on water content were found at the South Africa site (du Toit *et al.* 2000).

Higher growth of the trees obtained in the early years after burning of the residues, SL_b, highlight the temporary effect due to the high initial availability of nutrients released by burning and mineralisation. However, these treatments probably have undesirable effect such as loss of nutrients by volatilisation, and leaching and erosion in the long term (Gonçalves *et al.* 2000a).

Nutrient Uptake and Cycling

Nutrient uptake and cycling have close relationship with the growth phase and nutritional demands of plants. The faster the rate of growth in a season the larger is the corresponding uptake rate and nutrient cycling. Nutrient uptake by trees showed a close relationship among uptake and stages of aboveground growth (Fig.2). Nitrogen and K accumulation was fast up to 2.5 years, the period of leaf area expansion and then declined to somewhat stable values. From this stage, the amount of leaf and branch deposition (after closure canopy), increased the biogeochemical and biochemical cycling. Phosphorus accumulation was high even 3.5 years after planting, with higher proportions of P in bark and wood.

Biogeochemical Cycling

Gonçalves *et al.* (1999) showed the rate of litterfall in a stand of *E. grandis* (7-8 years old) was 7.8 t ha^{-1} yr^{-1} (60% leaves and 40% branches). Litterfall was high in spring and winter, and low in autumn. Annual rate of nutrient deposition was 42 kg ha^{-1} N, 2.3 kg ha^{-1} P, 20 kg ha^{-1} K and 47 kg ha^{-1} Ca. Theses values represent 10% of N, 6% of P, 10% of K and 17% of the Ca in aboveground biomass.

At this site, 6 months after clearcutting, the amount of forest-floor was reduced from 24 to 16 t ha^{-1}, a 33% reduction (Table 1). At the Congo site, Bouillet *et al.* (2000) found 38 to 65% of the logging residue decomposed in six months. Therefore, forest-floor and logging residues decay rapidly. We estimated that 75 kg ha^{-1} N, 5 kg ha^{-1} P, 11 kg ha^{-1} K and 73 kg ha^{-1} Ca are released through residue mineralisation in the first six months after clearcutting (Table 1). These amounts are very significant considering the quantity of nutrient uptake in the first year of growth, showing that residues constitute a large and available nutrient pool. It was found that in a 7-year-old stand, forest-floor accumulated 30% of total N, 18% of P, 14% of K, 43% of Ca and 31% of Mg found above- and belowground.

Figure 1. Basal area and stem solid volume (with bark) over 6.4 years in relation to treatments. Bars represent the LSD (p=0.001)

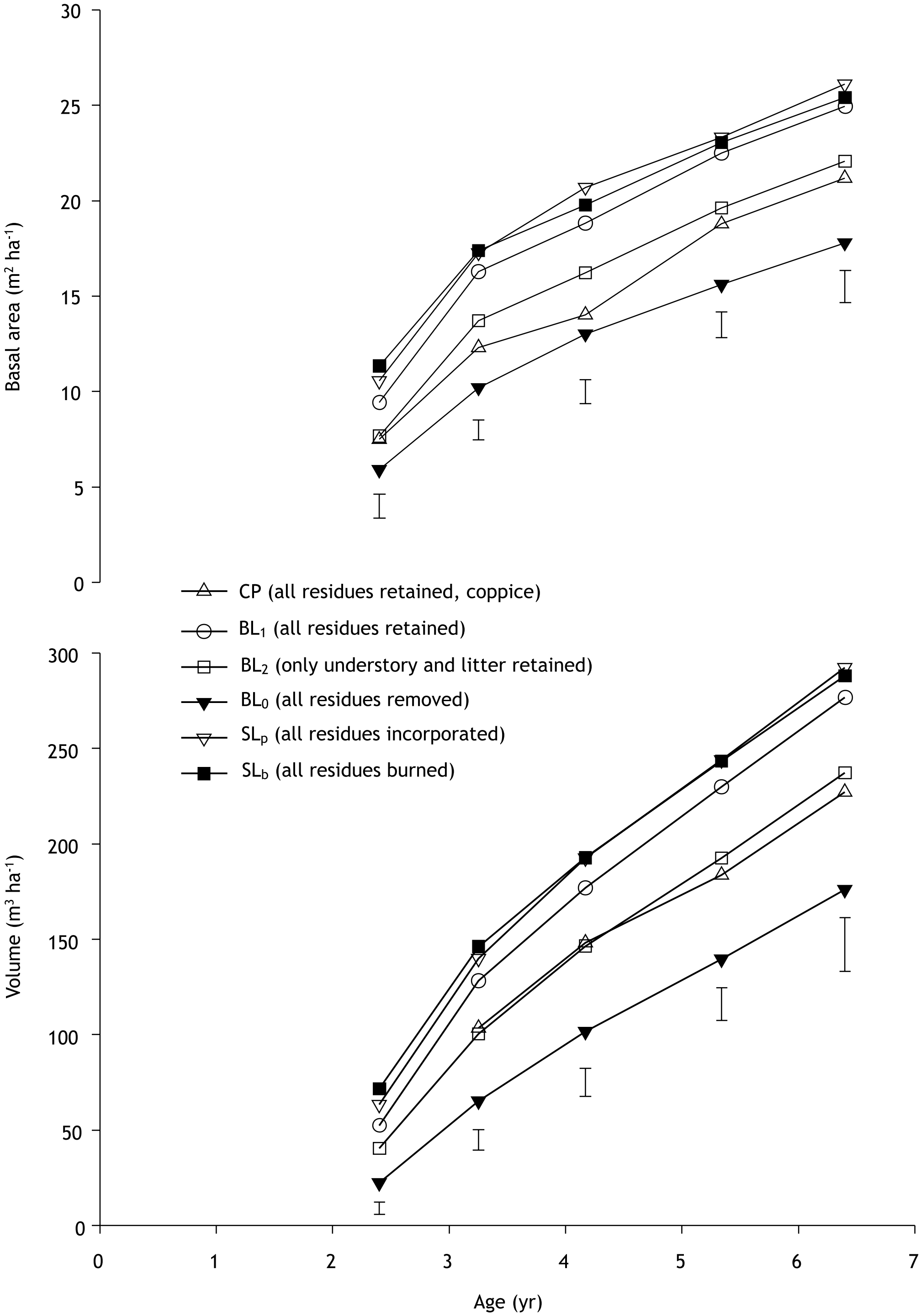


Table 1. Nutrient concentration, biomass and nutrient content in the accumulated forest-floor of a eucalypt stand (SC) and 6 months after clearcutting and replanting under BL_2 treatment (after Gonçalves *et al.* 1999)

Treatment	Biomass	N	P	K	Ca	Mg
				(g kg^{-1})		
SC		7.9	0.4	1.5	8.8	1.0
BL_2		7.2	0.3	1.6	8.7	1.0
	t ha^{-1}			(kg ha^{-1})		
SC	23.7 (1.8)	187	9.5	36	209	24
BL_2	15.6 (1.9)	112	4.5	25	135	16

Values in brackets are standard errors.

Table 2. Total-N mineralised over the first 21 months after planting (after Gonçalves *et al.* 2000a)

Treatment	Total-N mineralised (NH_4 N + NO_3N)				
	Litter	0-5 cm	5-15 cm	15-30 cm	Total
			(kg ha^{-1})		
SC	3 (4)	49 (64)	17 (22)	8 (10)	77
BL_1	3 (5)	20 (35)	18 (31)	17 (29)	58
BL_0	-	20 (44)	9 (20)	16 (36)	45
SL_p	-	26 (43)	23 (38)	12 (19)	61
SL_b	-	16 (57)	3 (11)	9 (32)	28

Values in brackets are the percentages in relation to the total N.

Biochemical Cycling

Gonçalves *et al.* (1997b) reported nutrient retranslocation from senesced leaves before fall amounted to 61% N, 79% P and 50% K present initially (Table 3). This equates to a net amount of 50 kg ha^{-1} yr^{-1} N, 6 kg ha^{-1} yr^{-1} P and 15 kg ha^{-1} yr^{-1} K, for a leaf fall rate of 4.6 t ha^{-1} yr^{-1}. From senesced branches smaller amounts of nutrients are transferred: 23% N, 67% P and 8% K. This equates to, 4 kg ha^{-1} yr^{-1} N, 2 kg ha^{-1} yr^{-1} P and 1 kg ha^{-1} yr^{-1} K, for a branch fall of 3.2 t ha^{-1} yr^{-1} (Table 3). The whole amount of nutrients biogeochemically and biochemically cycled by leaves and branches amounted to about 96 kg ha^{-1} yr^{-1} N, 10 kg ha^{-1} yr^{-1} P and 36 kg ha^{-1} yr^{-1} K. These amounts are greater than the amounts of annual uptake at 5 to 7 years of age (only aboveground, Fig. 2). Therefore, in stands of *E. grandis* the major part of annual demand of nutrients is met from nutrient cycling.

Impacts of Successive Harvests of Short Rotation Crops on Site Nutrient Store

An estimated nutrient budget for the site under a set of management scenario is presented in Table 4. Management practices which include burning of forest-floor and slash, removal of wood and bark, and low amounts of fertiliser application, have the highest impact on nutrient depletion. In this case, P availability may fall to critical levels beyond the first rotation, and K beyond the second rotation. In management scenario C, which does not include residue burning, there may be enough supplies of N to support more than two rotations, indicating a large effect of this practice on N stocks. Comparison of scenarios B and D show the role fertiliser application, a practical and economically proven strategy in sustaining production. Also note that the impact varies

Figure 2. Aboveground biomass and nutrient accumulation over 5.5 years in relation to treatments

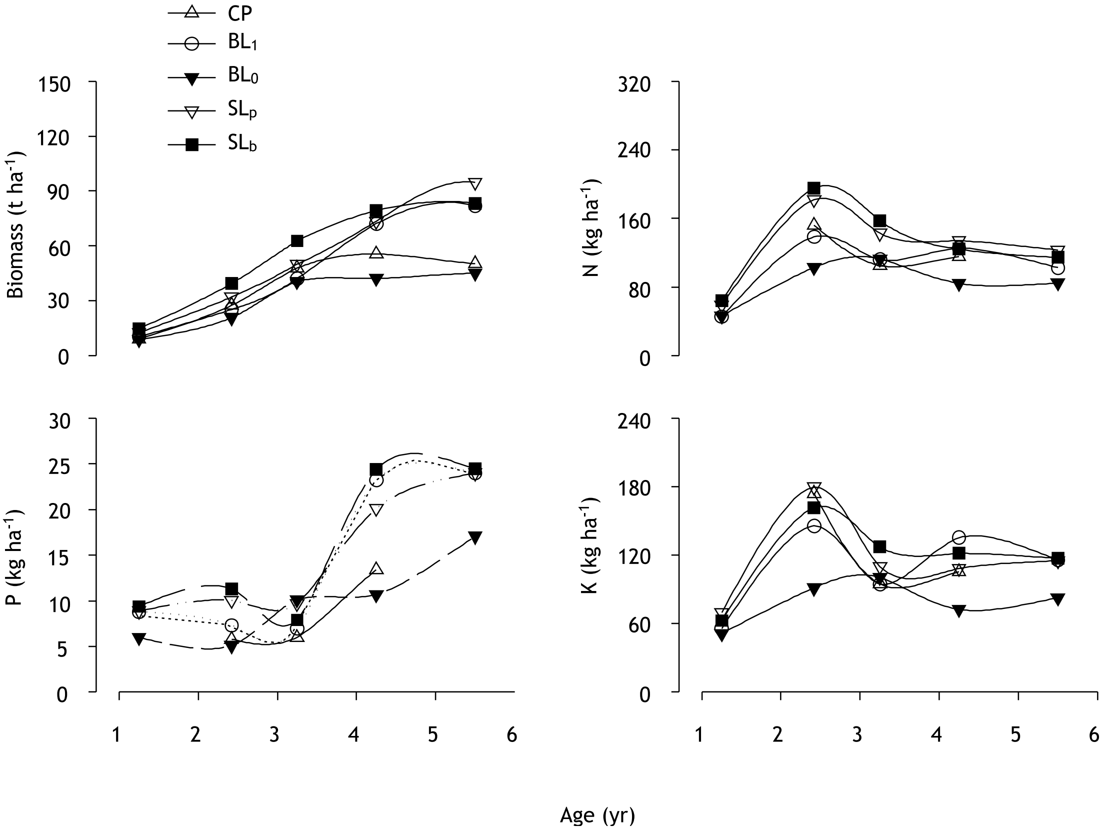


Table 3. Mean nutrient content in senesced and green leaves and branches, and nutrient retranslocated before fall throughout a year of growth in a *Eucalyptus grandis* stand, starting at age 8 years (after Gonçalves *et al.* 1997b)

Nutrient	Content				Nutrient retranslocated before fall			
	Senesced leaves	Green leaves	Senesced branches	Normal branches	Leaves		Branches	
	(g kg^{-1})				(%)	(kg ha^{-1} yr^{-1})	(%)	(kg ha^{-1} yr^{-1})
N	6.2	18.3	2.9	4.7	79	66	67	10
P	0.3	0.6	0.2	0.3	67	2	66	1
K	2.9	9.7	1.8	7.5	81	36	87	21
Ca	6.9	4.3	4.3	2.3	0	0	0	0
Mg	2.2	2.8	0.9	0.9	51	7	48	1

Nutrient translocation: NT = {1-[(NCDT/CCDT)/(NCNT/CCNT)]} x 100, where NT = translocation (%), MCDT = mean nutrient content in senesced tissue, CCDT = mean Ca content in deciduous tissue, NCNT = mean nutrient content in green tissue, CCNT = mean Ca content in green tissue. To calculate the amounts of nutrients translocated, the mean depositions of deciduous leaves (4600 kg ha^{-1} yr^{-1}) and deciduous branches (3200 kg ha^{-1} yr^{-1}) were multiplied by the relative translocation (%) of each nutrient.

Table 4. An estimated nutrient budget in a short-rotation crop of *Eucalyptus grandis* established close to CIFOR Network trial (7 years, MAI 30 m^3 ha^{-1} yr^{-1}, total aboveground biomass 188 t ha^{-1})

Component	N	P	K	Ca	Mg
	(kg ha^{-1})				
(S) Initial nutrient store in the soil (0-200 cm)[(a)]	1890	54	547	3804	798
Nutrient store in biomass					
Leaf	57	5	21	25	9
Branch	16	3	8	18	3
Wood	224	19	106	110	16
Bark	36	12	48	95	15
Litter	187	10	36	209	24
Root (coarse and fine)	98	4	29	23	10
Nutrient loss					
(F) By burning logging residues and litter[(b)]	260	10	34	65	22
(B) By bark removal	36	12	48	95	15
(W) By wood removal	224	19	106	110	16
(W + B) By wood and bark removal	260	31	154	205	31
Nutrient addition through fertilisation[(c)]					
(LF) Low application	7.5	11	16.5	-	-
(HF) High application	20	26	58	200	50
Nutrient budget[(d)]					
Management A: (S) - (W) + (HF)	1686	61	499	3894	832
Management B: (S) - (F) - (W + B) + (HF)	1390	39	417	3734	795
Management C: (S) - (W + B) + (LF)	1638	34	409	3599	767
Management D: (S) - (F) - (W + B) + (BI)	1378	24	375	3534	745

(a) Only potential mineralisable N (Gonçalves *et al.* 2001), P extractable by resin and exchangeable K, Ca and Mg;

(b) The estimates of the nutrient losses through residue burning were based on the data obtained by Maluf (1991): 88%, 33%, 30%, 47% and 43% of N, P, K, Ca and Mg losses from the total nutrient amounts, respectively;

(c) Low fertiliser application - forest plantation established with the following rates of nutrients: 15, 22 and 33 kg ha^{-1} of N, P and K each cultivation time, respectively; high fertiliser application - forest plantation established with the following rates: 40, 52, 115 and 200 kg ha^{-1} of N, P, K and Ca each cultivation time, respectively. It was assumed as 50% the efficiency of use of the sources of N, P and K; and

(d) Nutrients remaining at the site after each seven years (growth rotation).

between nutrients. The scenario A, which includes retention of residues and relatively high fertiliser application, provides the long-term option. This scenario analysis is hypothetical but provides a framework for further studies and for targeting site specific management practices in relation to the nutrient-supplying capacity of the site.

Experience with replacement of nutrients through fertilisation in eucalypt plantations has shown it is possible to maintain or to increase the productivity. Supporting the results of nutrient balance presented in Table 4, Gava (1997) demonstrated a high response to the application of K (Fig. 3), maintaining the productivity at levels equivalent to the previous rotation. Availability of K is one of the principal indicators of sustainable productivity of eucalypt plantations in these sites. Based on this trial and other field experience K fertilisation with rates ranges from 70 to 100 kg ha^{-1} K has become a common practice under similar site conditions. The increasingly widespread occurrence of K deficiency in second rotation sites, unlike in the previous rotation in Brazil, shows how nutrient depletion due to cropping requires close attention and diagnostic tools.

Figure 3. Response to potassium (K) application at age 5 years on a second crop of a coppice stand of *Eucalyptus grandis*; same site near the CIFOR Network trial (after Gava 1997)

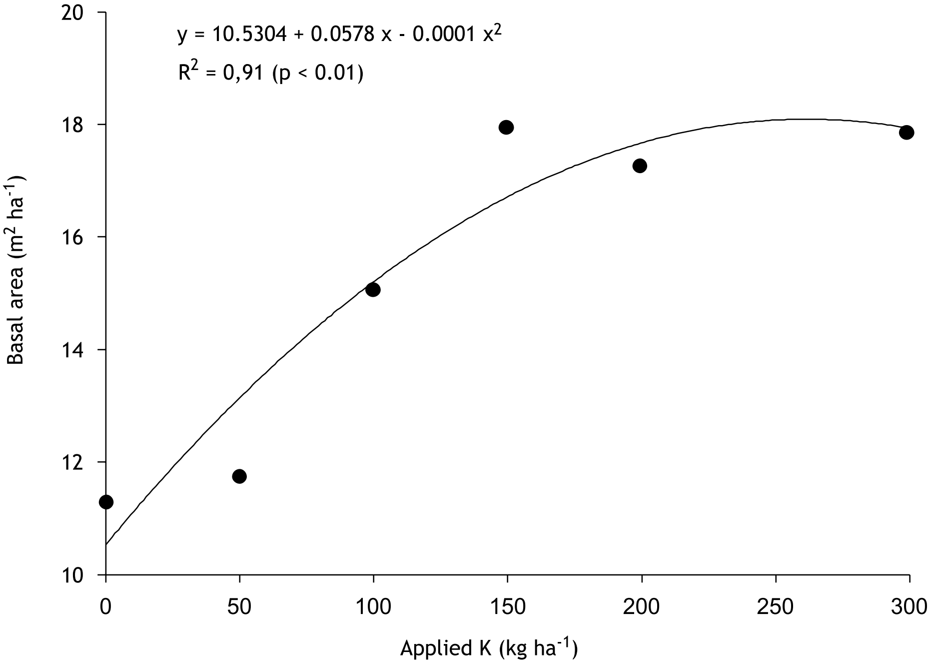
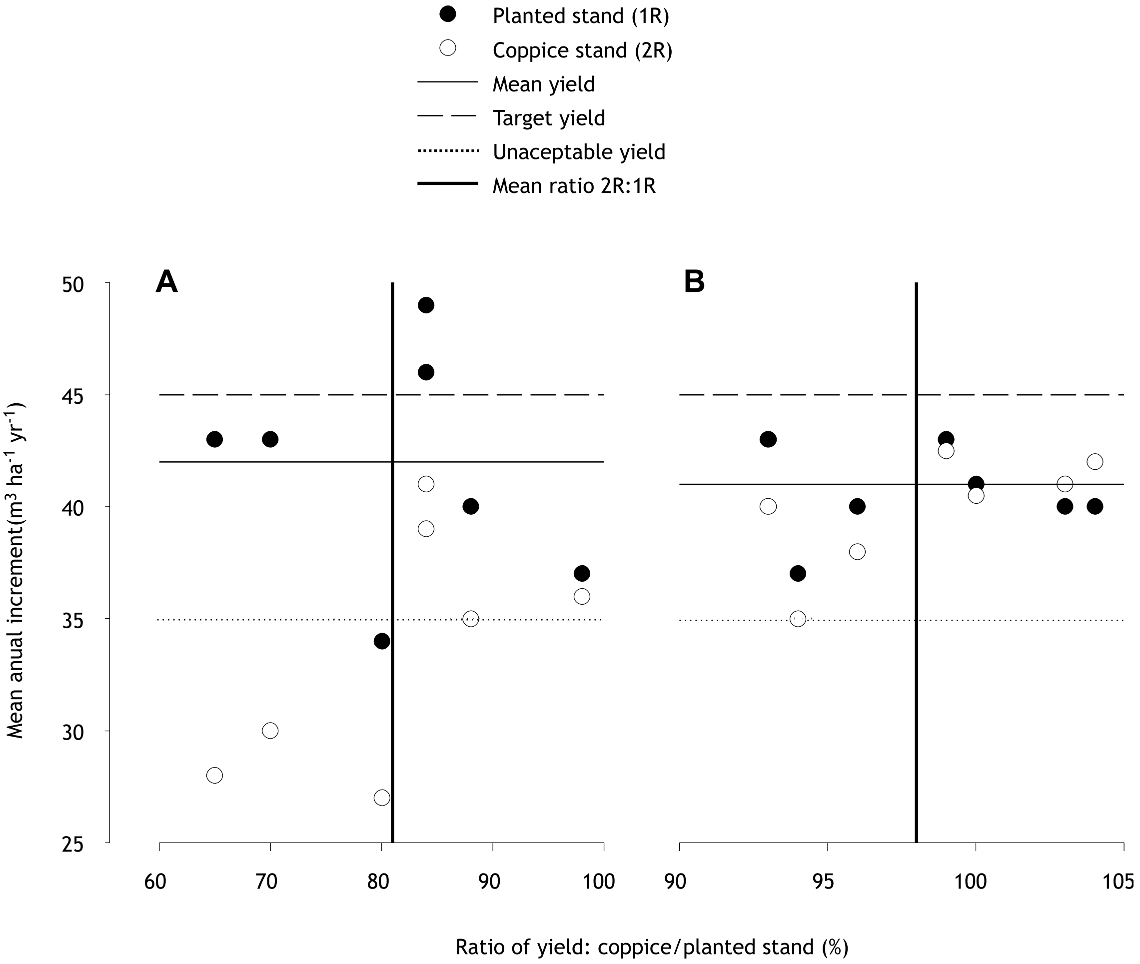


Figure 4 shows the pattern of changes in yield between the first (1R) planted and second (2R) coppice rotations. Data obtained by a forest company in several sites of the region indicate recovery of the yield in two successive rotations (each one with two crops) of coppice plantations. In the first rotation, with the use of the old technology (residue burnt, intensive soil preparation and application of a small dose of fertiliser), the ratio of yield between coppice and planted stand was around 80% (mean of all sites). With the use of minimum cultivation and application of higher rates of fertilisers, in the second rotation the mean yield was similar to the first rotation and the ratio of yield between coppice and planted stand was close to 100%, in other words no yield decline. If the planting of the genetically improved clones aims for increases of yield in the order of 10-15% such an increase can only be achieved with an appropriate replacement of nutrients through fertilisation and maximum conservation soil nutrient capital.

Importance of the Project for Brazilian Silviculture

The studies described here began when the practice of the minimum cultivation had just been initiated in Brazil. We had relatively little knowledge of processes and hence some technical decisions were made on empirical observations and a degree of general knowledge about Brazilian soils. This project aimed to evaluate and elucidate the main cause-effect relationships

Figure 4. Yield of wood in the second rotation (2R) coppice stands of *Eucalyptus grandis* in São Paulo and their ratio to those in the planted stand of first rotation (1R). A: With use of the old technology (residue burnt, intensive soil preparation with bedding harrow and small application of fertilisers); and B: with use of the new technology, the minimum cultivation of the soil and application of larger amount of fertilisers, mainly, P and K. The CIFOR Network site is average among these sites in terms of soil conditions. The climatic conditions and genetic material are similar. Source: data kindly provided by Suzano Pulp and Paper Cia



concerning to the management of forest harvest residues and soil preparation on processes and growth over the short and long term.

The project was conceived in 1994, and was structured as a cooperative and multi-institutional program of research and technical application. Partners included, Superior School of Agriculture Luiz of Queiroz (ESALQ) of the University of São Paulo (USP), the Institute of Research and Forest Studies (IPEF) and three forest companies of the pulp and paper sector (Suzano, Ripasa and Champion).

In the last seven years, the activities of this consortium have been expanded to include seven additional forest companies (pulp and paper, metallurgy, energy and sawmill sectors). From 1997, this consortium was called: 'Thematic Program of Silviculture and Management' (PTSM). Several main outcomes of this co-operation include:

- three scientific and technical workshops (with field visits) in different Brazilian regions every year. Participants include researchers lecturers, engineers and technicians involved in the production and the conservation of forest resources;
- two symposia, with the themes: 'Nutrition and Forest Fertilization' (May 2000, 150 participants, Piracicaba, SP) and 'Conservation and Cultivation of Soils for Forest Plantations' (November 2001, 110 participants, Piracicaba, SP). The papers presented were published in two books edited by IPEF. Because of these activities, PTSM is known widely in Brazil and other countries of Latin America;
- the research project linked to the CIFOR network provided the basis for research activities and reports by undergraduate and postgraduate students;
- the project has received recognition and support from Brazilian foundations; and
- the approach developed in this project has been adopted by others in Brazil and as a model by neighbouring countries.

CIFOR's project and other related studies have resulted in new technologies now used extensively in Brazilian forest plantations. Key elements are no burning of residues, wood debarking in the field and restricted soil cultivation using implements specifically designed for this purpose. Now, minimum cultivation is practised in about 75% of the harvested area.

Acknowledgements

We acknowledge the support of Suzano Pulp and Paper Company, on whose land the network trial is established, for all logistical support in the field, and for making available data from first and second rotation eucalypt plantations on their sites. Without this support these studies would not have been possible. We thank Sadanandan Nambiar, Jacques Ranger and Christian Cossalter for many discussions and suggestions about this paper. The Center for International Forestry Research (CIFOR) is thanked for providing financial support for attending the workshops in Congo and China.

References

Adámoli, J., Macedo, J., Azevedo, L.G. and Madeira Neto, J.S. 1986. Caracterização da região dos cerrados. *In*: Goedert, W.J. (ed.) Solos dos cerrados: tecnologias e estratégias de manejo, 33-74. EMBRAPA/CPAC, São Paulo, Nobel, Brazil.

Bouillet, J.P., Nzila, J.P., Laclau, J.P. and Ranger, J. 2000. Effects of site management on *Eucalyptus* plantations on the equatorial zone, on the coastal plains of the Congo. *In*: Nambiar, E.K.S., Cossalter, C., Tiarks, A. 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. du, 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., Cossalter, C., Tiarks, A. 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.

Eldridge, K., Davidson, J., Harwood, C. and van Wyk, G. 1994. Eucalypt domestication and breeding. Clarendon Press, Oxford. 288p.

Gava, J.L. 1997. Efeito da adubação potássica em plantios de *E. grandis* conduzidos em segunda rotação em solos com diferentes teores de potássio trocável. *In*: Stape, J.L. (ed.) 4ª Reunião técnica sobre manejo de brotação de *Eucalyptus*, 89-94. Piracicaba, Série Técnica IPEF, Brazil.

Gonçalves, J.L.M., Barros, N.F., Nambiar, E.K.S. and Novais, R.F. 1997a. Soil and stand management for short-rotation plantations *In*: Nambiar, S. and Brown, A. (eds.) Management of soil, nutrients and water in tropical plantation forests, 379-418. ACIAR Monograph No. 43. Australian Centre for International Agricultural 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., Mello, S.L.M., Mendes, K.C.F.S. and Jorge, L.A.C. 1997b. Efeito de práticas de cultivo mínimo e intensivo do solo sobre a ciclagem de nutrientes, fertilidade do solo, configuração do sistema radicular e nutrição mineral de povoamentos de *Eucalyptus grandis*. Piracicaba, 94p. (Final research report for FAPESP).

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., Serrano, M.I.P.S., Mendes, K.C.F.S. and Gava, J.L. 2000a. Effects of site management in a *Eucalyptus grandis* plantation in the humid tropics: São Paulo, Brazil. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A. 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.

Gonçalves, J.L.M., Stape, J.L., Benedetti, V., Fessel, V.A.G. and Gava, J.L. 2000b. Reflexos do cultivo mínimo e intensivo do solo em sua fertilidade e nutrição das árvores. *In*: Gonçalves, J.L.M. and Benedetti, V. (eds.) Nutrição e fertilização florestal, 1-57. IPEF, Piracicaba, Brazil.

Maluf, J.L.P. 1991. Efeito da queima, métodos de preparo do solo e da adubação no crescimento de *E. camaldulensis* em areia quartzosa. Universidade Federal de Viçosa, Viçosa, Brazil. 78p. (M.Sc. Thesis)

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., Cossalter, C., Tiarks, A. 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.

Santana, R.C., Barros, N.F. and Comerford, N.B. 2000. Above-ground biomass, nutrient content, and nutrient use efficiency of eucalypt plantations growing in different sites in Brazil. New Zealand Journal of Forestry Science 30:225-236.

Schumann, A.W. 1992. The impact of weeds and two legume crops on *Eucalyptus* hybrid clone establishment. South African Forestry Journal 160:43-48.

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., Cossalter, C., Tiarks, A. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 73-81. Center for International Forestry Research, Bogor, Indonesia.

Stape, J.L., Gonçalves, J.L.M. and Gonçalves, A.N. 2001. Relationships between nursery practices and field performance for *Eucalyptus* plantations in Brazil: a historical overview and its increasing importance. New Forests 22:19-41.

Tiarks, A., Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical forest plantations. CIFOR Occasional Paper No. 16. Center for International Forestry Research, Bogor, Indonesia. 11p.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Effects of Slash Management on Tree Growth and Nutrient Cycling in Second-rotation *Eucalyptus* Replanted Sites in the Congo

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Abstract

Since 1998 an experiment has been conducted in the Congo to evaluate harvesting methods with respect to sustainable management of eucalypt plantations. The results showed: (1) a marked negative effect on tree and stand growth when all slash materials were removed; (2) a risk of nutrient leaching after harvesting due to the high rate of decomposition of organic residues; (3) a production of inorganic nitrogen in the surface soil layer which depends on slash management; and (4) a high rate of nitrification and a risk of N losses in the early stage of stand development.

Introduction

Since 1978, a study has been in progress in clonal eucalypt plantations established in the Pointe-Noire region of the Congo. The hybrids used are well suited to local conditions and, with weeding and fertilisation, they grow well (MAI: 20-25 m^3 ha^{-1} yr^{-1} in total volume). However, little is known about the sustainability of the plantations with respect to long-term production and maintenance of site quality. In particular, processes governing nutrient availability in eucalypt stands and the impact of intensive cropping on soil fertility are not known. These questions are particularly relevant as the soils are sandy, acidic, and have low nutrient capital in terms of primary minerals, organic matter reserves or available nutrients. The sustainability of the plantations was therefore identified as a priority for research by UR2PI and studies focusing on this goal have been conducted since 1997 (Bouillet *et al.* 1997, 1999, Laclau *et al.* 2000a, b).

One of the tasks is to identify silvicultural practices and harvesting methods for sustainable management of the replanted sites. On the poor and sandy soils of the maritime coast of Congo, litter and crop residues need to be managed carefully throughout rotations to preserve soil fertility. Soil organic matter is an essential component that influences nutrients directly

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during decomposition and indirectly by fixing the available nutrients (Attiwill and Leeper 1987, Trouvé *et al.* 1994, Bernhard-Reversat 1996). It has been shown that burning slash and litter has a negative effect on eucalypt growth (Nzila *et al.* 1998), and that the availability of mineral nitrogen is the main factor limiting tree growth (Bernhard-Reversat 1996, Safou-Matondo and Bouillet 1999, Bouillet *et al.* 2001a). So, it is necessary to quantify the effects of slash and litter management practices on soil properties, tree nutrition and growth (Smethurst and Nambiar 1990a, Tiarks *et al.* 1998).

This study was designed to evaluate the effects of soil and site management practices on the productivity of replanted sites and the soil fertility over successive rotations. The experiment was included in the network of sites, as part of the CIFOR 'Site Management and Productivity in Tropical Plantation Forests' project. This paper presents results obtained four years after planting. Biomass and nutrient content, tree growth, litterfall, changes of soil chemical properties, soil nitrogen mineralisation, and litter decomposition rates were quantified. Management options for maintaining or increasing plantation productivity are discussed.

Location and Site Description

The plantations are located on coastal plains around Pointe-Noire, Congo (latitude 4°S, longitude 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 around 1200 mm, and mean annual temperature is 25°C with seasonal variations of about 5°C. The soils are very deep and are characterised by homogeneous sandy texture, acidic reaction, limited available nutrients, and low levels of organic matter (Bouillet *et al.* 1999).

Stand Description

The experiment was previously described in detail (Bouillet *et al.* 1999). Before establishment of the first rotation, the original savanna was burned, and regrowth was treated with glyphosate two months later. The soil was ripped along planting lines. *Eucalyptus* PF1 clone 1-41 was planted in April 1990 at a spacing of 4.0 m by 4.7 m. Fertilisers were 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 3 years after planting. At harvest 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, again using *Eucalyptus* PF1 clone 1-41. Spacing was 2.65 m x 4.70 m, superimposed on the previous rows. NPK fertiliser (15.6 kg ha^{-1} N, 15.6 kg ha^{-1} P, and 25.2 kg ha^{-1} K) was applied at planting. No additional fertiliser was applied. Weeds were chemically controlled with glyphosate.

Experimental Design and Methods

The experimental design is a randomised complete block with four replications. Each plot has 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 as follows:

BL_0	All aboveground organic residues 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, debarked, were removed.
BL_5	BL_4 + residue burned.

Twelve trees of the previous stand, distributed in 6 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). The same approach was used to estimate the aboveground biomass and nutrient content of BL_0,

BL_3, BL_4 and BL_5 treatments in block 1, one year and three years after planting. However, due to uncertainty with the samples taken at the thinner end of the trunk, stemwood and stembark at one year were estimated using equations established on 1-year-old commercial plantation similar to the BL_4 treatment (Deleporte personal communication). These equations were then applied to the inventory of each plot within treatment to evaluate the biomass and nutrient contents on a per hectare basis. At 3 years, all data collected were used to establish predictive models for biomass and nutrient contents for each compartment and each treatment.

Forest-floor was collected before stand harvest, in December 1997. Decomposition of forest-floor and slash was assessed in the BL_1, BL_2, BL_3 and BL_4 of blocks 1 and 3. Samples were collected every three months from September 1998 to December 1999 to quantify remaining biomass. The coefficients of decomposition were calculated according to Olson (1963).

Soil samples were taken before stand harvest at depths 0-10, 10-20, 20-50, 50-70 and 70-100 cm. Soil was re-sampled one year and three years after planting in all the treatments of blocks 1 and 3. *In situ* nitrogen mineralisation (Raison *et al.* 1987, Jussy 1998) was carried out during 2 years in the BL_0, BL_3 and BL_4 treatments of block 1 (from November 1998 to November 2000) between age 7 and 30 months (Bouillet *et al.* 2000).

The GLM procedure of SAS software (SAS Institute 1988) was used to analyse the variance of height, circumference, mean annual increment (MAI), biomass, nutrient content and nutrient concentration of trees, and for forest floor and soil properties. The statistical model used was:

$$Y_{ij} = \mu + R_i + T_j + \Sigma_{ij}$$

where Y_{ij} is the mean value of the trait measured in replication i for treatment j, μ the overall mean, R and T account for the effects of replication and treatment, and Σ_{ij} is the residual effect. Statistical analyses were based on Bonferroni test. Variance of soil nitrogen mineralisation was analysed using the model:

$$Y_{ij} = \mu + T_i + \Sigma_{ij},$$

where Y_{ij} is the mean value of the soil nitrogen mineralisation measured for treatment i during the incubation period j, μ the overall mean, T accounts for the effect of treatment, and Σ_{ij} is the residual effect. Statistical analyses were based on Bonferroni test.

Results

Tree Growth

At 12 months after planting, the circumference at breast height was significantly greater in BL_5 and BL_3 ($p < 0.05$) than in BL_0 (Table 1).

At 24 months, treatment BL_0 was significantly less productive than other treatments, except for BL_1 and BL_2 (height). At 36 months, the difference between the most and least productive treatments (BL_3 and BL_0) was 2.7 m in height, 8.9 cm in circumference, and 8.4 m^3 ha^{-1} yr^{-1} in MAI. This difference was significant for height and circumference but non significant for MAI owing to a block effect (Nzila *et al.* 2002). An illustration of this effect is given in Table 2. At 48 months this difference between BL_3 and BL_0 was still increasing and significant whatever the traits: 3.2 m in height, 9.5 cm in circumference and 11.2 m^3 ha^{-1} yr^{-1} in MAI. In contrast, the difference in MAI between BL_4 and BL_2 treatments tended to decrease (Table 1).

Biomass and Nutrient Content

One year after replanting, trees in BL_0 had the lowest total aboveground biomass 5.6 t ha^{-1} compared to 7.2 t ha^{-1} as a mean of the other treatments. The difference between BL_5 and BL_0 was statistically significant (Table 3).

The lowest values for nutrient content in aboveground biomass were observed in BL_0. The highest N content was found in BL_5, whereas the highest amounts of P, K Ca and Mg accumulated in BL_3. Foliage biomass represented a third of the aboveground biomass, but about 70% of the N accumulation and 50% of the P, K, Ca and Mg content (Nzila *et al.* 2002). Large differences in nutrient concentrations were observed in the leaves (Table 4). The lowest concentrations for all nutrients were observed in BL_0 whereas the

Table 1. Mean height, circumference at breast height (CBH), and mean annual increment (MAI) of trees in the different treatments, at 12, 24, 36 and 48 months

Treatments	BL_0	BL_1	BL_2	BL_3	BL_4	BL_5
12 months						
Height (m)	5.1a	5.2a	5.4a	5.7a	5.4a	5.8a
CBH (cm)	16.0b	16.9ab	17.9ab	19.3a	17.8ab	19.3a
MAI (m^3 ha^{-1} yr^{-1})	5.7a	6.2a	7.1a	8.3a	7.0a	8.2a
24 months						
Height (m)	11.2b	11.8ab	12.4ab	12.9a	12.5a	12.4a
CBH (cm)	26.6c	29.3bc	31.0ab	34.0a	31.8ab	31.6ab
MAI (m^3 ha^{-1} yr^{-1})	12.9c	15.8bc	18.3ab	22.2a	19.3ab	18.7ab
36 months						
Height (m)	13.5b	14.7ab	15.4ab	16.2a	15.5a	15.4a
CBH (cm)	29.5c	33.4bc	35.3ab	38.4a	35.9ab	35.3ab
MAI (m^3 ha^{-1} yr^{-1})	16.0a	17.5a	20.1a	24.4a	20.8a	19.7a
48 months						
Height (m)	16.3b	17.9ab	18.7a	19.5a	18.5a	18.4a
CBH (cm)	32.3c	36.4bc	38.4ab	41.8a	39.1ab	37.5abc
MAI (m^3 ha^{-1} yr^{-1})	13.8b	17.7ab	21.1ab	25.0a	21.5ab	19.6ab

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

Table 2. Tree height (m) for BL_0, BL_3 and BL_4 treatments according to the blocks, at 36 months

Treatments	Block 1	Block 2	Block 3	Block 4
BL_0	13.8	11.8	12.1	11.7
BL_3	14.7	14.5	14.2	14.2
BL_4	13.9	14.1	13.5	14.0

highest concentrations were measured in BL_5 for N, and in BL_3 for P, K, Ca and Mg. The largest differences concerned Ca, which were twice as high in BL_3 than in BL_0.

Three years after planting, the BL_0 treatment exhibited a total aboveground biomass 31% lower than the other treatments (22.3 t ha^{-1} *vs* a mean of 32.5 t ha^{-1}) (Table 5). Differences between BL_0 and BL_3 were always significant, except for the dead branches. BL_5 (burning) was not the most productive treatment any more, with a stand biomass of 30 t ha^{-1} compared to 36 t ha^{-1} in the BL_3 treatment, but this difference was not significant.

Three years after planting, foliage biomass represented only 5-6% of the total aboveground biomass, but the comparison of leaves nutrient accumulation by total nutrient accumulation varied from 28 to 33% for N, from 13 to 16% for P, from 19 to 21% for K, from 16 to 19% for Ca, and from 21 to 24% for Mg.

A gradient in the stand nutrient content was observed as follows: $BL_3 > BL_4 > BL_5 > BL_0$, with one exception ($BL_5 > BL_4$ for K). Furthermore the BL_0 treatment exhibited the lowest nutrient contents whatever the compartment.

Litterfall

Significant differences in mean annual litterfall were observed among the treatments where high amounts of slash were remaining after harvesting (BL_3 and BL_4) and those characterised by low amounts of residues (BL_0, BL_1, and BL_2) (Fig. 1). The burning treatment (BL_5) presented the same amount of litterfall than BL_4 (mean of 5 t ha^{-1} yr^{-1}).

Table 3. Total biomass and total nutrient accumulation in BL_0, BL_3, BL_4 and BL_5 treatments at age 12 months

Treatments	Biomass t ha^{-1}	N	P	K	Ca	Mg
		(kg ha^{-1})				
BL_0	5.6b	47.1b	4.8b	17.4c	12.6c	10.0c
BL_3	7.3ab	60.2ab	8.4a	27.8a	31.1a	20.2a
BL_4	6.4ab	57.3ab	5.3b	21.6b	19.3b	13.9b
BL_5	7.8a	71.4a	7.7a	23.3ab	21.0b	14.2b

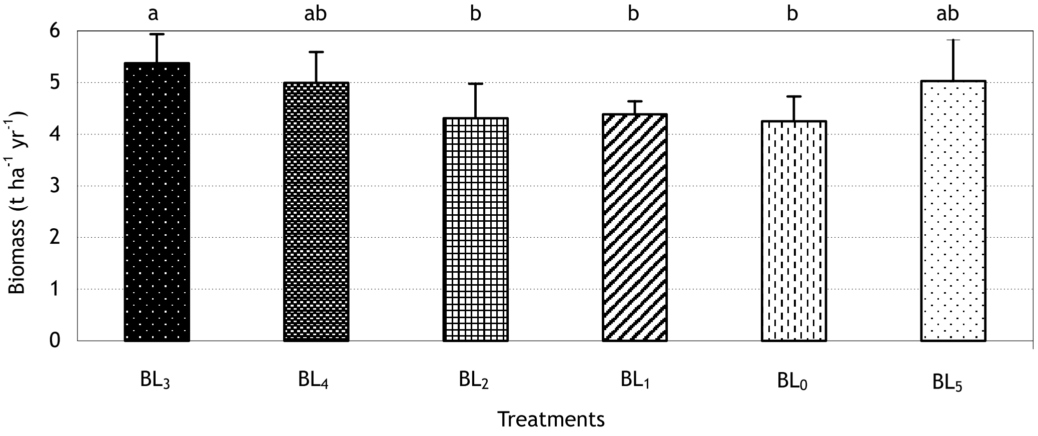
Letters a, b and c indicate significant differences ($p<0.05$) between treatments according to Bonferroni test.

Table 4. Nutrient concentration in leaves for BL_0, BL_3, BL_4 and BL_5, at 12 months

Treatments	Nutrients (g kg^{-1})				
	N	P	K	Ca	Mg
BL_0	17.3c	1.3b	4.6b	3.7d	3.5c
BL_3	18.4b	1.8a	5.7a	7.4a	4.9a
BL_4	20.6a	1.3b	5.0b	5.4b	4.2b
BL_5	20.9a	1.5b	4.6b	4.5c	3.5c

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

Figure 1. Mean annual litterfall biomass in different treatments from age 12 months to 55 months



Letters a and b indicate significant differences ($p < 0.05$) among treatments according to Bonferroni test.

Soil Properties

Changes occurred mainly in the surface soil layer (Table 6). Three years after planting the major observations were: (1) a slight decrease of total N, except for BL_3; (2) a statistically significant decrease in contents of exchangeable Ca, Mg and in S/T, irrespective of treatments; and (3) significant differences between treatments in contents of K: the highest concentrations were observed in BL_2, BL_1 and BL_5 treatments. No clear trend was observed for other soil properties. Effects of stand harvest and site preparation had no effect below 10 cm soil depth, except on Ca contents that were statistically lower regardless the treatments.

Table 5. Biomass and nutrient content in the different compartments of trees in treatments BL$_0$, BL$_3$, BL$_4$ and BL$_5$ at age 36 months

Compartments	Treatment	Biomass t ha^{-1}	N	P	K	Ca	Mg
			(kg ha^{-1})				
Stemwood	BL$_0$	15.3b	35.3c	5.4b	17.7c	7.5c	4.1c
	BL$_3$	25.3a	67.5a	9.6a	29.1a	13.4a	7.4a
	BL$_4$	22.1a	54.8b	8.8a	22.7b	10.0b	5.7b
	BL$_5$	21.0a	50.4b	6.4b	24.2b	9.0bc	5.3bc
Bark	BL$_0$	1.9b	10.2c	4.4b	8.1c	8.0c	5.9d
	BL$_3$	2.8a	18.1a	7.1a	14.2a	21.7a	13.2a
	BL$_4$	2.5a	15.1b	7.0a	11.2ab	15.2b	11.1b
	BL$_5$	2.4a	13.7b	5.1b	12.5b	14.0b	8.5c
Leaves	BL$_0$	1.4b	27.8b	2.1b	7.2c	4.7b	3.7b
	BL$_3$	2.3a	51.0a	3.7a	13.2a	10.7a	7.0a
	BL$_4$	1.6b	34.1b	2.9ab	9.2b	6.5b	5.4ab
	BL$_5$	1.8ab	35.4b	2.8b	9.9bc	6.9b	5.4b
Living branches	BL$_0$	1.9b	7.0b	1.8b	3.8b	3.2c	1.6b
	BL$_3$	3.7a	13.4a	3.2a	6.4a	7.9a	3.4a
	BL$_4$	3.1a	13.0a	2.8a	5.6a	6.1b	2.9a
	BL$_5$	2.9a	10.7a	2.6a	5.4a	4.3c	2.2b
Dead branches	BL$_0$	1.9a	4.5a	0.5c	0.3a	1.9c	0.6b
	BL$_3$	1.9a	5.0a	0.7b	0.3a	5.0a	1.1a
	BL$_4$	2.3a	6.0a	0.9a	0.4a	3.7b	1.1a
	BL$_5$	2.0a	4.5a	0.5c	0.3a	2.3c	0.8b
Total stand	BL$_0$	22.3b	84.9c	14.1b	37.1c	25.2c	15.9c
	BL$_3$	35.9a	155.0a	24.3a	63.2a	58.8a	32.1a
	BL$_4$	31.6a	122.9b	22.4a	49.2b	41.5b	26.2b
	BL$_5$	30.1a	114.6b	17.4b	52.3b	36.6b	22.2b

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

Nitrogen Mineralisation

Treatments had no effect on N mineralisation (Table 7). However highest values for N mineralisation were measured in BL$_3$. Mean annual amounts produced in BL$_0$, BL$_4$, and BL$_3$ during two years were respectively 48 kg ha^{-1}, 46 kg ha^{-1}, and 56 kg ha^{-1}.

Production of N-NH$_4^+$ and N-NO$_3^-$ was of the same order of magnitude during the first and the second year of measurement. Time-course of N mineralisation in each treatment indicated large variations related to soil water content (Fig. 2). After rainfall events a clear pattern of quick increase in net N mineralisation was observed, and followed by a net immobilisation. On average, net N mineralisation amounted to 4.9 kg ha^{-1} month^{-1} during the rainy season, but only to 2.8 kg ha^{-1} month^{-1} during the dry season.

The inter-annual variability was low since the mean net mineralisation of N amounted to 46 kg N ha^{-1} yr^{-1} on average for the 3 treatments during the first year (from November 1998 to November 1999), and 54 kg N ha^{-1} yr^{-1} during the second year (from November 1999 to November 2000).

Litter Decomposition

Initially, the amount of organic residues in treatment BL$_1$ was about half that of BL$_2$ and BL$_4$, and a third of that in BL$_3$ (Table 8). Eight months after harvesting, differences among treatments were no longer significant. During this period, about 36% of the initial mass of litter and slash was lost in BL$_1$, 47% in BL$_2$, 56% in BL$_4$, and 45% in BL$_3$. Using the concept proposed by Olson (1963), the coefficient of decomposition, k, was about 0.9, irrespective of treatments. It was estimated that a 50% loss in mass occurred within 6 to 8

Table 6. Properties of surface soil layer (0-10 cm) before stand harvest, at 1 year and 3 years after planting (standard error in brackets)

Treat-ments	Years after harvesting	Org. C (%)	Total N ($mg\ kg^{-1}$)	C/N	Exc.Ca	Exc. Mg	Exc. K	Exc. Na	Exc. Al	Exc. H	S	T=CEC	S/T
					($cmol_c\ kg^{-1}$)								(%)
BL_0	0	0.56 *(0.14)*	0.34 *(0.01)*	16.4	0.08 *(0.04)*	0.05 *(0.03)*	0.03 *(0.01)*	0.02 *(0.01)*	0.26 *(0.04)*	0.1 *(0.02)*	0.17 *(0.08)*	0.45 *(0.06)*	38.7
	1	0.5 *(0.11)*	0.31 *(0.06)*	16.2	0.01 *(0.01)*	0.02 *(0.01)*	0.02 *(0.01)*	0.01 *(0.004)*	0.27 *(0.05)*	0.08 *(0.005)*	0.06 *(0.01)*	0.45 *(0.04)*	12.3
	3	0.5 *(0.16)*	0.31 *(0.09)*	16.5	0.01 *(0.01)*	0.02 *(0.01)*	0.02 *0*	0.01 *(0.003)*	0.26 *(0.07)*	0.08 *(0.02)*	0.06 *(0.01)*	0.38 *(0.12)*	16.3
Changes after 3 years (%)		*-9*	*-10*	*1*	*-88*	*-52*	*-21*	*-58*	*0*	*-23*	*-64*	*-15*	*-58*
BL_1	0	0.55 *(0.01)*	0.34 *(0.01)*	16.2	0.07 *(0.002)*	0.04 *(0.01)*	0.02 *(0.005)*	0.01 *(0.01)*	0.29 *(0.01)*	0.1 *(0.002)*	0.15 *(0.01)*	0.45 *(0.04)*	32.2
	1	0.53 *(0.02)*	0.34 *(0.01)*	15.4	0.01 *(0.002)*	0.04 *(0.01)*	0.02 *0*	0.01 *(0.01)*	0.26 *(0.02)*	0.09 *(0.01)*	0.08 *(0.02)*	0.44 *(0.05)*	17.3
	3	0.55 *(0.04)*	0.33 *(0.03)*	16.7	0.01 *0*	0.02 *0*	0.04 *(0.01)*	0.01 *(0.01)*	0.31 *(0.02)*	0.08 *0*	0.08 *(0.001)*	0.43 *(0.05)*	17.5
Changes after 3 years (%)		*0*	*-3*	*3*	*-86*	*-53*	*64*	*-13*	*6*	*-13*	*-48*	*-5*	*-46*
BL_2	0	0.51 *(0.03)*	0.35 *(0.06)*	14.6	0.06 *(0.01)*	0.03 *(0.01)*	0.02 *(0.05)*	0.01 *(0.01)*	0.28 *(0.01)*	0.08 *(0.002)*	0.13 *(0.01)*	0.43 *(0.03)*	29.9
	1	0.55 *(0.05)*	0.36 *(0.04)*	15.1	0.01 *(0.01)*	0.03 *(0.01)*	0.04 *(0.002)*	0.01 *(0.00)*	0.29 *(0.01)*	0.1 *(0.01)*	0.09 *(0.01)*	0.46 *(0.02)*	19.5
	3	0.52 *(0.01)*	0.32 *(0.01)*	16.3	0.01 *(0.00)*	0.02 *(0.001)*	0.03 *(0.01)*	0.01 *(0.004)*	0.29 *(0.003)*	0.08 *(0.01)*	0.06 *(0.005)*	0.41 *(0.03)*	15.7
Changes after 3 years (%)		*2*	*-9*	*12*	*-84*	*-39*	*22*	*-61*	*4*	*0*	*-50*	*-5*	*-48*

Cont.

Table 6. *Continued*

Treat-ments	Years after harvesting	Org. C (%)	Total N (mg kg^{-1})	C/N	Exc.Ca	Exc. Mg	Exc. K	Exc. Na	Exc. Al	Exc. H	S	T=CEC	S/T
				(cmol$_c$ kg^{-1})									(%)
BL$_3$	0	0.52 *(0.06)*	0.33 *(0.04)*	15.6	0.09 *(0.03)*	0.04 *(0.01)*	0.03 *(0.01)*	0.02 *(0.01)*	0.27 *(0.03)*	0.09 *(0.01)*	0.18 *(0.04)*	0.45 *(0.02)*	40.9
	1	0.53 *(0.08)*	0.33 *(0.05)*	16.2	0.01 *(0.01)*	0.04 *(0.02)*	0.02 *(0.002)*	0.01 *(0.005)*	0.26 *(0.03)*	0.08 *(0.01)*	0.08 *(0.02)*	0.4 *(0.04)*	20.2
	3	0.56 *(0.07)*	0.34 *(0.03)*	16.5	0.02 *(0.004)*	0.03 *(0.01)*	0.02 *(0.002)*	0.01 *(0.004)*	0.31 *(0.05)*	0.09 *(0.01)*	0.07 *(0.01)*	0.47 *(0.08)*	15.7
Changes after 3 years (%)		*9*	*2*	*6*	*-84*	*-31*	*-23*	*-56*	*14*	*-7*	*-60*	*4*	*-62*
BL$_4$	0	0.54 *(0.09)*	0.34 *(0.06)*	15.8	0.08 *(0.02)*	0.04 *(0.02)*	0.03 *(0.003)*	0.02 *(0.004)*	0.27 *(0.01)*	0.09 *(0.001)*	0.17 *(0.04)*	0.45 *(0.04)*	36.9
	1	0.56 *(0.03)*	0.35 *(0.02)*	16	0.02 *(0.01)*	0.04 *(0.02)*	0.02 *(0.00)*	0.01 *(0.003)*	0.29 *(0.03)*	0.09 *(0.01*	0.08 *(0.03)*	0.41 *(0.08)*	19.4
	3	0.55 *(0.03)*	0.34 *(0.02)*	16.2	0.01 *(0.003)*	0.03 *(0.004)*	0.03 *(0.01)*	0.01 *(0.003)*	0.31 *(0.04)*	0.09 *(0.01)*	0.07 *(0.01)*	0.51 *(0.04)*	13.9
Changes after 3 years (%)		*2*	*-1*	*3*	*-89*	*-34*	*4*	*-59*	*15*	*0*	*-57*	*14*	*-62*
BL$_5$	0	0.55 *(0.02)*	0.37 *(0.02)*	14.9	0.06 *(0.02)*	0.04 *(0.01)*	0.02 *(0.005*	0.01 *(0.01)*	0.29 *(0.04)*	0.08 *(0.01)*	0.13 *(0.02)*	0.47 *(0.04)*	28.8
	1	0.51 *(0.04)*	0.32 *(0.02)*	16.2	0.03 *(0.01)*	0.04 *(0.02)*	0.02 *(0.005)*	0.01 *(0.00)*	0.26 *(0.04)*	0.06 *(0.01)*	0.1 *(0.03)*	0.42 *(0.07)*	23
	3	0.56 *(0.04)*	0.34 *(0.01)*	16.7	0.01 *(0.003)*	0.03 *(0.004)*	0.03 *(0.001)*	0.01 *(0.00)*	0.29 *(0.005)*	0.08 *(0.00)*	0.07 *(0.01)*	0.45 *(0.05)*	16.3
Changes after 3 years (%)		*3*	*-8*	*12*	*-84*	*-38*	*21*	*-14*	*2*	*-7*	*-45*	*-4*	*-43*

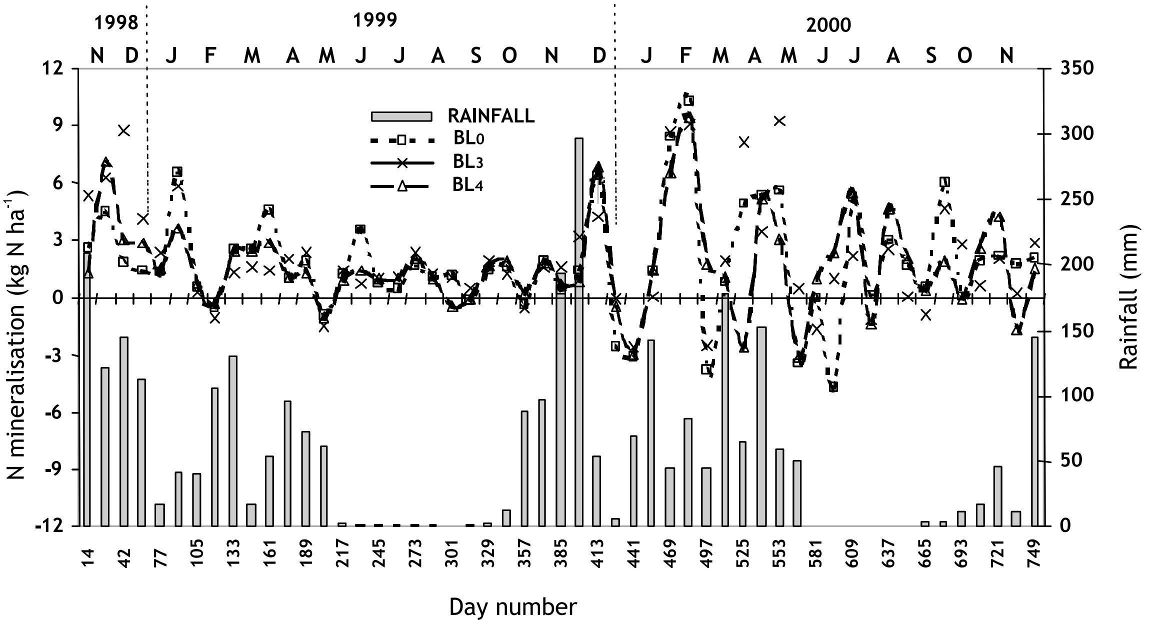
S/T= base cation saturation, with S = exchangeable cations sum (Ca+Mg+K+Na), and T = Cation Exchange Capacity (CEC).
Differences between treatments according to Bonferroni test are not presented to keep the table readable.

Table 7. Mean net nitrification, ammonification and total mineralisation produced during fortnightly (kg N ha^{-1}) in BL_0, BL_4 and BL_3 treatments for 53 periods of a two weeks interval. Standard deviation values are given in brackets

Treatments	Number of incubation period	$N\text{-}NO_3^-$	$N\text{-}NH_4^+$	Mineral N ($N\text{-}NO_3^-$ + $N\text{-}NH_4^+$)
BL_0	53	1.13 *(0.87)*	0.68 *(2.79)*	1.81 *(2.89)*
BL_4	53	1.17 *(0.90)*	0.56 *(2.44)*	1.73 *(2.46)*
BL_3	53	1.39 *(1.36)*	0.74 *(2.59)*	2.13 *(2.87)*

Treatments were not significantly different (p>0.05) according to Bonferroni test.

Figure 2. Dynamics of net nitrogen mineralisation (kg N ha^{-1} fortnightly) in BL_0, BL_4 and BL_3



months after clearcutting. Most of leaves and bark had decomposed, and the remaining slash mainly consisted of branches. The amount of remaining slash was similar between treatments, except in BL_3 where it was higher.

The mineral content of slash varied with time, depending on the nutrient concerned. Potassium and P were released rapidly during the decomposition process, but release of Ca was slow. Release of N and Mg was intermediate, and followed approximately the changes in dry matter amounts. Nutrients released during slash decomposition varied considerably between treatments. Maximum values were reached in BL_3 20 months after the initial harvest, with 329 kg N ha^{-1}, 41 kg P ha^{-1}, 99 kg K ha^{-1}, 73 kg Ca ha^{-1} and 52 kg Mg ha^{-1}. Comparisons of decomposition rates between treatments indicated that the dynamics of nutrient release depend on slash types. The main trends were: (1) changes in nutrient contents with BL_1 followed the pattern of decomposition of litter previously accumulated in the stand before harvesting; (2) differences between BL_2 and BL_1 corresponded to decomposition of branches and leaves; and (3) differences between BL_4 and BL_2 were associated with the dynamics of nutrient release from stembark.

Table 8. Changes in slash amount and nutrient content in BL$_1$, BL$_2$, BL$_3$, and BL$_4$

		Period (months after harvesting)	Treatment			
			BL$_1$	BL$_2$	BL$_3$	BL$_4$
Biomass	(t ha^{-1})	0	13.7a	25.2b	46.5d	31.4c
		8	8.8a	13.4a	25.8a	13.7a
		11	6.0a	8.5a	12.4a	8.4a
		14	5.5a	6.3a	9.4a	6.9a
		17	4.6a	5.4a	5.8a	5.4a
		20	2.1a	3.3a	4.5a	4.4a
N	(kg ha^{-1})	0	114.8a	212.3b	369.4d	249.7c
		8	81.4a	134.9a	202.9a	108.3a
		11	53.5a	86.2a	114.8a	65.0a
		14	44.1a	65.2a	85.4a	61.9a
		17	47.5a	52.7a	49.2a	60.2a
		20	10.1a	17.9a	40.3a	33.3a
P	(kg ha^{-1})	0	7.6a	18.6b	43.2d	28.5c
		8	3.1a	4.8a	10.7a	4.8a
		11	2.0a	3.3a	5.8a	3.5a
		14	1.8a	2.2a	3.1a	2.0a
		17	1.7a	1.9a	2.4a	2.0a
		20	0.4a	0.7a	1.6a	1.3a
K	(kg ha^{-1})	0	11.0a	40.8b	100.8d	62.9c
		8	7.8a	18.2a	29.3a	10.1a
		11	1.6a	3.6a	9.5a	4.6a
		14	1.1a	1.6a	3.7a	1.4a
		17	0.9a	1.5a	1.7a	1.2a
		20	1.0a	1.0a	2.0a	1.7a
Ca	(kg ha^{-1})	0	33.2a	43.2a	94.8b	78.6b
		8	22.7a	34.4ab	90.0b	48.1ab
		11	14.2a	23.1a	44.6a	32.7a
		14	13.7a	16.6a	33.2a	23.2a
		17	8.6a	11.5a	23.4a	20.3a
		20	5.1a	7.4a	21.1a	18.3a
Mg	(kg ha^{-1})	0	18.2a	26.4b	59.0c	45.3d
		8	8.6a	18.5ab	50.2b	24.0ab
		11	4.9a	10.5ab	27.3b	16.1ab
		14	6.1a	10.9ab	17.6b	11.6ab
		17	2.5a	4.1a	8.2a	6.3a
		20	1.4a	2.7a	7.0a	5.3a

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

Table 9. Value of foliar nutrient concentrations at 3 years old and corresponding ratios

	N	P	K	Ca	Mg	N:P	Ca:Mg	Mg:K	Ca:K
BL_3	2.22a	0.161b	0.574a	0.465a	0.304b	13.8	1.53	0.53	0.81
BL_4	2.13b	0.181a	0.575a	0.406b	0.338a	11.8	1.20	0.59	0.71
BL_0	2.06b	0.158c	0.533b	0.348d	0.274d	13.0	1.27	0.51	0.65
BL_5	1.99b	0.157d	0.556ab	0.388c	0.303c	12.7	1.28	0.55	0.70

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

Discussion

Tree Growth

Removing all slash material (BL_0) had a marked negative effect on tree growth. This effect increased with time. The opposite effect occurred when a large amount of slash was left on the soil after harvest (BL_3 and BL_4). Decomposition of leaves and branches from harvested residues had a positive impact on subsequent tree growth: BL_2 exhibited a greater productivity than BL_1 up to 48 months, and the difference between the two treatments tends to increase with stand age. The same pattern occurred for bark decomposition (BL_2 *vs* BL_4), but the difference in MAI between the two treatments tended to decrease regularly. The starter effect of slash burning was only observed the first year after planting. After 2 years the depressive effect of burning (BL_5 *vs* BL_3, BL_4 and BL_2) tends to increase with stand age even if no significant difference can be observed. The present experiment showed that the organic matter management is of paramount interest and may be the consequence of the very low nutrient availability from the soil minerals (Nzila *et al.* 2001).

Nutrient Content

Nutrient content in the aboveground biomass of the 1-year-old stand was dependent on slash and litter management practices. A marked increase in nutrient concentration in foliage was observed when organic residues on the soil surface increased.

Nutrient content in the aboveground biomass of the 3-year-old stand was higher in BL_3, BL_4 and BL_5 treatments than in BL_0 treatment. This result was mainly explained by the lower biomass production for BL_0 treatment. The higher nutrient accumulation in BL_3 than in BL_4 and BL_5 was mainly explained by a higher foliage development (+35%) and a greater nutrient accumulation in stemwood.

Foliar nutrient analysis has been commonly used in *Eucalyptus* plantations to determine the efficiency of fertilisers and to determine within-tree nutrient balances during the establishment phase (Herbert 1996, Judd *et al.* 1996). A review of nutritional characteristics of *Eucalyptus* spp. indicated optimum N:P ratios are between 15 and 18 (Herbert 1996, Judd *et al.* 1996). In the present study, N:P ratio in foliage was between 11.8 (BL_3) and 13.8 (BL_4) at 3 years (Table 9). These values may suggest N-limiting effect for tree and stand growth.

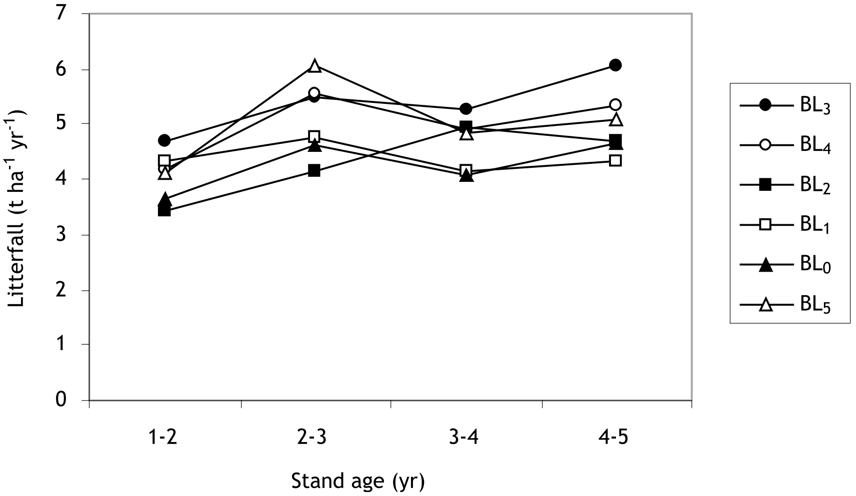
This result was consistent with the stand's increased need for N observed throughout successive rotations (Bouillet *et al.* 2001b). Therefore, N released during slash and litter decomposition might partly explain the growth differences observed among treatments.

Response to fertilisers based on other ratios (Ca:Mg, Mg:K, Ca:K) of foliar nutrients are more complex to interpret (Herbert 1996). However the very low Ca:Mg ratio in foliage (<1.6 in all treatments whereas the optimum for *Eucalyptus grandis* plantations in South Africa is >3.3) suggested that tree growth might be indirectly limited by Ca availability, even in BL_3 treatment (Table 9).

Litterfall

The comparison of BL_3 and BL_4 treatments to BL_0, BL_1 and BL_2 treatments showed higher amounts of slash remaining after harvesting led to a greater production of branches and leaves (Tables 3 and 5). BL_3 and BL_4 treatments tended therefore to present a higher litterfall biomass, and the only

Figure 3. Changes in litterfall rate (t ha^{-1} yr^{-1}) with age according to treatments



significant difference was observed with BL$_2$ during the third year (Fig. 3). BL$_3$, BL$_4$ and BL$_5$ treatments were not significantly different but slash burning tended to lead to higher amounts of litterfall during the third year, but lower amounts during the fourth and fifth year (Fig. 3). This pattern would be likely due to a rapid release of nutrient by litter combustion, leading to a higher crown biomass in the first two years (Table 3). But as early as 3 years, the initial loss of nutrients by volatilisation and leaching led to a lower biomass of leaves and living branches in BL$_5$ (Table 5) and then to a decrease in litterfall production.

Soil Properties

The decrease in base cation saturation between initial value and 3 years later might be the result of two processes: (1) a large part of the cations produced by mineralisation is taken up by trees (only a small part was then adsorbed on the soil exchange complex), and (2) enhancement in N mineralisation by about 50% after harvesting might lead to leaching losses of cations (Nzila *et al.* 2002). As 60% of the mineral N was nitrate, proton neutralisation was likely to increase the acidity of the soil exchange complex.

The low value of exchangeable Ca from age one year is from an analytical error of the laboratory. The actual decrease in Ca was therefore incorrectly estimated. However the values obtained were consistent with analyses made again on twin samples, and a study performed by Bouillet *et al.* (2001b) showing a decrease in Ca contents of about 80% between soils of 18-year-old eucalypt plantations and soils of original savanna. But this decrease should have low direct impact on stand production. Indeed, it was shown that, one year after planting, the root system of eucalypt trees extended to depth beyond 3 m (Bouillet *et al.* 2002) and that soil reserves in Ca and Mg are fairly high (about 2000 kg ha^{-1} and 4000 kg ha^{-1} up to a depth of 2 m (Nzila 2001)). So, the Ca decrease that represents about 20 kg ha^{-1} may be considered as negligible compared with the reserves, and consistent with the stand Ca accumulation (Table 5). This finding differs from those of O'Connell *et al.* (2001) and Xu *et al.* (2001) who observed an increase in exchangeable Ca, Mg and K in the surface soil of replanted sites.

Nitrogen Mineralisation

There was a trend of higher rates of N mineralisation when large amounts of residues were retained. A similar behaviour was reported in Brazilian *Eucalyptus* plantations located on Oxisols (Gonçalves *et al.* 2000). The authors pointed out the better conditions for mineralisation in comparison with treatment BL$_0$. Such results were also observed in Australia, in

Table 10. Comparison of mean net N mineralisation (kg ha^{-1}) produced fortnightly in treatments BL_0 and BL_3 for blocks 1 and 3 (standard deviation in brackets). Period: 5 December 2000 - 30 January 2001

Treatments	Block 1		Block 3	
BL_0	3.0a	*(2.5)*	1.7a	*(1.7)*
BL_3	2.5a	*(1.7)*	3.1b	*(1.4)*

Letters a and b indicate significant differences ($p<0.05$) between treatments.

Eucalyptus plantations located on red earth and grey sand sites (O'Connell *et al.* 2001) and in *Pinus* plantations established on sandy soils (Smethurst and Nambiar 1990a, b).

However in Pointe-Noire, soil-N mineralisation in BL_0 was not lower than in BL_4. This pattern might be a result of the soil heterogeneity among blocks. Whereas tree height was similar in block 1 for BL_0 and BL_4, the slash management practices had a stronger impact on tree growth in the three other blocks (Table 2). Chemical analyses performed before harvesting indicated the concentration of total N in the surface soil (0-10 cm) of BL_0 treatment of block 1 (0.43 mg g^{-1}) was higher than for BL_4 and BL_3 treatments in the same block (0.36 and 0.37 mg g^{-1} respectively). The same pattern was observed one year after replanting in the same block: concentrations of total N in the BL_0 treatment were around 20% higher than in the two other treatments.

A comparison of *in situ* N mineralisation in blocks 1 and 3 during four incubation periods (total duration: 2 months) showed that N availability was likely to be involved in the differences in tree growth observed according to the slash management practices (Table 10). N mineralisation in BL_3 was significantly higher than in BL_0 in block 3 ($p<0.05$) whereas in block 1 production of inorganic N in both treatments was not different. The small differences in N mineralisation between BL_0, BL_3 and BL_4 observed during 2 years in block 1 might then be a result of a spatial heterogeneity of N availability in this block. The area where BL_0 was installed in this block exhibited rates of N mineralisation particularly high compared to other areas sampled. In other blocks, N mineralisation would have been probably more closely related to the amount of residues retained at the soil surface.

Production of inorganic N in the replanted site was of the same as accumulation in the 1-year-old trees, which ranged from 50 (BL_0) to 62 (BL_3) kg N ha^{-1}. N mineralisation in the top soil was of the same order of magnitude in *Pinus* stands in Australia (Raison *et al.* 1987; Smethurst and Nambiar 1990a), and in *Eucalyptus* stands in Australia (Polglase *et al.* 1992) or in Brazil (Gonçalves *et al.* 2000). In the present study net nitrification was higher than residual net ammonification. This result differed from the higher rates of net residual ammonification commonly observed in *Eucalyptus* stands in Australia (Polglase *et al.* 1992, Connell *et al.* 1995) or in Brazil (Gonçalves *et al.* 2000). However, high nitrification rates may be observed when C:N ratio <15 (Attiwill *et al.* 1996), as observed in Congo. As a consequence, in the Pointe-Noire area, large amounts of N may be lost by leaching in the early growth period, when the root system is not yet well established. Losses of N represent a high risk for the sustainability of the plantations in the Pointe-Noire region, where soil N-reserves are low (about 700 kg ha^{-1} in the 0-15 cm layer) and where input-output N-budget were found to be unbalanced (Laclau 2001).

Litter Decomposition

The half-life for decomposition of residues ($t_{0.5}$) varied from 6 to 8 months. Such a high decomposition rate was observed in Brazil where $t_{0.5}$ was 10 months in *E. grandis* stands (Gonçalves *et al.* 1999). In Indian *E. tereticornis* plantations, $t_{0.5}$ varied from 3 months (leaves) to 10 months (branches) (Sankaran *et al.* 2000). However, lower decomposition rates have been measured in India, where Sankaran *et al.* (2000) found $t_{0.5}$ varying from 9 months (leaves) to 26 months (branches) in *E. grandis* stands.

In Congo, rates of nutrient release were higher than rates of dry matter loss for K and P, equivalent for N and Mg, and lower for Ca. The nutrient release pattern may vary considerably, according to *Eucalyptus* species and situation of the stand. Climate, microfauna, and litter composition (C:P ratio, lignin, tannins, etc.) are probably the main causes for this variability (Bernhard-Reversat 1993). The rapid release of nutrients observed in Congo potentially led to high risks of nutrient leaching, especially if there was a long delay between clearfelling and planting.

Conclusions

In Congo, clonal eucalypt plantations have been established on sandy and very poor soils. Their productivity is highly dependent on management practices which conserve organic matter and nutrients. This study showed that removing forest floor and slash residues after harvesting markedly reduced tree growth: MAI at 4 years was 35% lower when forest floor and slash residues were removed, compared to stem-only harvesting. Mineralisation of organic residues induced a rapid release of large amounts of nutrients: one year after planting it represented from 200% to 300% of the nutrient content in the stem-only harvested treatment. Soil N mineralisation may play a crucial role in stand productivity, as indicated by the low N:P ratio in foliage at three years old and the marked response to nitrogen fertilisation on the replanted sites.

A marked decrease in base cations, especially calcium and magnesium, was observed in the top soil layer, in relation to the very low contents of these nutrients in the soil, and the rapid nutrient uptake of eucalypt plantations. Field trials could be then established to quantify the effect of liming on stand production.

From an operational point of view, the following recommendations can be made:

1. debark stems in the field and spread the bark;
2. retain tree crowns on the site;
3. avoid slash burning; and
4. reduce the delay between stand harvesting and crop planting.

Fertiliser application will also be necessary to maintain high stand productivity in this soil.

In Congo, the current practice consists of debarking the stems in the field, and leaving the residues (branches, leaves and bark) on the ground. Slash burning and tillage are prohibited, and the planting hole is dug without disturbing the forest floor.

Acknowledgements

The authors are grateful to the Center for International Forestry Research (CIFOR) for its support, International Foundation of Science for its financial contribution for equipment and chemical analyses, Mr A. S. Dzomambou and A. Kinana for their technical assistance, and the Founders of UR2PI (Republic of Congo, CIRAD-Forêt and ECO SA) for providing financial support to conduct this experiment.

References

Attiwill, P.M. and Leeper, G.W. 1987. Forest soils and nutrient cycles. Melbourne University Press. 202p.

Attiwill, P.M., Polglase, J.P., Weston, C.J. and Adams, M.A. 1996. Nutrient cycling in forests of south-eastern Australia. *In*: Attiwill, P.M. and Adams, M.A. (eds.) Nutrition of eucalypts, 191-224. CSIRO, Australia.

Bernhard-Reversat, F. 1993. Dynamics of litter and organic matter at the soil-litter interface in fast growing tree plantations on sandy ferrallitic soils (Congo). Acta Oecologica 14:179-195.

Bernhard-Reversat, F. 1996. Nitrogen cycling in tree plantations grown on poor sandy savanna soils in Congo. Applied Soil Ecology 4:161-172.

Bouillet, J.P., Laclau, J.P., Arnaud, M., Thongo M'Bou, A., Saint-André, L. and Jourdan, C. 2002. Changes with age in the spatial distribution of roots of *Eucalyptus* clone in Congo. Impact on water and nutrient uptake. Forest Ecology and Management 171:43-57.

Bouillet, J.P., Nizinski G., Nzila J.D. and Ranger J. 1997. The sustainability of *Eucalyptus* commercial plantations: the Congolese approach. *In*: Proceedings IUFRO Conference on Silviculture and Improvement of *Eucalyptus*, Salvador, Brazil, Vol. 4, 232-237.

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. 108p.

Bouillet, J.P., Nzila, J.D., Laclau, J.P. and Ranger, R. 2001a. Slash management on tree growth and nutrient cycling in young *Eucalyptus* replanted sites in the Congo. Paper presented at the Fourth Workshop, Site Management and Productivity in Tropical Plantation Forests. Impact on soils and options for management over successive rotations, Pointe Noire, Congo 9-12 July 2001. 13p.

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., Safou-Matondo, R., Laclau, J.P., Nzila, J.D. and Ranger, J. 2001b. Changes over successive rotations in NPK fertiliser needs of Congolese clonal eucalyptus plantations. Relationships with changes in soil fertility. *In*: Proceedings of IUFRO International Symposium: 'Developing the Eucalypt of the Future', 10-15 September 2001, Valdivia, Chile.

Connell, M.J., Raison, R.J. and Khanna, P.K. 1995. Nitrogen mineralisation in relation to site history and soil properties for a range of Australian forest soils. Biology and Fertility of Soils 20:213-220.

Gonçalves, J.L.M., Poggiani, F. and Stape, J.L. 1999. Effect of minimum and intensive site cultivation on nutrient cycling, soil fertility, root system structure and mineral nutrition of *Eucalyptus grandis* stands. *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., Gava, J.L., Serrano, M.I.P. and Sorbelini Mendes, K.C.F. 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. 108p.

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, Australia.

Judd, T.S., Attiwill, P.M. and Adams, M.A. 1996. Nutrient concentrations in *Eucalyptus*: a synthesis in relation to differences between taxa, sites and components. *In*: Attiwill, P.M., Adams, M.A. (eds.) Nutrition of eucalypts, 123-153. CSIRO, Australia.

Jussy, J.H. 1998. Minéralisation de l'azote, nitrification et prélèvement radiculaire dans différents écosystèmes forestiers sur sol acide. Effets de l'essence, du stade de développement du peuplement et de l'usage ancien des sols. Thèse de Doctorat. Université Henri Poincaré, Nancy I, France. 156p.

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. 2000a. Dynamics of biomass and nutrient accumulation in a clonal plantation of *Eucalyptus* in Congo. Forest Ecology and Management 128:181-196.

Laclau, J.P., Bouillet, J.P. and Ranger, J. 2000b. Canopy and soil modification of precipitation chemistry in a clonal eucalypt stand in Congo. Comparison with an adjacent savanna ecosystem. *In*: Proceedings XXI IUFRO World Congress, Kuala Lumpur, Malaysia, Vol 1, 706-718.

Nzila, J.D. 2001. Caractérisation minéralogique des sols ferrallitiques sableux sous plantations d'*Eucalyptus* et sous savane naturelle de la région de Pointe-Noire (Congo). UR2PI Report. Congo. 51p.

Nzila, J.D., Bouillet, J.P. and Hamel, O. 1998. Effets de la litière et du travail du sol sur la fertilité des sols sableux sous *Eucalyptus* de replantation au Congo. *In*: Proceedings World Congress of Soil Sciences, Montpellier, France. 6p.

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., Turpault, M.P., Laclau J.P. and Ranger, J. 2001. Quantification of the input of nutrients by weathering of soil minerals, for ecologically sound management of tropical plantation forests. Paper presented at the Fourth Workshop, Site Management and Productivity in Tropical Plantation Forests. Impact on soils and options for management over successive rotations, Pointe Noire, Congo 9-12 July 2001. 4p.

O'Connell, A.M., Grove T.S., Mendham D., Corbeels M., McMurtrie R.F., Shammas K. and Rance S. J. 2001. Impact of inter-rotation site management on nutrient stores and flux rates and tree growth of eucalypt plantations in southwestern Australia. Paper presented at the Fourth Workshop, Site Management and Productivity in Tropical Plantation Forests. Impact on soils and options for management over successive rotations, Pointe Noire, Congo 9-12 July 2001. 13p.

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

Polglase, P.J., Attiwill, P.M. and Adams, M.A. 1992. Nitrogen and phosphorus cycling in relation to stand age of *Eucalyptus regnans* F. Muell. II. N mineralisation and nitrification. Plant and Soil 142:167-176.

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

Safou-Matondo, R. and Bouillet, J.P. 1999. Essai factoriel NPK 3^3 sur replantation. Parcelle R97-8. Mensurations à 9, 13 et 18 mois. Report UR2PI, Congo. 12p.

Sankaran, K.V. *et al*. 2000. Effects of site management on *Eucalyptus* plantations in 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: workshop proceedings, 7-11 December 1999, Kerala, India, 51-60. Center for International Forestry Research, Bogor, Indonesia. 108p.

SAS Institute, 1988. SAS/STAT user's guide. Release 6.03 edition. SAS Institute Inc., Cary, North Carolina, USA. 1028p.

Smethurst, P.J. and Nambiar, S. 1990a. 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.

Smethurst, P.J. and Nambiar, S. 1990b. Distribution of carbon and nutrients and fluxes of mineral nitrogen after clear-felling a *Pinus radiata* plantation. Canadian Journal of Forest Research 20:1490-1497.

Tiarks, A., Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical forest plantations. CIFOR Occasional paper No.16. Center for International Forestry Research, Bogor, Indonesia. 11p.

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.

Xu, D.P., Yang, Z.J. and Dell, B. 2001. Effects of site management on tree growth, soil properties and nutrient availability of a second rotation plantation of *Eucalyptus urophylla* in Guangdong Province, China. Paper presented at the Fourth Workshop, Site Management and Productivity in Tropical Plantation Forests. Impact on soils and options for management over successive rotations, Pointe Noire, Congo, 9-12 July 2001. 20p.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Effects of Harvesting and Site Management on Nutrient Pools and Stand Growth in a South African Eucalypt Plantation

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Abstract

Effects of intensive site management operations on nutrient capital and stand growth were studied in a stand of *Eucalyptus grandis* in South Africa. Macronutrient pools in the standing crop, belowground biomass, forest floor and soil were determined. The forest floor on this site is a large store for nutrients, particularly N, P and Ca. Nutrient additions and removals resulting from fertilisation, wood harvesting, slash burning and slash manipulation were quantified. Stem wood harvesting has a moderately small effect on the capital of most macronutrients in the system. Slash burning results in comparatively large losses from N and P pools (440 kg ha^{-1} and 26 kg ha^{-1}, respectively). Phosphorus lost through harvesting and slash burning is partially offset by fertilisation after establishment, but this is not the case with other nutrients. The plantation ecosystem is very resilient to the impact of nutrient losses by virtue of its large nutrient pools. Stand height and diameter growth responded strongly to changes in nutrient availability in the first two growing seasons (they immediately increased after slash burning or fertilising but decreased when slash was removed). It appears that the stand response to changes in resource availability was constrained by soil water stress. The effect of intensive treatments in the inter-rotational period has diminished by age three years and stand volume is currently increasing at nearly similar rates. The main impact of this research and its implementation by the southern African timber growing industry are discussed.

Introduction

Short-rotation plantations under intensive site management have a potentially large impact on the productivity and long-term sustainability of forest stands (Fölster and Khanna 1997, Gonçalves *et al.* 1997, Nambiar 1999, Fisher and Binkley 2000). Effects of intensive site management operations were studied at the Karkloof experimental site in KwaZulu-Natal, South Africa to improve our understanding of: (1) availability of soil resources for growth to trees, (2) response mechanisms of the stand to treatments, and (3) effect of operations on long-term nutrient supply. This paper summarises the effects of harvesting and site management operations on nutrient pools and growth of the replanted crop to 3.5 years of age.

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Materials and Methods

Karkloof trial site is located at latitude 29°24'S, longitude 30°12'E and altitude 1260 m above sea level. Mean annual precipitation of 950 mm falls mainly in summer and the mean annual temperature is 15.2°C. The soil is on average approximately 90 cm deep; it is clayey and rich in organic matter. Details of climatic conditions at the site, land-use history, and basic soil physical characteristics have been described (du Toit *et al.* 2000). Basic soil chemical properties have been published by du Toit (2003). The site originally supported grassland vegetation which was converted to an *Eucalyptus grandis* plantation in 1964.

Determination of Nutrient Capital in the Standing Crop

The stand on the site was seven years old at the time of harvest in December 1998. It had been the last of three coppice rotations and had a mean annual increment of 21 m^3 ha^{-1} yr^{-1}. The nutrient capital was determined in four components of the plantation system: the aboveground biomass, the belowground biomass, the forest floor and the soil. The following methods were used to estimate the biomass and nutrient content in each component:

Aboveground biomass

Diameter at breast height (dbh) of the standing crop was measured. The dbh data was divided into 18 equal (in terms of tree number per hectare) class intervals and one tree was randomly selected from the mid-point of each class for destructive sampling. The sample trees were felled and divided into: utilisable stem wood (> 70 mm end diameter overbark), the bark, stem top, branches, leaves and capsules. For each fraction of the standing biomass, wet mass was determined on the full sample in the field. Representative subsamples were collected for determination of moisture and nutrient contents. Leaf area of subsamples was determined by scanning.

Belowground biomass

Tree stump diameters were measured at ground level and stratified into three classes. A stump at the midpoint of each class (with its associated root system) was excavated in three random locations. The excavated volume around the stump was equal to the dimensions of the original spacing (2.44 x 2.44 m) and a depth of 1 m. The soil profile was stratified into three layers (0-20 cm, 20-40 cm and 60-100 cm). The mass of fine roots (diameter < 1 mm) was not determined. A soil corer with a volume of 1.27 dm^3 was used to collect four root samples per horizon to estimate medium diameter root mass, (roots between 1 and 10 mm in diameter). The soil in the entire block was then excavated and sieved through a 10 mm mesh to separate soil from the root and stump fractions > 10 mm in diameter. These fractions were separated into very coarse and coarse fractions (greater and smaller than 100 mm diameter, respectively), by sawing. Roots were separated from the stump by sawing at the soil surface. All fractions were weighed. Subsamples were oven dried at 65°C for moisture and nutrient content determinations.

Forest floor

Mass and nutrient content of the forest floor before harvesting were determined by collecting 18 random samples with a ring sampler of 30 cm diameter. After harvesting, the slash (harvesting residue plus forest floor) was sampled by cutting out a square of 0.07 m^2 with a chainsaw. Six slash samples were collected per plot and separated into fine, medium and coarse fractions. The fine fraction consisted of material passing through a 2 mm sieve, representing the humus fraction (H-layer). The medium and coarse fractions made up the L-layer. After sieving, each fraction was oven dried at 65°C and weighed separately. Ash-free masses of all layers were determined. Fine, medium and coarse fractions of groups of three samples within the same plot (nine units) were bulked into one fine, one medium and one coarse sample to determine macronutrient contents.

Soil

Soil was sampled from three depths (0-20, 20-40 and 40-90 cm) which correspond closely to the soil horizons. At each of 32 sampling locations, four samples of the A horizon (bulked) and one sample each of the B1 and B2 horizons were collected for analysis. 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. 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). After dispersion and ultrasonic treatment, particle size was determined by sieving (coarse fractions) and the pipette method (fine fractions) (Gee and Bauder 1986). Available P was estimated by extracting with 0.03 M NH_4F in 0.1M HCl (Bray and Kurtz 1945) and P was determined colorimetrically (molybdenum blue). Available pools of nutrients in the soil were estimated from Bray #2 extractions (P) as well as exchangeable fractions of cations (Ca, Mg and K). Results are expressed on a hectare basis using soil volume and bulk density.

Experimental Design and Treatments

The standing crop was clear felled in December 1998 and site management treatments implemented. 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. Responses observed in six of the site management treatments are discussed in this report, and so only these treatments are described below:

BL_0 Slash removed. All harvesting residue (including bark, branches and foliage) and litter layer manually removed from the plot.

BL_2 Regular slash load. Harvesting residue retained and broadcast on the plot.

BL_3 Double slash. Material from the BL_0 plot deposited on top of existing slash load.

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), followed by a localised application of a N, P and Zn mixture near each seedling after planting.

The new crop of genetically improved *E. grandis* seedlings was planted on 3 February 1999, using the same initial spacing as before.

Changes in nutrient pool sizes resulting from management operations (treatments) were calculated as follows: (1) harvesting losses were calculated as the nutrient removal in stem wood, estimated from sample trees, (2) losses from slash burning were estimated as the difference between the pre- and post-burn slash, (3) slash addition was estimated as the difference between the double slash and regular slash load, while slash removal was taken as the same numerical value, and (4) additions through fertilisation were scaled up from the quantity applied per tree.

Monitoring of Stand Growth

Tree growth (tree survival, tree diameter, tree height, crown diameter and crown length) was measured at approximately six-weekly intervals during the first two growing seasons in subplots of 16 trees per plot. Full plot measurements were conducted at three-monthly intervals during the first two growing seasons and six-monthly thereafter. Volume was calculated by the equation developed for *E. grandis* short-rotation crops by Coetzee (1992, cited in Bredenkamp 2000). Differences in tree height and diameter, stand volume macronutrient capital between treatments were analysed using a standard ANOVA procedure after performing an appropriate transformation on the dependent variables where necessary (McConway *et al.* 1999).

Table 1. Some soil properties before trial establishment. Standard errors are in brackets

Depth	Bulk density	PH in	C	N	P	Exchangeable cations				Sum of bases	Extr. acidity	ECEC
						Ca	Mg	K	Na			
(cm)	(Mg m^{-3})	KCl	(g kg^{-1})		(mg kg^{-1})	(cmol$_c$ kg^{-1})						
0-20	0.97	3.94	66.5	3.2	2.75	0.43	0.64	0.16	0.23	1.46	3.25	4.71
	(0.018)	(0.03)	(1.3)	(0.1)	(0.20)	(0.04)	(0.04)	(0.01)	(<0.01)	(0.09)	(0.09)	(0.10)
20-40	1.21	4.23	42.3	1.8	0.94	0.33	0.56	0.11	0.21	1.20	1.48	2.68
	(0.022)	(0.03)	(1.3)	(0.1)	(0.09)	(0.04)	(0.03)	(0.01)	(0.01)	(0.07)	(0.21)	(0.23)
40-60	1.35	4.4	23.5	1.2	0.34	0.31	0.55	0.09	0.21	1.16	0.81	1.97
	(0.040)	(0.03)	(1.0)	(<0.1)	(0.07)	(0.03)	(0.03)	(0.01)	(0.01)	(0.05)	(0.12)	(0.12)

Table 2. Nutrients contained in various ecosystem components. Total soil N pools are given while readily available soil nutrient pools were estimated for other elements (Bray-2 P and exchangeable cations)

Component	Mass	N	P	K	Ca	Mg
	(kg ha^{-1})					
Tree crowns	34 251	180	12	122	143	51
Stem bark	9 859	31	3	31	109	35
Stem wood	90 604	101	13	67	63	19
Total standing biomass	134 714	311	27	220	315	105
Roots+stumps	84700	235	19	84	181	33
Forest floor	69 600	1045	28	105	530	121
Crown+bark+forest floor	113 710	1255	43	258	782	208
A horizon (0-20 cm)	1 940 000	6 208[a]	5	120	167	151
B1 horizon (20-40 cm)	2 420 000	4 356[a]	2	104	159	165
B2 horizon (40-90 cm)	6 750 000	8 100[a]	3	241	416	455
Sum of soil horizons	11 110 000	18 664[a]	10	466	742	771

[a] A small fraction of these pools is considered plant-available – see discussion.

Results

Nutrient Capital

Basic soil properties are shown in Table 1. Impact of treatments on nutrient capital can be assessed more comprehensively if the quantities of nutrients in the entire system are known. Distribution of nutrient pools in the system before harvesting and treatment implementation is shown in Table 2. Nutrient pools were strongly affected by the implementation of treatments (du Toit 2003) (Table 3). Nutrient capital in the regular slash (harvest residue) was compared to that in some standing crop fractions (forest floor + tree crowns + bark) to test accuracy of measurements. Total mass and P, Ca and Mg pools were fairly similar in the above estimates. However, N and especially the K pools in slash were lower than 'potential slash' estimates. It is fairly certain that some portion of the K (and N) would have been released from the slash in the three-month period from clear felling until collection of the first slash samples just prior to planting. Data showing an especially rapid loss of K from freshly fallen litter has been presented by Mackensen *et al.* (1996).

Table 3. Effects of management operations on the nutrient capital in various pools of the system (after du Toit 2003). Values in parentheses are standard errors of the means

Treatments	Mass	N	P	K	Ca	Mg
		(kg ha^{-1})				
Slash loads						
Double slash	153 200a	1378a	67a	275a	1413a	286a
Standard error	(7 038)	(150)	(5)	(26)	(152)	(15)
Regular slash	116 527b	1044b	53a	193b	823b	201b
Standard error	(7 262)	(46)	(3)	(13)	(42)	(6)
Burnt slash	31 415c	604c	27b	96c	747b	151c
Standard error	(2 935)	(51)	(2)	(7)	(80)	(16)
Management additions						
Additional slash	36 673	334	14	82	590	85
Fertilisation	151	17	33	0	1	2
Management removals						
Utilisable stem wood	90 604	101	13	67	63	19
Losses through slash burning	85 112	440	26	97	76	50

Mean values for slash loads within the same column followed by the different letters are significantly different ($p<0.05$).

Stand Growth

Effects of treatments on tree height, diameter and stand volume are shown in Figs 1, 2 and 3. Development of leaf area and woody biomass has been documented by du Toit *et al.* (2000) and du Toit and Dovey (in preparation). The trial experienced a warm dry summer in the year of establishment, while the second growing season was wetter than average with low evapotranspiration. Some seedlings died in the first season, but tree survival in all treatments except the BL_3 plots exceeded 90% at two years of age. Mortality was ascribed to frost pockets in the deep slash layers of certain plots. Due to problems with stocking in treatment BL_3, the discussion is limited to only those treatments with adequate stocking.

Tree height increased at an exponential rate in all treatments up to the end of the second growing season, 1.3 years after planting (YAP), (Fig. 1). Mean tree height across treatments at this point ranged from 3.1 m to 4.7 m. The canopy started to lift (i.e. die back from below) at approximately 1.1 YAP in the fast-growing treatments (SB, SF and SD), but this process could only be detected around 1.6 YAP in the BL_0 treatment (data not shown). Mean tree height per treatment has increased linearly from 1.3 YAP to date with treatment BL_0 remaining significantly shorter than the other treatments (Fig. 1).

Tree diameter growth is shown in Fig. 2. Diameter was measured at 0.05 m above ground level for the first year and at breast height (1.3 m) from year one onwards (Fig. 2). Mean tree diameter increased fastest in treatments SF, SB and SD and these treatments remained statistically similar during the first 3.5 years of growth (Fig. 2). The diameter in the BL_0 treatment was significantly lower than all other treatments from 0.2 YAP to date. The fertilised treatment had a significantly larger diameter than BL_2 and BL_0 treatments for the greater part of the second and third growing seasons (up to 2.3 YAP in Fig. 2).

Woody biomass and volume growth followed very similar patterns over time, and hence, only the volume is presented in Fig. 3. Volume increased at exponential rates in all treatments during the second and third growing seasons (Fig. 3). Volume of the two fastest growing treatments (SF and SB) increased at a near constant rate during the fourth growing season, while the leaf area index over the corresponding period has decreased to levels slightly lower that the peaks recorded in the third season. Volume development in the BL_2

Figure 1. Mean tree height growth up to 3.5 years of age. The least significant difference (p=0.05) is shown as vertical bars for each measurement

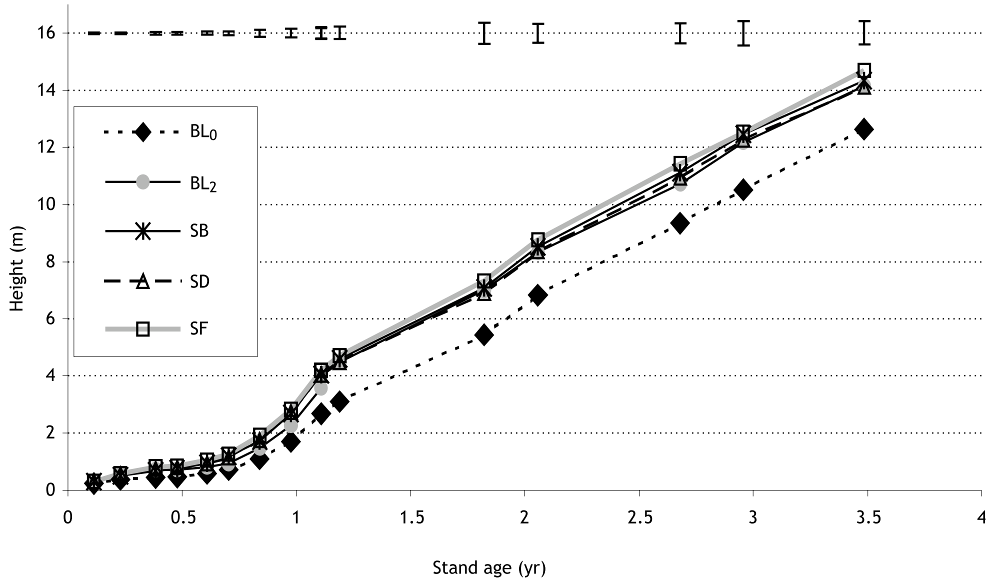


Figure 2. Development of tree diameter over time. Diameters measured near ground level (5 cm) up to one year of age and at breast height (1.3 m) thereafter. Vertical bars represent the least significant difference (p=0.05) for each measurement

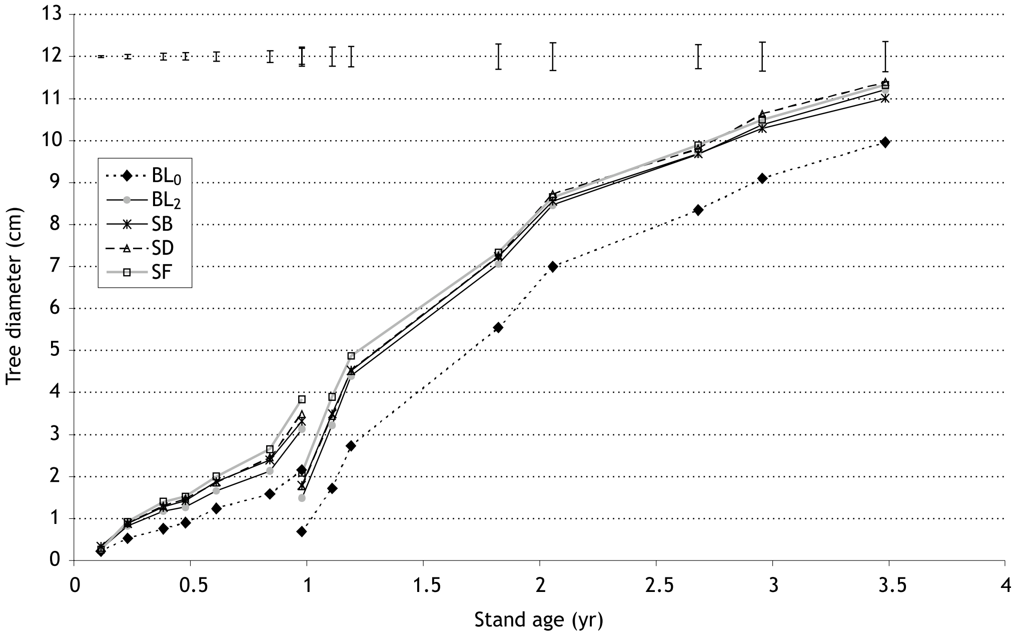
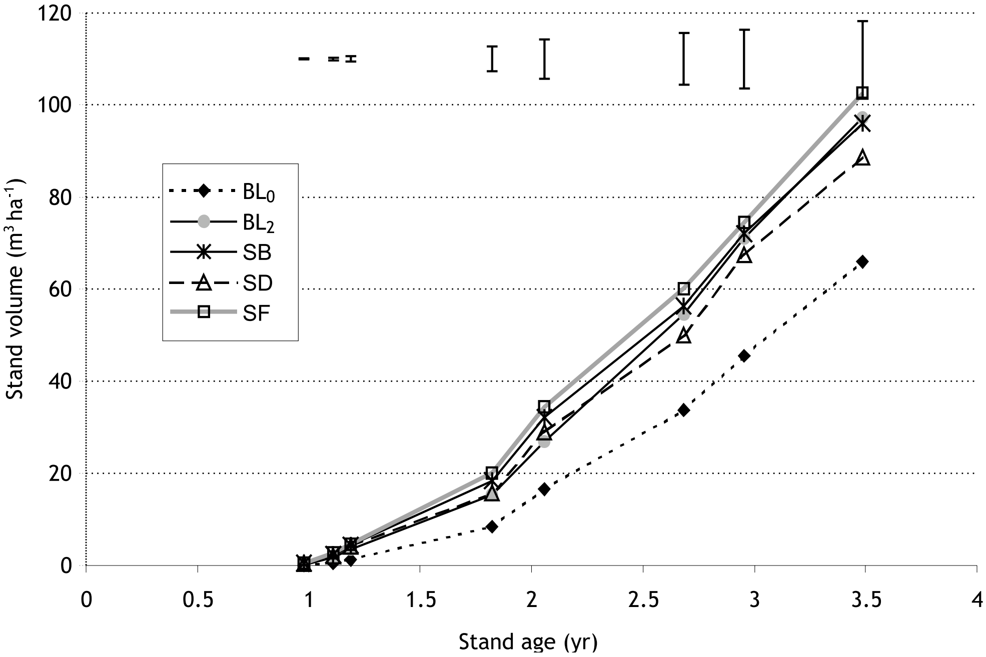


Figure 3. Stem volume growth up to 3.5 years of age. The bars represent the least significant difference (p=0.05) for each measurement



treatment lagged slightly behind treatments SB and SF, but at 3.5 years of age, the volumes are statistically similar. The SD treatment developed fast initially, but this rate of development has slowed during the third growing season. As indicated for dbh in Fig. 2, the volume of treatment BL_0 in Fig. 3 was significantly lower than all other treatments from the first year of growth to date.

Discussion

Nutrient Capital in the System

The soil is acidic, with high levels of salt-extractable acidity and low levels of exchangeable base cations, which is typical for the highly weathered soils found in wetter climates on the eastern seaboard of South Africa (ICFR 1998). These soils typically have a high portion of pH dependent charge, and for this reason, the effective cation exchange capacity (ECEC) has been estimated as the sum of exchangeable bases plus 1M KCl-extractable acidity at ambient pH (Table 1). The topsoil is 69% acid saturated. Levels of exchangeable Ca and K are low when compared to shale-derived soils in the region (ICFR 1998), while Mg levels are relatively high. The three soil horizons are all comparatively rich in organic carbon (Table 1). This highly weathered soil has very low levels of available P (Table 1). Large P-fixing capacities have been recorded for other soils in the region that belong to the same soil form as the Karkloof trial site. The so-called standard P requirement, i.e. P sorbed at an equilibrium P concentration of 0.2 mg L^{-1} in these soils ranged from 558 to 1174 mg P kg^{-1} soil (Bainbridge *et al.* 1995). The soil nutrient pool constitutes a large reservoir of nutrients but only a fraction can be considered to be readily available to plants. Exchangeable base cation fractions and Bray P extractions have been used as indices of plant available P, K, Ca and Mg in the soil (Table 2). The readily available soil pools make up the greatest fraction of nutrients in the system for K, Ca and Mg.

Total aboveground biomass was 134.7 t ha^{-1}, with 91 t ha^{-1} (67%) was made up of stem wood. The crown plus bark fractions, i.e. the portion that will be retained as part of the slash after harvesting, contained the remaining 33% of the aboveground biomass. A high percentage of non-utilised biomass will result from crops where individual tree size is small (Bradstock 1981, Judd 1996, du Toit 2003). Such a situation can be caused by harvesting at a young age or by harvesting compartments with high stand densities. In the Karkloof study, the foliage held large quantities of N and P, while large portions of Ca and Mg were found in the bark. The relatively high nutrient content of the crown and bark fractions meant that they contained between 54 and 82% of the aboveground biomass macronutrient pools. Root and stump biomass measured on the site was 69.5 t ha^{-1} and 15.2 t ha^{-1}, respectively, which sums to a total of 84.7 t ha^{-1} (Table 2). The large root mass is due to the stump carrying the third coppice crop and is larger than published accounts for similar stands (Negi and Sharma 1985, Tandon *et al.* 1988, du Toit 2003). Root and stump biomass represent a large store of nutrients (particularly for N, P and Ca) which will not be affected by harvesting and site management operations.

Mass of the forest floor was 70 t ha^{-1}. The forest floor contains large quantities of N, P and Ca relative to the nutrients in the entire system (Table 2). The forest floor mass is large compared to those from plantations in warm climates, (O'Connell and Sankaran 1997). The decomposition of organic matter is slow in dry and cool conditions (O'Connell 1990). During winter, rainfall is typically low for four to five months on average, coupled to low temperatures. These conditions are apparently responsible for the large build-up of the forest floor.

Nutrient Capital and Site Management Effects

Individual site management and harvesting operations impact primarily on nutrient pools in specific components (stem wood, bark, tree crown and forest floor pools) of the plantation system. The intensity of the operation and the nutrient content of the affected pool are the major determinants of the magnitude of the impact on the nutrient capital of the system as a whole. The forest floor and non-utilised biomass (crown, bark and belowground biomass) constitute large nutrient reserves for N and P, while K and Ca capital are mainly in the soil exchangeable fraction and the non-utilised biomass pool. System Mg capital is totally dominated by the soil exchangeable pool. This distribution of nutrients suggests that slash management operations will have the greatest impact on N and P capital in the system.

The double slash treatment added large quantities of nutrients to these plots, particularly N and Ca (Table 3). Re-implementation of these treatments over successive rotations will create a steep gradient in nutrient capital, which will provide a clearer understanding of the system's resilience to nutrient loss. Commercial fertiliser applications are aimed at maximum economic benefit, and hence, contain only those nutrients responsible for optimum growth response at low input cost (N, P and Zn). Nutrient addition through current fertilisation practice makes a very small impact on the N budget in the system, but contributes substantially towards system P pools. Recommended fertiliser mixtures contain no K and very low levels of Ca and Mg.

Wood harvesting was responsible for small to moderate losses of nutrients (Table 3) which made up relatively small fractions of the total nutrient pool in the system. Nutrient export is minimised by the removal of stem wood to a diameter of 7 cm overbark only. All fractions of the crown and stem bark are left on site. Stem wood in the Karkloof study had lower levels of K, Ca and Mg than found by Herbert (1996) for several eucalypt species growing on soils that are richer in base cations (Herbert and Robertson 1991). Values reported by Herbert may be partly due to luxury consumption of those nutrients in plentiful supply. Slash burning was responsible for greater nutrient losses than timber harvesting (Table 3). The large burning losses can be explained by the mass of slash consumed in the fire (Fisher and Binkley 2000). The fire burned with moderate intensity, however, the fuel load was large since the site had not been burnt after harvesting three previous coppice crops. The nutrient loss through burning listed in Table 3 is thus applicable to a management regime of a planted crop followed by several coppice crops and should not be taken as representative of the loss per single crop cycle (du Toit 2003). For example, N losses ranging from 200-300 kg ha^{-1} have been recorded after burning thinned eucalypt stands in South Africa which had much lower slash loads (du Buisson 2003). In the Karkloof study, the slash burning treatment consumed 73% of the slash mass and reduced the pools of N, P, K, Ca and Mg in the slash by 42, 49, 50, 9 and 25%, respectively.

Nutrient removal through management operations is likely to have the greatest impact on the N or P capital of the system: N was the element lost in greatest quantity while the largest loss (expressed as a fraction of the system nutrient captial) was recorded for P (Table 3). The total soil N pool in this system is large (Table 2), however, only a small percentage of it will be readily available to trees (Adams and Attiwill 1986, Attiwill and Leeper 1987, Fisher and Binkley 2000). The fairly high C:N ratio of the topsoil and the fact that litter seems to accumulate on the site suggests that N availability may limit the productivity of the current crop. Losses of N through burning and harvesting thus appear small when compared to the total pool, but such losses constitute a much larger percentage of the readily available N in the soil. More work is needed to gauge the size of the readily available N pool in soils. The potential loss of P through harvesting and slash burning is large relative to the total pool of P in the system (Table 3). However, the Bray-2 solution used to measure available soil P is a mild extractant and may have underestimated the soil P pool actually available to trees. Importantly, the quantity of P lost through slash burning or harvesting is small, which means that it can be replaced relatively easily by fertilisation. Inputs of P in the form of 'starter' fertiliser applications in this experiment (33 kg P ha^{-1}) partially offsets the losses incurred through burning and harvesting. Additional studies have been launched to determine the level of P availablility and tree P uptake as affected by treatments. Slash nutrient pools for K and Mg range from moderate to large (Ca), and in addition, large quantities of base cations are held on the soil exchange (Table 3). The large stores should not lead to complacency because there are no inputs of K, Ca and Mg under current management practice. The net effect of several management operations on the nutritional sustainability of this system has been assessed by du Toit and Scholes (2002) by contrasting net nutrient losses incurred through specific management regimes to nutrient pools in the system.

Effects of Treatments on Stand Growth

Fertilisation would increase nutrient availability though direct supply, while burning (Fisher and Binkley 2000) and topsoil disturbance (Smith and du Toit 1998) could indirectly increase nutrient availability, at least temporarily. A decrease in the level of N mineralisation following slash removal has been shown in Brazil (Gonçalves *et al.* 2000). In the Karkloof study, slash burning, slash disturbance and fertilisation increased the rate of leaf area and stem growth (du Toit and Dovey in preparation) above the regular slash (BL_2) treatment, while slash removal strongly decreased these (Figs 1, 2 and 3). Increased nutrient availability could allow the stand to deploy maximum leaf area to capture incoming radiation. Treatments SD, SF and SB developed leaf area indices in excess of 4.0 by the end of the second growing season (1.3 YAP) (du Toit and Dovey in preparation) while the development in treatment BL_0 was significantly slower. Similar results were obtained in fertilised stands of *E. grandis* by Cromer *et al.* (1993) and Hunter (2001).

However, it appears that the stand's potential to respond to increased levels of nutrient availability could have been suppressed by the dry conditions during the first growing season. Leaf area index in the trial developed slowly during the prolonged dry period of the late summer, autumn and winter of 1999 (0 to 0.7 YAP). The onset of spring rains in October 1999 triggered rapid growth in leaf area, which was supported by above-average rainfall (du Toit and Dovey in preparation) and the responses in leaf area index alluded to above. Fertilisation of eucalypts at establishment usually yields significant growth responses under most conditions and site types in and around the study area (Schönau 1983). A fertiliser trial had been conducted during a wetter period on a nearby compartment of the same plantation, using similar fertiliser levels, soil conditions and planting stock (du Toit and Freimond 1994). At stand age 7 years, an increase of 47 m^3 ha^{-1} of utilisable timber was recorded as a result of fertilisation in that trial. This strengthens the argument that soil water stress limited the response in the SF (and probably also in SB and SD) treatments.

Differences in height and diameter growth rate between treatment BL_0 and the fast-growing treatments stabilised after the second winter season. The end of the second growing season (*ca.* 1.3 YAP) also coincided with a stabilisation in the rate of leaf area development (du Toit and Dovey in preparation). This effect is probably due to diminishing differences in nutrient availability between these treatments over time. Leaf area index for all treatments have converged by the fourth growing season to statistically similar values (du Toit and Dovey in preparation). It is thus likely that the rate of stand volume growth from this point will not differ markedly between treatments.

Slash burning has the potential to increase nutrient availability in the short-term and boost early stand growth (Bouillet *et al.* 2000, Fisher and Binkley 2000, O'Connell *et al.* 2000 and this proceedings). However, slash burning carries the risk of nutrient shortages in the medium term with a subsequent decline in growth rate later in the rotation. This effect is particularly common on infertile sandy soils where the nutrient capital is small and the nutrient holding capacity is limited (Squire *et al.* 1991, Bouillet *et al.* 2000, O'Connell *et al.* 2000, Bouillet *et al.* 2001). Rapid early growth rates in the SB treatment of the Karkloof experiment have stabilised relative to other treatments but no decline has been detected to date. This is apparently due to the resilience of this site when compared to infertile, sandy soils. The modest impact of slash burning in this trial can be ascribed to large nutrient pools and the limited leaching and erosion potential following burning (flat terrain, high clay content and rich organic matter content of the soil).

Implementation of Research Recommendations by Industry

The concept of 'site-specific silviculture' or 'precision forestry' aims for the management of individual sites on a case-specific basis to maximise productivity and minimise risk. We have developed a management tool (an index of nutritional sustainability) based on research of the effects of management operations on nutrient capital in the Karkloof case study (du Toit and Scholes 2002). This 'Index of Nutritional Sustainability ' can be used to gauge site resilience and to assess the impacts of specific operations at representative intensities. This concept is supported by the local industry and is currently being implemented on a broader scale to assess the nutritional sustainability of specific sets of operations (silvicultural regimes) on some of the major site types of the country. The aim is to identify combinations of silvicultural regimes and sites that are unlikely to be sustainable with respect to the cycling of specific nutrients, which will: (1) highlight management regimes which should be avoided on sensitive sites, and (2) help to focus future research efforts.

Conclusions

The fraction of macronutrients in utilisable timber is relatively small compared to total reserves at the site. Slash burning has the most pronounced impact on N and P capital of the system. Current fertilisation practices will mitigate P losses to some degree, but additions of other macronutrients range from very low for N to none for K, Ca and Mg. The plantation system is very resilient to nutrient losses due to its large nutrient pools and extensive nutrient holding capacity.

Tree size and stand volume showed an exponential development in the young stand across all treatments, a trend that was also apparent in leaf area index measurements. Treatments that increased nutrient availability (slash burning and fertilisation) yielded the highest initial growth rate while treatments that decreased nutrient availability (slash removal) significantly retarded stand volume growth. It appears that tree height, diameter and volume and leaf area index development were driven largely by differences in nutrient availability during the first two growth seasons.

References

Adams, M.A. and Attiwill, P.M. 1986. Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. I: Nutrient cycling and nitrogen turnover. Plant and Soil 92:319-339.

Attiwill, P.M. and Leeper, G.W. 1987. Forest soils and nutrient cycles. Melbourne University Press, Carlton, Victoria, Australia. 202p.

Bainbridge, S.H., Miles, N., Praan, R. and Johnston, M.A. 1995. Phosphorus sorption in Natal soils. South African Journal of Plant and Soil 12(2):59-64.

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: a progress report: 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. and Ranger, J. 2001. Changes over successive rotations in NPK fertiliser needs of Congolese clonal eucalyptus plantations. Relationships with changes in soil fertility. Proceedings of IUFRO International Symposium: 'Developing the eucalypt of the future' 10-15 September 2001, Valdivia, Chile. Compact Disk.

Bradstock, R. 1981. Biomass in an age series of *Eucalyptus grandis* plantations. Australian Forest Research 11:111-127.

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. 2000. Volume and mass of logs and standing trees. *In:* Owen, D.L. (ed.) South African forestry handbook. Volume 1:167-174. V&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.

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.

du Buisson, S.S. 2003. The impact of post-harvesting residue burning on environmental sustainability in the Northern Timbers plantations, Tzaneen. Unpublished paper submitted in partial fulfilment of the requirements for the M.S.A. degree, Centre for Sustainable Agriculture, University of the Free State, Bloemfontein, South Africa.

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 Freimond, S. 1994. Fertilizing trees at planting. *In:* MacLennan, L. (ed.) Institute for Commercial Forestry Research annual research report 1994, 74-84. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit, B. and Dovey, S.B. (In preparation). Effect of site management on leaf area, growth efficiency and biomass development of a young stand of *Eucalyptus grandis* in 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., 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.

Fisher, R.F. and Binkley, D. 2000. Ecology and management of forest soils. 3rd ed. Wiley and Sons, 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, 339-378. ACIAR Monograph No. 43. Australian Centre for International Agricultural Research, Canberra, Australia.

Gee, G.W. and Bauder, J.W. 1986. Particle size analysis. *In*: Klute, A. (ed.) Methods of soil analysis. Agronomy Monograph No. 9 Part 1, 383-411. American Society of Agronomy, Madison, Wisconsin, USA.

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, 379-417. ACIAR Monograph No. 43. Australian Centre for International Agricultural Research, Canberra, Australia.

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* plantation in the humid tropics: São Paulo, Brazil. *In*: Nambiar, E.K.S., Cossalter, C., Tiarks, A. 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.

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, Australia.

Herbert, M.A. and Robertson, M.A. 1991. Above-ground biomass composition and nutrient content for *Eucalyptus* species in the south-eastern Transvaal. *In:* Schönau, A.P.G. (ed.) Intensive forestry: the role of eucalypts, Vol. 2, 662-674. Proceedings of IUFRO symposium, Durban, South Africa, 2-6 September 1991. Southern African Institute of Forestry, Pretoria, South Africa.

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.

ICFR 1998. Annual research report 1998, 134-136. MacLennan, L. (ed.) Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Judd, T.S. 1996. Simulated nutrient losses due to timber harvesting in highly productive eucalypt forests and plantations. *In*: Attiwill, P.M and Adams, M.A. (eds.) Nutrition of eucalypts, 249-258. CSIRO Publishing, Australia.

Mackensen, J., Hölsher, D., Klinge, R. and Fölster, H. 1996. Nutrient transfer to the atmosphere by burning of forests in eastern Amazonia. Forest Ecology and Management 86:121-128.

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

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, 16-20 February 1998, Pietermaritzburg, South Africa, 1-3. Center for International Forestry Research, Bogor, Indonesia.

Negi, J.D.S. and Sharma, S.C. 1985. Biomass and nutrient distribution in an age series of *Eucalyptus* hybrid plantation in Tamil Nadu. I. Distribution of organic matter. Indian Forester 111:1111-1122.

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.

O'Connell, A.M. 1990. Microbial decomposition (respiration) of litter in eucalypt forests of south-western Australia: an empirical model based on laboratory incubation. Soil Biology and Biochemistry 22(2):153-160.

O'Connell, A.M. and Sankaran, K.V. 1997. Organic matter accretion, decomposition and mineralisation. *In*: Nambiar, E.K.S. and Brown, A.G. (eds.) Management of soil, nutrients and water in tropical plantation forests, 443-480.

ACIAR Monograph No. 43. Australian Centre for International Agricultural Research, Canberra, Australia.

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., Cossalter, C., Tiarks, A. 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.

Schönau, A.P.G. 1983. Fertilization in South African forestry. South African Forestry Journal 100:27-31.

Smith, C.W. and du Toit, B. 1998. The combined effect of harvesting operations and fertilization on the growth of *E. grandis* x *camaldulensis* on a sandy fernwood soil in Zululand: early results. ICFR Newsletter, February 1998:15-19. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Squire, R.O., Flinn, D.W. and Campbell, R.G. 1991. Silvicultural research for sustained wood production and biosphere conservation in the pine plantations and native eucalypt forests of south-eastern Australia. Australian Forestry 54:120-133.

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

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Effects of Site Management on Tree Growth and Soil Properties of a Second-rotation Plantation of *Eucalyptus urophylla* in Guangdong Province, China

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Abstract

Effects of site management practices on *Eucalyptus urophylla* plantation establishment and productivity on degraded soils in southern China were evaluated. Tree growth in the treatment where all organic matter was removed and weeds were periodically controlled was better than in the whole tree harvest treatments because of reduced weed competition. Intercropping with N-fixing trees increased tree growth 69 months after planting and increased litterfall 36 months after planting. Retention of harvest residue increased foliar N and P concentration in leaves and tree growth. Retention of residue also increased the amount of litterfall in the new plantation. Application of N, P and K fertilisers increased foliar N, P and K concentration and tree growth substantially. Growth increment was much higher than those obtained by harvest residue management on this poor soil. Coppice trees grew better than replanted trees. At the high level of fertiliser application coppice and replanted trees grew at the same rate. Mean annual increment of coppice trees was much higher than that of replanted trees. Yield decline was obvious in second rotation without genetic improvement. Harvest residue retention, adequate fertilisation and coppice regeneration are therefore recommended as operational practices for eucalypt plantations in south China.

Introduction

There are more than one million hectares of eucalypt plantations in south China and most have been established recently (Xu *et al.* 2000a). Soils on sites available for most eucalypt plantations are poor because former land practices degraded the sites. Productivity on the poor sites is very low (5-10 m^3 ha^{-1} yr^{-1}) and variable (3-40 m^3 ha^{-1} yr^{-1}) compared with eucalypt plantations in other countries (Brown *et al.* 1997, Xu *et al.* 1999). On these sites, eucalypt plantations commonly have trees with very small crowns and grow slowly beyond age 4 years (Xu 1997). Consequently trees are harvested after a short rotation period (3-6 years). Even though productivity is already low, it appears to be declining with successive rotations in some areas. Some reports relate the low productivity to poor soil fertility (Dell and

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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 harvest (Xu 1996) may be contributing factors. Fertilisation in the first one or two years after planting, is a 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). 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). However, eucalypts in short-rotation plantations in south China are harvested before such withdrawal from tree tissues can become 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, improve nutrient cycling and support 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 successive 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 successive rotations in two experiments by studying:

- 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
- impacts of stand re-establishment practices and fertiliser application on tree growth and productivity.

Materials and Methods

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 degrees.

Main features of the climate are: average annual rainfall 2178 mm, maximum rainfall in a day 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 poor in available nutrients. Both total and available nutrient concentrations in the soil are low compared with undisturbed forest soils in south China. More information on the climate and soil is given by Xu *et al.* (1998, 2000b).

The site is typical for eucalypt plantations planted on degraded soils in south China. Due to 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}) 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) of the site was cultivated by a tractor to establish a plantation of *E. urophylla*. Spacing for the plantation was 2 x 3 m. At planting, 100 g of a NPK fertiliser (10.0% N; 4.4% P; 8.3% K) was applied per tree into planting hole as basal fertiliser. In 1992, fertilisation was repeated (applied into 2 small holes on opposite sides 0.3 m from tree).

Experimental Design and Layout

There are 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_0 All aboveground organic residue was removed from the plot (all aboveground tree components, understorey and litter).
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 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) was placed in each hole. On 8 April 1997, 4 month-old seedlings, grown from seeds collected in the plantation, were planted. 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 tree planting, and in the year after planting cut and 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 planted eucalypt seedlings. They were not fertilised

To measure the rate of decomposition, 24 sample bags of leaf slash or branch slash or mixed leaf and branch slash (50% each) were laid on site after tree harvesting. Initial weight of the litter sample in the bags was determined by drying subsamples. Four bags were collected at 2-month intervals. The litter was oven-dried at 85°C, weighed and saved for nutrient analysis. Soil contamination was minimal so the results are reported as total dry weight loss.

At year 3, five litter traps (1 x 0.6 m) were set in each plot to collect litterfall monthly.

At 2.5 years, foliar (first fully expanded leaves (YFEL), 2 from each tree) samples were collected in each plot (bulked within plot) for chemical analysis.

Soil samples in each plot were collected before tree planting, 2 and 4 years after tree planting. Five cores (3 cm in diameter) in fixed positions in each plot were collected. Then 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.

Methods for soil, plant and litter analysis have been described previously in Xu *et al.* (2000).

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

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

F_0 No additional fertiliser.
F_1 Low fertiliser rate, N 76.7 kg ha^{-1}, P 16.0 kg ha^{-1} and K 53.4 kg ha^{-1}.
F_2 High fertiliser rate, N 153.3 kg ha^{-1}, P 32 kg ha^{-1} and K 106.7 kg ha^{-1}.

The two subtreatments were:
C coppice; and
R seedlings planted.

Seedlings from the same batch as Experiment 1 were planted on April 8, 1997. The coppice subtreatment was thinned to two coppice stems per tree on 15 July 1997. The harvesting level on all of these plots was as for Experiment 1, BL_2. Two additional subplots were added in each block to compare the effects of different harvest levels when no fertiliser was added. They were BL_0 (all aboveground organic residue removed from the plot) and BL_3 (double slash). There were 72 trees in each plot (6 x 12) and 36 trees in each subplot. The spacing was 2 x 3 m. The area of each plot was 432 m^2. As in Experiment 1, the designated harvest intensity was applied to each plot in March 1997. Trees were harvested in March 1997 and the experiment was laid out soon after. Planting holes (40 x 40 x 30 cm deep) were prepared between first rotation stumps on the planted subplots while the coppice plots were left undisturbed.

F_1 plots were fertilised with 25 g urea, 40 g KCl and 150 g superphosphate per planting hole before planting and 25 g urea per tree was applied into two small hole 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 per tree were applied into two small holes, 30 cm on two sides of a tree at the same time as refertilisation for replanting trees (3 months after planting). Both the planted and coppice plots received 50 g urea and 40 g KCl one year after planting at the same way applied as coppice. The F_2 received 50 g urea, 40 g KCl and 150 g superphosphate per planting hole and a further 50 g urea and 40 g KCl were applied 3 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 for 3 months replanting trees (3 months after planting). On both planted and coppice F_2 subplots, 100 g urea, 80 g KCl and 150 g superphosphate per tree were applied one year after planting. Coppice from the first rotation stump was removed at three-month intervals. Foliar sampling was in the same way as for Experiment 1.

Results

Tree Growth

The harvest residue treatments significantly ($p<0.001$) affected tree heights 3 months after planting and this difference increased with tree age (Table 1) until 31 months and maintained from 31 to 69 months. At 69 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 than the trees on the BL_2 plots, indicating that interplanting with *Acacia holosericea* did not increase the growth of the eucalypts.

Tree diameters responded to the treatments in the similar pattern to heights. At 3 months, the best two treatments for diameter were BL_0 and BL_3 and the other three treatments were almost the same. At 46 months, tree diameter in BL_3 was higher than that in BL_1 and BL_2 (Table 2). 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. Tree diameter increased faster in BL_4 from 57 to 69 months old than other treatments, indicating that intercropping with *A. holosericea* increased tree diameter growth in the late stage of the rotation.

At 46 months, BL_3 was the best treatment in terms of stand volume and BL_1 was the poorest (Fig. 1). There was no difference among BL_0, BL_2 and BL_4.

At 69 months, BL_3 and BL_4 were the best treatments in terms of stand volume, although not significantly different from BL_0 and BL_2, and BL_1 was the poorest (Fig. 2).

Table 1. Effect of different harvest residue treatments on tree height (m) over 69 months

Treatment	Age (months)								
	3	8	16	20	25	31	46	57	69
BL_0	0.56b	1.7b	2.9b	3.4b	3.8b	5.5b	7.6bc	8.9a	9.4ab
BL_1	0.54b	1.5a	2.5a	3.1a	3.4a	5.0a	7.1a	8.9a	9.1a
BL_2	0.48a	1.5a	2.8b	3.4b	3.7b	5.4ab	7.4ab	9.0a	9.4ab
BL_3	0.55b	1.7b	3.3c	3.9c	4.3c	6.2d	8.1c	9.6b	10.1c
BL_4	0.48a	1.5a	2.9b	3.5b	3.9b	5.9cd	7.8bc	9.1ab	9.9bc

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

Table 2. Effect of different harvest residue treatments on tree diameters over 69 months

Treatment	Age (months)								
	3	8	16	20	25	31	46	57	69
BL_0	0.97b	3.1b	2.4b	3.0b	3.7b	4.5b	6.5bc	7.1a	7.6a
BL_1	0.75a	2.5a	2.0a	2.5a	3.0a	3.9a	5.9a	6.9a	7.3a
BL_2	0.70a	2.5a	2.3b	2.8b	3.4b	4.3b	6.3ab	7.3ab	7.8ab
BL_3	0.82b	2.9b	2.8c	3.2c	4.0c	4.9c	6.8c	7.7b	8.3b
BL_4	0.71a	2.5a	2.4b	2.8b	3.5b	4.5bc	6.6bc	7.4ab	8.2b

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

Stand volumes of the second rotation plantation at 69 months in BL_0 and BL_3 were 45% and 60% of that in first rotation (Fig. 3), respectively. Yield decline was obvious on this degraded land after successive rotation of eucalypt plantation without land cultivation and refertilisation in the second year after plantation establishment. Mean MAI in the second rotation was about 5.7 m^3 ha^{-1} yr^{-1}, around average productivity of eucalypt plantations in south China.

Nutrient Concentration in First Expanded Leaves

Nutrients in the first fully expanded leaves were measured in leaves taken when trees were 2 years old. Harvest residue intensity significantly ($p<0.05$) affected N and P concentrations in leaves. The N concentration of leaves increased from 14.5 to 16.2 g kg^{-1} as more residue was retained. The concentration of N in BL_3 was higher than that in BL_0 and BL_1 and N concentration in BL_2 and BL_4 was higher than that in BL_0. Phosphorus concentration of leaves in BL_3 was also higher than that in BL_0 and BL_1. The intercropping treatment had no significant effect on either the N or P concentration of leaves. Moreover, the concentration of N and P in the leaves was correlated with the N and P contents in harvest residue (Fig. 4). This indicated that nutrients from residue decomposition increased nutrient uptake by trees in the early stage of the second rotation.

Litterfall

Harvest residue intensity had a significant effect ($p<0.001$) on the amount of litterfall in the 36 to 46-month-old trees (Fig. 5). The amount of litterfall increased as the amount of residue retained increased. The litterfall in BL_4 was significantly higher than any of the other treatments because both the eucalypt and the inter-row acacia trees had produced litter. Litterfall in BL_3 and BL_2 were significantly higher than that in BL_0.

Figure 1. Stand volume of *E. urophylla* plantation at Yangxi at 46 months. Means of the treatment with same letter are not significantly different at p=0.05 using Newman-Keuls critical range test. Bars represent one standard deviation

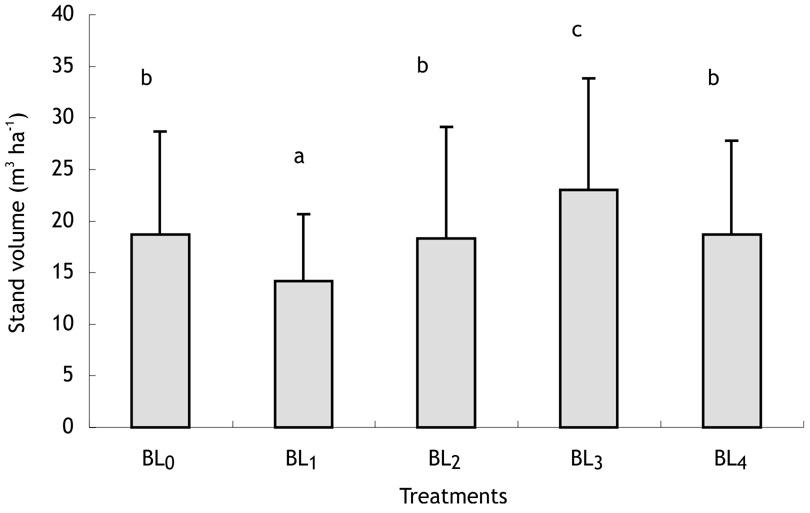


Figure 2. Stand volume of *E. urophylla* plantation at Yangxi at 69 months. Means of the treatment with same letter are not significantly different at p=0.05 using Newman-Keuls critical range test. Bars represent one standard deviation

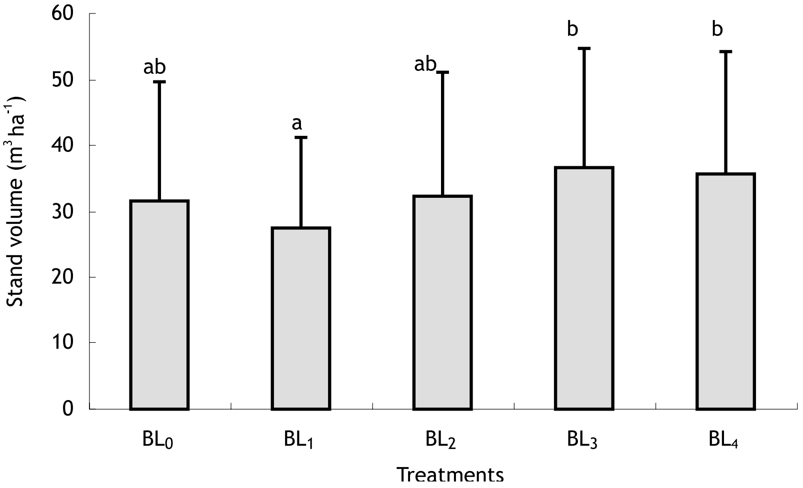


Figure 3. Stand volume of first rotation *E. urophylla* plantation at the site at 71 months (PR) compared to the two treatments (BL_1, BL_2) in the current study (2R) at 69 months. Bars represent one standard deviation

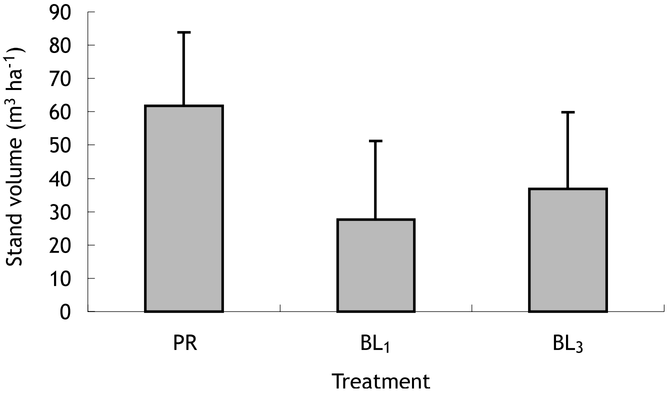


Figure 4. Relationship between N and P contents in harvest residue and concentrations of young fully expanded leaves (YFEL) in 2.5 year-old *E. urophylla*

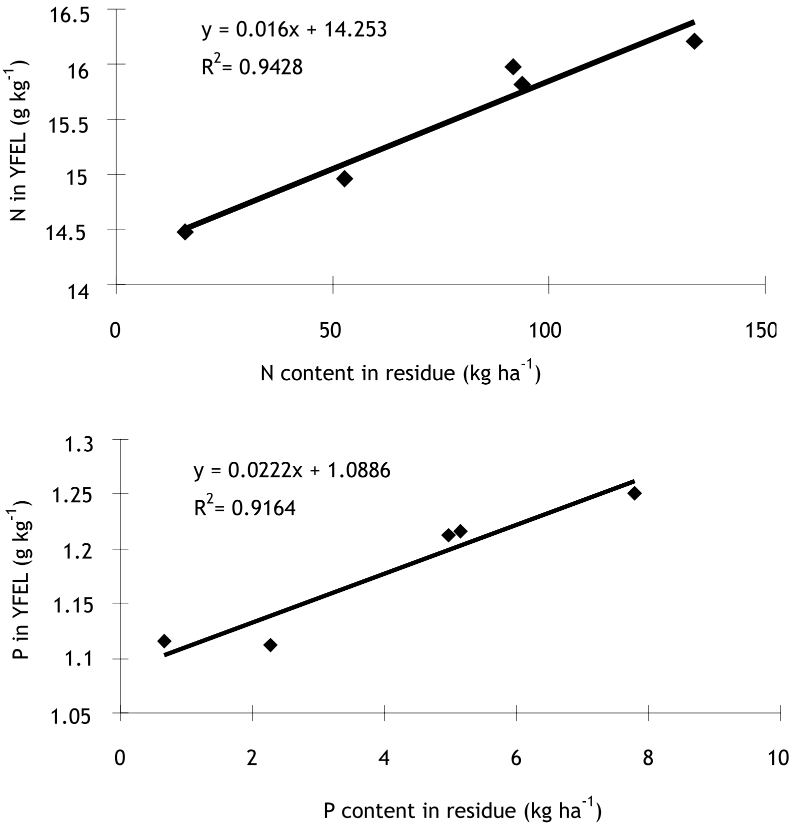
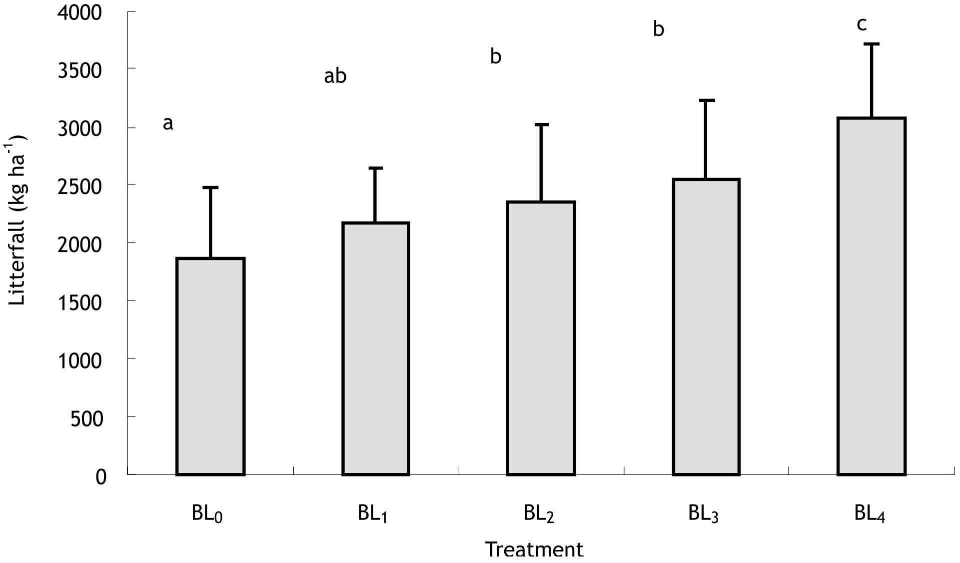


Figure 5. Effect of harvest residue management on amount of litterfall from 36 to 46 months of age in *E. urophylla*. Means of the treatment with same letter are not significantly different at p=0.05 using Newman-Keuls critical range test. Bars represent one standard diviation



Decomposition of Harvest Residue

Initial decomposition of leaf litter was rapid with 72% of the dry weight lost in the first 180 days after harvest (Fig. 6). After 180 days, the rate slowed as the total loss increased to 78% by 440 days after harvesting. In the same period, branch slash lost 41% of the original dry weight and the mixed slash of branch and leaves lost 63%.

Change of Soil Properties at Different Sampling Times

Across all treatments, organic C in top soil 2 years after planting (in 1999) was significantly lower ($p<0.001$) than that before tree planting (in 1997) in all three layers (0-10, 10-20 and 20-40 cm). However, organic C in soil 4 years after planting (in 2001) was higher ($p<0.001$) than that before tree planting (Fig. 7). It was clear that organic C decreased in the early stage of plantation establishment and increased in the late stage of the plantation in a 6-7-year rotation. The change in the surface soil (0-10 cm) was larger than that in lower layers (10-20 and 20-40 cm). Total N in soil before tree planting was significantly higher ($p<0.01$) than that after tree planting in 3 layers and the change in top soil was larger than in subsoil.

Both available N and exchangeable K were significantly higher after tree planting ($p<0.001$) than that before tree planting (Fig. 8). Available N, 4 years after planting was higher than 2 years after planting. Exchangeable K, 2 years after planting was higher than 4 years after planting in 0-10 and 10-20 cm soil layers.

There was no significant change in total P in surface soil at different sampling times. However, there was a significant change in available P ($p<0.05$) in soil. Available P in the surface soil (0-10 cm) 2 years after tree planting was significantly higher than that before planting (Fig. 9). Difference between before planting and 4 years after planting in available P was not significant.

Figure 6. Dry weight loss of leaf, branch and mixed slash retained from the first rotation

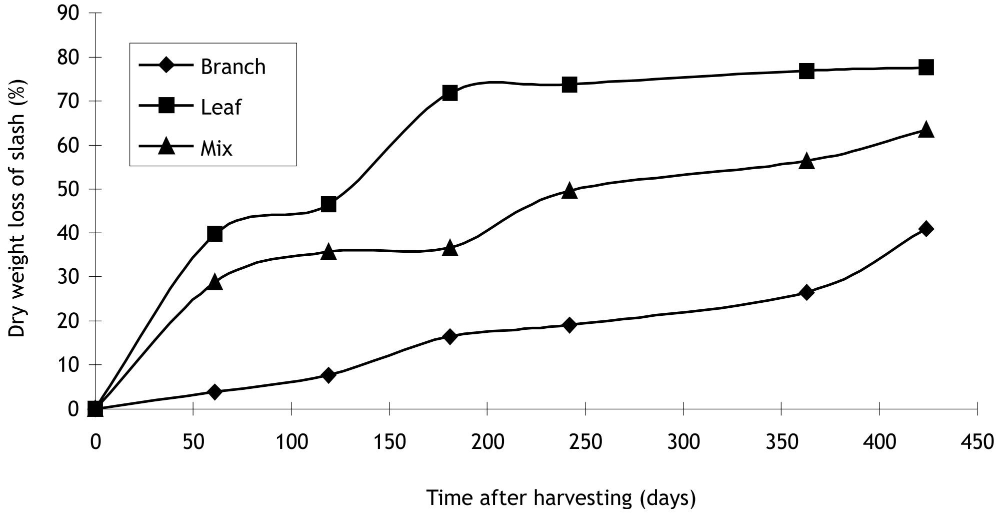


Figure 7. Change of the means of soil organic C and total N in different sampling times

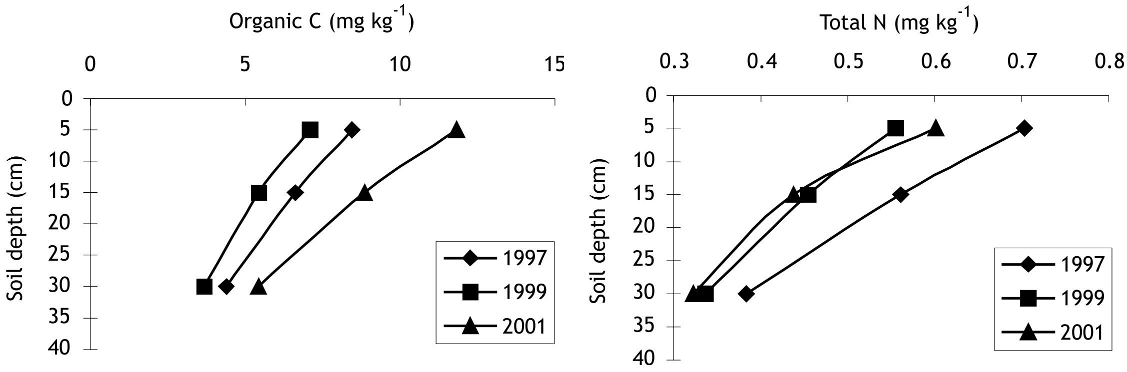


Figure 8. Change of the means of available N and exchangeable K in different sampling times

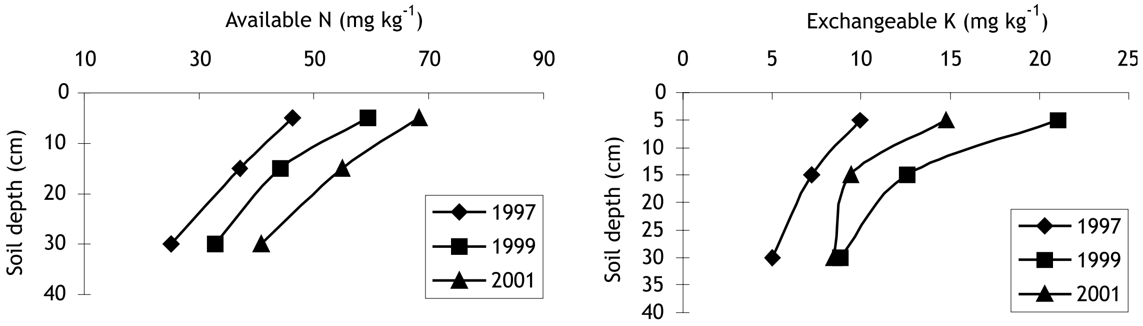


Figure 9. Change of available P in different sampling times

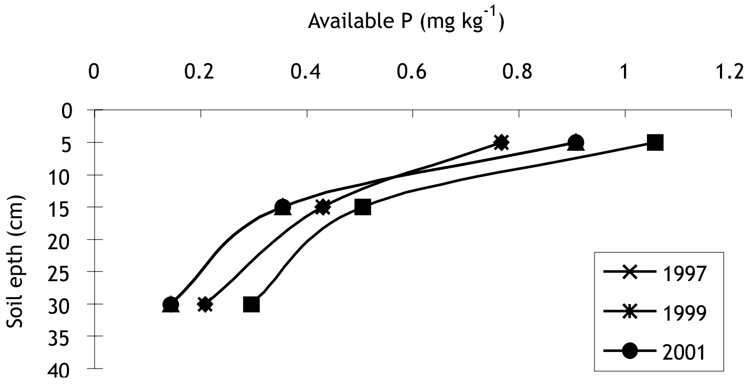
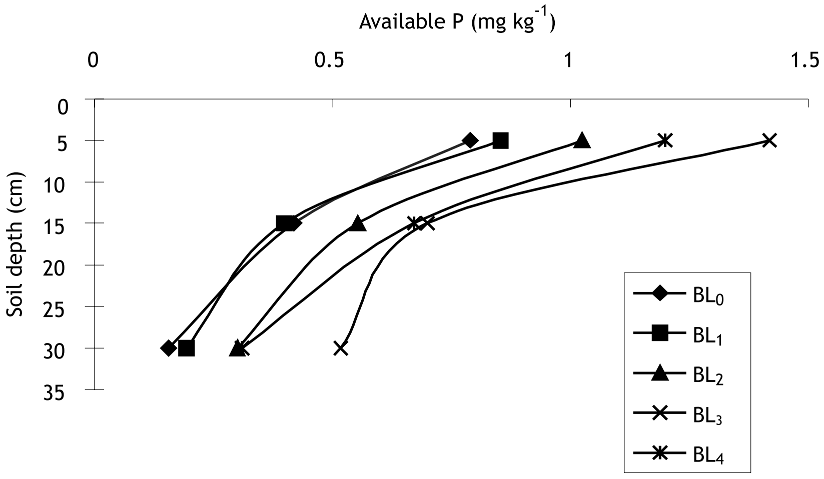


Figure 10. Change of available P in three depths of soil in different treatments 2 years after planting

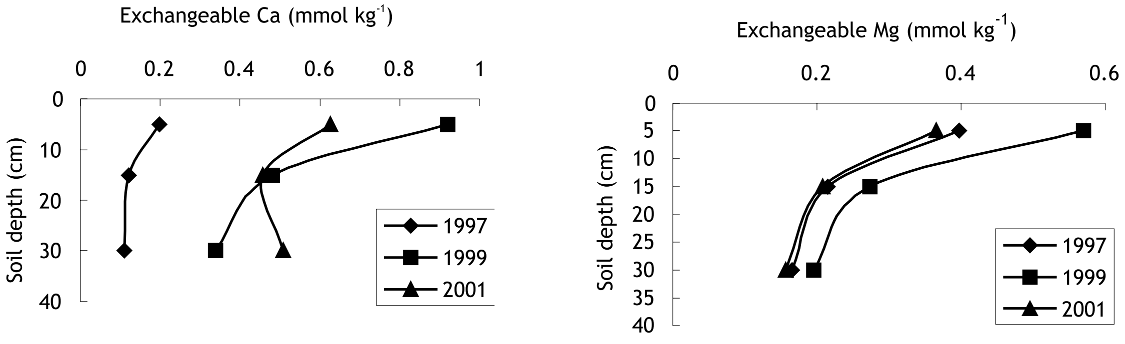


Available P was also not significantly different between 3 sampling times in 10-20 cm and 20-40 cm subsoil layers.

There was a significant ($p<0.01$) difference between treatments in available P in the surface soil 2 years after planting. Available P in BL$_3$ and BL$_4$ was higher than that in BL$_0$ and BL$_1$ (Fig. 10).

There was a significant ($p<0.001$) difference between sampling times in exchangeable Ca and Mg in the 0-10 cm soil layer. Exchangeable Ca two years after tree planting (1999) was higher than that before tree planting. In the 0-10 cm soil layer, exchangeable Ca 4 years after tree planting was lower than two years after tree planting. Exchangeable Mg two years after tree planting in soil was higher than either before tree planting or four years after tree planting in all three layers.

Figure 11. Changes in exchangeable Ca and Mg at different sampling times



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

Effect of fertilisation on growth of replanted trees was highly significant ($p<0.001$) (Fig. 12). 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 and 69 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. 12).

Up to 46 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. 13). 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 3.9 cm in diameter) but the advantage of coppicing declined with fertiliser application.

There was significant difference ($p<0.001$) between replanting and coppice in stand volume at 46 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. 14). MAI of coppice was about 6.6 m^3 ha^{-1} yr^{-1}, similar to that in the previous plantation.

There was no significant difference among BL_1, BL_2 and BL_3 without fertilisation (Fig. 15). Without fertilisation, trees in BL_0 treated plots grew faster than trees in BL_3 and BL_2 plots in the 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 late stage of a rotation. Productivity of the plantation without fertilisation was very low and is not acceptable in commercial operations.

Nutrient Concentration in Leaves

The higher level of fertilisation significantly ($p<0.05$) increased foliar N concentration (Fig. 16). Nitrogen concentration in both RF_2 and CF_2 was higher than that in other treatments. Nitrogen concentration in RF_1 was also higher that that in BL_0F_0. Only the higher level of fertilisation significantly increased P concentration in fully expanded leaves (FEL), with P concentration in both CF_2 and RF_2 higher than in any other

Figure 12. Effect of fertilisation on height and diameter growth of planted trees and coppice (the first two diameter measurements were at 0.1 m height, the later measurements at 1.3 m)

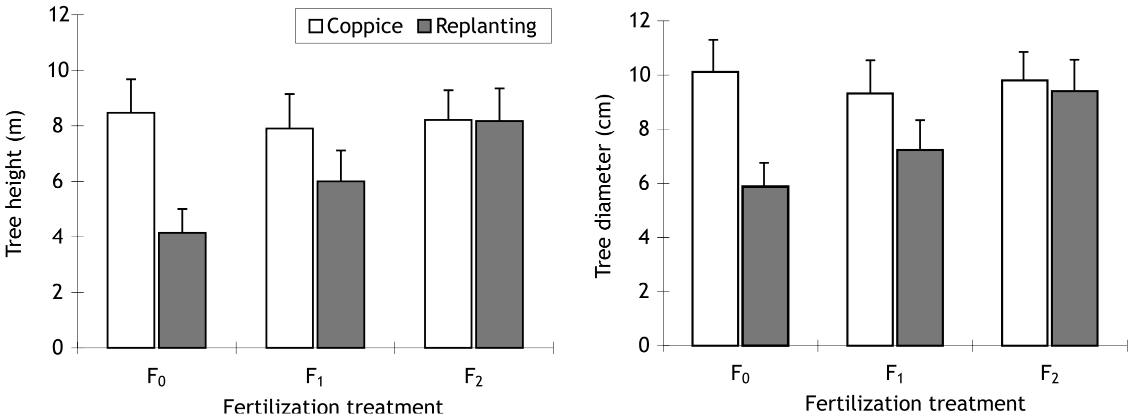
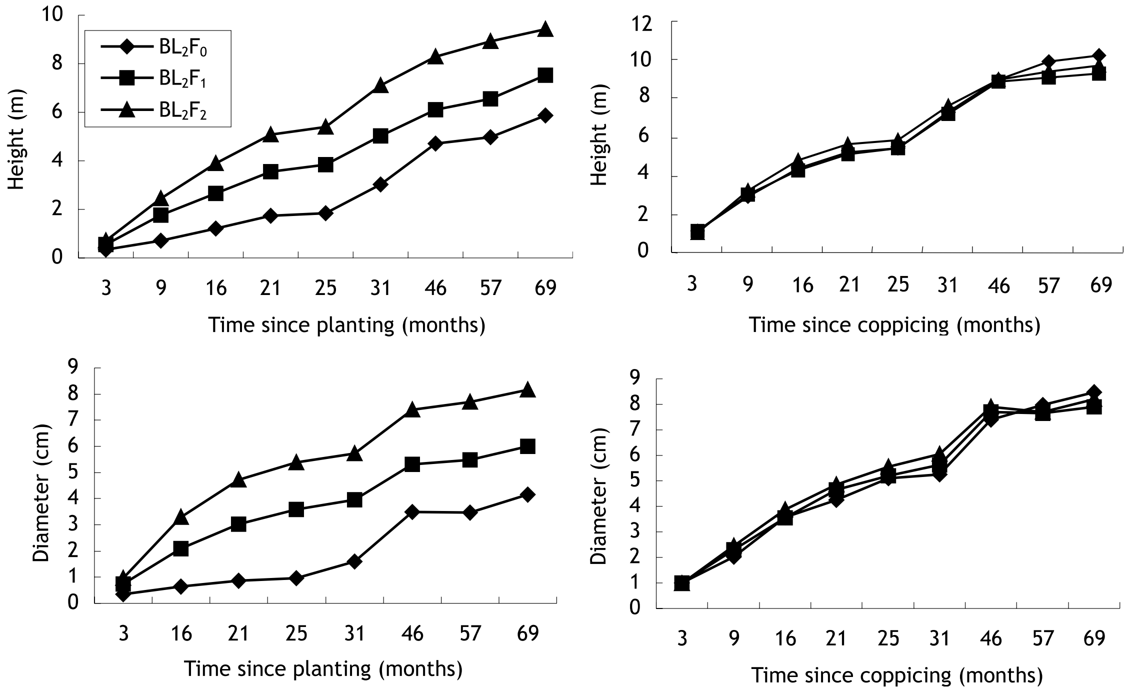


Figure 13. Interaction between re-establishment methods and fertilisation levels on tree height and stem diameter 69 months after treatments on planted trees (A) and coppice (B)



(A) **(B)**

Figure 14. Effect of fertilisation on stand volume of planted trees and coppice 69 months after re-establishment. Bars represent one standard diviation

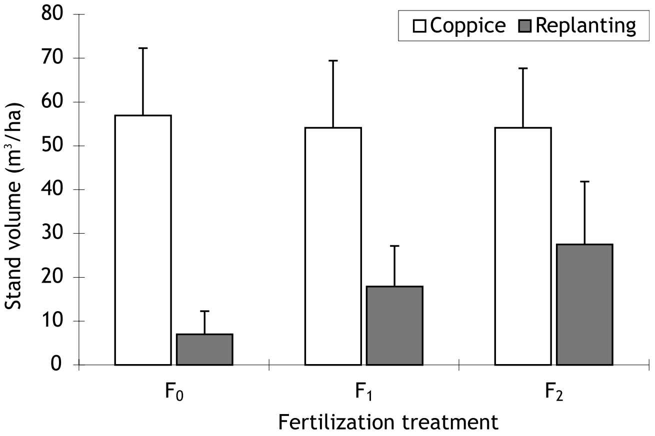
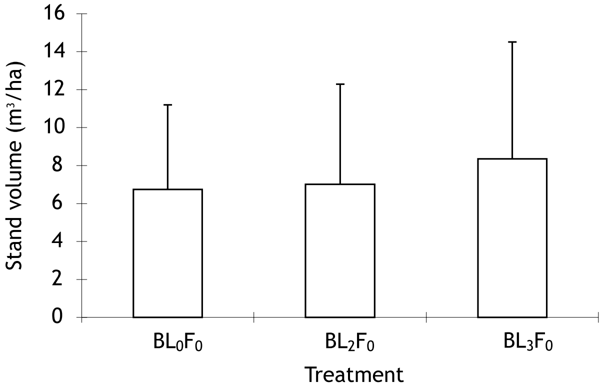


Figure 15. Tree height and diameter in BL_0 and BL_3 without fertilisation 46 months after re-establishment. Bars represent one standard diviation

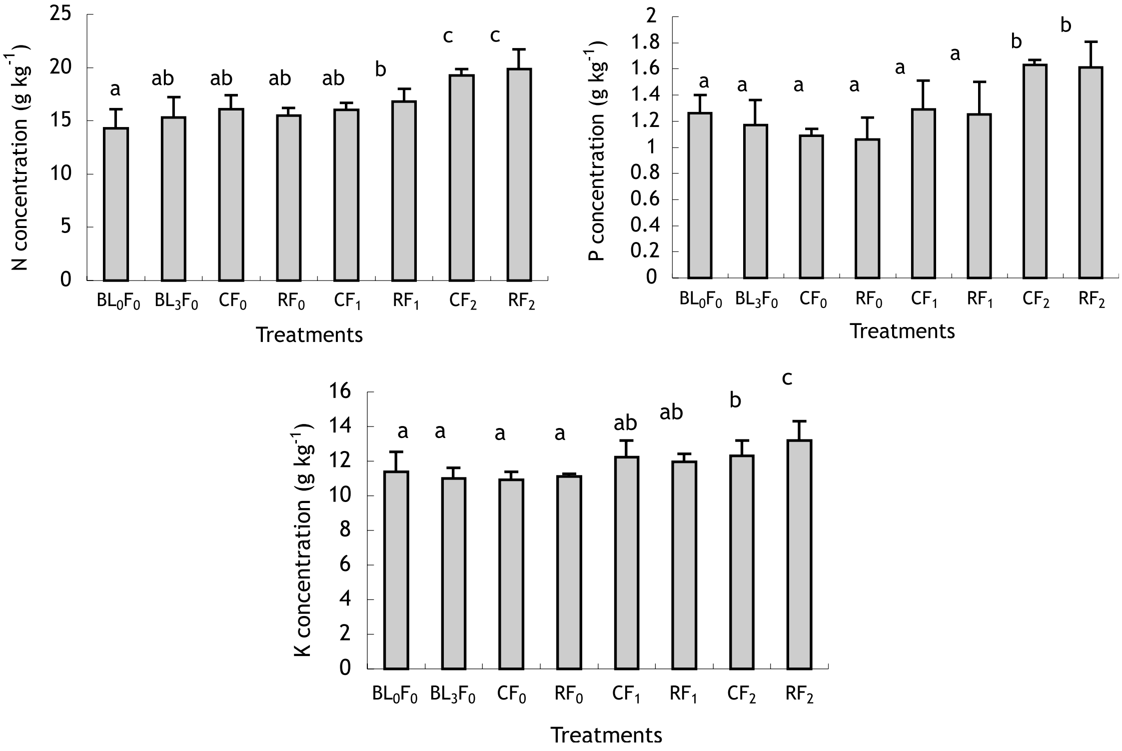


treatments. Fertilisation also increased K concentration in FEL. The K concentration in RF_2 was significantly higher than in any other treatment. The CF_2 treatment had the second highest K concentration among all treatments, but it was not significantly greater than when the lower level of fertiliser was applied. It is clear that fertilisation improved nutrient status for both seedling trees and coppice trees.

Discussion

Harvest residue management intensity had a significant impact on the amount of nutrients retained on site (Xu *et al.* 2000b). Decomposition of residue occurred mainly in the first two years after harvesting. Therefore, exchangeable K, Ca and Mg in soil, 2 years after tree planting were the highest among three sampling times (before tree planting, 2 and 4 years after tree planting). Residue retention increased available P in 0-10 cm soil, 2 years after tree planting and increased NO_3-N in topsoil in the first year after planting (Xu *et al.* 2000b). Residue retention also increased the amount of litterfall in the second rotation. Organic C additions in the late stage of plantation establishment could be litterfall from trees and understorey, most of which died during the dry winter, and slower rate of decomposition after canopy closure. However, the C change in top soil could partly related to the variation of soil core sampling locations. Concentration of N and P in young fully expanded leaves was also increased by N and P contents in residue left on site. It also indicated that lack of N and P could be a major constraint to tree growth and harvest residue retention is one of the key factors to

Figure 16. Nutrient concentrations in young fully expanded leaves of replanted (R) and coppice trees (C) of *E. urophylla* 2.5 years after re-establishment. Means of the treatment with same letter are not significantly different at p=0.05 using Newman-Keuls critical range test. Bars represent one standard deviation



maintain soil fertility and productivity on the poor degraded site.

Increased nutrients resulting from residue retention had a significant impact on tree growth in the early stage of the second rotation of the *E. urophylla*. This result was similar to an 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. Therefore, in this low productive land with a relatively small amount of slash, slash retention by itself was not sufficient to increase productivity to a high level. In this experimental site, MAI of the plantation in the previous rotation was about 10.3 m^3 ha^{-1}yr^{-1}, much higher than the average 5.7 m^{3}ha^{-1}yr^{-1} across all treatments in the second rotation. Although double slash (BL$_3$) increased MAI by 32% over all aboveground biomass harvest treatment (BL$_1$), MAI in BL$_3$ in second rotation was only 60% of the MAI in previous rotation. The fertilisation regime in the second rotation experiment was less than in the first rotation. This was to avoid the response to fertiliser overshadowing the effects of retaining harvest residue. Slash retention helped but was not enough to lift production. An intensive fertiliser program could be more important than harvest residue retention on this degraded site to raise productivity to a high level. Then slash retention and increased litter production in next rotation will conserve large amounts of nutrients. The addition of fertilisers and conservation of nutrients will reduce the amount of fertiliser required in future rotations and help maintain long-term productivity and soil fertility.

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 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. If new site preparation methods are adopted for soil fertility conservation and there is less and less understorey collection, weed control should be practised. More study is needed to develop good weed control options for farmers growing trees.

Intercropping with *Acacia* increased tree growth in the latter stage of the second rotation. If rotation lengths become shorter intercropping is probably not a viable management option. More study is needed to validate potential productivity increases by establishing the intercropping system between eucalypts and acacias.

Coppice was better than replanting for the second rotation at 69 months old. 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 retaining in the root system left from previous rotation. Productivity of the second rotation coppice on this poor site was slightly higher than average productivity of eucalypt plantations in south China. It is recommended that coppice be adopted for second rotations of eucalypt plantations unless improved genetic material is available for planting. Productivity of second rotation seedling trees was lower than average because the soil had been degraded. But fertilisation increased the productivity substantially. It is suggested that plantations on degraded lands should be adequately fertilised so that reasonable productivity can be achieved. Slash decomposition is rapid in this tropical climate. Thus, available nutrients were increased by slash retention in the first and second years after harvesting. The amount of fertiliser used in F_2 was similar to the amount in the first rotation and seems to be high enough to raise nutrient concentrations to a level compared with other experiments done in China (Xu *et al* 2001). However, MAI in this high fertilisation treatment with slash retention (BL_2F_2) was only 67% of the MAI in the first rotation. This indicates that yield declined in the second rotation on this poor degraded site without the benefits of genetic improvement.

Acknowledgements

We are grateful to the Center for International Forestry Research (CIFOR) for the support for the study. We express our sincere thanks to A.Tiarks and E.K.S. Nambiar for review and advice on this paper.

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. ACIAR Monograph No. 43. Australian Centre for International Agricultural Research, Canberra, Australia.

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 adubacão 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.

Wang, H. and Zhou, W. 1996. Fertilizer 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. 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, 251-258. University of Dresden, Germany.

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. 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, 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. and 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., Cossalter, C., Tiarks, A. 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. and 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.

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

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Improved Productivity of Eucalypt Plantations through Site Management Practices in the Monsoonal Tropics: Kerala, India

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Abstract

Impacts of site management practices on the productivity of *Eucalyptus tereticornis* and *E. grandis* in industrial plantations have been investigated at four forest sites in Kerala State, southwest India. Management practices studied were: (1) harvest residue management; (2) nutrient additions; (3) weed control; and (4) legume cover cropping. Significant removal of nutrients from eucalypt plantations occurs through harvest of wood and removal of other aboveground biomass. Conservation of nutrients on site through retention of harvest residues and/or nutrient addition will be required to ensure sustained productivity. Retention of harvest residues had no effect on soil total C, N and P at 2 years after establishment. Tree growth did not respond to residue management or legume cover cropping at any of the sites at 4 years, but was significantly enhanced at 2 sites by N application, and at 1 site by P application. Weed control resulted in productivity increases at the *E. tereticornis* sites. There is a major opportunity for improving productivity of eucalypt plantations in Kerala through adoption of intensive management practices.

Introduction

Eucalypt plantations occupy 4.8 million ha across India and represent about 25% of the country's plantation estate (FAO 2000). They are increasingly important for the supply of industrial wood and fuel wood in the country, because timber harvesting from native forests has been declared illegal. In Kerala, the area under eucalypt plantations is approximately 40 000 ha. The two major species are *Eucalyptus grandis* Hill ex Maiden and *E. tereticornis* Sm. *Eucalyptus tereticornis* is grown at lower elevation (<500 m asl) on the undulating coastal plains and *E. grandis* at higher elevation (500-2000 m asl) in the Western Ghats. Productivity of these plantations is low, averaging less than 10 m^3 ha^{-1} yr^{-1}, and has been declining over successive rotations at many sites. Many other regions in India also have relatively low eucalypt plantation productivity, and have had declining production over multiple rotations. Currently, eucalypt plantations supply only about one-third of the annual demand of

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Kerala's paper and pulpwood industries (Jayaraman and Krishnankutty 1990). Kerala State has limited land available for increasing the area under plantations, but has a high demand for eucalypt pulpwood (350 000 t yr^{-1}). Thus it is imperative that the productivity of the plantations should be improved and sustained.

Soils under eucalypt plantations in Kerala generally have low nutrient status (Balagopalan and Jose 1983, 1986, Sankar *et al.* 1988, Ghosh *et al.* 1989). Successive rotations of plantations at the same site with minimal inputs, use of poor quality planting stock, weed competition and detrimental management practices (eg, burning of harvest residues), contribute to the low productivity. Water stress experienced in some areas (Kallarackal and Somen 1997) and the incidence of fungal diseases are also factors limiting growth of eucalypts in the region (Sharma *et al.* 1985).

Long-term studies have shown that management practices aimed at conservation of soil organic matter and improved soil nutrient status can contribute to sustainable productivity (Nambiar 1996, Tiarks *et al.* 2000). The present study applied these principles in a tropical monsoonal environment to maximise productivity of forest plantations. It aims at manipulating site organic matter, nutrients and available water so as to optimise resources for improving productivity from eucalypt plantations. Data on total aboveground biomass and nutrients and organic matter turnover have been reported previously (Sankaran 1999, Sankaran *et al.* 2000). In this paper we report on: (1) tree crop biomass, nutrient stores and nutrient export at harvest; (2) impact of harvest residue management on soil nutrient stores; and (3) effect of harvest residue management, nutrient additions, weed control, and legume cover cropping on tree growth at age 4 years, which is approximately half of the typical rotation length of 7 years.

Location, Climate and Site Description

Kerala State is located in southwest India between latitudes 8-13°N and between the Arabian Sea and the Western Ghat mountain ranges. A detailed account of the climate of the experimental sites has been provided (Sankaran 1999, Sankaran *et al.* 2000). The climate is tropical warm humid monsoonal, with two monsoon periods. The southwest monsoon, the main monsoon, starts in early June and extends until October. The northeast monsoon brings occasional rains from December to February. The dry season begins in March and continues through May. Average rainfall is 3000 mm (range 2200-3600 mm) spread over 120 rainy days. Mean atmospheric temperature is 27°C (range 20-42°C) and relative humidity ranges between 64% (February-March) and 93% (June-July) (Menon and Rajan 1989). The geographical position, altitude, rainfall and selected characteristics of the study sites are given in Table 1.

There are four study sites, two each planted with *E. tereticornis* and *E. grandis*. At all sites, the parent material of soils was saprolite or saprolitic colluvium derived from Precambrian granites and gneiss. These igneous and metamorphic rocks contain abundant ferro-magnesium minerals that contribute to the chemical fertility of sites where rocks are present at shallow depth or in outcrops. Most soil profiles contained a ferralic B horizon (FAO 1990). 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 adjacent to the coastal plain. These sites were originally under degraded moist deciduous forests, with the first plantation crop planted in 1977. Trees were first harvested in 1991 and the first coppice crop (second rotation) was harvested in early 1998. The two *E. grandis* sites (Surianelli and Vattavada) are located in the high ranges of the Western Ghats. Surianelli was a grassland (mainly composed of *Chrysopogon* sp.) before planting with *E. grandis* in 1968. After three rotations of the first crop, the site was replanted in 1991. The study site at Vattavada was planted with *E. grandis* in 1958 after clearing a natural semi-evergreen forest. The trees were clearfelled after three rotations of the crop and replanted in 1991. Stands at both the sites were harvested in May-July 1998 as a part of this study.

Experimental Design

Following harvesting of stands, 5 or 6 experiments were established at each of the sites during June-September 1998. Each experiment is in a randomised block design with 3-6 treatments and four replicates. The plot size is 20 x 20 m, tree spacing 2 x 2 m with 100 trees per plot (36 measurement trees). At Kayampoovam 18 x 18 m plots were used due to restricted available area (retaining the same spacing). *E. grandis* grew rapidly and canopies closed early at both sites, so stands were thinned to 1667 stems ha^{-1} in May-June 2000. For a detailed description of the experiments see Sankaran *et al.* (2000). In summary, the core experiments included: (1) manipulation of harvest residues; (2) use of inter-row legumes as cover crops (at the two *E. tereticornis* sites); (3) conservation of soil and water using trenching; (4) weed control; (5) nutrient addition (application of N and P with basal addition of other major and minor nutrients); and (6) a tree spacing (833, 1250, 1667 and 2361 stems ha^{-1}) experiment was established at the two *E. grandis* sites when they were at age 2 years.

The harvest residue management study includes six treatments viz., **BL$_0$**, **BL$_1$**, **BL$_3$**, **L** (leaf residue only retained) **BS** (Burn-BL$_1$ residues burnt) and **B** (burn without added starter fertiliser). All treatments except B received a starter fertiliser (100 g N:P:K 17:7:14) in two doses at planting and three months later.

In the N addition experiment, five rates of N (as urea at: **N1**-0 kg, **N2**-18 kg, **N3**-60 kg, **N4**-187 kg, **N5**-375 kg N ha^{-1}yr^{-1}) were applied in the first two years. Another application was made in the 4th year after establishment, at 50% (*E. tereticornis*) and 33% (*E. grandis*) of the original rates. In the P addition experiment, five rates of P (**P1**-0 kg, **P2**-6.3 kg, **P3**-21 kg, **P4**-63 kg, **P5**-131 kg P ha^{-1}) were applied as superphosphate in the first two years. In both experiments, the trees received a basal dressing of other major and minor nutrients. Basal dressing of P in the N experiment was equivalent to the P4 treatment, and basal dressing of N in the P experiment was equivalent to the N4 treatment.

The weed control study had 3 weeding treatments: (1) no weed control except around the tree base (**NW**); (2) 1 metre strip weed control along the tree rows (**SW**); and (3) complete weed control (**CW**). The effects of a legume understorey on tree growth and soil properties were examined at the lowland *E. tereticornis* sites, where the perennial *Mucuna bracteata* DC. and *Pueraria phaseoloides* (Roxb.) Benth. and the annual *Stylosanthes hamata* Taub. were established. Additional phosphorus fertiliser (42 kg P ha^{-1}) was applied to all plots in the legume experiment.

Experimental Details

Tree Biomass and Nutrient Content

Before harvesting the stand, DBH (diameter at breast height - 137 cm) of all trees at each site, was measured. At each site, 6-8 trees representing the range in DBH were harvested to determine the tree biomass and nutrient content. Total height, height at the base of the crown and stem diameter at different heights (over and under bark) were measured and trees separated into leaves, branches (<1 cm, 1-3 cm and >3 cm diameter), stem wood and stem bark. Subsamples of each component were dried at 70°C and weighed to determine the biomass of tree components. Subsamples were ground and analysed for N, P, K, Ca and Mg. Biomass and nutrient content of the trees at each site were calculated on a dry-weight basis by relating DBH of trees to component dry-weight or nutrient content using allometric functions. Biomass of understorey and forest floor was determined by sampling in randomly placed quadrats. These were also used for nutrient content determinations (Sankaran *et al.* 2000).

Soil Sampling

Soils at each site were described using two 1 m deep soil pits. Soils were sampled using stainless steel corers. Two replicate soil cores were taken about 0.5 m from the face of each pit. Soils were analysed for total C, N and P, and exchangeable K, Ca and Mg (Rayment and Higginson 1992). Surface soil samples (0-10 and 10-20 cm) were sampled within each experimental plot in May

Table 1. Selected characteristics of the experimental sites (from Sankaran *et al.* 2000)

	Site and plantation species			
	Kayampoovam *E. tereticornis*	Punnala *E. tereticornis*	Surianelli *E. grandis*	Vattavada *E. grandis*
Latitude	10°41’ N	9°06’ N	10°02’ N	10°08’ N
Longitude	76°23’ E	76°54’ E	77°10’ E	77°15’ E
Altitude (m)	120	150	1280	1800
Rainfall (mm yr $^{-1}$)	2700	2000	3000	1800
Soil texture	Coarse sandy light clay to medium clay	Sandy loam to clay loam	Fine sandy light medium	Silty clay loam to medium clay clay to sandy loam
Surface soil properties (0-10 cm)				
pH (1:5 H_2O)	5.3	5.1	4.8	5.3
Organic 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
Original plantation Density (stems ha^{-1})	1355	972	1056	3897
Basal area (m^2 ha^{-1})	12.9	7.3	10.3	33.7

Table 2. Total soil stores of organic C and nutrients to 1.0 m at each of the sites. Standard error of the mean is in brackets

Location	Species	C	N	P
			(t ha^{-1})	
Kayampoovam	*E. tereticornis*	106 (4)	9.0 (0.4)	8.76 (0.92)
Punnala	*E. tereticornis*	141 (15)	9.3 (1.4)	2.91 (0.88)
Surianelli	*E. grandis*	296 (30)	15.9 (4.6)	5.22 (0.72)
Vattavada	*E. grandis*	215 (34)	16.2 (1.4)	8.58 (0.46)

1998 to provide base-line soil chemical characteristics of the applied harvest residue treatments. Annual sampling of soil from selected treatments is being conducted in July-September each year to evaluate impacts of treatments.

Tree Growth

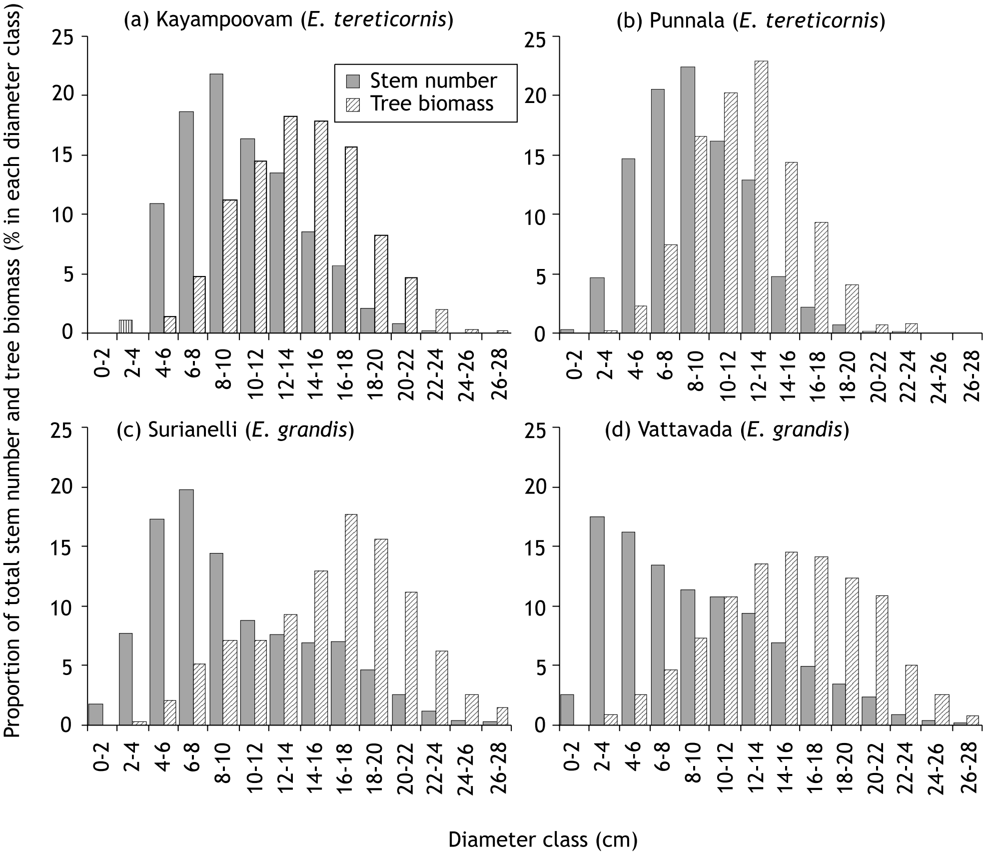
Tree stem diameter and height were measured regularly. Stem volume (v) was calculated as the volume of a cone according to the equation: $v = \frac{1}{3}\pi r^2 h$, where *r* was the radius at the tree at ground level (predicted from the diameter measured at breast height) and *h* was the height of the tree.

Results

Pre-harvest Stand Characteristics

Figure 1 shows the distribution of stem density and standing biomass with diameter class at each of the sites. At Vattavada the original stand density of *E. grandis* was relatively high (3897 stems ha^{-1}), but most stems were relatively small, with 2-4 cm the most populated class (Fig. 1d). The largest proportion of total tree biomass was in trees in the 16-18 cm diameter class. The other sites had lower stand densities, and the maximum proportion of trees was in diameter classes 8-10 cm at Kayampoovam and Punnala and 6-8 cm at

Figure 1. Tree number and aboveground biomass in relation to stem diameter class distribution at the four study sites



Surianelli. Punnala had the lowest stand density, and it also had fewer trees in the largest diameter classes (14 cm) than the other sites.

The majority of the aboveground standing biomass at each site was in the stem wood (Fig. 2a). However, wood had the lowest nutrient concentrations, so that the proportion of nutrients in the other components was high relative to their weight. Stem wood had 22-47% of the tree N, 38-54% of P and 38-44% of K, and 15-27% of both Ca and Mg. Leaves were the largest store of N at the highland sites whilst stem bark was the highest store of Ca and Mg across all of the sites in both species (Fig. 2b-f).

Soil Organic Carbon and Nutrients

Concentration of organic C and N in soil decreased with depth (Fig. 3), but changes in P concentration with depth were small. Highland sites (Surianelli and Vattavada) had higher organic C and total N than the lowland sites, especially at depth (Table 2, Fig. 3). Total cumulative N to 1 m depth at the two highland sites (average 16 t ha^{-1}) was close to double that at the lowland sites (average 9 t ha^{-1}). Soils at Kayampoovam had relatively low C and N but relatively high P in the surface soil, compared to Punnala. The Vattavada site had high P concentrations but relatively low C concentrations at depth, compared to Surianelli.

Biomass and Nutrient Export Following Harvest

Removal of biomass and nutrients was evaluated for two scenarios: (1) harvest of stem wood only; and (2) harvest of all aboveground biomass from

Figure 2. Partitioning of (a) biomass, (b) nitrogen, (c) phosphorus, (d) potassium, (e) calcium, and (f) magnesium between the leaves, branches, stem bark and stem wood components of the tree crop at Kayampoovam (*E. tereticornis*), Punnala (*E. tereticornis*), Surianelli (*E. grandis*), and Vattavada (*E. grandis*). Bars show standard error of the mean

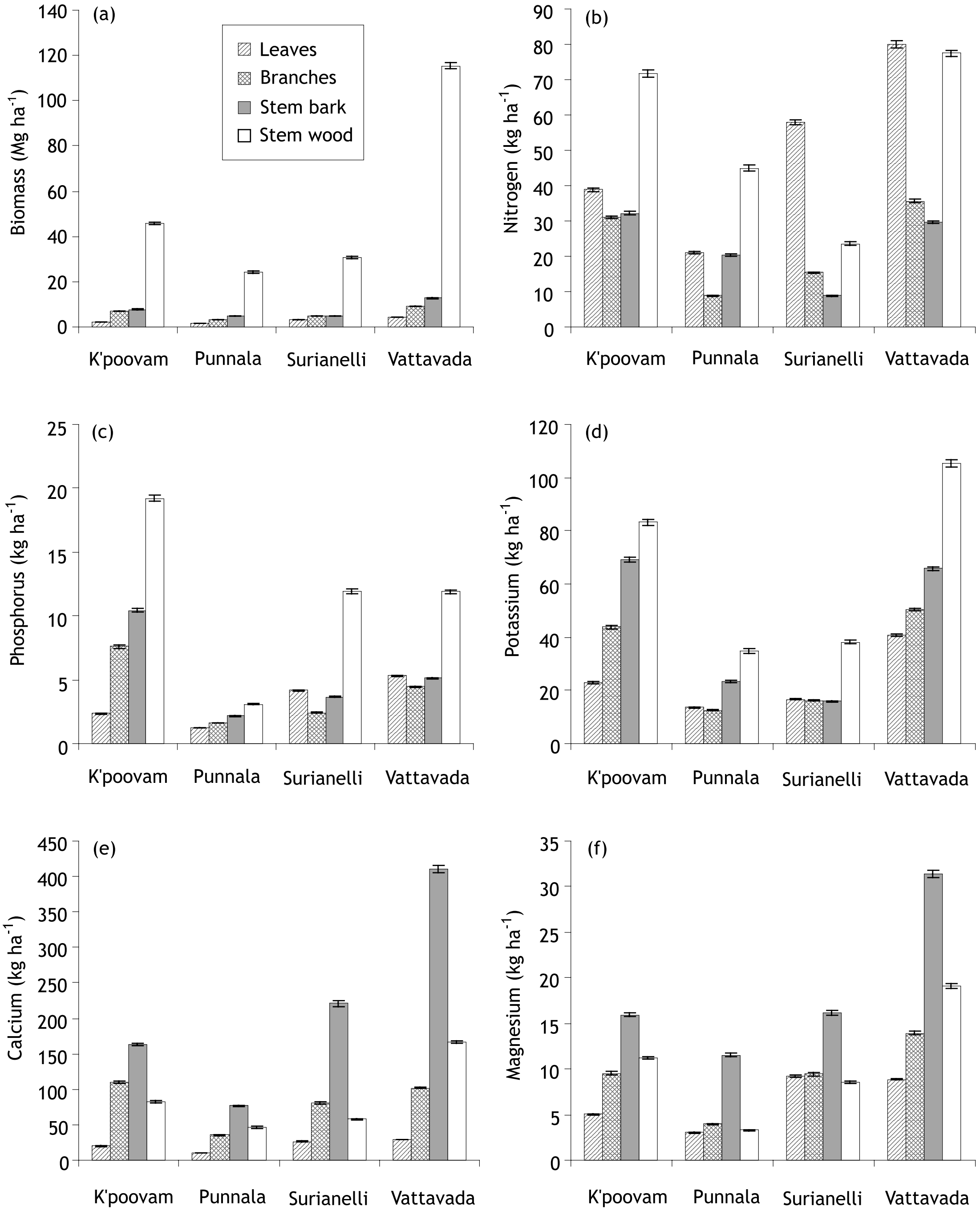
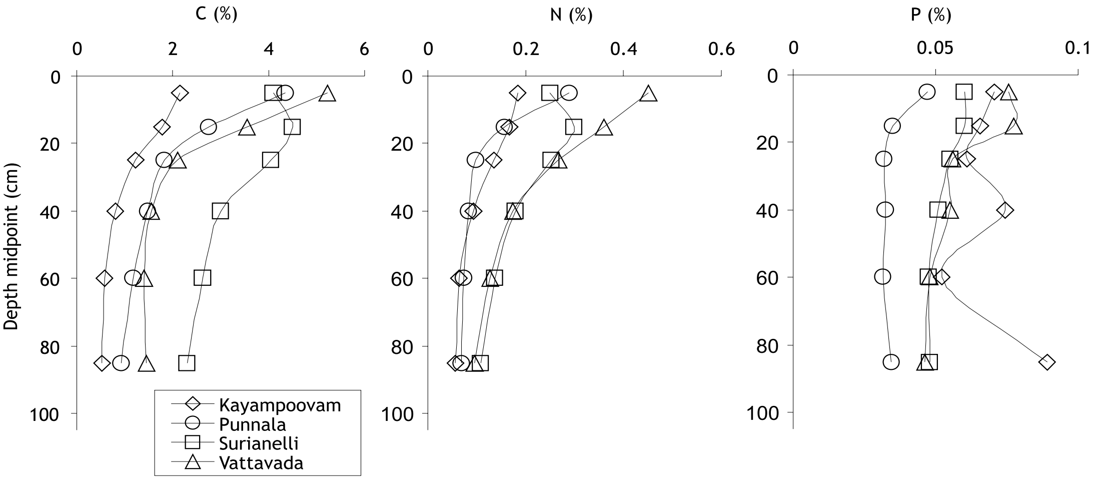


Figure 3. Concentrations of (a) soil organic carbon, (b) total soil nitrogen, and (c) total soil phosphorus in relation to depth (samples collected in 2000)



the sites (Tables 3 and 4). The second scenario occurs at some locations where wood is harvested and harvest residues, understorey and forest floor litter are collected by local people for firewood. Burning of residues is also a common practice as a part of site preparation for planting. Annual production of dry stem wood was 6.6, 3.5, 4.4 and 16.5 t ha^{-1} yr^{-1} for Kayampoovam, Punnala, Surianelli and Vattavada respectively. If the stemwood only was harvested at the end of the seven-year rotation, 24-115 t ha^{-1}yr^{-1} wood (Table 3) and 24-77 kg ha^{-1} of N (Table 4) would be removed from the site. However, if all the aboveground biomass were harvested, removal of N would be 247-358 kg ha^{-1} which is equivalent to an average of 2.6% of total site pools (soil and tree) down to 1 m depth. Removal of P under the same conditions would be 20-56 kg ha^{-1}, equal to a mean of 0.6% of total site pools.

Quantities of total C, N and P in soil were much higher than those found in the aboveground biomass. However, the quantities of K, Ca and Mg in the aboveground biomass were relatively high proportions of the stores of exchangeable nutrients in the top 1 m of soil (Table 4).

Impact of Harvest Residue Management on Nutrients in Surface Soil

Changes in soil chemical properties have been monitored annually in the harvest residue management plots. The most recent results (August-September 2000, Fig. 4) showed few significant effects of harvest residue treatment on total C, N and P.

Tree Growth in Response to Harvest Residue Treatments

Residue management had no significant effect on tree growth at 4 years at all sites (Table 5). An earlier trend with higher growth in the BS treatment, apparently due to an increase in available nutrients due to ash additions following burning, was not significant at 4 years.

Tree Growth in Response to Nutrient Additions

Addition of N significantly increased growth of *E. tereticornis* at Punnala ($p<0.05$, Fig. 5) and *E. grandis* at Surianelli ($p<0.01$). Significant growth increases were also found with P addition at

Table 3. Removal of biomass under two harvest regimes

Location and species	Harvest regime	
	Stem wood only	All aboveground biomass
	(t ha^{-1})	
Kayampoovam (*E. tereticornis*)	46	82
Punnala (*E. tereticornis*)	24	51
Surianelli (*E. grandis*)	31	67
Vattavada (*E. grandis*)	115	155
Mean	54	89

Table 4. Removal of nitrogen, phosphorus, potassium, calcium and magnesium under two harvesting regimes at age 7 years

Site	Nutrient	Harvest regime	
		Stem wood	All aboveground biomass
		(kg ha^{-1})	
Kayampoovam	N	72 (0.8)	358 (3.8)
	P	19 (0.2)	56 (0.6)
	K	83 (10.0)	334 (40.1)
	Ca	83 (1.0)	627 (7.2)
	Mg	11 (0.6)	89 (5.0)
Punnala	N	45 (0.5)	247 (2.6)
	P	3 (0.1)	20 (0.7)
	K	35 (5.6)	175 (27.9)
	Ca	46 (4.2)	349 (31.6)
	Mg	3 (0.7)	72 (14.8)
Surianelli	N	24 (0.1)	344 (2.1)
	P	12 (0.2)	39 (0.8)
	K	38 (7.7)	205 (41.2)
	Ca	58 (5.9)	674 (68.3)
	Mg	9 (3.1)	116 (41.1)
Vattavada	N	77 (0.5)	338 (2.1)
	P	12 (0.1)	38 (0.4)
	K	105 (3.5)	358 (11.8)
	Ca	167 (1.5)	882 (7.8)
	Mg	19 (1.0)	102 (5.3)
Mean	N	54 (0.5)	322 (2.6)
	P	12 (0.2)	38 (0.6)
	K	65 (6.7)	268 (30.3)
	Ca	88 (3.1)	633 (28.7)
	Mg	11 (1.3)	95 (16.5)

Numbers in brackets show the net amount exported (%) as a proportion of total nutrient stores aboveground plus soil stores of total N and P and exchangeable cations to 1 m depth.

Figure 4. Influence of harvest residue management on total soil (a) carbon, (b) nitrogen, and (c) phosphorus in the surface 0-5 cm soil at 2 years after establishment. ANOVA significance levels (*: P<0.05, **: P<0.01) shown where treatment differences were significant

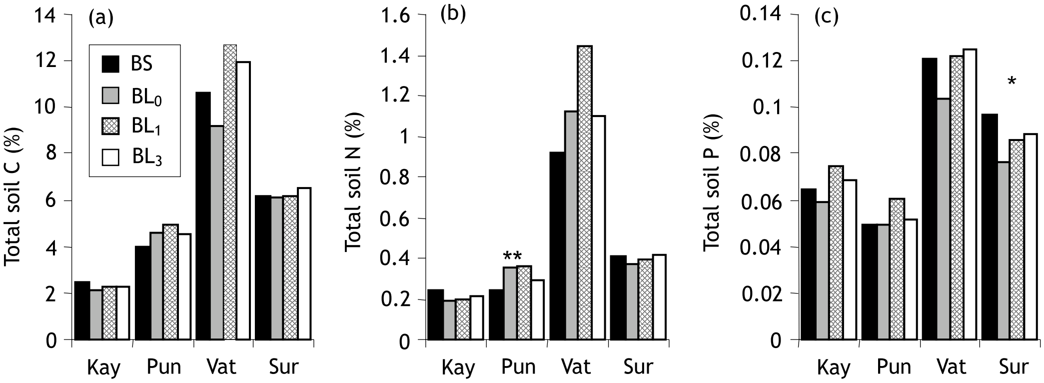


Figure 5. Stand growth response to nitrogen application at age 4 years. Bars represent LSD (p=0.05) where treatment differences were significant

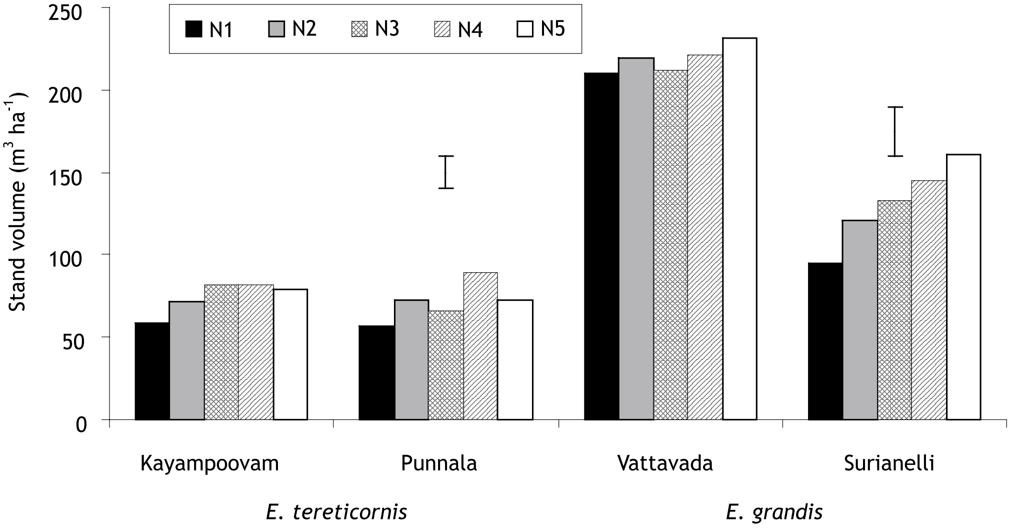
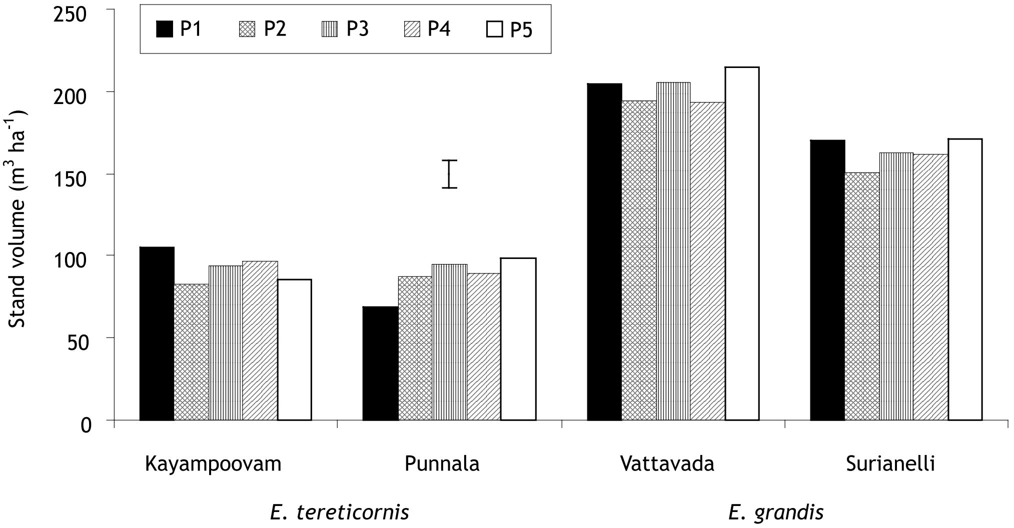


Table 5. Growth at age 4 years in the slash management experiments. Treatment differences were not found at any of the sites

Site	Species	Height (m)	DBH (cm)	Volume (m^3 ha^{-1})
Kayampoovam	*E. tereticornis*	752	6.3	72.4
Punnala	*E. tereticornis*	815	6.6	57.7
Vattavada	*E. grandis*	982	9.4	208.1
Surianelli	*E. grandis*	633	6.3	97.1

Figure 6. Growth response to phosphorus application at age 4 years. Bar represents LSD (p=0.05) where treatment differences were significant



Punnala ($p<0.05$, Fig. 6). A small response to N at Kayampoovam (*E. tereticornis*) and Vattavada (*E. grandis*) and responses to P at Vattavada and Surianelli observed at 18 months were not significant at 4 years. The largest response to N was in *E. grandis* at Surianelli, where application of N at the highest rate increased stand volume by 66 m^3 ha^{-1} at age 4 years.

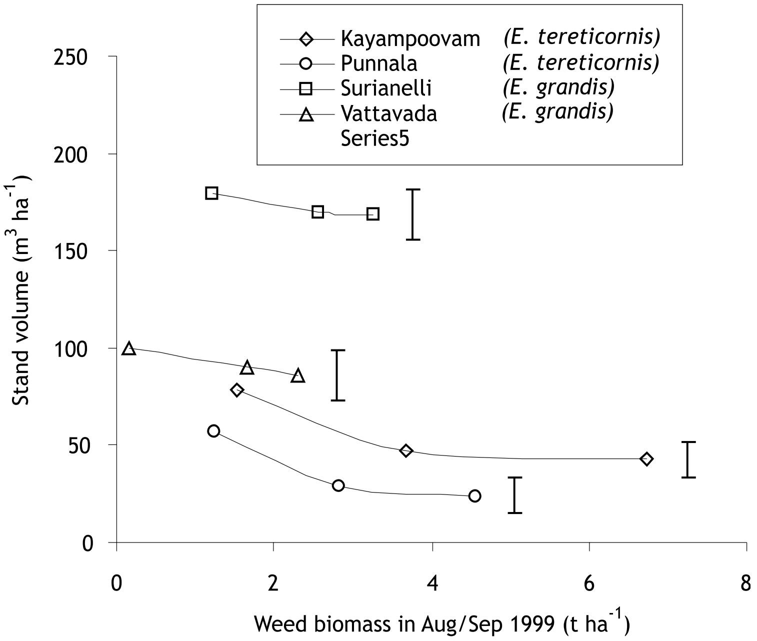
Tree Growth in Response to Weed Management

Biomass of weeds at the sites was determined periodically. Biomass of weeds estimated in August-September 1999 showed a relationship with tree growth at 4 years (Fig. 7). The relationship was significant at both *E. tereticornis* sites but early responses at the *E. grandis* sites had become non-significant by 4 years. Trees in the complete weeding treatment (CW) had significantly higher growth rates ($p<0.01$) compared to the no weeding (NW) and strip weeding treatments (SW) at Kayampoovam and Punnala (Fig. 8).

Tree Growth in Response to Legume Cover Cropping

Stylosanthes and *Mucuna* plants grew well from the start of the experiment at both sites, but *Pueraria* establishment was initially poor, with significant biomass only produced after resowing in May 1999 (12 months after tree establishment). Dry matter production peaked after the main monsoon period (June to August) and was at its lowest during the dry period prior to the monsoon. *Stylosanthes* produced the highest biomass, with a peak of approximately 6 t ha^{-1} at both sites in the first 2 years. *Mucuna* had a lower biomass, with a maximum of approximately 2 t ha^{-1} at both sites. The response of *Pueraria* differed between the sites, with a relatively high biomass at Kayampoovam at 15 months (4.6 t ha^{-1}), but a lower biomass at Punnala until after 24 months.

Figure 7. Tree growth at 4 years in relation to weed biomass at 1 year. Bars represent least significant difference (p=0.05) between weeding treatments in the tree biomass at each site



Although the eucalypt overstorey had reached near-maximum leaf area by 24 months, *E. tereticornis* has a relatively open canopy, and there was adequate light for continued legume growth after that time.

Although there were early trends for depression in growth of the trees at both Kayampoovam and Punnala (Fig. 9), the only significant effects were at 18 months at Punnala, where tree volume was significantly lower in the *Mucuna* (29% growth depression) and *Stylosanthes* treatments (20% depression), compared to the control. After 18 months, the absolute differences between treatments and control reduced, and were minimal (not significant) by 4 years. Legume intercropping may have a useful role in plantation management if it has longer-term impacts on sustainability (not yet shown in this study), or if the land resource can be used for dual purposes such as animal production as well as wood products.

Discussion

Surianelli (*E. grandis*) and Punnala (*E. tereticornis*) had the lowest productivity in the previous rotation, whilst Kayampoovam (*E. tereticornis*) and Vattavada (*E. grandis*) had higher productivity. Productivity at sites other than Vattavada was generally lower than reported for eucalypt plantations elsewhere (O'Connell *et al.* 2000, Spangenberg *et al.* 1996, Ares and Fownes 2000). Generally low productivity on these sites is attributable to poor genetic stock, minimal nutrient input and competition from weeds. The four sites are representative of areas where eucalypts are grown in Kerala. Soil at the Vattavada *E. grandis* site had relatively high concentrations of most nutrients while Punnala and Surianelli had relatively low concentrations. Kayampoovam had high concentrations of P but low concentrations of organic C and total N. In the previous rotation, biomass production across sites was generally related to soil nutrient levels, with the highest production of stemwood at Vattavada followed by Kayampoovam.

Figure 8. Tree growth in response to weed management at age 4 years. Bars represent LSD (p=0.05) where treatment differences were significant

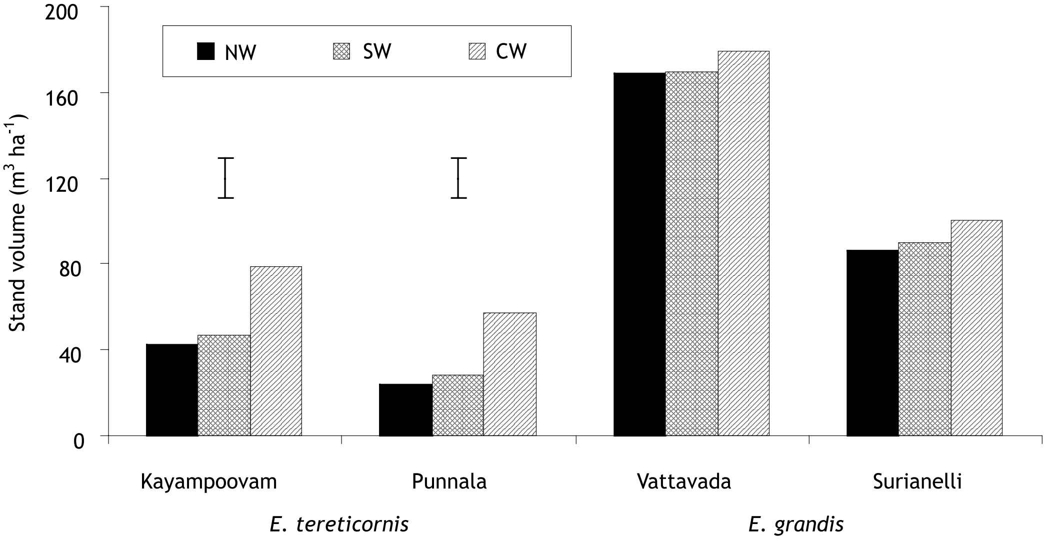
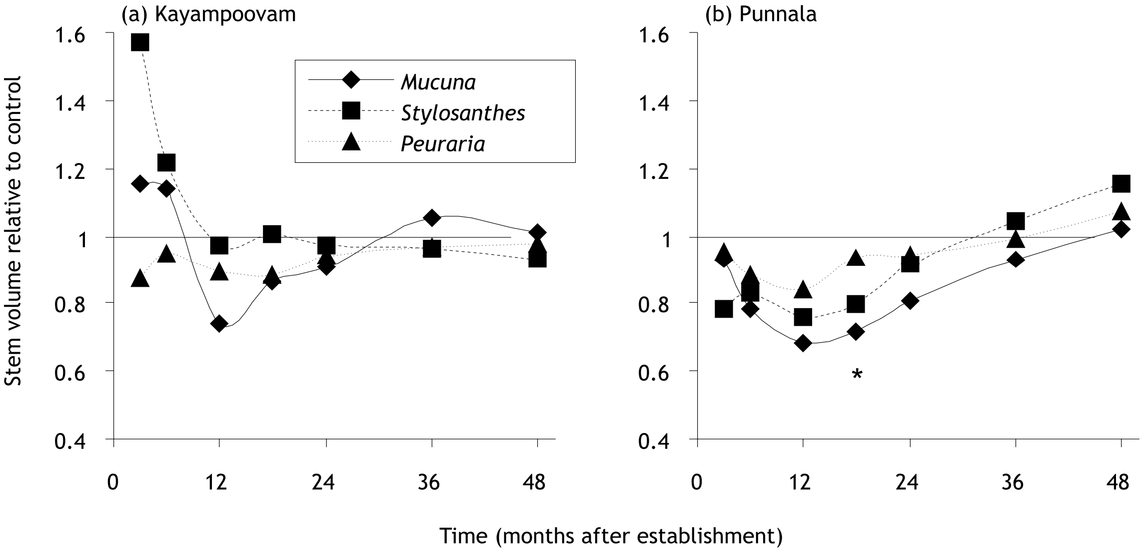


Figure 9. Stem volume relative to untreated control in legume experiment. * Denotes significant treatment effect at 18 months at Punnala (p<0.05)



In Kerala, much of the aboveground biomass is removed after harvest. Stem wood is removed for pulping, whilst local villagers remove bark, branches and twigs for fuel. Understorey and leaf residues are also often removed for green manuring of agricultural crops or for fuel. Any remaining residues or understorey material are routinely burnt during site preparation for the next rotation. These practices result in significant losses of nutrients from the site. For example, removal or burning of all aboveground biomass would result in loss of up to 247-358 kg ha^{-1} of N and 20-56 kg ha^{-1} of P at our sites. This loss will not be replaced by atmospheric or weathering inputs during the rotation. The harvest residue material contains 1.6-3% of the total site pools of N and the equivalent of up to 34%, 60% and 38% of the site pools of extractable K, Ca and Mg respectively. Thus, retention of residues will contribute significantly to maintenance of site nutrient capital (Xu *et al.*, Hardiyanto *et al.*, O'Connell *et al.* these proceedings). The impact of harvest residue management on tree growth and stores and fluxes of soil nutrients is likely to be most significant in nutrient-poor soils (O'Connell *et al.* these proceedings). The harvest residues may also play an important role in moderating the fluxes of mineral N during the inter-rotation phase, and early in the rotation (Aggangan *et al.* 1999, O'Connell *et al.* these proceedings).

Despite the relatively large nutrient losses caused by slash removal, the effect of retaining harvest residues on tree growth was minimal at 4 years at all sites, and there were no significant effects on the concentrations of total soil C, N or P at 2 years. This result was similar to that found early in the rotation for *E. globulus* in southwestern Australia (O'Connell *et al.* 2000) and for *Acacia mangium* in South Sumatra, Indonesia (Hardiyanto *et al.* these proceedings). Marked growth responses due to slash retention have been obtained for *E. urophylla* plantations in Guangdong Province, China (Xu *et al.* 2000, Xu *et al.* these proceedings), *Pinus* plantations in Queensland (Simpson *et al.* 2000 and Simpson *et al.* these proceedings), *E. grandis* in Brazil (Goncalves *et al.* these proceedings), *E. globulus* in SW Australia (O'Connell *et al.* these proceedings) and for Chinese fir plantations in Fujian Province, China (Fan *et al.* these proceedings). The lack of growth response may be attributed in part to the nutrients applied at the establishment of the experiment. Trees in all treatments, except the burn-only, received starter fertiliser (42 kg ha^{-1} N, 18.5 kg ha^{-1} P) which resulted in increases in tree growth at most sites. The shape of the P response curve at Punnala suggested that more than 60 kg P ha^{-1} was required for maximum growth. Likewise, growth could be maximised by applying 60 kg of N ha^{-1}yr^{-1} at the least responsive sites (Kayampoovam and Vattavada), but more fertiliser than this would be required for maximal gains at Surianelli and Punnala. Hence, some of the initial nutrient requirement would have been supplied by the starter fertiliser, reducing the likelihood of showing growth differences due to harvest residue removal. Conservation of site resources through retention of residues is likely to have a greater effect on long-term productivity and sustainability as demands on site nutrient reserves increase (O'Connell *et al.*, Hardiyanto *et al.* these proceedings).

Significant tree growth responses to nutrient addition indicated that there are good prospects for increasing productivity at some sites through fertiliser inputs. However, we observed variable responses amongst the four sites to N and P applications ranging from no growth increase to up to a 70% increase in standing volume. Enhanced tree growth in response to fertiliser applications was also reported by Xu *et al.* (these proceedings) for *E. urophylla* in China. In South Sumatra, Indonesia, application of N, K and Ca fertilisers had no significant influence on growth of *Acacia mangium* at 1.5 yr whereas application of P improved tree growth significantly (Hardiyanto *et al.* these proceedings). The challenge for future research will be to identify soil and plant chemical characteristics that can be used as diagnostic indicators of the likely response of trees to added nutrients.

Initial growth depression found in the legume treatments at 18 months at Punnala was probably due to competition for nutrients between the trees and legume understorey but this effect disappeared after 18 months, and there was a consistent trend from then until the 4-year measure of improving growth compared to that in the control treatment at Punnala. Although differences between treatments were not significant at the 4-year measure, the trend is diverging, and effects of legume cover cropping may become more apparent with time. This effect may be associated with nitrogen fixation by the legumes, and subsequent enhanced supply of N to the trees at Punnala, where significant responses to N fertiliser were obtained. The trees at Kayampoovam did not respond to nitrogen fertiliser, thus explaining the lack of response to legume treatment at that site. Similarly, Simpson *et al.* (these proceedings), found no improvement in tree growth and N status of soil when hybrid pine was intercropped with legumes in Queensland, Australia.

Weed competition is a reason for poor productivity of eucalypts in Kerala State. Control of the weeds resulted in substantial increases in productivity (up to 138% in the case of *E. tereticornis* at Punnala). The magnitude of the response to weed control varied between sites, partly due to species differences in leaf area, and partly because the degree of competition from weedy vegetation varied depending on the site resource most limiting (water or nutrients). Within the *E. tereticornis* sites, Kayampoovam had relatively shallow soils (less than 5 m depth) with high levels of soil nutrients, so water was most likely to be the most limiting factor, whereas the Punnala site had a deeper soil profile and a much larger response to nutrients (Figs 5 and 6), so weedy vegetation probably competed strongly for nutrients, rather than water. Within the *E. grandis* sites, the responses were not significant, although there was a relationship between weed biomass and tree growth (Fig. 7). The smaller response to weeds in *E. grandis* at Vattavada was probably due to the high fertility and deeper soil at that site. Surianelli had relatively low fertility (i.e. a large response to nutrients), but the response to weeding appeared to be relatively small. This result appeared anomalous, but may have been due to a lower intensity of initial weeding. The length of time that weeds need to be controlled will depend on how long they compete for site resources. In *E. grandis* plantations canopy closure occurs at approximately 2 years, so weed control may be necessary only until this time. However, the canopy of *E. tereticornis* remains more open throughout the rotation, so weeds may need to be controlled for longer periods to achieve maximum tree growth.

The significance of proper weed management in improving productivity of forest plantations has also been shown by Xu *et al.* (these proceedings) for *E. urophylla* plantations in southern China and hybrid pine plantations in Queensland, Australia (Simpson *et al.* these proceedings).

Conclusions

There is potential for improving the productivity of eucalypt plantations in India through adoption of more intensive silvicultural practices. Nitrogen application increased tree growth by up to 70% at one *E. grandis* site and one *E. tereticornis* site, whilst P addition also significantly improved tree growth at one of the *E. tereticornis* sites (43% increase). Establishment of legumes had no significant effect on *E. tereticornis* tree growth at 4 years, although there is a trend of increased tree growth in the legume treatments at the N-responsive site (Punnala). Early control of weeds increased growth (up to 138%) at the *E. tereticornis* sites. Harvest residue management had little impact on tree growth or total soil C, N or P. However, residue removal or burning would result in significant losses of site nutrients, thus leading to a degradation of site productivity potential over several rotations.

Impact

The significance of (1) intensive weed management, (2) nutrient addition, and (3) use of good quality planting stock for enhancing productivity of eucalypt plantations in Kerala has been appreciated by the main growers of eucalypts in the State viz., the Kerala Forest Department, Kerala Forest Development Corporation and the Hindustan Newsprint Ltd. These stakeholders have started practising these methods in their new planting programmes (ca.

4000 ha yr^{-1}) and they have entered into collaboration and consultancy arrangements with the Kerala Forest Research Institute for their proper implementation. Though the value of harvest residue management has been realised by most growers, there is widespread reluctance in implementing it during the inter-rotation period for practical reasons, including access for planting and the practice of collecting firewood from the site after harvest by local communities.

Acknowledgements

The Australian Centre for International Agricultural Research (ACIAR) is providing funding for this research through collaborative arrangements with CSIRO Forestry and Forest Products and Kerala Forest Research Institute (KFRI). Assistance and in-kind support provided by Kerala Forest Department, Kerala Forest Development Corporation and Hindustan Newsprint Limited for establishment and maintenance of the experimental sites is gratefully acknowledged. We are grateful to Dr. J.K. Sharma, Director, KFRI for support and advice. Thanks are also due to several colleagues at KFRI and CSIRO (Australia) for technical assistance. The Center for International Forestry Research (CIFOR) provided financial support to participate in workshops in Congo and China.

References

Aggangan, R.T., O'Connell, A.M., McGrath, J.F. and Dell, B. 1999. Impact of *Eucalyptus globulus* leaf litter on C and N mineralization in soils from pasture and native forest. Soil Biology and Biochemistry 31:1481-1487.

Ares, A. and Fownes, J.H. 2000. Productivity, nutrient and water-use efficiency of *Eucalyptus saligna* and *Toona ciliata* in Hawaii. Forest Ecology and Management 139:227-236.

Balagopalan, M. and Jose, A.I. 1983. Changes in organic carbon and different forms of nitrogen under first and second rotation (coppiced) eucalypt plantations. Agricultural Research Journal of Kerala 21:57-62.

Balagopalan, M. and Jose, A.I. 1986. Distribution of organic carbon and different forms of nitrogen in a natural forest and adjacent eucalypt plantations at Arippa, Kerala, India. *In*: Sharma, J.K. *et al.* (eds.) Eucalypts in India: past, present and future, 112-119. Kerala Forest Research Institute, India.

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.

FAO 2000. Global forest resources assessment. Tables available online: http:// www.fao.org/ forestry.

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 8:67-82.

Jayaraman, K. and Krishnankutty, C.N. 1990. A data bank for forestry sector in Kerala. KFRI Research Report No. 66. Kerala Forest Research Institute, India. 27p.

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

Menon, P.A. and Rajan, C.K. 1989. Climate of Kerala. Classic Publishing House, Cochin, India. 136p.

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.

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: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 61-71. Center for International Forestry Research, Bogor, Indonesia.

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. 330p.

Sankar, S., Mary, M.V. and Alexander, T.G. 1988. Foliar analysis in *Eucalyptus tereticornis* and *E. grandis* to assess soil test methods for nitrogen, phosphorus and potassium. KFRI Research Report No. 53. Kerala Forest Research Institute, India. 16p.

Sankaran, K.V. 1999. Eucalypt plantations in monsoonal tropics - Kerala, India. *In*: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) Site management and productivity in tropical plantation forests: workshop proceedings 16-20 February, Pietermaritzburg, South Africa, 45-51. Center for International Forestry Research, Bogor, Indonesia.

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.

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, India. 268p.

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: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 73-82. Center for International Forestry Research, Bogor, Indonesia.

Spangenberg, A., Grimm, U., Sepeda da Silva, J.R. and Fölster, H. 1996. Nutrient store and export rates of *Eucalyptus urograndis* plantations in eastern Amazonia (Jari). Forest Ecology and Management 80:225-234.

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: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 101-103. Center for International Forestry Research, Bogor, Indonesia.

Xu, D.P., Yang, Z.J., Dell, B. and Gong, M. 2000. Effects of site management in *Eucalyptus urophylla* plantations 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: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 31-40. Center for International Forestry Research, Bogor, Indonesia.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Impacts of Inter-rotation Site Management on Nutrient Stores and Fluxes and Growth of Eucalypt Plantations in Southwestern Australia

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Abstract

Impacts of alternative strategies for managing harvest residues in second rotation *Eucalyptus globulus* plantations are being examined at sites of contrasting soil fertility in southwestern Australia. Treatments being examined in a randomised block experiment are complete harvest residue removal, residue retention, increased residue and residue burning. We studied: (1) decomposition rates of harvest residues and their associated nutrient release rates; (2) impact of treatments on soil carbon and nutrient stores; (3) dynamics of soil N mineralisation and; (4) nutrient uptake and tree growth. Results up to 7 years after stand re-establishment following harvest of the first plantation rotation are reported. Decomposition rate of harvest residues in plantations is rapid compared to decay rates of residues in natural forests in the same region. Nutrient release from residues is dominated by leaves. Application of harvest residues at high rates (up to 160 t ha^{-1}) had a surprisingly small effect on organic C levels in the surface soil. There were significant impacts of harvest residue management on stores and fluxes of C, N, P, Ca and Mg. Dynamics of soil N were particularly affected by residue treatments; higher rates of retention of residues leading to higher rates of mineralisation and potentially available N. Nevertheless, the rate of supply of N through mineralisation from soil organic matter and residues may be less than the requirement for N of newly established seedlings on many sites. Hence conservative harvest residue management will only partially satisfy tree nutrient requirements at these sites. In such circumstances, N supply needs to be augmented with fertiliser to achieve increase in plantation productivity. At the more fertile site, harvest residue treatments had little effect on growth of the second rotation plantation and wood production rates are similar to those achieved in the first rotation. At the less fertile site, residue treatments significantly affected tree growth with highest volumes associated with greatest amounts of retained residues. Furthermore, at this site, production rates of the second rotation are markedly lower than in the first rotation, suggesting increased nutritional limitations to tree growth.

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Introduction

In southwestern Australia eucalypt plantations cover more than 230 000 ha, and the area is expanding at a rate of about 25 000 additional hectares per year. Most of these plantations are on land previously used for various forms of agriculture, primarily grazing of cattle and sheep on improved pastures. In some areas trees are planted to reverse the effects of severe land and water degradation processes, such as waterlogging and salinisation, which have developed following clearing of the natural perennial vegetation. However, the main impetus for the establishment of most plantations has been the development of a commercial hardwood plantation industry. Although individual landholders have established some plantations, the majority of the plantation estate is owned and managed by industrial companies. The main species is *Eucalyptus globulus*, grown on 10-year rotations to provide wood chip for export.

The landscape of southwestern Australia has developed over long time scales without major rejuvenation processes. As a consequence, the majority of soils are highly weathered and low in natural fertility. Following clearing for agriculture, large amounts of phosphate-based fertilisers have been applied to these soils to promote improved legume-based pastures. These management practices have improved soil fertility and increased production potential for the region as a whole. Consequently, where pastures are planted to eucalypts, the supply of soil nutrients supports high growth rates of trees. However, recent research has indicated that this change in land use may, in the longer term, lead to a decline in availability of some plant nutrients, especially nitrogen and phosphorus (Grove *et al.* 2001, O'Connell *et al.* 2003). Therefore, implementing management strategies that aim to maintain and enhance soil fertility will be critical for ensuring sustainable levels of productivity.

In southwestern Australia, the majority of plantations have been established since 1990. Harvesting of older stands has commenced and the management of second rotation crops will become an increasingly important aspect of stand management during the next few years. At harvest, large amounts of tree residues are deposited on the soil surface. One option for managing soil productivity is to develop judicious site management systems that are applied during the inter-rotation period of stand harvest and plantation re-establishment. Our research is focusing on options for treating harvest residues and the impact these strategies may have on soil organic matter, soil nutrient status, nutrient flux rates and tree growth. The aim is to develop guidelines to manage soil fertility in order to maintain high productivity of plantation eucalypts over successive rotations. Previously in this series (O'Connell and Grove 1999, O'Connell *et al.* 2000) we have reported on early responses and changes in soil properties. In this paper we present the most recent growth responses and changes in soil properties (data from 1999 to 2002). Additionally, we examine decomposition rates and nutrient release from harvest residue materials, and soil N supply and demand by the tree crop.

Location and Site Description

Detailed descriptions of the climate, soils and experimental sites and location of this research on *E. globulus* plantations have been presented (O'Connell *et al.* 2000) and are only briefly reiterated here to provide context for this paper.

Southwestern Australia has a seasonal Mediterranean type climate with cool wet winters and warm, dry summers. The *E. globulus* plantation estate is limited to the southern part of this region where annual rainfall is in the range 600 to 1500 mm. Rainfall at the experimental sites ranges from 800 to 1000 mm annually. Ancient Archaean crystalline rocks, primarily granites and granitic gneisses, dominate the geology of the region. These have weathered *in situ* resulting in deep soil profiles that are frequently mantled by laterite. Surface soils reflect the highly weathered nature of these parent materials and generally have low levels of plant-available nutrients (Turton *et al.* 1962).

We established three inter-rotation site management experiments when the stand was harvested (first rotation) and replanted as second rotation plantations. Two of these (at Busselton and Manjimup), established in 1995 and described in detail previously (O'Connell *et al.* 2000), have been the focus of the majority of our research. These sites are in similar rainfall zones but have contrasting soils. At Busselton, the soil is an infertile grey sand (Podzol), total aboveground biomass of the first rotation crop was low (98 t ha^{-1} after 9 years) and about 31 t ha^{-1} of harvest residues was left on the soil surface after logging. At Manjimup, the soils were more heavily textured red earths (Ferralsol) with relatively high levels of plant-available nutrients. Total aboveground biomass of the first rotation plantation was high (275 t ha^{-1} after 9 years) and 81 t ha^{-1} of harvest residues (including 30 t ha^{-1} coarse woody debris) was left on site after logging. A third site, also at Manjimup, was established in 1998 as an industry demonstration and has also been used for some process-based studies, notably experiments on harvest residue decomposition rates and their contribution to nutrient cycling.

Experimental Methods

At the two main experimental sites at Manjimup and Busselton, harvest residue management experiments were established using a randomised block design with four replicate blocks and a planting density of 1250 stems ha^{-1}. The design incorporated the core CIFOR treatments:

BL$_0$	No slash – all litter and slash materials removed.
BL$_2$	Single slash – uniformly distributed.
BL$_3$	Double slash – addition of slash from the 'no slash' (BL$_0$) treatment.
B	Burn – (BL$_2$ with retained slash burnt).

At the same sites, separate randomised block experiments were conducted to evaluate responses to added N and P and to assess the role of inter-row agricultural legumes in early stages of the rotation.

Details of sampling protocols and analytical methods have been given (O'Connell *et al.* 2000). Impacts of harvest management options on soil fertility were assessed through two sampling regimes: (1) soil samples were collected annually to evaluate changes in stores of organic carbon and nutrients over time (results from nine sample collections are now available) and (2) samples were collected monthly over a five-year period after stand establishment to examine the dynamics of soil mineral N (Raison *et al.* 1987) in relation to management of harvest residues.

Decomposition of five harvest residue components (leaves, bark and wood up to 2 cm diameter) was evaluated using mesh bags over 2 years. Decomposition of larger woody residues (up to 30 cm diameter) was determined from density changes of logs at both sites over about 5 years. Tree growth (stem diameter and height) was measured annually. Aboveground biomass and N accumulation were estimated using allometric relationships with conical volume derived after harvesting some trees.

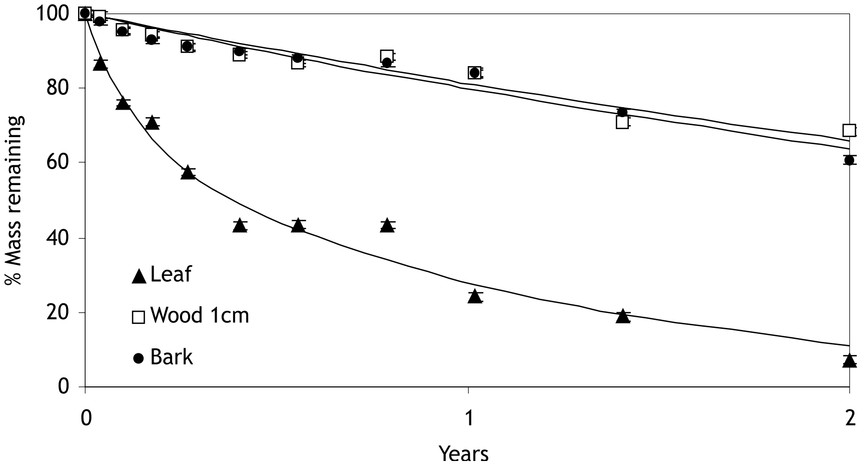
Results

Decomposition and Nutrient Release from Harvest Residues

We evaluated weight loss of samples from mesh bags by fitting a double exponential decay model (Lousier and Parkinson 1976, O'Connell 1997) to leaf and small wood (0.5 cm diameter) data and a single exponential model (Olson 1963) to data for bark and larger wood fractions (1 and 2 cm diameter). Leaves decomposed rapidly, losing more than 50% weight during the first 6 months (Fig. 1). Decomposition of wood and bark fractions was slower, model-predicted half lives ranged from about 3.5 to 4.5 years for wood, and about 3 years for bark, respectively.

During decomposition, nutrient dynamics differed markedly between fractions. Most of the N and P in leaves was released during the 2 years with similar patterns of release (Fig. 2). There was little release of N from the wood and bark throughout the experiment, but these components immobilised N, especially during the initial stages of decomposition. Bark in particular continued to accumulate N progressively, and after 2 years contained 50% more N than the initial fresh material. The patterns of P release from the different fractions were similar to N except that wood and bark components released a greater

Figure 1. Time course of decomposition of leaf, bark and wood in harvest residues. Fitted double exponential (leaf) and single exponential (bark and wood 1 cm diameter) models are shown together with standard errors for each collection



proportion of their P, again following an initial period of net accumulation. After decomposition for 2 years, about 90% of the P in leaf residues had been released. During the same period 40% to 50% of the P in wood and about 25% of the P in bark had been released (Fig. 2).

The average proportional mass loss of larger woody residues, estimated from density changes, was 79% at the grey sand site and 83% at the red earth site. There was a weak relationship between log diameter and wood decomposition rate. The average rate constant of decay, assuming a first order decomposition model (Olson 1963), was about 0.3 yr^{-1} over all size classes for both sites. Amounts of N remaining in the decomposing wood, expressed as a percentage of the initial N content, were not significantly different between both sites for all wood size classes (Fig. 3). However, size classes had a significant ($p<0.01$) effect on the net N release, with the exception of the two smaller size classes on the grey sand site. In general, N release increased as log diameter decreased.

Pattern of nutrient release from harvest residue materials differed between components and specific nutrients. A nutrient budget for decaying harvest residues during the first year after harvest at one of the Manjimup sites (Table 1) illustrates the large contribution of the leaf component to nutrient release from these harvest residues. This is especially so for the nutrients N and Ca, which are relatively immobile during decomposition. For both N and Ca, wood and bark fractions became sinks during the early stages of decomposition when they accumulated these nutrients in excess of the initial amounts present in fresh residues.

Impact of Harvest Residues on Soil Nutrient Stores

Changes in soil nutrients, carbon (total organic and labile C) and pH have been monitored annually since December 1994 (red earth site) and June 1995 (grey sand site). Detailed descriptions of the effects of harvest residue management on these soil characteristics during the period from harvest to December 1998 have been reported previously (O'Connell *et al.* 2000). Here we focus on changes measured during the last four sampling periods (1999 to 2002). The major effects in this period relate to soil pH, exchangeable cations and soil C. At both sites, the latest measurements indicate that the pH of surface soil (0-5 cm) is higher by about 0.3 units on burn (B) and high residue treatments (BL_3)

Figure 2. Amounts of (a) N and (b) P remaining during decomposition for 2 years of harvest residue fractions

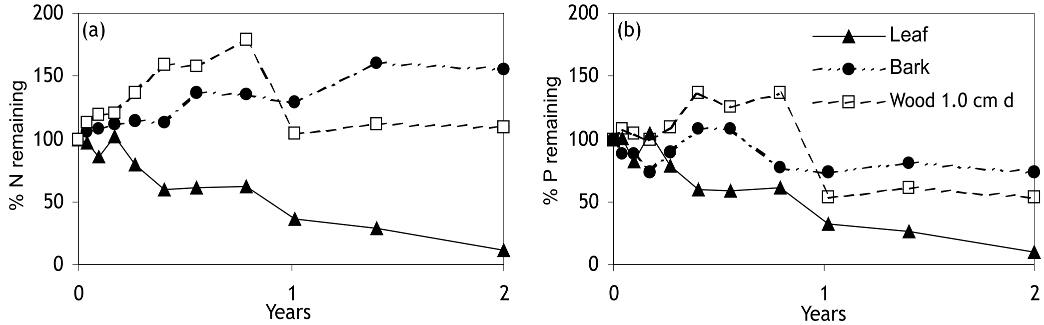
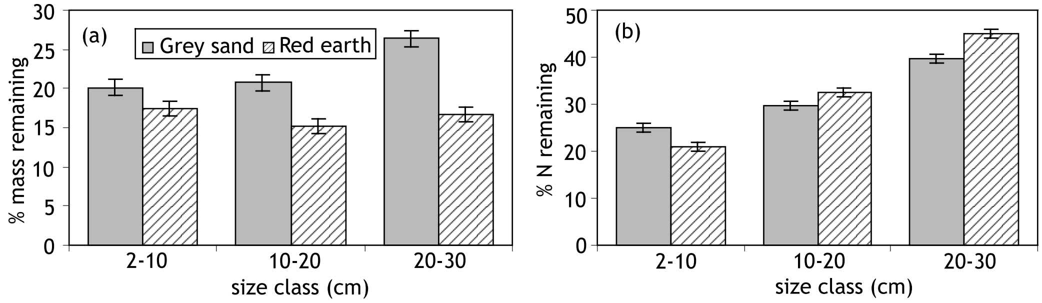


Figure 3. Mass and N remaining in relation to log diameter of larger wood residues. Results are calculated after 5 years at the grey sand site and 5.5 years at the red earth site. Standard errors are shown for each log size class



compared to zero and single residue treatments (BL_0 and BL_2). At the red earth site, the effects of applied treatments on surface soil pH have been significant at all sampling times since harvest. The two most recent samplings (2001 and 2002) also show similar effects in 5-10 cm soil samples. At the grey sand site effects of treatments on surface soil pH have been significant at five of nine sampling periods.

During the last three sampling periods (2000, 2001 and 2002), significant effects of treatments ($p< 0.05$) on surface soil (0-5 cm) organic C were found at the grey sand site (Fig. 4), with high residue treatments resulting in higher organic C. Although greater amounts of residues were present at the red earth site than the grey sand site, the effects on soil C are less evident. Of the recent samplings at the red earth site, only surface soil collected in 2000 showed significant effects of treatments on soil C concentrations. Furthermore, there were no significant effects of residue management on soil C for soil depths below 5 cm at either site during any of the sampling periods following harvest of the original stands. Increased total organic C levels are also associated with correspondingly higher labile soil C concentrations at both sites (significant at the red earth site in 2000 and 2002 and at the grey sand site in 2000 and 2001).

There were major changes in concentrations of soil cations in response to residue treatments. For exchangeable Ca, there were significant

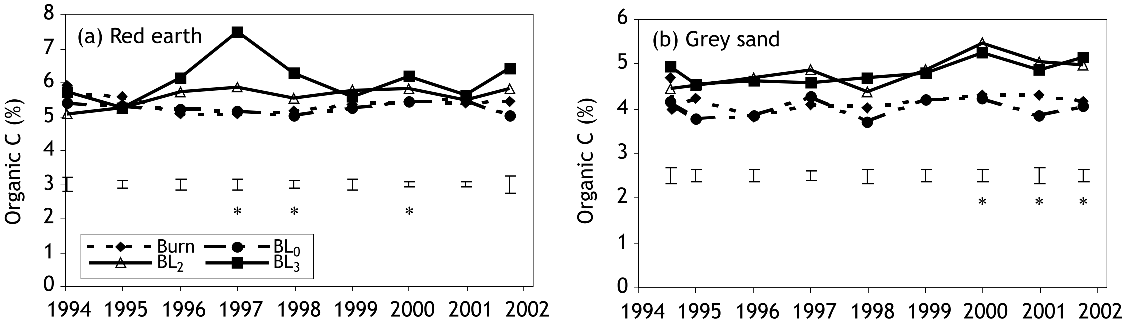
Table 1. Initial dry weight and nutrients in harvest residues and the amounts of dry weight and nutrients lost from various fractions during decomposition for 1 year at one of the experimental sites at Manjimup

	Dry weight ($t\ ha^{-1}$)		N		P		K ($kg\ ha^{-1}$)		Ca		Mg	
Fraction	Initial	Loss	Initial	Loss	Initial	Loss	Initial	Loss	Initial	Loss	Initial	Loss
Leaf	25	19	349	222	17	12	150	145	274	158	45	35
Bark	14	2	31	-9[b]	4	1	65	52	258	-64[b]	21	8
Wood a[a]	14	3	59	-3[b]	6	3	69	58	97	-9[b]	16	4
Wood b[a]	9	1	29	-1[b]	3	1	37	32	41	-8[b]	8	2
Wood c[a]	6	1	13	-2[b]	1	0	18	15	28	2	6	2
Total	69	27	481	207	32	17	339	301	698	79	95	52

[a] Size classes for wood are; a: 0-0.75 cm diameter, b: 0.75-1.5 cm diameter, c: 1.5-3 cm diameter.

[b] Negative values for N and Ca indicate immobilisation of these nutrients in residue components.

Figure 4. Impact of harvest residue treatments on concentrations of total organic C in surface 0-5 cm soil at (a) the red earth and (b) grey sand experimental site. Standard errors and ANOVA significance levels (*: $p<0.05$) are shown for each year



differences at seven of nine post-harvest sampling periods at the red earth site and six of nine sampling periods at the grey sand site. Surface soil Ca concentrations for the highest rates of residue retention (BL_3) were about double those where residue had been removed (BL_0 - Fig. 5a, data only shown for red earth site). At the red earth site, these changes were also associated with changes in exchangeable Mg (Fig. 5b) and again there was approximately a 2-fold difference in Mg concentrations between the extremes of treatments. For both cations the responses at the red earth site were due to a decline over time in their levels in BL_0 and an increase in BL_3. In contrast, exchangeable Mg concentrations in soil from the grey sand site declined consistently with time since harvest on all residue treatments. Thus, seven years after harvest at the grey sand site, concentrations of exchangeable Mg in surface soil had decreased by about 30% compared to initial samples.

Following harvest, exchangeable soil K decreased for up to 3 years at both sites (O'Connell *et al.* 2000) with concentrations in surface soil reduced to about one third (red earth site) to one half (grey sand site) those in initial soil samples (Fig. 6). Thereafter this trend reversed, with increasing exchangeable K at both sites. However, concentrations of exchangeable K in surface soil at the 2002 sampling were still below the levels measured in soil immediately following harvest by 15% (red earth) to 25% (grey sand).

Figure 5. Effect of harvest residue treatments on concentrations of exchangeable (a) Ca and (b) Mg in surface soil (0-5 cm) at the red earth site. Standard errors and ANOVA significance levels (*: p<0.05, **: p<0.01, ***: p<0.001) are shown for each year

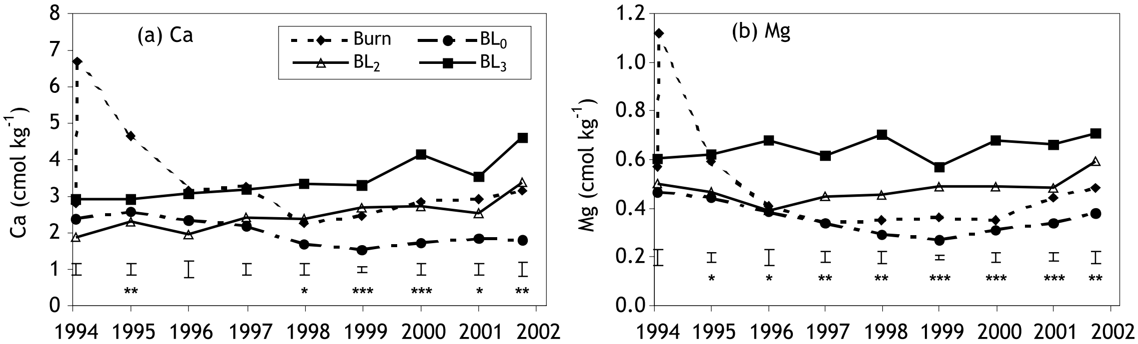
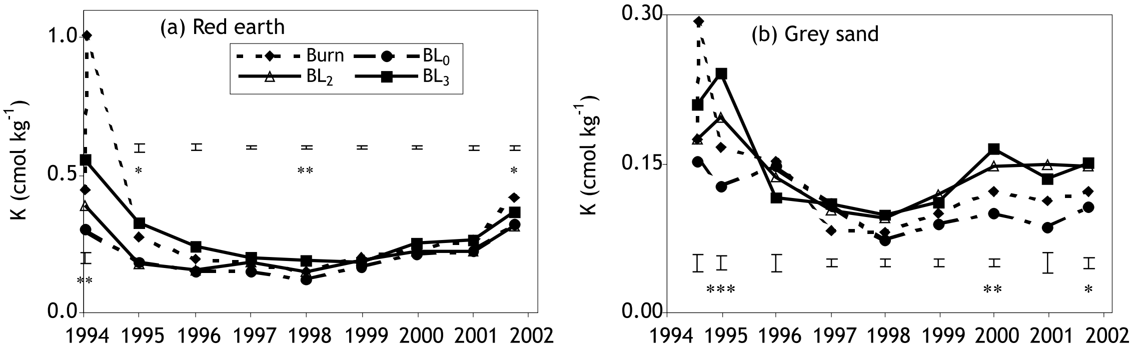


Figure 6. Changes in exchangeable K in surface soil (0-5 cm) since stand harvesting at (a) the red earth and (b) the grey sand sites. Standard errors and ANOVA significance levels are shown for each year



Amongst the other nutrient elements, the most recent soil samplings indicate no significant effect of residue treatments on total soil N, total soil P or Bray extractable P for any of the soil depths examined at both sites.

Impact of Harvest Residues on Soil Mineral N

Management of harvest residues had a significant impact on the concentrations of mineral N in soil and on the way this pool changed over time. As reported previously (O'Connell *et al.* 2000), concentrations of mineral N were high immediately after harvest but declined over time through leaching and plant uptake. Two years after stand re-establishment (second rotation) the amounts of mineral N in soils were uniformly low in all treatments. Thereafter, at the red earth site, residue retention caused increased soil mineral N. At the grey sand site, residue management had no effect on soil mineral N concentrations after 2 years.

Temporal patterns of N mineralisation were markedly influenced by the seasonal climate of southwestern Australia. Rates were high in late winter and spring (July-October) when soils were moist and decreased to low values as soil dried during summer and autumn (December-May). Patterns were similar at both experimental sites and for each of the harvest residue treatments. A model based on daily measures of soil temperature and monthly measures of soil moisture (O'Connell and Rance 1999) provided a good simulation of seasonal variation in rates of

Figure 7. Seasonal pattern of N mineralisation (red earth site, BL_0 treatment) in surface (0-10 cm) soil. Bold line shows monthly measured values; broken line the daily-simulated values

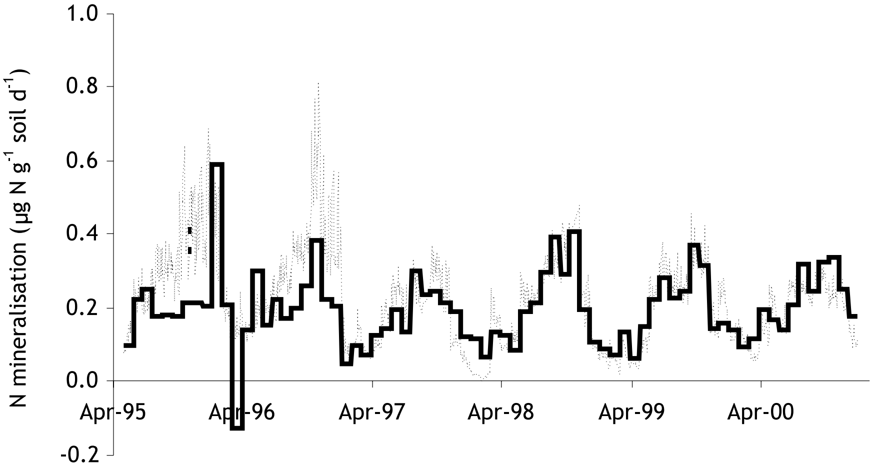


Table 2. Net N mineralisation in 0-20 cm soil in relation to harvest residue treatments

	1995a	1996	1997	1998	1999	2000
			(kg N ha^{-1})			
Red earth						
B	42.7	70.5	75.1	85.1	85.6	82.4
BL_0	29.7	64.9	72.5	89.1	84.5	92.5
BL_2	44.8	81.2	88.7	109.5	95.6	89.5
BL_3	44.2	84.5	85.6	97.6	93.4	95.6
LSD ($p<0.05$)	28.3	25.8	11.1	15.5	9.0	16.2
ANOVA sig.	ns	ns	*	*	*	ns
Grey sand						
B	54.3	84.4	56.5	70.3	71.3	64.9
BL_0	54.9	69.6	53.3	65.6	61.2	43.2
BL_2	61.7	78.4	54.4	68.8	66.8	57.5
BL_3	77.2	90.1	72.6	83.7	69.5	63.1
LSD ($p<0.05$)	22.5	48.9	12.5	19.3	14.1	17.3
ANOVA sig.	ns	ns	*	ns	ns	ns

[a] In 1995 N mineralisation was measured only during the period May to December (252 days) at the red earth site and during July to December (196 days) at the grey sand site. Data shown for 1995 refer to net N mineralisation measured during these periods.
ANOVA significance: ns not significant; * significant $p<0.05$.

N mineralisation over most of the measurement period (Fig. 7). The model fit was poorest during the first 2 years after stand establishment. This is the period when large pools of mineral N are present in soil (O'Connell *et al.* 2000) and N mineralisation measured against this high background is subject to larger experimental errors. When soil mineral N pools declined (1997 onwards), there was a better correspondence between observed and predicted N mineralisation values.

Annual rates of mineralisation per unit weight of soil were generally higher (up to about 2-fold) in the more heavily textured and fertile red earth soil than in the grey sand (Fig. 8). At the red

Figure 8. Annual mineralisation rates in surface (0-10cm) soil at the two experimental sites. Standard errors and ANOVA significance levels (*: p<0.05, **: p<0.01, ***: p<0.001) are shown for each year

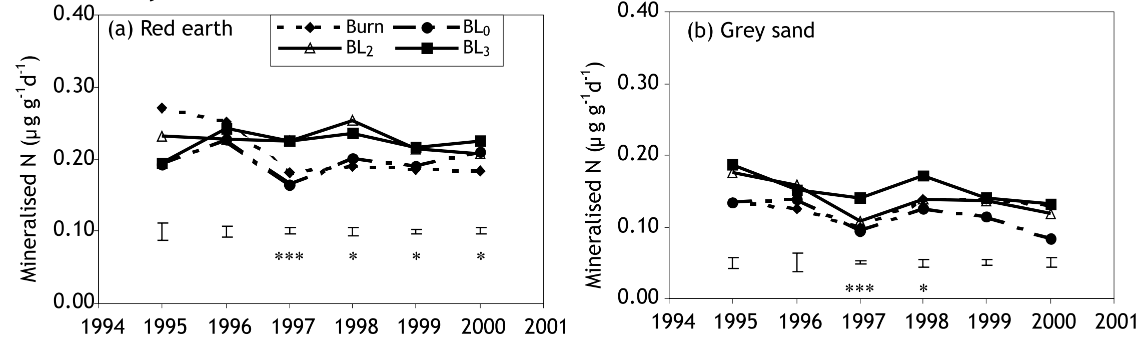
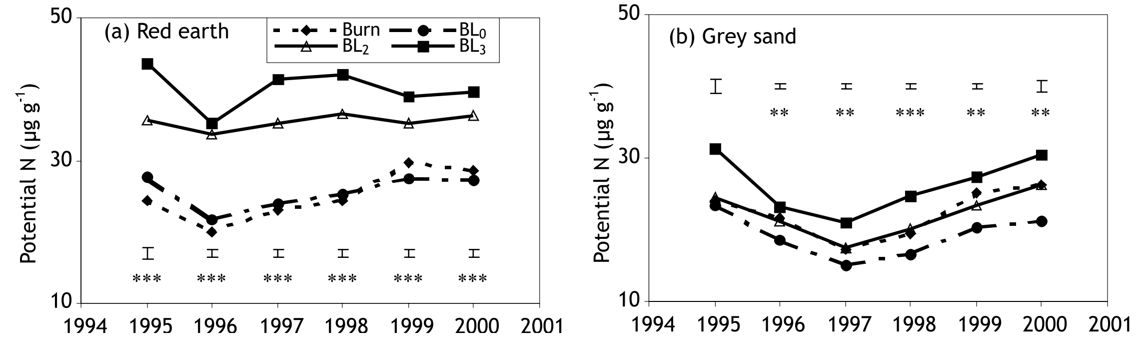


Figure 9. Potentially mineralisable N in surface (0-10 cm) soil. Standard errors and ANOVA significance levels are shown for each year



earth site, mean annual rates of N mineralisation per unit soil weight were significantly higher on residue retained treatments compared to low residue treatments in the third to sixth years of measurement (1997 to 2000). At the grey sand site, annual N mineralisation rates were significantly enhanced by residue retention, but only in the third and fourth years of measurement (1997 and 1998). Thereafter, mineralisation rates were similar between treatments.

Amounts of N mineralised annually in surface 0-20 cm soil also differed between treatments (Table 2). The significantly greater mineralisation at the red earth site from 1997 to 1999 was associated with high residue treatments. At the grey sand site, annual amounts of mineralised N were only different in one measurement year (1997).

Response of potentially mineralisable N in soil to treatments reflected similar trends to those found for measured rates of *in situ* N mineralisation. High residue treatments resulted in significantly higher average annual concentrations of potentially mineralisable N at both sites during each measurement period (Fig. 9). As with rates of N mineralisation measured *in situ*, potential for N mineralisation was systematically higher in the red earth soil compared to the grey sand. At both sites there was an initial 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. The lack of a clear trend in the residue-retained treatments at the red earth site may be due to the relatively high quantity of harvest residues masking the root turnover effect.

Impact of Harvest Residue Management on Tree Growth

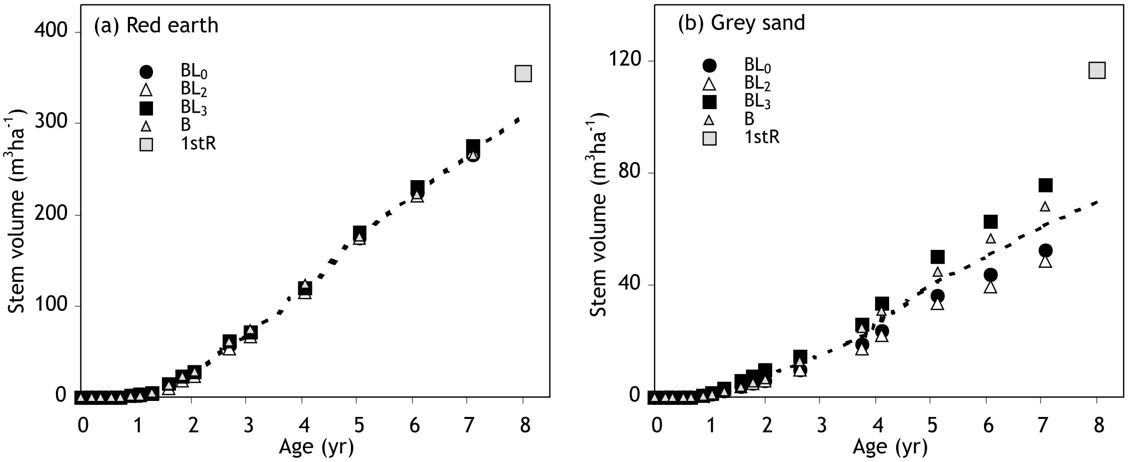
Initial responses in tree growth to harvest residue treatments differed between sites (O'Connell *et al.* 2000). Retention of residues enhanced growth during the first year after planting at the red earth site and initially depressed growth at the grey sand site (O'Connell *et al.* 2000). These effects declined over time. Seven years after plantation re-establishment there were no significant effects of harvest residue management on tree growth at the more fertile red earth site (Fig. 10). Projected stem volume for 8-year-old trees at this site is within 13% of the volume at harvest of the first rotation stand. At the grey sand site, tree volume at the last four annual measurement periods (1999 to 2002) was significantly different between residue treatments ($p< 0.01$). Growth was greatest at the highest level of residues (BL_3) and on the burn treatment and lowest on zero (BL_0) and single (BL_2) residue treatments. By the end of the first year following plantation re-establishment, stand volume on the BL_3 treatment plots was more than 40% greater than on the BL_0 treatment. This relative difference between treatments has been maintained in subsequent years. Average stem volume over all treatments, projected to age 8 years, is markedly lower (by about 40%) than stand volume at this age when the first rotation was harvested, indicating a decline in second-rotation productivity. Growth of the second rotation at this site was also much lower (about one fourth) compared to growth at the red earth site, reflecting differences in the fertility of soils.

Discussion

Although large quantities of harvest residues were retained on the soil surface in some treatments in this study (up to 160 t ha^{-1} on BL_3 treatments at Manjimup), these quantities have made only minor impacts on the soil stores of organic C. Despite the statistically rigorous design and sampling procedures, changes in soil C were difficult to detect against the variable background levels. In the last three sampling periods (2000, 2001 and 2002), significant treatment effects were observed in organic C concentrations in surface soil (0-5 cm) at the grey sand site. Amongst recent samplings, differences at the red earth site, where greatest amounts of residues had been applied, were only statistically significant in 2000. In absolute terms, changes since harvesting in soil C storage to a depth of 20 cm on all treatments at both sites were small (within the range of about +/- 4 t ha^{-1}).

Decomposition rates of *E. globulus* harvest residues are markedly faster than rates for equivalent residues from native forests growing in the same region (O'Connell 1997). For example, the half-life of karri (*E. diversicolor*) leaves in southwestern Australia was 17 months (O'Connell 1987), compared to the half-life for *E. globulus* leaves of less than 6 months. Likewise, release of nutrients from plantation residues is rapid compared with native forest litter. Thus, harvest residues have the potential to make a major contribution to nutrient cycling in plantations and, depending on the productivity of the previous tree crop, they can represent a significant store of the plant-available site nutrient pools. At Manjimup, stores of N in residues amounted to about 380 kg ha^{-1} (Table 1). Where harvest residues are burnt as a site preparation practice, there would be loss of most of this N in volatile forms (Raison *et al.* 1985). Other nutrients such as S, K and P may also be lost in varying amounts (Raison *et al.* 1993, O'Connell and McCaw 1997). Where residues are retained, decomposition of the leaf component of *E. globulus* is rapid, with a concomitant release of plant nutrients to soil. Leaf contained more than 70% of harvest residue-N and about 50% of the P. About two thirds of these leaf nutrient stores were released during the first year following harvest, with these amounts exceeding the quantities of nutrients likely to be taken up by the newly replanted trees. Immobilisation of N in decomposing bark and woody residues may act as a buffer against N loss (Carlyle *et al.* 1998), but at our site this represented only a minor component (less than 10%) of the N released from harvest residues in the first year of decomposition (Fig. 2, Table 1). Over longer time scales, larger woody residues become sources of N, with release rates approaching rates of dry weight loss (Fig. 3). In terms of conservation of mineral N early in the

Figure 10. Stem volume of trees during the first 7 years since establishment in 1995 of second rotation *E. globulus* plantations at (a) the Red earth and (b) the Grey sand sites. Planting density is 1250 stems ha^{-1}. Stem volumes at time of harvesting the 8-year old first rotation plantations are indicated for each site. Dashed line indicates mean growth rate across all treatments. At Red earth site, growth was significantly different between treatments only in the first year of growth (February and April 1996; $p<0.05$). At Grey sand, growth differences were also significant in the first year (October 1995, $p<0.01$; and November 1995, $p<0.001$) and at each annual measurement from age 4 to 7 years (1999 to 2002; $p<0.01$)



rotation phase, immobilisation of N in the soil by extractives leached from the eucalypt leaves (Aggangan *et al.* 1999) is an important mechanism for limiting N loss. At one of our sites, where nitrate was the predominant form of mineral N, retention of residues significantly reduced standing pools of mineral N and presumably also the loss of N through leaching (O'Connell *et al.* 2000).

Of the other nutrients in harvest residues, K is probably most at risk in regard to leaching loss. Our results indicate that more than 90% of the K in harvest residues will be released during the year after harvest (Table 1). Much of this release will occur rapidly with the first rains that follow harvest. In sandy soils or on sites with low cation exchange capacity, there is a strong possibility of leaching of K down the soil profile. Even where new seedlings have been planted soon after harvest, the limited spatial extent of root systems of the small plants will restrict the capture of much of this labile K. Annual soil sampling indicated a decline in surface soil exchangeable K in the first 3 to 4 years after logging (O'Connell *et al.* 2000), followed by a reversal of this trend in later samplings. The data indicate that for the most recent sampling (2002), concentrations of exchangeable K in surface soil were 1.5 (grey sand) to 2.3-fold (red earth) greater than the values found in 1998 (Fig. 6). This suggests uptake of K may now be occurring from deeper strata in the soil profile and contributing, through recyling in litterfall, throughfall, stemflow, and root turnover, to increases of K in surface soil.

Early in the rotation, before stand canopy closure, soil mineral N accumulates due to soil environmental conditions (moisture and temperature) favourable for mineralisation of soil organic matter and limited uptake of N by new plantations (O'Connell *et al.* 2000). This accumulation will, on many sites, result in leaching of N below the rooting zone. Leaching will be most likely where mineral N is present as nitrate or where soils are coarse textured (sandy) and have low cation exchange capacity. After canopy closure this situation is reversed, as tree roots occupy the site and take up a higher proportion of mineralised N. This will lead to lower concentrations of mineral N in soil and no leaching losses.

At the Busselton (grey sand) site, additional experiments to provide information on the dynamics of tree nutrient uptake indicated significant growth responses to N added during the first two years (BL_2 residue treatment common to all plots, Fig. 11a). Part of this demand for N can be met through appropriate harvest residue management. For example, retention of residues may induce N immobilisation early in the rotation resulting in reduced leaching losses and increase N mineralisation later in the rotation when the root system is more fully developed. At Busselton, cumulative N mineralisation over 5 years differed by 100 kg N ha^{-1} between BL_0 and BL_3 treatments (Fig. 11b). However, because of the asynchrony between the time of supply of N through mineralisation, and the ability of young plants to take up this N, even differences of this magnitude are insufficient to meet N demand by the developing plantation. A comparison of amounts of N released through mineralisation of soil-stored N with aboveground accumulation of N in tree biomass at two levels of applied N is shown in Fig. 12. Results illustrate the differences over time in the N requirement of the developing stand compared to the rate of N supply from mineralisation of soil organic N. Early in the rotation, mineral N supply from soil and residue stores is high but is spatially dispersed in relation to the root system. After the first year, N demand increases and additional sources of N are required to achieve potential growth rates. Thus, even when harvest residues are retained, application of N in fertilisers will still be necessary to maximise plantation productivity on many sites (Fig. 12).

Our research was concentrated at two sites in southwestern Australia. Plantation productivity differs markedly at these sites, due principally to differences in their soil characteristics (soil texture and nutrient supplying capacity). There are also marked differences between the sites in the relative growth rates of first and second rotation tree crops. Whereas at the more fertile red earth site, projected harvest volume of the second rotation crop is within 13% of first rotation productivity, at the grey sand site, second rotation productivity is much lower (by about 25% to 50%) than achieved in the initial tree harvest (Fig. 10). Where N was applied at the grey sand site (Figs. 11a, 12), growth rates were more similar to those achieved in the first rotation, suggesting increased nutrient limitations to tree growth in the second rotation at this site. Our other research in southwestern Australia (Grove *et al.* 2001, O'Connell *et al.* 2003) has shown that marked reductions in nutrient supply (especially N and P) can occur during the first rotation when farmland is converted to continuous tree cropping. At sites where soil fertility status is already relatively low this may lead to reduced wood production in second and subsequent rotations of tree crops. Consequently, for many sites in this region, future plantation silviculture will need to focus more on proactive management of stand nutrition in order to sustain production levels achieved in the first rotation.

Currently, experimental results extend over a period up to eight years following stand harvesting and it is planned to continue monitoring the sites through the complete rotation to age approximately 10 years. Explaining and generalising research outcomes will be a key focus of future activities. A whole system model (G'DAY – Comins and McMurtrie 1993) is being used to simulate scenarios based on alternative options for managing harvest residues under different site and productivity conditions. Model predictions are being used to assess the likely impact of site management on long-term soil N status and plantation productivity (Corbeels *et al.* 2002).

Impacts on Management

The majority of eucalypt plantations in Western Australia have been established since 1990 (Wood *et al.* 2001) and the average rotation period is expected to be about 10 years. Based on historical data on annual planting rates, current harvesting and re-establishment of second rotation plantations is estimated to be only 1000 to 2000 ha yr^{-1}. These rates will increase and within 5 years are expected to be about 15 000 ha yr^{-1}. On the limited area of second rotation plantations

Figure 11. Growth response of trees to applied N, measured at age 5 years (N applied during years 1 and 2) (a) and (b) cumulative soil N mineralisation on BL$_0$ and BL$_3$ treatment at the grey sand site

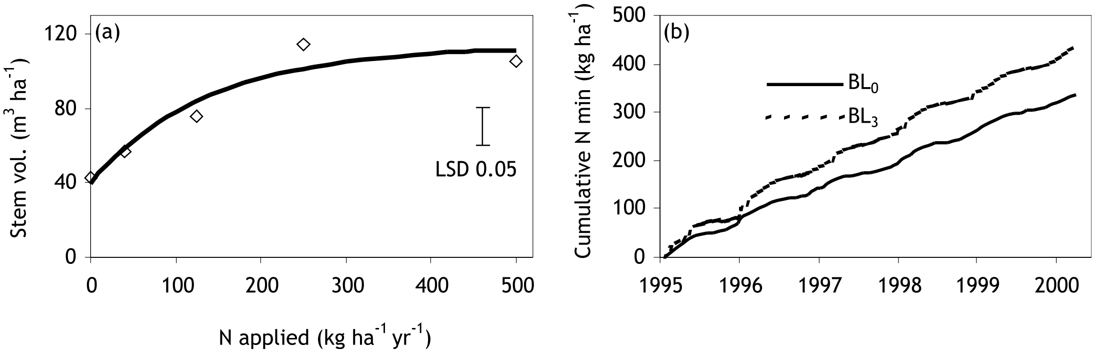
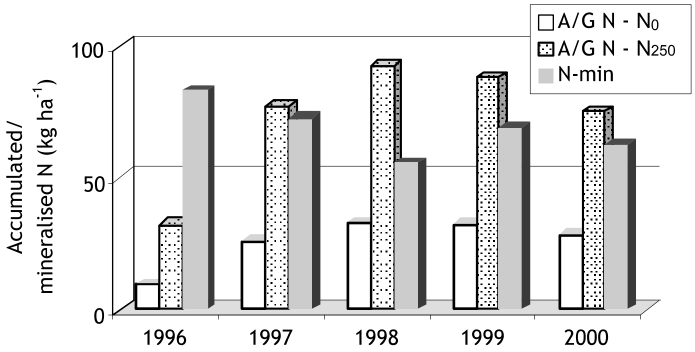


Figure 12. Annual above-ground accumulation of N by trees at the grey sand site (Busselton) for 2 levels of applied N (0 and 250 kg ha^{-1} for 2 years), together with cumulative annual soil N mineralisation on the BL$_2$ treatment during the first 5 years of the plantation rotation at the Busselton site



currently being re-established on harvested areas, there is a range of site preparation treatments used, including burning of harvest residues. However, amongst local plantation managers there is a general recognition of the importance of soil organic matter conservation, partly arising from dissemination of research results from this network project. As the industry moves to a more mature phase, and techniques and machinery are developed to better manage harvest residues, it can be expected that plantation managers will seek to incorporate silvicultural protocols aimed at retaining slash following logging. As a consequence, there is currently scope for research and demonstration to show the best practical and cost effective options for managing the harvest residues retained on replanted and also on coppice-regenerated second rotation sites.

Current and related research (Grove *et al.* 2001, O'Connell *et al.* 2003) has demonstrated that site-specific changes in nutrient supply rates are likely over successive plantation rotations in southwestern Australia. These changes have the potential to impact adversely on long-term production rates. Thus, there is a need for research and inventory across the plantation estate to identify and stratify site types according to their likely susceptibility to nutrient decline. This would allow industry to better target fertiliser additions to maximise wood production and the economic outcomes from plantation management. In the increasingly competitive global market for forest products, maintenance of high production rates will be crucial for viability of the local plantation industry. Managing nutrients and other constraints to productivity (including water) will be critical for achieving this objective.

Acknowledgements

Funding for this research was initially provided through Australian Government Industry Statement Funds to the CSIRO and subsequently by the Australian Centre for International Agricultural Research (ACIAR) as a collaborative research project with Kerala Forest Research Institute, India. Support was also provided by the Rural Industries Research and Development Corporation (RIRDC), Bunnings Treefarms and the Western Australian Department of Resources Development. Field assistance, in-kind support and land provided by Bunnings Treefarms Pty Ltd (now WA Plantation Resources Pty Ltd), Mr M. Cox and Mr C. Winfield are gratefully acknowledged. Many CSIRO colleagues, particularly G. Wan, P. Damon, T. Pham and S. Snelling provided technical support. CIFOR provided financial support for attending the workshops in Congo and China.

References

Aggangan, R.T., O'Connell, A.M., McGrath, J.F. and Dell, B. 1999. Impact of *Eucalyptus globulus* Labill. leaf litter on C and N mineralization in soils from pasture and native forest. Soil Biology and Biochemistry 31:1481-1487.

Carlyle, J.C., Bligh, M.W. and Nambiar, E.K.S. 1998. Woody residue management to reduce nitrogen and phosphorus leaching from sandy soil after clear-felling *Pinus radiata* plantations. Canadian Journal of Forestry Research 28:1222-1232.

Comins, H.N. and McMurtrie, R.E. 1993. Long-term response of nutrient-limited forests to CO_2 enrichment: equilibrium behaviour of plant-soil models. Ecological Applications 3:666-681.

Corbeels, M., O'Connell, A.M., McMurtrie, R.E., Grove, T.S. and Mendham, D.S. 2002. Modelling changes in nitrogen mineralization following conversion of improved pasture to eucalypt plantation. Agronomie 22:801-815.

Grove, T.S., O'Connell, A.M., Mendham, D., Barrow, N.J. and Rance, S.J. 2001. Sustaining the productivity of tree crops on agricultural land in south-western Australia. RIRDC/LWA/FWPRDC Joint Venture Report 01/09. Canberra. 69p.

Lousier, J.D. and Parkinson, D. 1976. Litter decomposition in a cool deciduous forest. Canadian Journal of Botany 54:419-436.

O'Connell, A.M. 1987. Litter dynamics in karri (*Eucalyptus diversicolor*) forests of south-western Australia. Journal of Ecology 75:781-796.

O'Connell, A.M. 1997. Decomposition of slash residues in thinned regrowth karri forest. Journal of Applied Ecology 34:111-122.

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, Pietermaritzburg, South Africa, 16-20 February 1998, 53-59. Center for International Forestry Research, Bogor, Indonesia.

O'Connell, A.M. and McCaw, W.L. 1997. Prescribed burning of thinning slash in regrowth stands of karri. 2. Nitrogen budgets in pre- and post-fire fuel. International Journal of Wildland Fire 7:41-49.

O'Connell, A.M. and Rance, S.J. 1999. Predicting nitrogen supply in plantation eucalypt forests. Soil Biology and Biochemistry 31:1943-1951.

O'Connell, A.M., Grove,T.S., Mendham, D. 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: 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. and Rance, S.J. 2003. Changes in soil N status and N supply rates in agricultural land afforested with eucalypts in South-Western Australia. Soil Biology and Biochemistry 35:1527-1536.

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

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.

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

Raison, R.J., O'Connell, A.M., Khanna, P.K. and Keith, H. 1993. Effects of repeated fires on nitrogen and phosphorus budgets and cycling processes in forested ecosystems. *In*: Trabaud, L. and Prodon, R. (eds.) Fire in Mediterranean ecosystems, 347-363. CEC, Brussels-Luxembourg.

Turton, A.G., Marsh, N.L., McKenzie, R.M. and Mulcahy, M.J. 1962. The chemistry and mineralogy of lateritic soils in the south-west of Western Australia. Soil Publication No. 20. CSIRO, Australia.

Wood, M.S., Stephens, N.C., Allison, B.K. and Howell, C.I. 2001. Plantations of Australia – a report from the National Plantation Inventory and National Farm Forest Inventory. National Forest Inventory, Bureau of Rural Sciences, Canberra.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

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

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Abstract

This paper presents the early results of the effect of harvesting and site management on the growth of a second rotation *Acacia mangium* plantation at PT Musi Hutan Persada, South Sumatra, Indonesia. Impacts of various harvest and residue management options, including litter and slash removal, whole tree harvest, only stems of commercial size removal, and double slash retention were examined. Growth responses to application of N, P, K fertilisers and Ca were studied in another set of experiments. At age 2 years, the complete removal of litter and slash from the site reduced tree height, stem diameter and stem volume slightly. At 2 years the application of N fertiliser up to a rate of 27.6 g tree^{-1} had no significant effect on growth, while P fertilisation increased tree height, stem diameter and volume with the optimum level at a rate of 14 g P tree^{-1}. The combined effect of N and P was not detected. Application of K fertiliser (75 g K tree^{-1}) and hydrated lime (335 g Ca tree^{-1}) had no significant effect on growth. The decomposition rate of *A. mangium* litter was slow. Litterfall of young plantations (14 to 22 months) was high amounting to 4.45 t ha^{-1} over 8 months. Estimates of the amounts of nutrients removed by different biomass harvesting regimes in relation to nutrient capital in the soil provide a sound basis for developing sustainable management practices.

Introduction

This study examined impacts of inter-rotation management on productivity of *Acacia mangium* plantation at PT Musi Hutan Persada, South Sumatra, Indonesia. Hardiyanto *et al.* (2000) reported the establishment details of the experiments. The project aimed to address the growing concern of the company about the productivity and sustainability of *A. mangium* over successive rotations. Research focused on the impact of slash management on soil nutrient stores and tree nutrition. Studies were initially established in January 1999 at Toman site. Unfortunately three months after planting, access to the experimental site was prevented due to a land dispute involving the local community. Despite this unexpected event, the core experiment (slash management) recovered but the nutrition study failed due to lack of maintenance. All experiments were re-established

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in January 2000 at a different site located at Sodong, approximately 15 km from the first site (Toman). Results from both studies are presented in this paper. The first and second sites are referred to as Toman and Sodong, respectively.

Site, Soil and Stand Description

The overall company area is geographically located at 103°10'-104°25'E longitude and 3°05'-5°28'S latitude. The altitudinal range is 60-200 m above sea level. The area is located in lowland humid environment with the average daily temperature about 29°C (range 22-33°C). The annual rainfall ranges from 1890 to 3330 mm, which falls mostly between October-May with a dry spell in June-September. The terrain of the total company land area is mostly flat to undulating (0-8% slope) but with some areas 8-15% slope. The Toman site has a very gentle slope (0-3%), and Sodong is flat.

Soil in the area 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). Typically they have an Ap horizon of dark red to dark brown clay (0-25 cm) overlaying a yellowish to brownish red B horizon clay (20-80 cm) over a well-defined red to yellowish red clay BC horizon (50-180 cm).

Hardiyanto *et al.* (2000) described the soil at the Toman site. Sodong has a typical soil profile consisting of an Ap horizon of dark brown (7.5 YR 3/3) silty-clay (0-20 cm) overlying yellowish-red (5 YR 5/6) clay Bt_1 horizon (20-55 cm) and yellowish-red (5 YR 5/6) clay Bt_2 horizon (55-80 cm); this was followed by a very clear boundary of red (2.5 YR 5/6) clay BC horizon (80-180 cm) containing iron concretion. The soil is Red Yellow Podsolic or Typic Plynthudults (Soil Survey Staff 1992).

Stand

The previous *A. mangium* stand where the two experimental trials were established was typical of the first rotation plantations at PT Musi Hutan Persada. They were established using seed from a genetically unselected local seed source on former alang-alang (*Imperata*) grassland. The sites were ploughed twice using a wheeled tractor and harrowed once. 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. Most trees in first rotation plantations are multistemmed, as they were not singled.

Toman Site

Hardiyanto *et al.* (2000) have described the Toman stand in detail. The first rotation plantation was established in January 1990 with a spacing of 3 m x 3 m. The stand stocking was 1382 stems ha^{-1}, 19% of trees were dead. The predominant height was around 22 m and basal area 30.4 m^2 ha^{-1} at clear felling at age 9 years. The stem diameter at breast height (DBH) ranged from 5 to 38 cm and the average stem diameter was 17.7 cm. Marketable wood (diameter >10 cm over bark) was 228 m^3 ha^{-1}.

Sodong Site

The first rotation stand was established in January 1991, spaced at 3 m x 2 m. Average stand stocking was 1966 trees ha^{-1}, of which 37% were standing dead trees. When the stand was felled at 10 years of age the predominant height was about 24 m and the basal area 39.6 m^2 ha^{-1}. Stem diameter ranged from 6.0 to 50.9 cm and average stem diameter was 14.1 cm. Commercial wood volume (diameter > 8 cm over bark) was 262 m^3 ha^{-1}.

Experiment Details

Core Experiment

Toman site

The core experiment at Toman has four slash management treatments (Hardiyanto *et al.* 2000):

BL_0	Litter and all slash removed after harvesting wood.
BL_1	Whole live trees harvest.
BL_2	Only stem of commercial size (diameter > 8 cm over bark) removed.
BL_3	Double slash.

An additional set of BL_2 (BL_{2B}) plots was included for sequential biomass sampling of trees as the stand develops. The experiment was arranged in a randomised complete block design, replicated four times. Plot size was 40 m x 36 m with tree spacing of 4 m x 2 m. Seedlings raised from improved seed (provenance stand of Wipim, Papua New Guinea) were planted in early January 2000. Fertilisers were applied at following rates per tree: 30 g urea (13.8 g N) and 87.5 g SP_{36} (14 g P) at planting time. Trees were singled three months after planting and pruned from the base at six months, retaining about 70% of live crown.

Sodong site

Experimental design, treatments and planting method of the core experiment were similar to those at Toman, except for the plot size and spacing. Here the plot size was 36 m x 36 m and the tree spacing 3 m x 3 m. A standing crop of 2 ha area close to the experimental plot was set aside. Trees were felled and treatments applied from October to November 2000. Seedlings were planted at the end of January 2001 using seedlings collected from a seedling seed orchard (Oriomo River, Papua New Guinea provenance). As at Toman, trees were singled when they were three months old and pruned at six months, leaving about 70% of live crown.

A decomposition study conducted at Sodong, is described in Hardiyanto *et al.* (2000). Litterfall was also measured by placing five litter traps at random locations on the forest floor of every BL_2 plot. Each trap was 1 m x 1 m, with 10 cm high wooden sides, and fitted with a perforated plastic sheet at the base. Litter traps were installed at the end of March 2002 when trees were 14 months old.

Optional Treatment (Sodong Site)

Two optional studies (Nutrition studies A and B) were laid out in an area adjacent to the core experiment.

Nutrition study A is a 3 x 3 factorial experiment involving three different levels of N and P using urea and SP_{36} fertilisers. Fertilisers were applied at the following rates per tree: 0, 13.8 and 27.6 g N, and 0, 14.0 and 28.0 g P.

Nutrition study B is a missing element trial involving K and Ca. There were four treatments: control, K, Ca and K+Ca. Rates of application per tree were: 0 and 75 g K (150 g KCl), and 0 and 335 g Ca (815 g hydrated lime). Each combination of treatment received the basal fertiliser application: 30 g urea (13.8 g N $tree^{-1}$) and 87.5 g SP_{36} (14.0 g P $tree^{-1}$). Experiments, A and B were laid out as a randomised complete block design, replicated four times. Plot size was 36 m x 24 m and the spacing 3 m x 3 m. Seedlings were planted in early February 2001.

Measurements

At Toman, measurements of height, stem diameter at breast height, slash cover and weed cover were taken in the core experiment when the trees were one-year-old. Slash cover was assessed using a visual scale of 1-5 (1: no slash, 5: most slash). Weed cover was measured as percentage area occupied by the weeds in the plot, and dominant weeds were recorded. At 14 and 24 months, tree biomass was sampled in the BL_{2B} plot, and two trees were felled in every block. Biomass was separated into: stem wood (>5 cm), stem (<5 cm), bark, branches (<1 cm, 1-5 cm, >5 cm), and leaf (phyllodes). Subsamples of each biomass component were oven-dried at 76°C to constant weight. Half of the subsamples were used for chemical analysis.

At Toman, the optional nutritional experiment was not measured because of the lack of vegetation control as mentioned in the introduction. For the litter decomposition study, samples were taken monthly for the first 3 months and then annually. Three litter bags were recovered from the BL_2 plot and standing crop at each sampling time. Samples were oven-dried at 70°C for 48 hours, and weighed.

At Sodong, litterfall was collected at two-weekly intervals. Litter from each trap was placed in a plastic bag separately. Samples were oven-dried at 76°C to constant weight. Samples from each four-week period (2 collections) were combined and subsampled, half of the samples were sent for foliar analyses and the remainder kept for future use.

Table 1. The effect of slash treatment on weed cover and survival rate of trees at one year, and height growth and stem diameter at Toman

Treatment	Weed cover (%)	Survival (%)	Height (m)			Diameter (cm)			Volume (m^3 ha^{-1})		
	1 yr	1 yr	1 yr	2 yr	3 yr	1 yr	2 yr	3 yr	1 yr	2 yr	3 yr
BL_0	4.8	95	4.6	9.1	14.5	5.6	11.7	13.4	5.8	48.8	108.2
BL_1	6.8	90	4.8	9.3	14.9	6.0	12.3	13.9	6.8	50.9	115.6
BL_2	7.8	82	4.8	9.8	14.7	6.1	12.4	14.2	6.6	51.8	109.5
BL_3	45.0	73	4.5	9.3	15.3	5.8	12.7	14.6	5.2	46.7	110.2
CV[a]	132.3	13.4	5.6	6.8	7.4	7.7	8.6	3.3	18.4	9.6	11.1

[a] Coefficient of variation.

At Sodong, before the establishment of the experiment, the amount of aboveground biomass and nutrient contents in it were measured. Soil was sampled to characterise physical and chemical properties. Procedures used for estimating biomass, litter and understorey, soil sampling, as well as for plant and soil analyses were similar to those at Toman (Hardiyanto *et al.* 2000), except the minimum stem diameter for the commercial wood component was set at 8 cm, instead of 10 cm. Soil samples were taken using a soil borer from five points within each plot in the core treatments at soil depths: 0-10, 10-20 and 20-40 cm. Samples for bulk density were taken at the soil depths similar to those for chemical analyses from three points in each plot in every block. Soil samples were dried and sieved through a 2 mm screen for chemical analysis. The samples were subsampled and some subsamples sent to the laboratory for soil analyses and the remainder kept for future use.

In Nutrition study B, leaf samples were collected at 1.5 years of age (end of rainy season). The youngest, fully expanded leaf was sampled from outer branch positions in the bottom, middle and top of the tree crown. Leaf samples were randomly collected from 10 trees per plot taken in the five inner rows of the plot. Soil and leaf were subsampled and the subsamples of soil and leaf were sent for soil and foliar analysis respectively. At Sodong, tree heights were measured in the core and optional experiments at one and 1.5 years after planting.

Results

Toman Site

Tree growth

Table 1 shows the weed cover and survival rate of trees at age 1 year and tree growth at age 1, 2 and 3 years. At 3 years of age, slash treatments had no significant effect on height and diameter growth. The BL_0 plot (with removal of litter and slash) had slightly slower growth than those plots having litter and slash. In BL_3, the survival rate of trees was much lower than other plots and tree growth was poorer than other slash treatments (BL_1 and BL_2) due to the considerably higher weed cover (Table 1). Dominant weeds, particularly in BL_3, are: *Mikania micrantha, Imperata cylindrica, Cromolaena odorata* and *Melastoma malabathricum*.

The amount of slash remaining one year after planting was related to the quantity of slash applied to the plot at the beginning of experiment. The remaining slash cover at each plot was scored on a 5 point scale (1= low, 5= high). The average score of slash cover was: 1, 1.25, 3.80 and 5, respectively for BL_0, BL_1, BL_2 and BL_3 showing a considerable amount of slash remaining on the BL_2 and BL_3 plots.

The nutrient concentration of standing biomass at 14 and 24 months is presented in Table 2, while the total dry biomass and their nutrient contents are given in Table 3. Nutrient content was calculated based on the amount of biomass per

Table 2. Nutrient concentration in the standing biomass of young *A. mangium* trees (Toman site)

Biomass components	Nutrient concentration (%)				
	N	P	K	Ca	Mg
14 months:					
Wood	0.207 (0.008)[b]	0.019 (0.001)	0.213 (0.017)	0.101 (0.007)	0.029 (0.002)
Bark	0.847 (0.020)	0.031 (0.001)	0.300 (0.005)	0.539 (0.059)	0.046 (0.005)
Branch and upper stem[a]	0.494 (0.079)	0.027 (0.003)	0.385 (0.032)	0.504 (0.031)	0.079 (0.007)
Foliage	2.242 (0.058)	0.055 (0.006)	0.725 (0.059)	0.790 (0.096)	0.168 (0.018)
24 months:					
Wood	0.162 (0.022)	0.023 (0.003)	0.125 (0.019)	0.025 (0.005)	0.069 (0.008)
Bark	1.131 (0.067)	0.040 (0.006)	0.343 (0.059)	0.665 (0.062)	0.096 (0.015)
Branch and upper stem[a]	0.527 (0.054)	0.037 (0.005)	0.394 (0.038)	0.381 (0.049)	0.127 (0.021)
Old branch	0.278 (0.058)	0.025 (0.006)	0.078 (0.013)	0.508 (0.072)	0.118 (0.017)
Foliage	2.325 (0.158)	0.068 (0.009)	0.698 (0.040)	0.648 (0.060)	0.245 (0.006)
Reproductive parts	2.190 (0.070)	0.111 (0.005)	1.516 (0.060)	0.400 (0.034)	0.204 (0.014)

[a] Diameter < 5 cm, [b]Numbers in brackets are 1 SE.

hectare on BL$_2$ plot multiplied by the mean concentration of nutrient in that biomass. Foliage has the highest concentration followed by reproductive parts, bark, branches, upper stem, and wood, which has the lowest concentration.

Dry weights of branches and foliage at 14 months are slight underestimates because the trees were pruned and biomass of pruned branches and foliage was not measured. This could have been up to 10% of the total biomass. At 24 months, the standing biomass accumulation was almost double that at 14 months. As trees increased in age the proportion of woody component (wood and branches) tended to increase, while that of foliage tended to decrease. At 24 months the nutrient contents of K and Ca in the tree were lower than those at 14 months.

Sodong Site

Soil properties

Soil physical and chemical properties at Sodong are shown in Table 4, and nutrient storage status of the site is given in Table 5. Soil has a high clay content and low pH. The N and organic C contents are medium and decreasing with soil depth, while C/N ratio is low. Phosphorus, K, Ca and Mg are also very low. Nitrogen level is highly correlated with soil organic C ($R^2 = 0.94$). Correlation between the organic C content and P concentration (available P or total P) is very weak.

Biomass

Dry weights of biomass of the stand at Sodong are given in Table 6. The total weight of standing live biomass was 241 t ha^{-1}. Over 74% of this was merchantable stem, of which 67.3% was wood and 7.3% bark. Leaves (1.9%) and branches/upper stem (23.4%) made up the remaining biomass. Litter mass was 7.4 t ha^{-1} and understorey was 1.7 t ha^{-1}. The estimated average biomass in BL$_1$, BL$_2$ and BL$_3$ following treatment application is shown in Table 7.

Tree Growth

Core experiment

At Sodong early growth of trees was good. Survival was 100% except in two plots where it was 98%. At 2 years, tree height in BL$_0$ was only slightly less than other slash treatments. Stem

Table 3. Standing biomass and its nutrient content (Toman site)

Biomass component	Biomass	Nutrient content (kg ha^{-1})				
	(t ha^{-1})	N	P	K	Ca	Mg
14 months:						
Wood	5.50(31.1)[b]	11.4	1.0	11.7	5.6	1.6
Bark	1.78(10.1)	15.1	0.6	5.3	9.6	0.8
Branch and upper stem[a]	5.54(31.4)	27.4	1.5	21.3	27.9	4.4
Old branch	-	-	-	-	-	-
Foliage	4.84(27.4)	138.5	2.7	35.1	38.2	8.1
Reproductive part	-	-	-	-	-	-
Total	17.67	192.4	5.8	73.4	81.3	14.9
24 months:						
Wood	20.85(45.2)	33.8	4.8	26.1	5.2	14.4
Bark	4.02(8.7)	45.5	1.6	13.8	26.7	3.9
Branch and upper stem[a]	12.76(27.7)	67.2	4.7	50.3	48.6	16.2
Old branch	1.57(3.4)	4.4	0.4	1.2	7.9	1.8
Foliage	6.84(14.8)	159.0	4.7	6.7	44.3	16.8
Reproductive parts	0.07(0.4)	1.5	0.1	1.1	0.3	0.1
Total	46.13	311.4	16.3	99.2	133.0	53.2

[a] Diameter < 5 cm, [b] Numbers in brackets are percentage of the total.

Table 4. Soil physical and chemical properties measured before trial establishment (Sodong)

Properties	Soil depth					
	0-10 cm		10-20 cm		20-40 cm	
Bulk density (g cm^{-3})	1.12	(0.03)	1.25	(0.02)	1.33	(0.02)
Sand (%)	9.8	(1.49)	9.8	(1.54)	7.8	(1.25)
Silt (%)	16.8	(1.65)	15.0	(1.47)	25.5	(5.31)
Clay (%)	73.5	(2.63)	75.25	(2.25)	66.75	(4.80)
pH (H_2O)	4.08	(0.025)	4.12	(0.024)	4.24	(0.021)
pH (KCl)	3.92	(0.016)	3.97	(0.017)	4.03	(0.022)
Organic C (%)	3.10	(0.101)	2.61	(0.080)	1.65	(0.055)
N total (%)	0.24	(0.007)	0.21	(0.005)	0.15	(0.004)
C/N	12.70	(0.112)	12.35	(0.196)	11.40	(0.224)
P total (mg kg^{-1})	164.7	(7.595)	157.1	(9.753)	118.2	(9.024)
Available P (mg kg^{-1})	5.35	(0.414)	3.21	(0.287)	1.39	(0.190)
Exchangeable K (mg kg^{-1})	61.10	(3.923)	45.10	(2.239)	33.15	(2.152)
Exchangeable Ca (mg kg^{-1})	175.05	(14.561	83.25	(5.820)	50.55	(3.461)
Exchangeable Mg (mg kg^{-1})	45.26	(3.051)	27.80	(1.470)	23.65	(1.498)

Number in brackets represent 1 SE; Available P by Bray-1; Exchangeable cations by ammonium acetate extraction. For details see Hardiyanto *et al.* (2000).

Table 5. Organic carbon (OC) and nutrient content of soil assessed before trial establishment (Sodong)

Soil depth (cm)	Nutrient content (kg ha^{-1})					
	OC	N	Available P	Exch. K	Exch. Ca	Exch. Mg
0-10	34 753	2727	6.0	68.4	196.0	50.7
20-Oct	32 650	2644	4.0	56.4	104.1	34.7
20-40	44 143	3894	3.7	88.1	134.5	52.9
Total	111 546	9265	13.7	212.9	434.6	138.3

Table 6. Biomass and nutrient content of *A. mangium* stand at 10 years of age at Sodong

Component	Biomass (t ha^{-1})	Nutrient (kg ha^{-1})				
		N	P	K	Ca	Mg
Living tree biomass						
Leaves	4.7	127(5.4)	4.9(0.4)	40.9(1.1)	24.0(3.2)	6.6(0.2)
Branches and stem (< 8 cm)	56.4	311(26.9)	5.9(0.2)	76.6(4.8)	200.8(18.4)	25.4(2.4)
Stem wood (>8 cm)	162.2	338(19.0)	12.2(1.4)	59.7(6.4)	181.1(37.6)	17.6(2.0)
Bark	17.7	187(18.0)	1.8(0.3)	30.9(1.7)	175.5(16.2)	8.4(0.8)
Total living biomass	241.1	962(23.5)	24.3(1.3)	208.1(7.5)	639.5(38.2)	58.0(4.3)
Standing dead wood	3.5	19.3(5.4)	0.4(0.06)	2.9(0.6)	17.1(5.8)	1.1(0.3)
Litter	7.4	95.4(3.6)	1.5(0.07)	10.2(1.2)	49.8(4.2)	8.8(0.6)
Understorey	1.7	36.0(2.3)	1.0(0.08)	14.9(1.3)	6.6(0.7)	3.2(0.08)

Numbers in brackets represent 1 SE.

Table 7. Amount of harvest residues retained at the site and their nutrient content

Plot	Biomass residues (t ha^{-1})	Nutrient (kg ha^{-1})				
		N	P	K	Ca	Mg
BL_1	8.7	125.3	2.5	24.3	53.6	11.5
BL_2	72.1	578.5	12.6	156.5	345.3	53.9
BL_3	124.5	959.3	21.2	270.3	582.4	93.2

diameter and volume in BL_0, on the other hand, were significantly less than other slash treatments (Table 8).

Nutrient concentration in the standing biomass BL_{2B} at age one year is in Table 9. The dry weight of the biomass and its nutrient content are in Table 10. Foliage contained the major portion of nutrients, followed by bark and branch and upper stem, while wood contained the lowest concentration. The dry weights of branches and foliage included the mass of pruned branches and foliage when trees were pruned at six months old.

Nutrition experiments

In Nutrition study A, N fertiliser had no significant effect on tree height at 1 and 2 years. In contrast, P fertiliser increased growth (P=0.001). The levels of P from 0 to 14 g P tree^{-1} enhanced tree height, stem diameter and stem volume significantly. Further increase in the rate of application increased height, stem diameter and volume although not statistically significantly. Response to P fertiliser at one year was maintained to 2 years of age (Fig. 1). At 2 years the mean tree heights were 11.8, 12.2 and 12.8 m for 0, 14 and 28 g P tree^{-1} respectively, while the corresponding stem volumes were 65.3, 75.6 and 83.4 m^3 ha^{-1}. There was no significant N x P interaction.

Table 8. The effect of slash treatment on tree height, stem diameter and volume at 1 and 2 years at Sodong

Treatment	Height (m)		Diameter (cm)		Volume (m^3 ha^{-1})	
	1 yr	2 yr	1 yr	2 yr	1 yr	2 yr
BL_0	4.6a	11.3a	6.2a	12.2a	7.3a	63.3a
BL_1	4.9a	11.5a	6.9b	12.9b	9.2b	70.1b
BL_2	4.9a	11.6a	7.2c	12.9b	10.3b	74.2b
BL_3	5.0a	12.0a	7.4c	13.0b	10.9b	78.6b
CV (%)	4.9	3.0	2.9	1.7	8.0	4.4

Treatment means with the same letter are not significantly different at the level of p=0.05 using Duncan's Multiple Range Test.

Table 9. Nutrient concentration in the standing biomass of one year old trees at Sodong

Age and biomass component	Nutrient concentration (%)									
	N		P		K		Ca		Mg	
Wood	0.107	(0.005)[b]	0.028	(0.042)	0.209	(0.023)	0.086	(0.004)	0.109	(0.008)
Bark	1.074	(0.043)	0.041	(0.004)	0.478	(0.045)	0.675	(0.022)	0.119	(0.009)
Branches and upper stem[a]	0.543	(0.010)	0.031	(0.008)	0.582	(0.027)	0.429	(0.023)	0.167	(0.006)
Foliage	2.587	(0.123)	0.090	(0.008)	1.122	(0.062)	0.925	(0.114)	0.220	(0.018)

[a]Diameter <5 cm, [b]Numbers in brackets represent 1 SE.

Table 10. Standing biomass and nutrient content of one-year-old trees at Sodong

Biomass component	Biomass		Nutrient (kg ha^{-1})				
	(t ha^{-1})	(%)[b]	N	P	K	Ca	Mg
Wood	6.32	36.9	6.8	1.8	13.2	5.4	6.9
Bark	1.21	7.1	13.0	0.5	5.8	8.2	1.4
Branch and upper stem[a]	5.97	34.9	32.4	1.9	34.7	25.6	10.0
Foliage	3.64	21.2	94.2	3.3	40.8	33.7	8.0
Total	17.15	100	146.4	7.5	94.5	72.9	26.3

[a]Diameter <5 cm, [b]Pecentage to total biomass.

In Nutrition study B, differences between treatments were not detected up to 2 years of age for tree height, stem diameter and stem volume. Addition of K and Ca fertilisers did not increase growth (Table 11). Foliar samples taken at 1.5 years indicated that there were no significant treatment effects on K and Ca concentrations (Table 12). However, foliar K content tended to be higher in the treatment containing potassium. Calcium content in foliage was not significantly different between the treatments

Litter decomposition

At Toman, one year after placement on BL_2 plot, the weight loss of litter was 55.8, 39.4 and 36.7% for leaf, small twig and medium twig, respectively; while under the standing crop the

Figure 1. Effect of P fertiliser on stem diameter of *Acacia mangium*

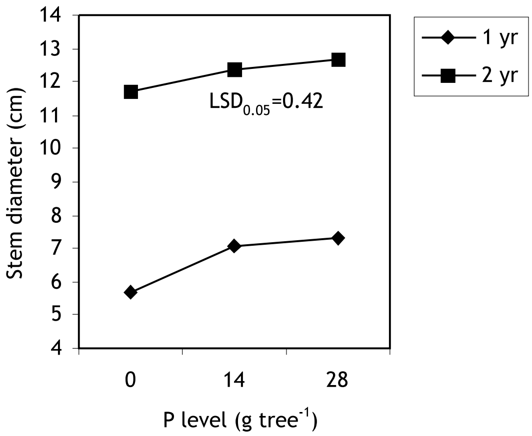

Table 11. Effect of K and Ca fertilisers on growth of *Acacia mangium*

Treatment	Height (m)		Diameter (cm)		Volume (m^3 ha^{-1})	
	1 yr	2 yr	1 yr	2 yr	1 yr	2 yr
Control	4.8	12.0	6.9	12.8	9.2	74.4
K	5.1	12.1	7.2	13.1	10.7	79.7
Ca	4.9	12.6	6.7	12.8	8.9	77.7
K + Ca	5.1	12.1	7.0	12.8	10.0	75.7

Table 12. Effect of K and Ca fertilisers on foliar nutrient concentration of *Acacia mangium* at 1.5 years of age

Treatment	Nutrient (%)			
	N	P	K	Ca
Control	1.96 (0.01)	0.08 (0.01)	0.53 (0.05)	1.24 (0.08)
K	2.02 (0.05)	0.08 (0.01)	0.71 (0.03)	1.28 (0.02)
Ca	2.02 (0.11)	0.11 (0.03)	0.59 (0.04)	1.31 (0.13)
K + Ca	2.03 (0.03)	0.09 (0.01)	0.67 (0.06)	1.18 (0.05)

Numbers in brackets represent 1 SE.

corresponding values were 51.6, 71.7 and 64.3% (Table 13). During the first three months of sampling coefficients of variation (CV) of the weight loss in samples were in the range 8.1-16.4% for leaf, 1.5-14.7% for small twig and 3.3-4.9% for medium twig, while those under the standing crop ranged 4.4-12.1% for leaf, 0.7-12.2% for small twig and 1.3-13.8% for medium twig.

At Sodong, three months after placement, the weight loss of litter in BL_2 plot was 22.5, 27.4 and 22.4% for leaf, small twig and medium twig, respectively; while under the standing crop the values were 30.0, 30.0 and 28.6%. CV of the weight loss were: leaf 2.8-11.3%, small twig 0.1-3.4% and medium twig 0.2-2.3%, and those under the standing crop were: leaf 7.3-8.1%, small twig 4.6-8.2% and medium twig 2.3-8.5%.

At Toman, the decomposition rate was slow in the first month and then increased steadily both on BL_2 and under standing crop, whereas at Sodong the rate of decomposition was fast in the first month, then decreased on both the BL_2

Table 13. Litter weight loss with time and decomposition rate constant at Toman and Sodong sites

Litter component and placement	Site	Decomposition time (months)	Dry weight loss (%)	Annual decomposition rate (k)
BL_2 plot:				
Leaf	Toman	12	55.8	0.84 (R^2=0.99)
	Sodong	19	78.1	0.73 (R^2=0.89)
Small twig: <1 cm	Toman	12	39.4	0.57 (R^2=0.83)
	Sodong	19	69.8	0.70 (R^2=0.88)
Medium twig: 1-5 cm	Toman	12	36.7	0.44 (R^2=0.99)
	Sodong	19	68.9	0.57 (R^2=0.91)
Standing Crop:				
Leaf	Toman	12	51.6	0.86 (R^2=0.95)
	Sodong	19	96.2	1.50 (R^2=0.97)
Small twig: <1 cm	Toman	12	71.7	1.24 (R^2=0.98)
	Sodong	19	86.6	1.39 (R^2=0.97)
Medium twig: 1-5 cm	Toman	12	65.3	0.98 (R^2=0.98)
	Sodong	19	76.8	1.01 (R^2=0.97)

and under the standing crop. At both sites, the rate of decomposition under the standing crop was faster than on the BL_2 plot. The phyllodes (leaf) of *A. mangium* decomposed slowly. Table 13 shows litter dry weight loss with time and decomposition rate constants (k) determined from fitted first order decay functions (Olson 1963). It should be noted that the sample weight of litter was not adjusted for ash weight to correct potential soil contamination.

Litterfall

The litterfall in BL_2 plots from age 14 to 22 months (March to October 2002) was 4.45 t ha^{-1} over 8 months. The litterfall was entirely comprised of foliage in this young stand. The mean of nutrient concentration was: N 1.35 %±0.048, P 0.02 %±0.002, K 0.25 %±0.023, Ca 1.20 %±0.046 and Mg 1.16 %±0.005. Nutrient contents in the litter per hectare were: N 60.1 kg, P 1.0 kg, K 11.1 kg, Ca 53.4 kg and Mg 7.3 kg.

Discussion

Core Experiment

Nutrient capital and loss

Hardiyanto *et al.* (2000) noted nutrient depletion due to harvesting is a cause for concern in relation to the long-term site productivity at Toman because, with the exception of N, nutrient reserves in the soil are very low. There were similar findings at Sodong; the nutrient concentration of P, K and Ca in the soil is very low, whereas N is high (Table 3). Removal of P, K and Ca at both sites is high in relation to the available or exchangeable nutrient pools in the soil (Table 14). The magnitude of depletion of all nutrients from Sodong is greater than at Toman. This may partly be due to the size of merchantable wood harvested: at Sodong all stem wood >8 cm diameter over bark was removed, whereas at Toman it was >10 cm diameter over bark. The amount of biomass removed at Sodong was also higher (178.9 t ha^{-1}) than at Toman (138.9 t ha^{-1}). At both sites the N loss compared with the N pool in the soil is proportionally very low and is not of immediate concern, especially because of the N-fixing capacity of *Acacia*.

The quantity of P, K and Ca taken off site by harvest at both sites highlights the importance of retaining on-site the harvest residues, litter and understorey, which have high nutrient reserves, for the sustainability of highly productive *A. mangium* plantations (Table 14). A reduction in the upper diameter stem size harvested as merchantable wood would result in greater amount of wood removal and also increase the amounts of nutrients removed from the site

Table 14. Nutrient capital and nutrient removed in wood harvest at Toman and Sodong

	Site	Age (yr)	Standing biomass (t ha^{-1})	Amount of nutrient (kg ha^{-1})^a				
				Total	Available	Exchangable		
				N	P	K	Ca	Mg
Nutrient capital	Toman	9	189.5	6600	17.4	116	411	198
	Sodong	10	241.1	9265	13.7	213	435	138
Nutrient removed	Toman	9	138.9	375	9.3	73	267	18
				(6)	(53)	(63)	(65)	(9)
	Sodong	10	178.9	532	14.0	91	357	26
				(6)	(102)	(43)	(82)	(19)

The numbers in brackets are the nutrient removed expressed as percentage of nutrient capital in the soil (based on a soil depth of 40 cm).

[a] Nutrient capital at Toman from Hardiyanto *et al.* (2000) and at Sodong calculated based on the results in Table 5.

because smaller and younger sections of stem and bark contain higher nutrient concentrations. Restoring depleted nutrients to the site through judicious use of fertiliser is also essential for maintaining and increasing production.

Tree growth

At Toman, the slash retention improved tree growth although statistically not significant after 3 years of age. Tree growth in BL_3 was poorer than in BL_1 (Table 1). Slash retention gave no positive response. The higher mortality in BL_3 increased space available to the remaining trees. Weed presence had an adverse effect on tree growth, and needed a practical implication. Weeds compete for site resources (water, nutrient and light) (Lowery *et al.* 1993, Richardson 1993) and in this experiment the dominant understorey of *Mikania micrantha, Imperata cylindrica* and *Cromolaena odorata* competed with *A. mangium* trees for nutrient and water but not light.

In BL_3 the herbicide applied after planting would have been intercepted by the large amount of slash making the herbicide less effective in weed eradication. In addition, the large amount of slash seems to have affected the quality of the planting operation. These factors combined caused high mortality in BL_3. The optional experiment (nutrition study) therefore had a heavy weed infestation, mostly alang-alang (*Imperata cylindrica*) grass, causing the loss of this experiment.

At Sodong, the response of trees to the slash retention was quite positive up to 2 years. The removal of all organic matter (BL_0) reduced tree growth significantly. There is evidence of the positive effect of organic matter improving physical, chemical and biological properties of acid soil (Ultisol and Oxisol) for agricultural crops and rubber plantations in the Southeast Asian region (Pushparajah 1991). Improved growth, resulting from the harvest residue retention, has been reported in studies on other species, e.g. *Eucalyptus grandis* in Brazil (Gonçalves *et al.* 2000), *E. urophylla* in China (Xu *et al.* 2000), and pines in Australia (Simpson *et al.* 2000).

Compared with the results of a similar study carried out in Riau, Sumatra (Nurwahyudi and Tarigan, these proceedings) the *A. mangium* at Sodong at 1.5 years was slightly less in height, but had larger stem diameter.

Response to nutrient additions

Lack of response to N fertiliser suggests there is adequate N in the soil (Table 4) and in the decomposing litter. A number of fertiliser trials carried out at nearby sites, previously dominated by *Imperata* grass, showed N fertilisation increased significantly the growth of first rotation *A. mangium* (Hardiyanto 1993). *Acacia mangium* has a capacity to fix atmospheric N. Given this and providing the N status in the soil in the second rotation remains reasonably high, N fertilisation for planting *A. mangium* is not recommended in the second rotation.

Phosphorus fertilisation increased production. Up to 2 years, the optimum level of P is 14 g (87.5 g SP36) tree^{-1}. As stated previously, the content of soil P at this site is very low, which is typical of Ultisols. Fertiliser trials of *A. mangium* in the first rotation had the same result (Hardiyanto 1993); this P level has been used operationally for plantations at PT. Musi Hutan Persada. Wan Rasidah *et al.* (1988) and Nik Muhamad and Paudyal (1999) have also reported the positive effect of P on *A. mangium* growth on Ultisol soil. Nik Muhamad and Paudyal (1999) found that combined N and P fertilisers increased significantly tree height of *A. mangium*. However in this experiment, the combined effect of N and P was not detected.

In this study, although the soil content of K and Ca at Sodong was low, the application of K fertiliser and Ca (hydrated lime) did not increase tree growth. However, tree growth was slightly better in treatment containing K or K + Ca (Table 11). Differences between treatments in foliar K concentration were not significant, but foliar K levels tended to be higher in the treatment containing K (Table 12). Mead and Miller (1991) proposed the satisfactory and critical levels of foliar K in *A. mangium* were >1 % and 0.6 %, respectively. Compared with their suggested level, the foliar K concentrations found in this study were lower than satisfactory level and for the treatment not receiving K fertiliser were lower than the critical level. However, it should also be noted that the so-called critical and satisfactory foliar levels proposed by these authors are not based on adequate research results. It is plausible that the K fertiliser rate given in the present study was still too low to produce satisfactory growth. Some of the K fertiliser applied at planting time might also be lost through leaching due to low exchange capacity of the soil and high rainfall in the study site. The lack of response to the application of K fertiliser beyond that achieved with N and P addition was also reported from fertiliser trials of other species, such as *Eucalyptus globulus* (Bennett *et al.* 1996, Judd *et al.* 1996, Pereira *et al.* 1996) and *E. nitens* (Bennett *et al.* 1996).

Foliar Ca concentrations found here were all above critical level of 0.2% proposed by Mead and Miller (1991). It is possible that *A. mangium* accumulates Ca in excess of its nutrient need as found in other tree species.

Foliar N concentrations found in Nutrition study B were not considered growth limiting, while those of P were below satisfactory level of 0.13% as suggested by Mead and Miller (1991). As pointed out previously in Nutrition study A, the application of P fertiliser had positive effect on the growth of *A. mangium*; however, increasing fertiliser rate from 14 to 28 g P tree^{-1} gave only small additional stem and volume growth. Considering that all treatments in Nutrition study B received 14 g P tree^{-1}, it seems that the P level in the study was not limiting for normal growth of *A. mangium*, even though the foliar content of P was less than satisfactory level according to Mead and Miller (1991).

To meet the demand of K and Ca for new growth, trees might use available K and Ca from the decomposing litter, however, the available K and Ca in the litter seem inadequate to meet the K and Ca requirements. The K and Ca contents of the standing biomass of one-year-old trees amounted to approximately 94.5 and 72.9 kg ha^{-1} respectively (Table 10), while the total K and Ca in the litter prior to establishment was only 10.2 and 49.8 kg ha^{-1} respectively (Table 6). Some of the nutrients from the decomposing litter is likely leached out; therefore, the greater portion of K and Ca demands has to be taken from the soil. It seems likely that the contribution of nutrient pool from litter plays an important role in meeting the nutritional demands of trees early in the crop cycle.

Reapplication of K fertiliser and hydrated lime (223 g K tree^{-1} and 167 g Ca tree^{-1}) was conducted to assess the further response of these nutrients. Potassium fertiliser was applied in split doses, half of the rate was applied in March 2003 while the remainder will be applied at the beginning of next rainy season. Hydrated lime was applied at once in March 2003. These fertilisers were broadcast on the plot receiving the respective treatment. The rate of K and Ca was based on the nutrient contents of trees at one year old at Sodong (Table 10) assuming fertiliser utilisation efficiency of 50%.

In this experiment trees started closing canopy at 10 months. Following the canopy closure a greater portion of K requirement by trees will likely be met by retranslocating K from old foliage before it falls and another portion will be taken up from the soil, as well as from decomposing litter. As reported from other species, retranslocation of mobile nutrients, including K is a common mechanism to reuse nutrients to support new growth (Nambiar and Fife 1991, Saur *et al.* 2000). As biomass increases, the K requirement will also increase; trees will likely extract more K from the soil and perhaps from soil depths below the level sampled in this study. A study to quantify the amount of nutrient retranslocation in *A. mangium* is in progress.

Two fertiliser trials carried out on Ultisol soil in Malaysia showed the beneficial effect of K in combination with P on the growth of *A. mangium* (Nik Muhamad and Paudyal 1999). Hardiyanto (1993) reported that K fertiliser (40 g KCl tree^{-1}) had no significant effect on *A. mangium* growth in the first rotation plantation grown at a site formerly dominated by *Imperata* grass. Potassium has not been applied when planting at PT. Musi Hutan Persada. However, it is clear that the amount of cations removed by harvested wood represents a large proportion of the nutrient capital and more detailed studies on the cycling of these nutrient pools and their relationship to productivity are a priority.

Decomposition

The decomposition rate of *A. mangium* litter was slow. After three months, the leaf weight loss varied from 20-30%. Litter decay rate at Toman in the beginning was slightly slower than at Sodong, which might be due to the lower rainfall at Toman during the first 3 months of litter decomposition; 192, 145 and 166 mm at Toman, and 294, 191, and 183 mm at Sodong. Nutrient contents of the litter could also affect the decomposition rate (O'Connell and Sankaran 1997). At both sites the nutrient contents of the litter were not measured, but the differences were likely to be small.

Decay rate of *A. mangium* leaf litter in this study was slower than that of litter from other tree legumes, such as *Leucaena leucocephala and Paraserianthes falcataria*, but comparable with *A. auriculiformis* and *Dalbergia latifolia;* 76%, 56%, 33% and 39% respectively after 4 months (Wijaya 1980). The leaf litter decomposition rate of *A. mangium* in this study is comparable with that in other studies with the same species. Hilman (1993) estimated the dry weight loss of *A. mangium* leaf litter at Sukabumi, West Java as 34% after 3 months, and Mindawati (1999) found a value of 27.4% after 3 months at Majalengka, West Java. A study conducted in Subanjeriji, South Sumatra gave the weight loss of leaf and twig under an 8-year-old *A. mangium* plantation as 38.9 and 35.5% respectively after 4.5 months (Setiawan 1993), and 47.4 and 59.1 % respectively after 1 year (SEAMEO BIOTROP 1998). The *k* values of leaf litter found in this study were comparable with those recorded in *A. auriculiformis* (*k*= 0.72 – 1.44) (Sankaran *et al.* 1993), *E. tereticornis* (*k* = 0.74) (Sankaran 1993), *E. grandis* (*k* = 1.12) (Sankaran *et al.* 2000). Litter decay rate is partly determined by its lignin content (O'Connell and Sankaran 1997). SEAMEO BIOTROP (1998) found that the leaf of *A. mangium* contains 52.4% lignin, and twig approximately 29.6%. The relatively slow decay rate of litter rich in N content has been found in other tree legumes (Sankaran 1993).

Decomposition rate under the standing crop was faster than in BL_2. This may be the effect of higher relative humidity and litter moisture content under the standing crop since litter temperature is unlikely to be limiting under both conditions. Sankaran (1993) found that moisture is one of the limiting factors for the breakdown of tree litter in tropical forest.

Litterfall

The amount of litterfall recorded in this young plantation (14-22 months of age) is high (4.45 t ha^{-1} over 8 months); Rachmawaty (1993) from a similar study under a 2-year-old first-rotation plantation of *A. mangium* at the nearby site reported 3.47 t ha^{-1} yr^{-1}. This is apparently due to much faster growth of the stand in the present study compared with that reported by Rachmawaty (1993).

Impacts on Operational Management

Retention of harvest residue on site (comparable to BL_2 treatment) is now an operational practice in the company. Results of this project have provided further clear evidence that this silvicultural practice needs to be continued and refined. Results of the nutrition study have been used by the management of the company for fertiliser prescriptions at an operational scale, namely no application of N fertiliser and application of P fertiliser at 14 g P tree^{-1} at planting time.

Overall results from this study, though based on early results, have also provided to the management evidence that the productivity of the second rotation plantation is not declining in yield, but can be increased so long as the proper silvicultural practices, including the use of genetically improved planting stock, retention of harvest residue, nutrient input and weed control, are fully adopted. Results also provide a sound basis for identifying the critical ecosystem processes and management systems upon which company can invest in further research.

Conclusions

The magnitude of removal of P, K and Ca, (but not N and Mg), due to harvesting was high in relation to the nutrient pools at two sites in South Sumatra. Management of organic matter by retaining on site the harvest residues, litter and understorey, which contain significant amounts of nutrients, and judicious application of fertiliser are very important for the sustainability of highly productive *A. mangium* plantations. The decomposition rate of *A. mangium* litter is slow. The amount of litterfall of young stands is high and its role as a source of nutrients may be critical at an earlier stage of plantation growth.

Acknowledgements

We would like to express our sincere gratitude to the management of PT Musi Hutan Persada for their strong commitment to this site productivity study. We also acknowledge the Center for International Forestry Research (CIFOR) for arranging and sponsoring the workshops. Our special thanks are extended to Dr Sadanandan Nambiar of CSIRO Forestry and Forest Products for his advice.

References

Bennett, L.T., Weston, C.J., Judd, T.S., Attiwill, P.M. and Whiteman, P.H. 1996. The effects of fertilisers on early growth and foliar nutrient concentrations of three plantation eucalypts on high quality sites in Gippsland, southeastern Australia. Forest Ecology and Management 89:213-226.

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: Sao Paulo, Brazil. *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, 3-9. Center for International Forestry Research, Bogor, Indonesia.

Hardiyanto, E.B. 1993. Rekomendasi pemupukan untuk *Acacia mangium* di lapangan. Technical Notes R&D PT. Musi Hutan Persada Vol. 3, no. 3. (Internal publication). 2p.

Hardiyanto, E.B., Ryantoko, A. and Anshori, S. 2000. Effects of site management in *Acacia mangium* plantations at PT Musi Hutan Persada, South Sumatra, Indonesia. *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, 41-50. Center for International Forestry Research, Bogor, Indonesia.

Hilman, I. 1993. Production, decomposition rate and allelopathic effect of pine (*Pinus merkusii* Jungh. and de Vriese) and *Acacia mangium* litters. Technical Notes 5:33-46.

Judd, T.S., Bennett, L.T., Weston, C.J., Attiwill, P.M. and Whiteman, P.H. 1996. The response of growth and foliar nutrients fertilizers in young *Eucalyptus globulus* (Labill.) plantations in Gippsland, southeastern Australia. Forest Ecology and Management 82:87-101.

Lowery, R., Lambeth, C.C., Endo, M. and Kane, M. 1993. Vegetation management in tropical forest plantations. Canadian Journal of Forestry Research 23:2006-2014.

Mindawati, N. 1999. Litterfall production and decomposition rate of *Acacia mangium* Willd. Bulletin Penelitian Hutan 618:65-77.

Mead, D.J. and Miller, R.R. 1991. The establishment and tending of *Acacia mangium*. *In*: Turnbull, J.W. (ed.) Advances in tropical acacia research, 116-122. ACIAR Proceedings No. 35. Australian Centre for International Agricultural Research, Canberra.

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

Nik Muhamad, M. and Paudyal, B.K. 1999. Growth response of *Acacia mangium* plantation to N, P, K fertilisation in Kemasul and Kerling, Peninsular Malaysia. Journal of Tropical Forest Science 11:356-367.

O'Connell, A.M. and Sankaran, K.V. 1997. Organic matter accretion, decomposition and mineralisation. *In*: Nambiar, E.K.S. and Brown, A. (eds.) Management of soil and water in tropical plantation forests, 443-480. ACIAR Monograph No. 43. Australian Centre for International Agricultural Research, Canberra.

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

Pereira, J.S., Tome, M., Madeira, M., Oliveira, A.C., Tome, J. and Almeida, M.H. 1996. Eucalypt plantation in Portugal. *In*: Attiwill, P.M. and Adams M.A. (eds.). Nutrition of eucalypts, 371-387. CSIRO, Melbourne, Australia.

Pushparajah, E. 1991. Soil organic matter: its role and management. *In*: ASIALAND Workshop on the establishment for the management of acid soils, 31-54. IBSRAM Technical Notes No. 5. IBSRAM, Bangkok.

Rachmawaty, V.A. 1993. Pengukuran produktivitas seresah *Acacia mangium* Willd. Di hutan tanaman industri Subanjeriji, Sumatera Selatan. (Unpublished Thesis). Fakultas Kehutanan Institute Pertanian Bogor, Bogor. 93p.

Richardson, B. 1993. Vegetation management practices in plantation forests of Australia and New Zealand. Canadian Journal of Forestry Research 23:1989-2005.

Sankaran, K.V. 1993. Decomposition of leaf litter of albizia (*Paraserianthes falcataria*), eucalypt (*Eucalyptus tereticornis*) and teak (*Tectona grandis*) in Kerala, India. Forest Ecology and Management 56:225-242.

Sankaran, K.V., Balasundaran, M., Thomas, T.P. and Sujatha, M.P. 1993. Litter dynamics, microbial associations and soil studies in *Acacia auriculiformis* plantations in Kerala. KFRI Research Report No. 91. Kerala Forest Research Institute, Kerala, India. 56p.

Sankaran, K.V. *et al.* 2000. Effects of site management on *Eucalyptus* plantations in the monsoonal tropics. *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.

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

SEAMEO BIOTROP 1998. Laporan penelitian produktivitas lahan hutan tanaman industri *Acacia mangium* di areal pengusahaan. PT. Musi Hutan Persada, Bogor, Indonesia. 62p.

Setiawan, I. 1993. Studi proses dekomposisi *Acacia mangium* Willd. di hutan tanaman industri Subanjeriji, Sumatera Selatan. (Unpublished thesis). Fakultas Kehutanan, Institut Pertanian Bogor, Bogor, Indonesia. 98p.

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: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 73-82. 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. 541p.

Wan Rasidah, A.K., Aminah, H. and Sundralingram, P. 1988. Effect of nitrogen and phosphorus on the early growth of three plantation species in Peninsular Malaysia. Journal of Tropical Forest Science 1:178-186.

Wijaya, M.C. 1980. Results of decomposition study in Ubrug Forest, Jatiluhur. (Unpublished Thesis). Department of Biology, University of Pajajaran, Bandung, Indonesia.

Xu, D.P., Yang, Z.J., Dell, B. and Gong, M. 2000. Effects of site management in *Eucalyptus urophylla* plantations 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: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 31-40. Center for International Forestry Research, Bogor, Indonesia.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Logging Residue Management and Productivity in Short-rotation *Acacia mangium* Plantations in Riau Province, Sumatra, Indonesia

Nurwahyudi[1] and Tarigan M.[1]

Abstract

This paper reports progress on effects of inter-rotation site management of *Acacia mangium* plantations in Riau Province, Sumatra, Indonesia. Growth of the previous stand in relation to soil is discussed. Pre-harvest tree biomass and nutrient content measurements indicate the 7-year, first rotation crop (R_1) had an aboveground live standing biomass of 151 t ha^{-1} made up of 71% stem wood (> 7 cm top diameter), 17% branches and stem (< 7 cm end diameter), 8% bark, 4% foliage, and 0.2% flowers/pods. Total nutrients per hectare in these components were 593 kg N, 16 kg P, 357 kg K, 254 kg Ca and 42 kg Mg. Ground litter and understorey accumulation was 39 t ha^{-1}; mainly from foliage 34%, wood 23% and twigs 24%, bark/partly decomposed 13% and understorey 5%. Treatment applications in the core experiment and in optional studies on the second rotation (R_2) are described and planned measurements indicated. Removal and/or loss of nutrients during harvest and site preparation are having a major impact on the total and available pool of nutrients at the site. These are quantified. Results of early growth of the second rotation show slash removal reduced tree growth at age 18 months.

Introduction

PT Riau Andalan Pulp and Paper (RAPP) started its plantation forest development program in 1993. A pulp mill was commissioned in January 1995 to produce bleached kraft pulp from mixed hardwood. The company obtains wood from government-granted concessions on logged-over forest areas. From an initial production of about 319 000 tonnes of pulp in 1995, the company is increasing to produce 2 million tonnes of pulp per annum by 2004. In 2000, the company began using acacia wood (mainly from *Acacia mangium* Willd.) harvested on a 7-year rotation from its plantations. The expectation is by 2008-9 wood requirements of the mill will be fully met by plantations.

A total of about 300 000 ha of pulpwood plantation will eventually be managed, mostly on degraded land of low fertility. The company is committed

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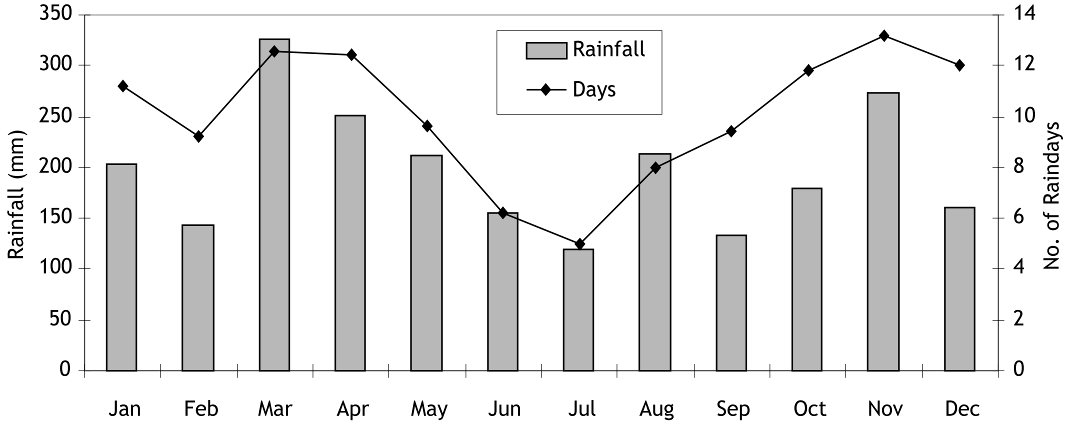
Figure 1. Baserah - Mean Monthly Rainfall and No. of Raindays in 1996-2000



to managing these lands for long-term, sustainable pulpwood production. It strives to adopt best forestry practices and ensure healthy, high-yielding pulpwood stands will be grown economically with minimal impacts on soil and the environment. Present harvesting operations only remove logs of more than 7 cm diameter from the field. Smaller stems, slash and most bark are left on site.

Best practices for inter-rotation site management to achieve sustainable wood production from short rotation plantations are important. This study will provide information to guide such practices in order to sustain productivity.

Location and Site Description

The forest concessions of RAPP are located between 1°N and 1°S of the equator located on undulating to hilly topography in Riau Province, Sumatra. Land elevations are below 400 m above sea level.

The study site is between latitude 0°20'46' S and longitude 101°47'04' E and latitude 0°20'37' S and longitude 101°47'31' E with an altitude of about 100 m asl. The nearest town, Baserah, is about 10 km southwest of the site.

The region has a mean annual temperature of 27°C with 4-5°C differences for the mean maximum and mean minimum temperatures. Relative humidity is commonly above 80%. Mean annual rainfall for the Baserah area was 2438 mm for 1996-2000. There was an average of 129 rain days in a year. February, July and September have less than 150 mm rainfall with other months 160-325 mm (Fig.1).

The study site has undulating to rolling terrain with most slopes 4-8%. Typical upland soil is thin, dark yellowish brown, sandy loam to clay loam topsoil overlying strong brown clay. The soil typically has firm consistency to at least 110 cm depth. This is the major soil type found in RAPP's forest concessions. The soil has been classified as a Typic Hapludult (USDA), a Ferric Acrisol (FAO) and a Podsolik Ortoksik (Indonesian Classification System). Recent riverine alluvial soils occur in low-lying areas and stream valleys.

Characteristics of the First Rotation Stand before Harvest

Details of the first rotation stand have been given by Mok *et al.* (2000). *Acacia mangium* seedlings of Claudie River provenance from northeastern Australia were planted in November 1993 at 3x2 m spacing (1667 trees ha^{-1}). At planting, each seedling received 100 g triple superphosphate (20.2 g P) and 20 g urea (9.2 g N). Singling took place 4 and 8 months after planting. Weeds were controlled by chemicals five times in the first year. When tree enumeration was conducted in September 1999, there were 200-300 living trees per plot in all except three of the experimental plots. These trees had a mean diameter (overbark) of 16.0 cm, and a range of 2.2 to 38.5 cm. Variation in mean diameter between the blocks was small. In each block, 84-91% of living trees were 8-24 cm diameter. Only 1.2% of the experimental trees were multistemmed so the impact on stand diameter distribution was minimal.

Methods

Core Experiment

The experimental design is a randomised complete block with five core treatments. There are four replicates instead of five as originally planned. Block IV in the original layout had the lowest number of living trees among all the blocks. It was decided that this block be used for another experiment (see Mok *et al.* 2000).

The core treatments are:

BL_0	All aboveground biomass, understorey vegetation and litter removed.
BL_1	Whole-tree harvest. All crop trees with bark and including tops, branches, and leaves removed. Understorey vegetation and litter retained.
BL_2	Commercial wood harvest with all stems of >7 cm diameter including bark removed. Non-commercial wood components, leaves, litter and understorey retained and evenly distributed.
BL_2 + bk	Similar to BL_2 but with bark retained and evenly distributed together with other components.
BL_3	Double slash. Commercial wood including bark removed. Non-commercial residues from BL_1 plot brought in and distributed evenly, adding to the slash already present.

An undisturbed, Standing Crop (SC) representative of the stands harvested for the core experiment has been retained as a benchmark stand. This single block of five plots is for future comparisons of changes in soil and other site properties arising from the treatments. The block is located beside a main road and subjected to dust pollution. A new SC block of two plots had been established as a supplement.

After implementation of the core treatments, the trial area was planted in February 2001 with seedlings of an improved selection of the same provenance as first rotation. Each treatment plot is 48 x 48 m with a net area of 33 x 33 m containing 121 trees for measurement. Applications of 25 g triple superphosphate (5 g P) and 35 g rock phosphate (5 g P) per tree were applied at planting.

Tree Biomass Sampling and Biomass on Singling

Tree growth was measured at 4, 8, 12, 18 and 24 months of age, then annually. Tree biomass samples were collected based on height intervals at 4 and 8 months, after that on diameter intervals. Tree biomass sample was collected from gross plot of BL_2 treatment; 16 sample trees were felled to sample the range of tree sizes.

The purpose of singling was to retain a single stem. Samples were collected at 4 and 8 months. Biomass from net plots was collected and weighed fresh from every row from all treatments across 4 replications. Fresh samples were collected and delivered for laboratory nutrient analysis.

Optional Fertilisation Trial

This study is a self-contained experiment and complementary to the core treatments. It is a 3 x 4 x 3 factorial involving different rates of N, P and K application with 3 replicates. The objective of the experiment is to formulate a fertiliser regime for achieving optimum growth of *A. mangium*. The N rates tested are 0, 18 and 36 g N tree^{-1} supplied as urea; P rates of 0, 18, 36, and 54 g P tree^{-1} supplied as triple super phosphate and rock phosphate; and K rates of 0, 18, and 36 g K tree^{-1} supplied as muriate of potash. The experimental site is in the immediate vicinity of the core experiment and on a similar soil type. The site was previously planted with seedlings of the same provenance as first rotation, at 3 x 2 m spacing. All the experimental plots received BL_2 treatment and were replanted on June 2001 with *A. mangium* seedlings of Claudie River provenance at 3 x 3 m spacing. The gross plot of 15 x 21 m has a net area of 135 m^2 (9 x 15 m). Soil sampling at two points per plot was undertaken and the samples were bulked by block for physical and chemical analyses. All trees in each plot were measured before harvest in which all commercial wood was removed manually.

Pre-harvest Measurements

Measurements made in the stand before felling have been presented by Mok *et al.* (2000). All trees were measured before the stand was logged and all commercial-size wood removed manually. No vehicular traffic was allowed in the plots. A 'push test' was given to standing dead trees; those that fell were classified as litter. Twenty-six trees from BL_2 treatment (see Experiment details) plots were randomly sampled by diameter class for the determination of aboveground biomass components and nutrient stores in trees.

The polynomial function $Y = a + b x + cx^2 + dx^3$ describing the relationship between diameter and biomass components was used to determine estimates of biomass and nutrient content in each plot. Biomass and nutrient content of litter and understorey vegetation were determined from four 1 m^2 sample plots randomly selected within each plot. The litter was sampled down to the mineral soil surface and separated into various components for determination. All biomass, litter, understorey vegetation samples were oven dried at 70° C for nutrient analyses.

Before replanting, soil samples were collected from five points within each plot, at depths 0-10, 10-20 and 20-40 cm bulked for physical and chemical analyses. Bulk density measurements were made on core ring samples of known volume from one point in each plot. Samples oven dried at 105° C for the determination.

Plant and soil analyses for the above were conducted by the Research and Development Centre of PT. Asian Agri Abadi at Bahilang, Tebing Tinggi, North Sumatra.

Methods of soil analysis were (Tan 1993) :

- particle size distribution by pipette,
- pH (H_2O, KCl) in 1:2.5, soil : solution,
- organic C by K_2CrO_7 digestion, Walkley and Black titration,
- total N by Kjeldahl digestion/distillation,
- total P by 1:1 $H_2SO_4/HClO_4$ digestion, colorimetric,
- total K, Ca and Mg by 25% HCl extraction, flame photometer,
- available P (Bray II) by 0.1N HCl, 0.03N NH_4F extraction, colorimetric, and
- exchangeable K, Ca and Mg by NH_4Ac extraction at pH 7.0.

Soil moisture retention (pF) characteristics were determined at the Laboratory of the Center for Soil and Agroclimate Research, Bogor. Determinations for pF 1.2 and 2.54 were by pressure plate apparatus and pF 4.2 by pressure membrane apparatus (Staf Laboratorium Fisika Tanah 2001).

Results

Soil Properties before Replanting

Physical and chemical properties of the soil in the plots are given in Table 1.

The soil type is Typic Hapludult as described by Mok *et al.* (2000). The soil is clay, with clay loam topsoil. It is very strongly acid with very narrow C/N ratios down to 40 cm depth. The soil is predisposed to rapid N mineralisation. There are moderate levels of organic C and N in the top 10 cm, decreasing to low levels at depth. Nitrogen concentration is highly correlated with the organic C in the soil (Fig. 2).

Exchangeable cation capacity is moderate to low and reflects the kaolinitic nature of the clay minerals. Except for the surface horizon (0-10 cm), the base saturation is very low, less than 12% throughout the soil profile.

Soil nutrient storage at the trial site is shown in Table 2. The availability of P in the soil is

Table 1. Soil physical and chemical properties of experimental site

Properties	Soil depth (cm)		
	0-10	10-20	20-40
Bulk density (g cm^{-3})	1.09 ± 0.03	1.21 ± 0.04	1.25 ± 0.03
Coarse sand (%)	22.3 ± 2.8	19.1 ± 2.5	17.2 ± 2.4
Fine sand (%)	14.4 ± 1.4	14.3 ± 1.2	13.4 ± 1.2
Silt (%)	23.9 ± 1.7	21.9 ± 0.9	21.0 ± 0.9
Clay (%)	39.8 ± 2.0	45.1 ± 2.2	48.4 ± 2.3
pH (H_2O)	3.60 ± 0.04	3.61 ± 0.02	3.60 ± 0.03
pH (KCl)	3.42 ± 0.04	3.41 ± 0.03	3.40 ± 0.03
Organic C (%)	2.49 ± 0.17	1.43 ± 0.09	0.89 ± 0.05
N Total (%)	0.26 ± 0.02	0.18 ± 0.01	0.13 ± 0.01
C/N	9.52	7.98	6.57
Total P (mg kg^{-1})	398.6 ± 34.2	347.0 ± 33.7	305.4 ± 39.7
Available P (mg kg^{-1})	3.40 ± 0.26	2.27 ± 0.21	1.73 ± 0.16
Total K (mg kg^{-1})	418.9 ± 34.8	411.1 ± 31.8	407.5 ± 33.7
Total Ca (mg kg^{-1})	236.0 ± 47.7	109.0 ± 23.7	58.3 ± 16.9
Total Mg (mg kg^{-1})	589.2 ± 50.6	623.3 ± 48.5	649.1 ± 51.2
CEC pH 7 (c mol kg^{-1})	13.58	12.38	1.66
Ex. K (c mol kg^{-1})	0.35 ± 0.03	0.24 ± 0.03	0.19 ± 0.03
Ex. Ca (c mol kg^{-1})	1.03 ± 0.22	0.46 ± 0.12	0.21 ± 0.07
Ex. Mg (c mol kg^{-1})	0.81 ± 0.11	0.55 ± 0.06	0.32 ± 0.04
Ex. Na (c mol 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 ± 1.50

Note: The number following ± represent 1 SE.

Figure 2. Relationship between organic Carbon and total nitrogen in soil

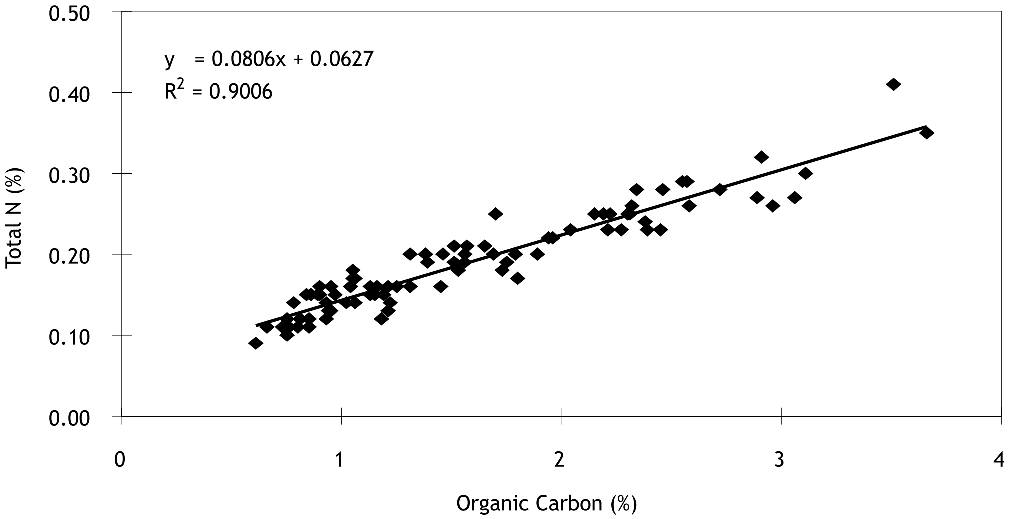


Table 2. Nutrient content of soil at the experimental site

Soil depth (cm)	Nutrient content (kg ha^{-1})									
	Organic C	Total N	P		K		Ca		Mg	
			Avail.	Total	Exch.	Total	Exch.	Total	Exch.	Total
0–10	27129	2849	4	435	148	457	225	257	107	642
10–20	17357	2174	3	420	113	497	113	132	81	754
20–40	22146	3371	4	763	187	1019	107	146	97	1623
Total	66632	8394	11	1618	448	1973	445	535	285	3019

Table 3. Soil moisture retention characteristics at the experimental site

Soil depth	Bulk density	Total pore space	Drainage pores (% vol.)		Water content (% vol.)		Available water
(cm)	(g cm^{-3})	(% vol.)	Rapid	Slow	Field capacity	Wilting point	(% vol.)
0 – 25	1.29	51.4	10.1	4.8	36.6	22.4	14.2
25 – 50	1.29	51.2	10.2	4.8	36.2	23.2	13.0
50 – 75	1.27	52.1	9.7	4.9	37.5	23.9	13.6
75 –100	1.22	54.0	10.0	4.8	39.2	26.7	12.5

approximately 0.7% of the total P content, compared to 22.7% for K, 83.0% for Ca and 9.5% for Mg. The low P availability is attributed to the high fixing capacity of the clay in the soil. A relatively large percentage of the total Ca is in the exchangeable form the opposite is the case for Mg.

Soil moisture retention characteristics were determined on samples collected at four depths from each block (table 3). The average total pore space throughout the 1 m soil profile is 52.2% by volume, with rapid drainage pores occupying about 10%. Available water throughout the profile averaged 13.3% by volume.

Pre-harvest Tree Biomass and Nutrient Content

Biomass estimation

Regression analyses were conducted to determine the relationship of stem diameter with the dry weight of various biomass components such as stem wood, branches, leaves, flowers and pods.

The relationship of diameter with total standing biomass in a cubic regression is given in Fig. 3 and that with stem wood in Fig. 4.

Biomass distribution

General information and methods relating to stand growth and biomass have been reported (Mok *et al.* 2000). Variations in the dry mass of components of live standing trees between plots within a block and between blocks were generally small (<10%).

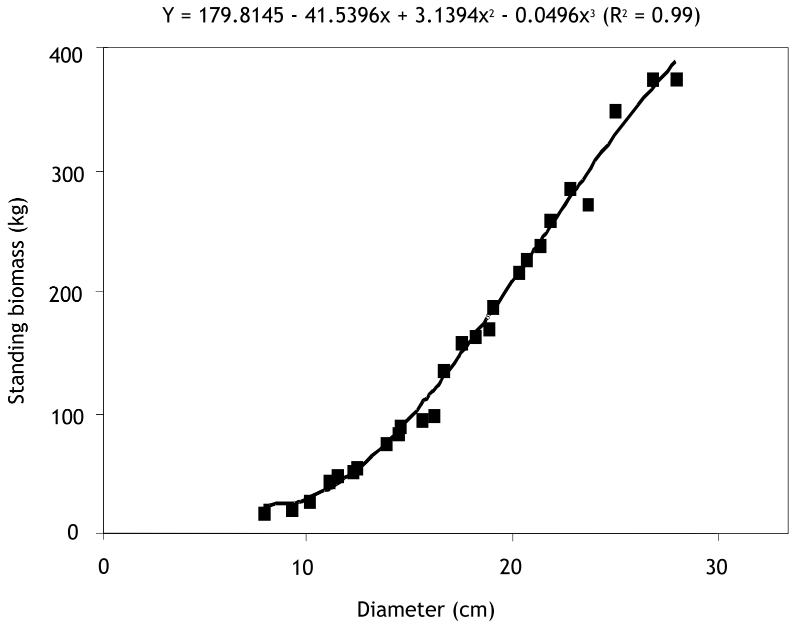
Aboveground biomass and nutrient content of the stand in the core experiment is shown in Table 4. Total dry weight of live standing biomass was 151 t ha^{-1}; merchantable stem wood contributing 71%, bark 8%, branches and stem (<7 cm diameter) 17%, leaves 4%, flowers and pods 0.2%. Litter accumulation was 39 t ha^{-1}; from leaves 34%, wood 23%, twigs 24%, and understorey vegetation 5%.

Nutrient content

The nutrient concentrations of live tree biomass components are given in Table 5 and those of litter and understorey vegetation in Table 6.

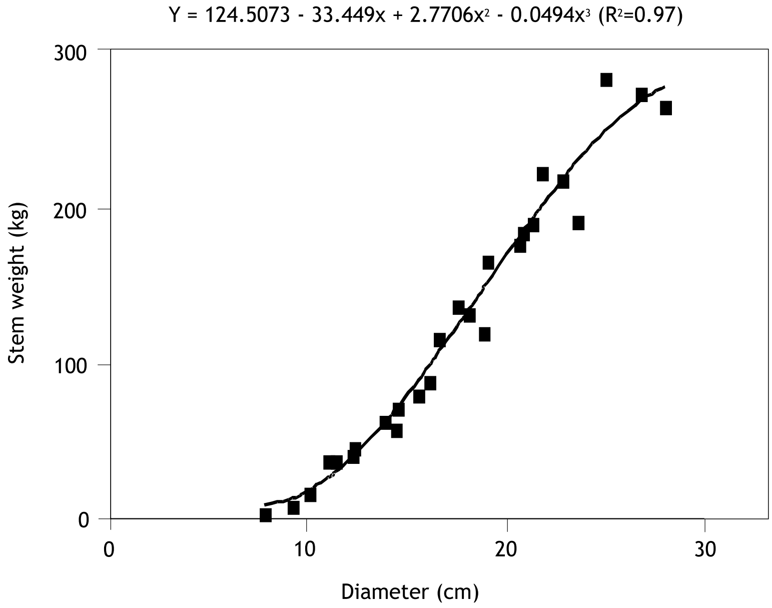
It is apparent from the nutrient estimates that N, K and Ca are in very high demand for biomass production while Mg and P are required in relatively small quantities. Within the tree the highest concentration of nutrients is generally found in the leaves (phyllodes) and flowers, followed by pods, stem bark, branches and stem wood.

Figure 3. Relationship between diameter and dry weight of total standing biomass



$Y = 179.8145 - 41.5396x + 3.1394x^2 - 0.0496x^3$ ($R^2 = 0.99$)

Figure 4. Relationship between diameter and dry weight of stem wood



$Y = 124.5073 - 33.449x + 2.7706x^2 - 0.0494x^3$ ($R^2=0.97$)

Table 4. Aboveground biomass and nutrient content of the *A. mangium* stand at 7 years

Component	Dry weight (t ha^{-1})	Nutrient (kg ha^{-1})					
		%	N	P	K	Ca	Mg
Tree (living) A							
Stem (>7 cm top diameter)	106.9	70.9	159	4	117	79	14
Bark	11.9	7.9	126	3	54	91	4
Branches and stem (<7 cm)	26.3	17.4	147	4	101	61	13
Leaf	5.4	3.6	153	5	79	23	11
Flower	0.1	0.1	4	0	3	0	0
Pod	0.2	0.1	4	0	3	0	0
Sub Total	150.8	100.0	593	16	357	254	42
Litter and understorey B							
Leaf	13.0	33.8	310	6	29	93	29
Wood	8.9	23.1	34	0	9	12	2
Twigs	9.3	24.2	78	1	13	56	8
Bark/partly decomposed comp.	5.0	13.0	56	1	8	38	7
Pod	0.4	1.0	5	0	1	1	1
Understorey	1.9	4.9	32	1	27	7	3
Sub Total	38.5	100.0	515	9	87	207	50
Total biomass (A+B)	189.3	100.0	1108	25	434	461	92

Table 5. Nutrient concentration of tree biomass components

Tree biomass component	Nutrient (%)				
	N	P	K	Ca	Mg
Stem wood	0.15 ± 0.012	0.004 ± 0.0012	0.11 ± 0.022	0.06 ± 0.043	0.01 ± 0.004
Bark	1.05 ± 0.13	0.02 ± 0.007	0.49 ± 0.10	0.72 ± 0.17	0.04 ± 0.004
Branch < 1 cm	1.03	0.04	0.87	0.38	0.10
Branch 1-5 cm	0.50	0.01	0.30	0.21	0.04
Branch > 5 cm	0.46	0.01	0.32	0.21	0.04
Leaf	2.85	0.09	1.47	0.21	0.43
Flower	2.84	0.17	2.10	0.22	0.18
Pod	1.85	0.06	1.40	0.16	0.09

Note: The number following ± represent 1 SE.

Table 6. Nutrient concentration of litter and understorey

Litter and understorey component	Nutrient (%)				
	N	P	K	Ca	Mg
Leaf	2.38	0.04	0.22	0.71	0.22
Wood	0.39	0.01	0.10	0.13	0.02
Twigs	0.84	0.02	0.14	0.60	0.09
Bark/partly decomposed	1.12	0.03	0.15	0.13	0.75
Pod	1.45	0.03	0.34	0.41	0.18
Understorey	1.72	0.07	1.44	0.38	0.20

Table 7. Estimated amounts of biomass residue and nutrient contents retained at the study site

Treatments	Total biomass residue ($t\ ha^{-1}$)	Total nutrients ($kg\ ha^{-1}$)				
		N	P	K	Ca	Mg
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

Table 8. Height, diameter and survival rate of *Acacia mangium* at the study site

Treatment	Height (m)				Diameter (cm)				Survival (%)
Age (months)	4	8	12	18	4	8	12	18	18
BL_0	1.1a	3.1a	5.3a	8.6a	-	-	6.8a	9.3ab	99
BL_1	1.3b	3.4b	5.5a	8.3a	-	-	7.6a	9.2a	96
BL_2	1.3b	3.4b	5.5a	8.5a	-	-	7.1a	9.6b	95
BL_3	1.3b	3.4b	5.4a	8.7a	-	-	7.6a	10.0c	93
BL_2+bk	1.2b	3.4b	5.4a	8.7a	-	-	7.4a	9.7c	92

Treatment means with the same letter are not significantly different at the level of P=0.05 using Duncan's Multiple Range Test.

In the litter, decaying leaves and pods had higher N, K and Ca concentrations than the other components. Decomposing bark had the highest Mg concentration. This is expected as these residues are from the standing biomass.

Understorey vegetation had P and K concentrations higher than in litter components and can therefore be a significant source of these nutrients for the standing crop.

The live standing biomass of 151 t ha^{-1} includes 593 kg N ha^{-1}, 16 kg P ha^{-1}, 357 kg K ha^{-1}, 254 kg Ca ha^{-1} and 42 kg Mg ha^{-1}. Together with the litter and understorey, the experimental stand with a total biomass of 189.3 t ha^{-1} contained an estimated 1108 kg N ha^{-1}, 25 kg P ha^{-1}, 434 kg K ha^{-1}, 461 kg Ca ha^{-1} and 92 kg Mg ha^{-1}.

Biomass Residue and Nutrient Content in Treatments

Estimates of biomass residue and nutrient content in the respective treatment plots after treatment application are in Table 7. The estimates were made from the regression analyses of the various biomass components.

Early Growth of *Acacia mangium*

Mean diameter and height at 12 months are not significantly different between treatments (Table 8). There were significant differences between treatments on diameter at 18 months. Tree height has no significant difference at 18 months. There were significant differences in biomass growth between treatments at 18 months (Table 9).

Biomass Removed in Singling

The first singling at 4 months had mean biomass production of 0.18 t ha^{-1} (Table 10). The second singling at 8 months had mean biomass production of 1.15 t ha^{-1}. The biomass reduction after singling was 46% at 4 months and 24% at 8 months.

Discussion and Conclusions

Accumulation of aboveground biomass in 7-year-old *A. mangium* translates to a mean annual

Table 9. Biomass growth of Acacia mangium trees at the study site

Treatments	Biomass (t ha^{-1})			
	4 months	8 months	12 months	18 months
BL_0	0.29a	4.84a	13.25a	21.85a
BL_1	0.45b	5.97b	14.11a	20.89b
BL_2	0.44b	5.85b	12.09a	22.11a
BL_3	0.42b	5.67b	13.71a	23.44a
BL_2+bk	0.40b	5.60b	12.89a	22.28a
Average	0.40	5.59	13.21	22.12

Treatment means with the same letter are not significantly different at the level of P=0.05 using Duncan's Multiple Range Test.

Table 10. The biomass removed by singlings at the study site

Treatments	4 months (t ha^{-1})	8 months (t ha^{-1})
BL_0	0.15a	1.55a
BL_1	0.19b	0.99b
BL_2	0.21b	0.93b
BL_3	0.20a	1.16b
BL_2+bk	0.14a	1.11b
Average	0.18	1.15

Treatment means with the same letter are not significantly different at the level of P=0.05 using Duncan's Multiple Range Test.

increment (MAI) of 21.5 t ha^{-1}yr^{-1}. This productivity is more than that recorded for sites in Subanjeriji, South Sumatra (Hardiyanto *et al.* 2000, Siregar *et al.* 1999) where MAI ranged from 16.3 to 21.0 t ha^{-1} yr^{-1}. Litter accumulation was very high, at 39 t ha^{-1} or about twice that recorded in Subanjeriji for a 9-year-old stand (Hardiyanto *et al.* 2000). Biomass and nutrient accumulation in the understorey was similar to that of the stand in Subanjeriji. The understorey makes up about 1% of the total aboveground biomass and is expected to make only a small contribution to site productivity. It can be a significant source of K as plantation fertilisation practices until recently do not include this nutrient element.

Until recently harvesting and slash management practice has corresponded to the BL_2 treatment; now stems are debarked in the field. Removal of stem wood up to 7 cm diameter with bark is estimated to remove 285 kg N ha^{-1}, 7 kg P ha^{-1}, 171 kg K ha^{-1}, 170 kg Ca ha^{-1} and 18 kg Mg ha^{-1}. Harvest residues left on site would return 308 kg N ha^{-1}, 9 kg P ha^{-1}, 186 kg K ha^{-1}, 84 kg Ca ha^{-1} and 24 kg Mg ha^{-1} to the soil. This results in a net removal of 84 kg Ca ha^{-1} and 6 kg Mg ha^{-1} from the site. However, contributions from the litter and understorey vegetation would lead to an accumulation in the aboveground total nutrient store of 823 kg N ha^{-1}, 18 kg P ha^{-1}, 263 kg K ha^{-1}, 291 kg Ca ha^{-1} and 74 kg Mg ha^{-1}. If all these nutrients were released into the soil without losses the total soil nutrient content (to 40 cm depth) would be 9.2 t N ha^{-1}, 1.6 t P ha^{-1}, 2.2 t K ha^{-1}, 0.8 t Ca ha^{-1} and 3.1 t Mg ha^{-1}. These amounts of nutrients may be adequate for five rotations (7 years each) of *A. mangium* without further additions of any of these nutrients except Ca at the current level of production. Now that on-site debarking is practised, greater amounts of nutrients will be retained at the site.

Depletion of nutrients in the soil can be very rapid in short rotation *A. mangium* plantations. Without nutrient contributions from harvest residues, litter, and understorey vegetation, the total nutrient pool in the soil at the experimental site would have been depleted by about 9% K and 32% Ca in one rotation. The large requirements of N, K, and Ca need to be viewed seriously. However the N-fixing ability of the tree species minimises concerns of N requirement.

The dominant weed during the first 10 months was *A. mangium* natural regeneration, heaviest in BL_0 treatment, followed by BL_1, BL_2, BL_3 and BL_2+bk. Perhaps mulching of slash has suppressed wildings. This result was similar to *Eucalyptus* in Coastal Plain of Congo (Bouillet *et al.* 2000).

The lowest diameter growth at 18 months was BL_1 (9.2 cm), this result is the same as *Eucalyptus urophylla* in Guangdong Province, China where BL_1 had lowest diameter compared to other treatments in age 16 and 31 months (Xu *et al.* 2000).

Diameter growth at 18 months was greater in the treatments with more logging residue (BL_3 and BL_2+bk). In the treatments that retain slash and bark residue (BL_2+bk) which is slow to decompose, the effect is lower compared to treatments that decompose more rapidly (BL_3). This was also found with *Eucalyptus* in the Coastal Plain of Congo (Bouillet *et al.* 2000). Higher slash residue results in higher growth.

Acknowledgements

The authors wish to thank the staff of Forestry Research and Development Department and Baserah Sector of PT Riau Andalan Pulp and Paper for all the fieldwork and measurements conducted. Thanks to the Center for International Forestry Research (CIFOR) for sponsoring participation at the workshop.

References

Bouillet, J.P., Nzila, J.D., Laclau, J.P. and Ranger, J. 2000. Effect of site management on *Eucalyptus* plantations in equatorial zone, on the coastal plains of the Congo. *In*: 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.

Hardiyanto, E.B., Ryantoko, A. and Anshori, S. 2000. Effects of site management in *Acacia mangium* plantations at PT Musi Hutan Persada, South 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, 41–49. Center for International Forestry Research, Bogor, Indonesia.

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.

Siregar, S.T.H., Hardiyanto, E.B. and Gales, K. 1999. *Acacia mangium* plantations in PT Musi Hutan Persada, South Sumatra, Indonesia. *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, 39-44. Center for International Forestry Research, Bogor, Indonesia.

Staf Laboratorium Fisika Tanah 2001. Penuntun analisa fisika tanah no. 2/1979. Pusat Penelitian Tanah dan Agroklimat, Lembaga Penelitian Tanah, Bogor, Indonesia.

Tan, Y.T. 1993. Methods of analysis for soil. Research and Development Centre, PT Asian Agri Abadi, Bahilang Estate, Tebing Tinggi, North Sumatra, Indonesia.

Xu, D.P., Yang, Z.J., Dell, B. and Gong, M. 2000. Effect of site management in *Eucalyptus urophylla* plantations 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.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

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

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Abstract

Encouraged by the implementation of the national forestry development program, public and private investors are establishing *Acacia* plantations for industrial wood production in South Vietnam. These operations are mostly small to medium enterprises. Their expectations of productivity from short rotation (6-7 years) pulpwood plantations are high but the knowledge and technology required for high and sustained production are inadequate. This paper describes a project on site management and productivity of *Acacia auriculiformis* plantations in the south of Vietnam. The project aims to investigate the effect of various management options including harvesting intensity organic matter retention, vegetation management and nutrient management on production at the end of the rotation. Initial results are described. The volume of the *A. auriculiformis* stand in the first rotation was 130 m^3 ha^{-1} with a mean annual increment (MAI) of 18.6 m^3 ha^{-1} yr^{-1}. Harvesting removed 35.23 t ha^{-1} of stem wood, 4.50 t ha^{-1} of bark, 9.53 t ha^{-1} of branches, and 1.91 t ha^{-1} of leaves. Nutrients in the stem wood and bark removed in the harvesting included 107.6 kg ha^{-1} N, 49.16 kg ha^{-1} Ca and 115.8 kg ha^{-1} K, and 4.42 kg ha^{-1} P. These represent a significant part of the available nutrient pool in the soil and are far greater than the amount currently added as fertilisers. Initial results clearly show the importance of conserving organic matter and nutrients at the site in order to sustain productivity of the site.

Introduction

Vietnam is located in Southeast Asia and has a total area of about 330 000 km^2 between latitude 9^{O}N and 23^{O}N. Formerly Vietnam had 20 million ha of forest land, about 60% of country's area with abundant and diverse flora containing about 12 000 plant species. Due to war, shifting cultivation, illegal logging and other activities, natural forest was reduced from about 43% in 1943 to 28% in 1987. It is estimated that approximately 60 000-100 000 ha of forest is lost annually. At the end of 1993, natural forest and plantations were estimated to cover 9.65 million ha.

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The Government of Vietnam has embarked upon a five million ha afforestation program to increase forest cover to 40% of the country by 2010. According to this program (1998-2010), there will be 1 920 000 ha for protection, 80 000 ha for special uses, and 3 million ha for productive plantations requiring the forestry sector to plant 260 000-400 000 ha annually (Nguyen Duong Tai 2002). The Forest Development Department (FDD) has planned 1 million ha for pulpwood, 400 000 ha for plywood, 200 000 ha for timber and 200 000 ha for special uses. FDD has also aims to apply advanced technology to increase a mean annual increment (MAI) to about 20 $m^3 ha^{-1} yr^{-1}$ in new plantations (Forest Development Department 2002).

In recent years, acacias have made a considerable contribution to large-scale plantations in Vietnam. In the early 1960s, about twenty *Acacia* species from Australia were introduced into Vietnam for trial but only *A. auriculiformis* has become an important species for planting. Large plantations of *A. auriculiformis* have been successfully planted on many sites especially in southern provinces. Important attributes of *A. auriculiformis* are rapid growth, good wood quality for pulp, and tolerance to a range of climatic and soil types in tropical environments. In Vietnam, acacia wood is used as raw material for the paper industry and the planted area will increase to about 10 000-15 000 ha yr^{-1} (Nguyen Hoang Nghia and Le Dinh Kha 1998a).

There has been active research in Vietnam aimed at increasing the yield of *Acacia* plantations by selecting suitable provenances and applying vegetative propagation. There has been some preliminary work in relation to soil suitability, planting techniques such as planting density, fertiliser application and land preparation. A nationwide study examined 5 species and 84 provenances of *Acacia* from 1982 to 1995 (Nguyen Hoang Nghia and Le Dinh Kha 1998b) and developed methods to propagate *A. auriculiformis* and *A. mangium* by cuttings. Studies to assist the establishment of plantations by land preparation, fertiliser application and selection of suitable provenances for *A. auriculiformis, A. mangium and Eucalyptus* spp. have been made in South Vietnam (Pham The Dung 1996). It was found that a harvesting age of 10-12 years for *A. auriculiformis* plantations is most suitable for pulpwood processing (Nguyen Thi Anh Nguyet 2000).

In the last 10 years, the term 'industrial plantation' has been used in Vietnam for man-made plantations in which advanced techniques must be applied to increase yield. However, there is still little scientific basis and essential knowledge on which to decide the application of these techniques to enable sustainable productivity of plantations.

Do Dinh Sam (2001) showed the 'preliminary picture' of the relationship between site and productivity of man-made plantation throughout Vietnam.

In the North

An 8-year-old plantation of *Eucalyptus urophylla* in Phu Ninh, on shallow soil has a MAI of 5.6 m^3 $ha^{-1} yr^{-1}$, while in Tam Nong on deep soil the MAI is 13.7 $m^3 ha^{-1} yr^{-1}$, This species produced at 4 years a MAI of 10.7 $m^3 ha^{-1} yr^{-1}$ on degraded red-yellow ferric soil and 13.5 $m^3 ha^{-1} yr^{-1}$ on non-degraded soil on the plateau.

On red-yellow ferric soil at Vinh Phu, an 8-year-old plantation of *A. mangium* had a MAI of 6 $m^3 ha^{-1} yr^{-1}$ on thin soil (< 50 cm) and 15.7 $m^3 ha^{-1} yr^{-1}$ and 25.7 $m^3 ha^{-1} yr^{-1}$ on soils 80 cm and over 100 cm deep respectively.

On the Plateau

On red-yellow ferric soil of plateau, *A. mangium* has a MAI of 12.4 $m^3 ha^{-1} yr^{-1}$ on a flat site, and 7.8-8.5 $m^3 ha^{-1} yr^{-1}$ on a sloping area. The productivity of *A. auriculiformis* on degraded bazan soils is only 9-10 $m^3 ha^{-1} yr^{-1}$.

In the South

On a thin alluvial soil in the southeast (Bau Bang), 5-year-old *Eucalyptus camaldulensis* has a MAI of 5.8-10.2 $m^3 ha^{-1} yr^{-1}$, while on a deep (>50 cm) ferrallite soil the MAI is 24-29 $m^3 ha^{-1} yr^{-1}$.

An 8-year-old plantation of *A. mangium* in Bau Bang on a deep grey soil has a MAI 16-22 m^3 $ha^{-1} yr^{-1}$

while on shallow soil at Song May the MAI is 15-19 $m^3 ha^{-1} yr^{-1}$. Productivity of *A. auriculiformis* is lower than *A. mangium*. On a grey soil, a 9.5-year-old plantation of *A. auriculiformis* has a MAI of 12-16 $m^3 ha^{-1} yr^{-1}$ on deep soil and 6-10 $m^3 ha^{-1} yr^{-1}$ on shallow soil. However, on a fertile soil, where natural forest had just been cleared, the MAI of *A. auriculiformis* was 22-23.5 $m^3 ha^{-1} yr^{-1}$ in Phu Tan and 35-45 $m^3 ha^{-1} yr^{-1}$ at Minh Duc (Do Dinh Sam 2001).

In general, productivity of *Acacia* species in northern Vietnam is lower than in southern regions (Nguyen Hoang Nghia and Le Dinh Kha 1998a). Many plantations of *A. mangium* in the north have a mean annual height increment of about 2 m yr^{-1} and diameter increment of 2.5 cm yr^{-1} but in the south this species grows with mean height increment of more than 2.5 m yr^{-1} and more than 3.0 cm yr^{-1} diameter. *A. auriculiformis* has quite good growth in commercial plantations in the south with 2.4-2.8 m yr^{-1} for height and 2.5-2.8 cm yr^{-1} for diameter. On dry and poor sites such as in parts of Vinh Phu, Quang Tri and Binhthuan provinces, growth of this species was slow.

It is clear that productivity of plantations varies considerably depending on the characteristics of site including soil fertility, slope, terrain, soil depth, vegetation, climate and management. For industrial plantations, most research so far has 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. Plantation forestry poses many challenges if it is to become a sustainable land use system. Productivity of plantations needs to be high and sustainable because of high initial investments required and to ensure a continuous flow of wood for the industry within the reach of the mills. Plantations must be economically viable whether publicly or privately owned.

The risk to sustainable plantation forestry depends on the degree of alignment of interdependent variables that include ecological capability of site, intensity management, impact on soil, water and other environmental values, economic benefit and social goals (Nambiar 1996, Nambiar and Brown 1997). Of these, ecological capability is tied directly to a site. Nambiar and Brown (1997) defined the ecological capability of a site as:

- bounded by the inherent soil and biophysical constraints;
- responsiveness of the soil to management inputs; and
- genetic potential of the species and their interaction with the environment of the site.

Very few studies have been carried out to understand and manage sustainable productivity of *A. auriculiformis* plantations, although their development is increasing rapidly in Vietnam. The industry is in its infancy and is largely managed by small-scale private and public investment. Therefore, obtaining knowledge and assistance from other countries and international organisations are important for Vietnam's forestry sector.

In March 2002, the Forest Science Institute of Vietnam (FSIV) in collaboration with CIFOR set up a long-term research project as part of the CIFOR project 'Site Management and Productivity in Tropical Plantation Forests' (Tiarks *et al.* 1998, Nambiar *et al.* 1999).

In this paper we report on the overall experimental approach and experimental details. Soil and stand characteristics and the impact of harvesting and slash management treatments on site organic matter and nutrient pools are described. Details of re-planting the second rotation crop and the effects of treatment on growth of new crops will be reported later.

Objectives

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

In this project we aim to develop management practices for increased and sustained production of *A. auriculiformis* plantations in South Vietnam. The focus is on three key variables which come into play during the inter-rotation management; impacts of different harvesting and site management practices on soil and productivity of the next crop; effect of vegetation management on production; and effect of fertiliser application during early establishment on growth. Specific goals are:

- To develop an information system on *A. auriculiformis* plantations which are grown and harvested with different soil and organic matter (slash, litter) management methods. This objective has four components.
    1. Information on the amount of biomass at the site including stand litter and understorey,
    2. Information on the nutrient pools in soils and the nature of their availability,
    3. Information on nutrient (N, P, K, Ca, and Mg) content so that impact of harvest and site management on site nutrient capital can be estimated, and
    4. Information on site conditions and climate factors.
- To analyse and determine the changes of forest productivity and site conditions under different soil and organic matter conservation treatments.
- To determine optimum vegetation (weed) management regimes for maximum tree production.
- To evaluate the response to application of fertiliser at planting.
- To prepare (based on the above results) guidelines and options for site management of *A. auriculiformis* plantations.
- To communicate the results to forest managers through reports and field demonstrations.

Experimental Details

Study Site

The site is located at the Phu Binh Experiment Station belonging to Forest Science Sub-Institute of South Vietnam, at Vinh Hoa Commune, Phu Giao District, Binh Duong Province, (latitude 11°18'87'N, longitude 106°52'68'E and altitude 75-80 m).

Climate

Climatic data were taken from the Dong Phu meteorological station about 30 km from the study site (Figs 1a, 1b). The climate is warm humid tropical with a mean annual temperature of 27.3°C, mean annual humidity 81% (range 71-87%) with small seasonal variations. Mean annual rainfall is 2686 mm (range 2333-2900 mm), and total annual evaporation is about 850 mm (range 773-955 mm). The rainy months are May to November and the dry months are December to April.

Soil

The site geomorphology is similar to that of much of southeastern South Vietnam. The site is a hill, relatively flat on the top with slopes of 1-3° and a southerly aspect.

The soil type is a Chromic Acrisol. Features of the soil profile in the harvesting and slash management study area are described in Table 1. Soil depth decreased towards the south where the surface soil was clay loam and the B horizon had significant amounts of iron nodules, described as Endohyperferric-Chromic Acrisol. The parent material is schist.

Stand

The site had degraded native remnant vegetation. This was cut and the slash burned. The site was ploughed before planting *A. auriculiformis* in 1995 at a spacing of 3 x 4 m (833 trees ha^{-1}). The stand was weeded by hand and ploughed between rows periodically to control vegetation. Details of the growth of the stand are described later. The understorey vegetation was high and dense with dominant species being *Panicum maximum, Imperata cylindrica, Bauhinia cadinale, Memecylon* sp. and *Cratoxylon formosum*.

An area of 8.3 ha in 2 discontinuous blocks was identified suitable for the project based on a survey of the available area.

Experimental Design

The experimental structure consists of core and optional treatments (Tiarks *et al.* 1998), and a demonstration of best management practices compared to current practice in the area.

Figure 1. Climate (1997-2002) at Dong Phu meteorological station. a) Monthly average values of daily maximum and minimum (triangles) and mean (circles) of air temperature. b) Average value of monthly rainfall

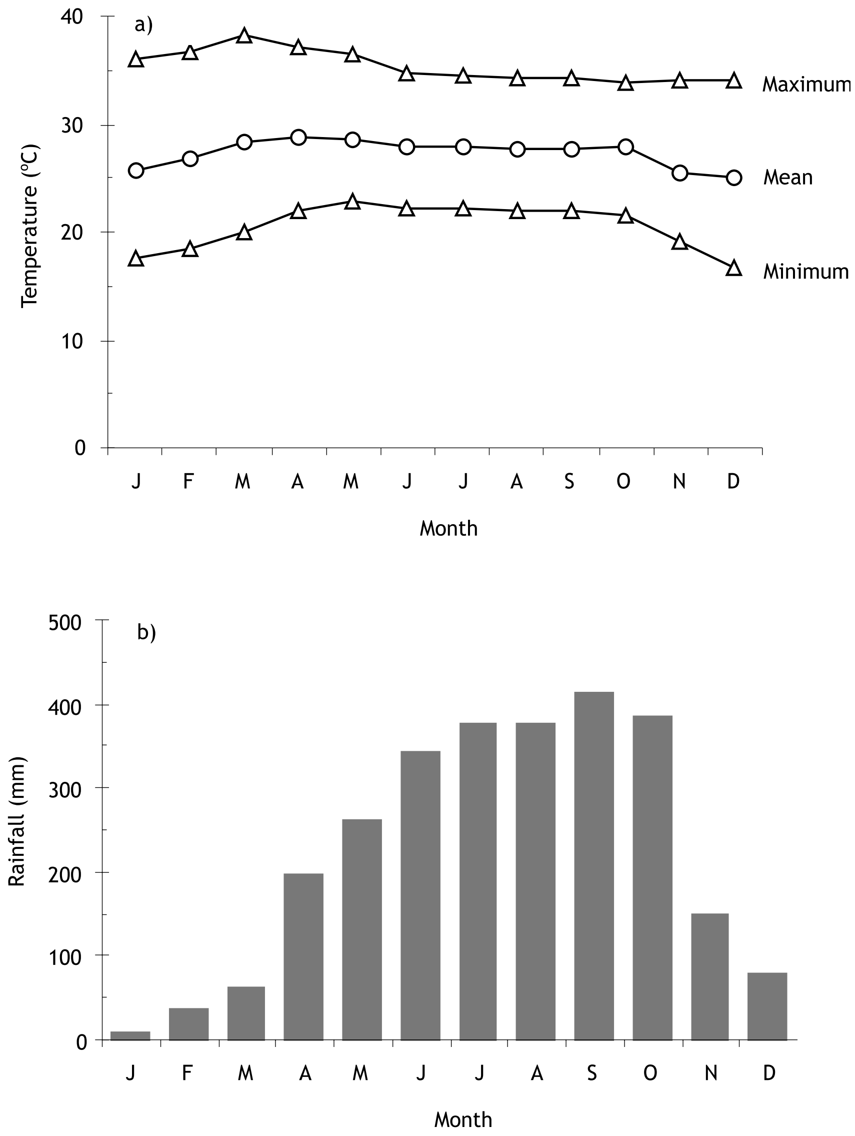


Table 1. A typical soil profile at the harvesting and slash management experimental sites

Soil horizon	Depth (cm)	Properties
A	0 -19	Greyish brown yellow (10 yr 6/2), dry, sandy clay loam, weak-medium, sub-angular blocky structure; friable, soft, slightly plastic, slightly sticky, many fine fresh roots; poor in organic matter, some vertical cracks (2–3 mm in width, few vesicular pores (2–3 cm diameter), gradual smooth boundary.
BA	19-45	Greyish brown yellow (10 yr 6/2), dry, sandy clay, moderate medium, sub-angular blocky structure; friable, slightly hard, plastic, sticky, many fine fresh roots, common vertical cracks (2–3 mm in width), few vesicular pores (2–3 cm diameter), gradual smooth boundary.
B1	45-80	Dull yellowish brown (10 yr 5/3), dry, sandy clay, moderate medium, sub-angular blocky structure parting to weak medium sub-angular blocky structure; friable, hard, plastic, sticky, few fine fresh roots; some vertical crack (2–3 mm in width), few yellowish brown (10 yr 5/
6),		gradual smooth boundary.
B2	80-120	Dull yellowish brown (10 yr 5/4), dry, sandy clay, moderate medium, sub-angular blocky structure parting to weak medium sub-angular blocky structure; friable, hard, plastic,sticky, few fine fresh roots; some vertical cracking, gradual smooth boundary.

Harvesting and Slash Management Study

Treatments are similar to the CIFOR network project (Tiarks *et al.* 1998). The experimental area consists of: (1) treatment plots; (2) additional plot areas designated for tree biomass sampling; and (3) standing crop. Treatments are:

BL$_0$ All aboveground organic matter including the crop trees, understorey, slash and litter is removed. Where present, the soil organic matter (organic residue that is decomposed beyond recognition) on the surface is not removed.

BL$_2$ Stem wood + bark harvested. Stand is felled and the tops and branches are cut and retained in the plot. Only the commercial sized stems and bark on them is removed. All other organic residue is left with minimum disturbance.

BL$_3$ Double slash. Branches, leaves (phyllodes) and other non-commercial components (excluding litter) of the trees from BL$_0$ treatment are transported and distributed evenly over the plot.

Total treatment area of fifteen gross plots is 1.73 ha, each of the 15 plots is 1152 m^2 (12 rows x 16 trees; spaced 3 x 2 m) comprising measured area of 576 m^2 (8 rows x 12 trees) and buffer area of 576 m^2 (96 trees). The experimental design was a randomised complete block with three treatments and five replications.

Biomass plot (**BP**): An additional area of 0.7508 ha (1251 trees) was set up for sequential biomass harvest to determine the relationship between the growth of biomass and nutrient uptake.

Standing crop (**SC**): An uncut area (not replicated) close to and representative of the harvested stand is left in a block (0.6 ha) as a control for comparison and for measuring changes in soil and other site properties as required.

Vegetation Management Study

Current weed control practice in acacia plantations in Vietnam comprises hand weeding initially, and ploughing twice a year from three years after planting. This is not very effective and repeated ploughing may be undesirable for maintaining soil fertility. The purpose of this study is to determine the degree of weed control required for maximum growth based on an understanding of the competition between weed and trees. The treatments are:

C1 Pre-planting herbicide spray once (control).
C2 Pre-planting herbicide plus post-planting 1.5 m wide spray (spanning 0.75 m on both sides of tree rows), 2-3 times per year.
C3 Pre-planting herbicide plus post-planting spray in full plot area, once per year.
C4 Pre-planting herbicide plus post-planting spray in full plot, 2-3 times per year.

The experimental design is a randomised complete block with four treatments and four replicates. The total area of sixteen gross plots is 1.25 ha, each of the 16 plots is 780 m^2 (10 rows x 13 trees; spaced 3 x 2 m) consisting of measured area of 324 m^2 (6 rows x 9 trees) and buffer area of 456 m^2 (76 trees).

The site was prepared as in BL_2 treatment of the harvesting and slash management study.

Nutrient Management Study

The objective of this trial is to evaluate the growth response of trees to application of nutrients at planting. The treatments are:

Nil (no fertilisation);
C (current practice): 50 g NPK (16-16-8) fertiliser (8g N, 8g P, 4g K) $tree^{-1}$;
P_1 (phosphorus): 100 g superphophate containing 7.2% P (16.5% P_2O_5) fertiliser $tree^{-1}$(7.2 g P $tree^{-1}$) and 50 g NPK (16-16-8) fertiliser $tree^{-1}$;
P_2 (phosphorus): 200 g superphophate $tree^{-1}$ (14.4 g P $tree^{-1}$) and 50 g NPK (16-16-8) fertiliser $tree^{-1}$;
Ca 500 kg $Ca(OH)_2$ ha^{-1} (270 kg Ca ha^{-1}) applied on soil surface and 50 g NPK (16-16-8) fertiliser $tree^{-1}$.

Phosphorus fertiliser was placed in the planting hole, while NPK fertiliser was placed in a furrow about 10 cm from the seedling. Calcium was broadcast on the soil surface before planting.

The total area of twenty gross plots is 0.86 ha, each plot is 432 m^2 (8 rows x 9 trees; spaced 3 x 2 m) comprising a measured area of 120 m^2 (20 trees) and a buffer area of 312 m^2 (52 trees). Since the plot size of this study is small (< 300 m^2), tree growth of all trees in gross plots will be measured and analysed. The experimental design was a randomised complete block with five treatments and four replications.

Demonstration Plots

Communication of results through technology transfer and demonstration is an important aim of this project. Plots to demonstrate the potential value of improved management compared to current practices have been established. There are three comparisons:

DFp (current practice): This includes burning slash and ploughing land before planting, 50 g NPK fertiliser (16-16-8) was applied at planting, understorey vegetation controlled by ploughing, care of planted trees by cultivating the soil near the trees. Total area 0.37 ha, tree spacing 3 x 2 m.
DFb (best management): This includes retention of slash (based on results of CIFOR trials in other countries), weed control with herbicide applied 2-3 times per year, 50 g NPK fertiliser and 200 g superphosphate $tree^{-1}$ applied at planting. Total area 0.46 ha, tree spacing 3 x 2 m.
DFf Slash retained and weeds controlled as in DFp, 500g RIZOBIOM (trade name, microorganism fertiliser) applied per tree.

Methods

Estimation of Stand Variation and Optimum Plot Size

The total area available and suitable for experimental study of this nature was restricted because most local first rotation plantations are in small fragmented blocks. Therefore it was necessary to determine the plot area more systematically. It is known that the larger the experimental plot the smaller will be the sampling error of the mean of estimated plot characteristics (mean plot biomass, mean plot tree height etc.). However, the larger the experimental plot the higher the cost of managing the experimental area and the greater the experimental error. To assess this, a test on how the plot size affects the coefficient of variation (a main component of sampling error) of plot wood volume was carried out.

Ten randomly located points were marked as centres for circular plots. From these points 8 concentric circular plots of 25 m^2, 50 m^2, 100 m^2, 200 m^2, 300 m^2, 400 m^2, 500 m^2, 600 m^2 were set up. Diameters at breast height of all trees in these plots were measured. Standing volumes in each plot were calculated applying the regression equation below. The equation was established from data collected on 20 trees representing the range diameter class in the block:

$$V = - 0.00206d + 0.000895d^2 – 0.0000115d^3$$

Where V is stem volume (m^3) and d is stem diameter at breast height (cm).

Plot volume and coefficient of variation for each plot size were calculated. In addition to plot size, it was also necessary to determine the number of buffer rows required for each plot. To determine this, stem diameters of trees in 7 rows from the edge of a stand inward from the exposed side were measured. Then the mean tree basal area was calculated for each row.

Biomass and Nutrient Content

Before harvesting the stand, heights and diameters of all trees in the plots were measured. Thirty trees were identified for biomass sampling. They were spatially representative of the five replicates (blocks) in the core study, and covering the range of diameter classes. A subsample of ten of these was selected for nutrient analyses.

After felling the trees, stem diameter at breast height and tree length up to the top-end diameter of 5 cm were measured. Each tree was divided into five equal length sections; wood and bark in each section were weighed and samples were taken for dry mass determination. Fresh weight of branches, foliage, and reproductive parts (flowers, fruits) 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 component 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.

Regression equations for each biomass component were determined then used for estimation of biomass and nutrient quantities in each plot.

Litter and Understorey Vegetation

Four 1 m^2 sample plots were set up in each BL_0 and BL_2 plot by using a systematic square grid system. Litter was separated into leaf, wood, bark, branches, flowers, seeds, pods, and stalks. The understorey vegetation was separated into woody and non-woody plants; each category was separated further to leaf, wood, bark and branches.

Litter components were weighed. Samples from each component were oven-dried at 76°C to a constant weight. Oven-dried samples were subsampled, half for chemical analysis and the remainder kept for future use.

Plant Analysis

Nutrients concentration of each organ were measured in a single digest using concentrated sulphuric acid and 30% hydrogen peroxide (Lowther 1980).

- N - Kjeldahl.
- P - Spectrophotometer.
- K - Flame photometer.
- Ca and Mg - Atomic absorption.

Soil Sampling and Analysis

Soil cores were taken from 5 points in each plot from four soil depths: 0-10 cm, 10-20 cm, 20-

Table 2. Soil properties (mean with 1 SE) in the core experimental area

Properties	Soil depth (cm)							
	0-10	SE	10-20	SE	20-30	SE	30-50	SE
Bulk density (g cm^{-3})	1.41	0.13	1.56	0.11	1.56	0.10	1.54	0.10
Sand 50-2000 mm (%)	56.5	4.0	65.7	4.4	67.7	4.0	69.8	4.2
Silt 2-50 mm (%)	25.8	2.0	21.4	1.8	19.6	1.2	18.5	1.0
Clay <2 mm (%)	17.7	1.5	12.8	0.9	11.9	0.7	11.7	0.7
pH H$_2$O	4.8	0.2	4.6	0.2	4.6	0.2	4.5	0.2
pH KCl	4.0	0.2	4.0	0.2	4.0	0.2	4.0	0.2
Organic C (%)	1.12	0.18	0.99	0.10	0.83	0.05	0.71	0.05
Total N (%)	0.12	0.01	0.09	0.01	0.07	0.05	0.06	0.04
Total P (mg kg^{-1})	325.9	15.0	315.8	14.0	241.6	12.0	220.7	10.0
Available P (mg kg^{-1})	10.8	0.6	8.5	0.5	7.7	0.4	6.1	0.3
Total (mg kg^{-1})	1504	70	1350	60	1292	60	1407	65
Total Ca (mg kg^{-1})	216	15	152	10	133	9	112	7
Total Mg (mg kg^{-1})	62	5	59	4	57	4	50	3
Ex. K (c mol kg^{-1})	2.03	0.09	1.29	0.06	1.14	0.05	0.97	0.04
Ex. Ca (c mol kg^{-1})	9.36	0.60	9.17	0.60	8.92	0.55	8.82	0.55
Ex. Mg (c mol kg^{-1})	2.35	0.15	2.12	0.15	2.23	0.14	2.04	0.12
CEC (c mol kg^{-1})	14.32	1.20	13.79	1.00	13.41	0.90	13.13	0.90

30 cm and 30-50 cm. Samples of the same depth were then bulked to obtain 4 composite samples, one for each soil depth. From each composite sample, two subsamples of 1.0 kg were air-dried for about 7 days. Half of this subsample was used for analysis and the remaining half stored. Chemical analysis was carried out on soil fraction less than 2 mm. Methods for soil analysis (van Reeuwijk 1995) were:

- Organic carbon- Walkley-Black procedure.
- Total N- sulphuric acid- selenium mixture digestion with hydrogen peroxide; Kjeldahl.
- Total P- sulphuric acid and perchloric acid mixture digestion; colorimetric molybdate blue.
- Total K, digestion as per total P; flame photometer.
- Available P- citric acid 1% solution extraction; colorimetric molybdate blue.
- Exchangeable K, NH4Oac 1M extraction; by flame photometer.
- Exchangeable Ca, Mg; NH$_4$Oac 1M extraction; atomic absorption.
- CEC - by percolated with NH$_4$Oac 1M.
- pH- 1:2.5 water solution.

Site survey, tree harvest, soil sampling, plot layout, biomass sampling and other experimental work were carried out in April 2002 before the rainy season. Details of planting the second rotation crop and post-planting silviculture will be described in another publication.

Results and Discussion

When this report was prepared only results related to layout, stand biomass, soil nutrients and impacts of core treatments on nutrient loads were available.

Soil Characteristics

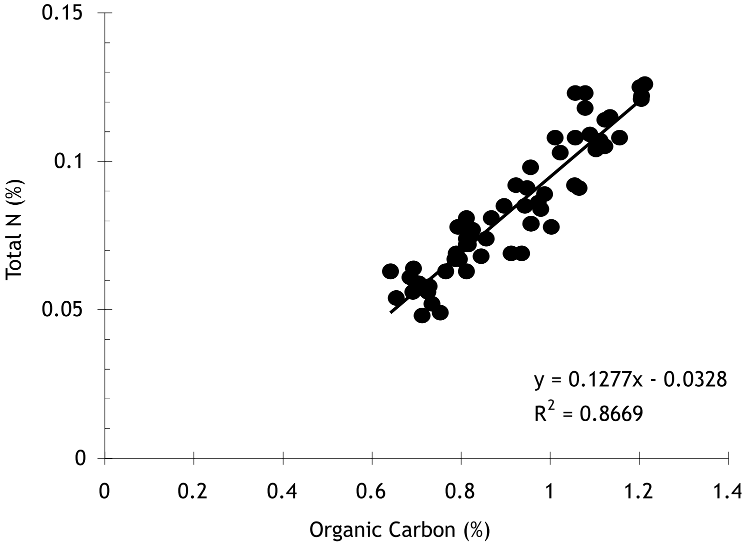
Soil physical and chemical properties in the core experimental area are given in Table 2. The soil has a high sand content, 57%-70%, which increased with depth. Bulk density is generally high, as might be expected from the profile description. Soil pH is acidic throughout the profile with little change with depth. Total N, organic carbon and available P decreased with depth. There was a close correlation between soil organic carbon and total N when samples from

Table 3. Organic C and nutrient content of soil in the core experimental size

Soil depth (cm)	Nutrient content (kg ha^{-1})					
	Organic C	N^{a}	P^{b}	K^{c}	Ca^{c}	Mg^{c}
0-10	15 792	1622	15.2	111.6	263.9	39.8
10-20	15 288	1399	12.8	78.5	286.1	39.7
20-30	12 948	1136	12.0	69.4	278.3	41.7
30-50	21 868	1774	18.6	116.5	543.3	75.4
Total	65 896	5931	58.9	376.0	1371.6	196.6

[a] total; [b] available; [c] exchangeable.

Figure 2. Relationship between soil organic matter and total nitrogen in soil



all depths are included in the relationship (Fig. 2). The N concentration (range 0.11-0.05 %) and available-P, in general, are low. The CEC and exchangeable cations are low throughout the profile and there was no decline with soil depth. Total soil organic carbon and nutrient contents included total N, available-P, and exchangeable K, Ca, Mg to 50 cm soil depth are shown in Table 3.

Stand Characteristics

Plot size and variation of tree size

Table 4 shows the estimated wood volume at ten locations and as a function of plot area. From this result CV values for a given plot area were estimated and fitted in a regression (Fig. 3). The relationship can be explained by the regression:

$$Ln\mathrm{CV} = 0.53558 - 0.29022\ Ln\mathrm{S},$$

Where: *Ln* is natural log, CV is coefficient of variation and S is plot size.

The coefficient of variation decreased rapidly as plot size increased, to approximately 300 m^2, after which the rate of decrease was much less. Based on this result, 300 m^2 was selected as minimum plot size (referred to as plot core), excluding buffer belt for the core study in this project.

Table 4. Variations in estimated standing volume of trees as a function of plot area

Plot size (m^2)	Plot number										Mean
	1	2	3	4	5	6	7	8	9	10	
	(m^3 $plot^{-1}$)										
25	0.348	0.173	0.229	0.158	0.215	0.041	0.478	0.052	0.068	0.191	0.195
50	0.348	0.688	0.455	0.475	0.486	0.238	0.474	0.052	0.068	0.417	0.538
100	0.667	0.742	0.763	1.172	0.835	0.543	1.012	0.211	1.264	0.489	0.770
200	1.449	2.388	0.977	3.339	2.428	1.409	2.000	0.835	2.462	1.617	1.891
300	2.596	3.310	2.115	4.790	3.637	3.254	3.873	1.740	3.845	2.694	3.185
400	3.922	4.018	3.896	7.652	4.379	4.464	6.601	3.066	5.535	3.343	4.688
500	4.305	5.794	4.901	8.687	5.177	5.123	8.460	3.870	8.391	4.962	5.967
600	5.551	7.033	6.275	9.630	6.129	6.362	9.768	5.182	9.883	9.229	7.504

Figure 3. Effect of plot size on the coefficient of variation of plot stem wood volume

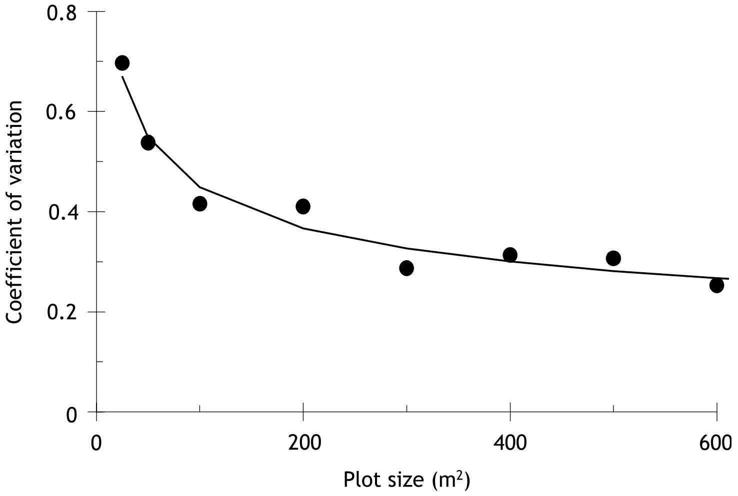


Figure 4. Effect of location of tree row on tree basal area (location 1 = edge row)

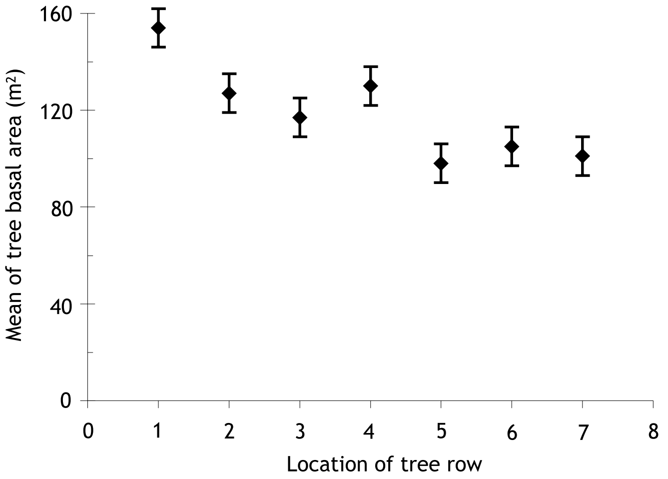


Figure 5. Frequency distribution of tree diameter in the harvesting and slash management experimental site

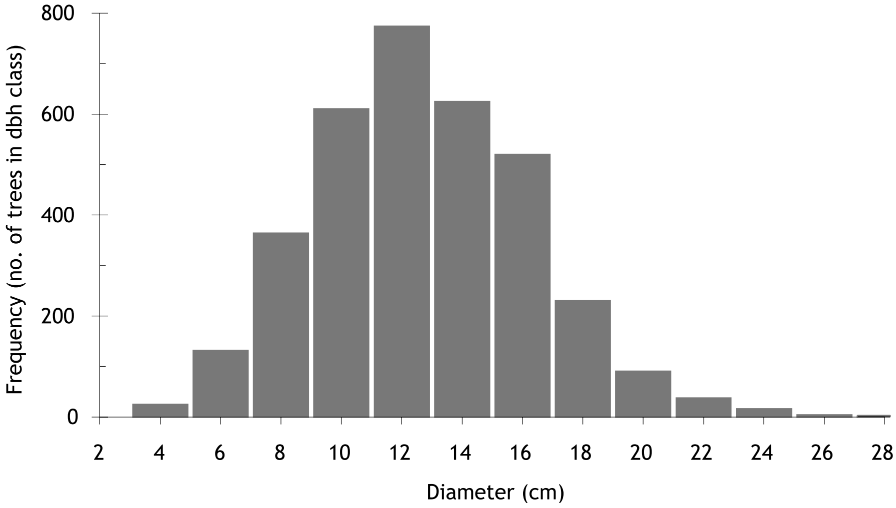


Figure 4 shows the changes in tree basal area as the position of the tree shifted inwards from the edge (position 1) of the plot. Tree basal area decreased rapidly from the edge to the first two rows, after which the size was stable. Based on this result, we concluded that two rows of buffer rows around each plot would be adequate for our study.

Size of trees

Tree heights ranged from 4 m to 16.5 m with a mean height of 11.7 m. Tree diameter ranged from spindly 6 cm diameter trees to more than 25 cm; mean diameter was 14 cm. Tree diameter size distribution is shown in Fig. 5. In the slash management experiment 71% of trees were with in the range 10-16 cm. Stem volume ranged from 124 m^3 to 145 m^3. The mean for the area was 130 m^3 ha^{-1}, giving a mean annual increment of 18.6 m^3 ha^{-1}.

Allometric relationships

Regression analyses between stem diameter breast height (dbh) and total dry standing biomass (Fig. 6a) and stem wood were conducted (Fig. 6b). In both cases the power equations have highly significant correlations explaining 98% of the variation. Similar regressions between diameter and branches and leaves were established. These regressions were used to estimate all the biomass components.

Stand Aboveground Biomass and Nutrient Distribution

Nutrient concentration in plant materials

Nutrient concentration of live tree biomass components, litter and understorey are shown in Table 5. Nutrient concentrations of N, Ca and K were high, compared to P. Highest concentrations of nutrients were in the leaves and bark followed by branches and stem wood. Highest nutrient concentration of litter was found in the leaves and pod, followed by branches and stem wood. The nutrient concentration of understorey had medium value compared with litter components.

Biomass Distribution

The dry mass of the *A. auriculiformis* stand is shown in Table 6. Total dry weight of live stand biomass was 51 t ha^{-1}, comprising stem wood (68.9%), bark (8.8%), branches (18.6%), leaves (3.7%). Litter and understorey components were 8.1 t ha^{-1}, mainly from understorey (37.3%),

Figure 6a. Allometric relationship of stem diameter and total standing dry biomass

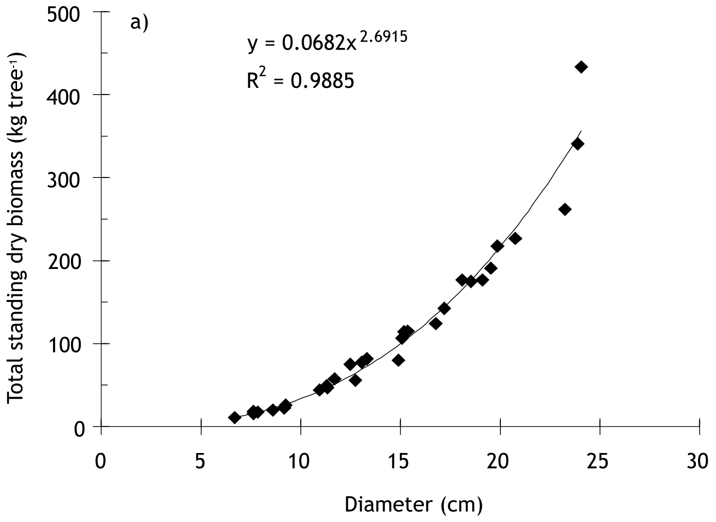


Figure 6b. Allometric relationship of stem diameter and total dried stem weight

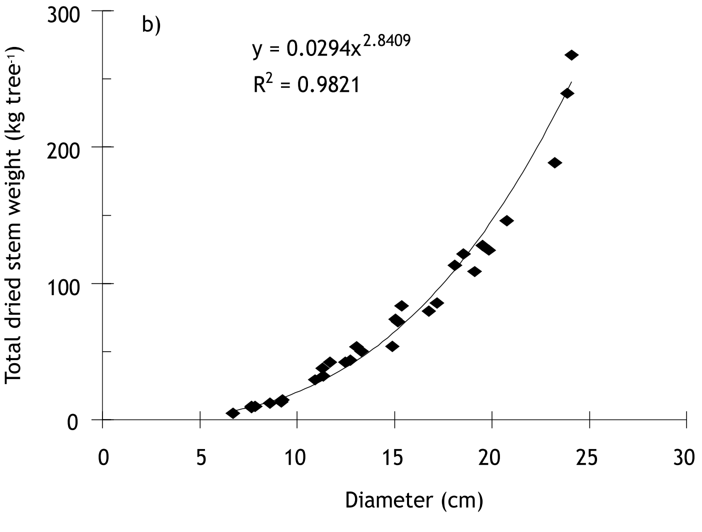


Table 5. Nutrient concentrations mean and 1SE in live tree biomass components, litter and understorey

Component	Nutrient concentration (%)									
	N	SE	P	SE	K	SE	Ca	SE	Mg	SE
Tree (living)										
Stem wood (> 5 cm)	0.15	0.01	0.01	0.001	0.27	0.02	0.04	0.003	0.01	0.001
Bark	1.25	0.08	0.02	0.001	0.46	0.03	0.78	0.06	0.02	0.001
Branches (< 1 cm)	0.78	0.05	0.03	0.002	0.52	0.04	0.23	0.02	0.11	0.005
Branches (1-5 cm)	0.40	0.03	0.02	0.001	0.09	0.007	0.16	0.01	0.05	0.003
Branches (> 5 cm)	0.33	0.02	0.01	0.001	0.16	0.01	0.13	0.01	0.02	0.001
Leaves	2.27	0.15	0.03	0.002	0.48	0.03	0.22	0.015	0.10	0.005
Litter										
Leaves	1.48	0.10	0.02	0.001	0.53	0.03	0.20	0.015	0.08	0.006
Branches	0.84	0.06	0.02	0.001	0.20	0.01	0.18	0.01	0.05	0.003
Wood	0.58	0.04	0.01	0.001	0.33	0.02	0.10	0.005	0.01	0.001
Pods	1.20	0.08	0.03	0.002	0.40	0.02	0.20	0.015	0.02	0.001
Understorey	0.91	0.07	0.04	0.003	0.54	0.03	0.05	0.004	0.01	0.001

branches (21.5%), leaves (17.0%), wood (16.1%) and pod (8.1%).

Aboveground living biomass of the *A. auriculiformis* (7 years old) is 51.2 t ha^{-1} and is lower than the biomass reported from some sites in other countries (Table 7). Productivity of litter and vegetation understorey is low (8.1 t ha^{-1}) and less than half the litter productivity of *A. mangium* in Indonesia (16.8 t ha^{-1}) reported by Hardiyanto *et al.* (2000).

The amount of slash retained varies between treatments. Total slash retained in BL$_2$ is 15.3 t ha^{-1} and in BL$_3$ is 32.2 t ha^{-1}. Nutrient content retention per hectare in BL$_2$ is 141.6 kg N, 3.5 kg P, 47.2 kg K, 54.1 kg Ca, and 8.7 kg Mg; and in BL$_3$ is 298.4 kg N, 7.3 kg P, 99.5 kg K, 114.1 kg Ca and 18.3 kg Mg.

Slash burning is a common practice in Vietnam either between rotations or during the rotation as a fire prevention strategy. Losses from such practices may be large, based on the nutrient content measured in slash in this study. While *A. auriculiformis* is known to fix nitrogen in the soil, there is no good estimation of this ability. Losses of P and cations may be even more critical. Initial results show the importance of developing sound site management practices appropriate for conditions in Vietnam in order to maintain sustainability of the new plantation forestry enterprises.

Conclusions

We have established a comprehensive research program to study the effect of site and soil factors on the sustained productivity of *A. auriculiformis* in the southeast part of South Vietnam. Our focus is on inter-rotation management phase.

The available pool of P and exchangeable cations is low compared to soils in Southeast Asia where *Acacia* plantations are grown extensively.

Standing volume of 7-year-old trees at the experimental site was 130 m^3 ha^{-1}. Total aboveground biomass was wood (39.7 t ha^{-1}), branches (9.5 t ha^{-1}), leaves (1.9 t ha^{-1}), litter (5.1 t ha^{-1}) and understorey (3.0 t ha^{-1}). This level of productivity is significantly lower than other *Acacia* stands described in the literature.

Intensive harvesting would have major impacts on the amount of nutrients exported from the site. It is estimated that harvesting of wood and bark alone will remove from the site 4.4 kg ha^{-1} available P, 49.2 kg ha^{-1} of exchangeable Ca, and 115.8 kg ha^{-1} exchangeable K. If all the biomass were removed this depletion would increase further. Debarking at the site and distributing the

Table 6. Biomass and nutrient content of 7-year-old *Acacia auriculiformis*

Components	Dry weight		Nutrient content (kg ha^{-1})				
	(t ha^{-1})	(%)	N	P	K	Ca	Mg
Tree (living)							
Stem wood (> 5cm)	35.23	68.9	51.44	3.52	95.12	14.09	3.52
Bark	4.50	8.8	56.21	0.90	20.68	35.07	0.90
Branches (< 1cm)	2.46	4.8	19.16	0.74	12.77	5.65	2.70
Branches (1-5cm)	6.96	13.6	27.84	1.39	6.26	11.14	3.48
Branches (> 5cm)	0.11	0.2	0.37	0.01	0.18	0.15	0.02
Leaves	1.91	3.7	43.43	0.57	9.18	4.21	1.91
Total tree	51.17	100.0	198.45	7.14	144.21	70.31	12.53
Litter and understorey							
Leaves	1.38	17.0	20.42	0.28	7.31	2.76	1.10
Branches	1.75	21.5	14.70	0.35	3.50	3.15	0.88
Wood	1.31	16.1	7.60	0.13	4.32	1.31	0.13
Pod	0.66	8.1	7.92	0.20	2.64	1.32	0.13
Understorey	3.03	37.3	27.57	1.21	16.36	1.52	0.30
Total litter and understorey	8.13	100.0	78.21	2.17	34.13	10.06	2.55
Total	59.30		276.66	9.31	178.34	80.37	15.08

Table 7. Dry weight biomass comparison of *Acacia auriculiformis* in this study with other species at other sites

Species	Site	Age (yr)	Biomass (t ha^{-1})	Biomass (t ha^{-1} yr^{-1})	Data source
A. auriculiformis	Binh Phuoc, Vietnam	7	51.2	7.3	This study
A. auriculiformis	Vung Tau, Vietnam	7	136.1	19.4	Yamada (2002)
A. mangium	South Sumatra, Indonesia	9	189.5	21.9	Hardiyanto *et al.* (2000)
A. mangium	Sarawak, Malaysia	6	123.2	20.5	Helenda (1988)
Eucalyptus grandis	Sao Paulo, Brazil	7	160.9	23.0	Gonçalves *et al.* (1999)

bark uniformly would reduce nutrient depletion substantially, especially available P and exchangeable Ca and K.

The current rate of addition of fertiliser at planting as practised by forest managers is much lower than the amount removed. The importance of retaining as much organic matter as possible and conserving nutrients at the site is clear, the potential benefit of growing plantations with improved genetic stock will not be realised if the soil fertility at these sites is allowed to deteriorate.

Investigation of the nature of the variation in growth as estimated by different plot size allowed decisions on optimum plot sizes required for measuring the productivity of the next experimental crop.

Acknowledgements

We would like to express our gratitude to the Center for International Forestry Research (CIFOR) for sponsoring the research network and supporting participation in the workshop. We also acknowledge the leaders and staff of FSIV for their support, guidance and advice during the implementation of this project. Our special thanks are extended to Dr Sadanandan Nambiar of CSIRO, Australia, Dr Takeshi Toma of CIFOR, Indonesia and Dr Eko B. Hardiyanto of Gadjah Mada University, Indonesia for their valuable advice.

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 scientific and technology, 1996-2000. FSIV-APAFRI-TREELINK. Agriculture Publishing House, Hanoi.

Forest Development Department 2002. Planning, progress and solution to carry out Five Million Hectare Reforestation Programme to year 2010. MARD Magazine No 3, Hanoi.

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.

Hardiyanto, E.B., Ryantoko, A. and Anshori, S. 2000. Effects of site management in *Acacia mangium* plantations at PT. Musi Hutan Persada, South Sumatra, Indonesia. *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, 41-50. Center for International Forestry Research, Bogor, Indonesia.

Helenda, C.J. 1988. The ecology of an *Acacia mangium* plantation established after shifting cultivation in Niah Forest Reserve. Forest Research Report, Forest. Ecology 1. Ecology Unit Forest Department, Kuching, Sarawak, Malaysia. 59p.

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. 1996. Sustained productivity of plantation forests is a continuing challenge to tree improvement. *In*: Dieters, M.J., Matheson, D.G., Harwood, C.E. and Walker, S.M. (eds.) Tree improvement for sustainable tropical forestry. Proceedings QFRI-IUFRO Conference, 27 October - 1 November 1996, Caloundra, Queensland, Australia, 6-18. Queensland Forestry Research Institute, Gympie, Australia.

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, water and nutrient in tropical plantation forests, 527 - 557. ACIAR Monograph No. 43. Australian Centre for International Agricultural Research, Canberra.

Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) 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.

Nguyen Duong Tai 2002. Seedling production for five reforestation programmes. MARD special subject on forest breeding. DANIDA-Ministry for Agriculture and Rural Development (MARD), Hanoi.

Nguyen Hoang Nghia and Le Dinh Kha 1998a. *Acacia* species and provenance selection for large-scale planting in Vietnam. *In*: Results of scientific research on silviculture in Vietnam, 72-82. Agricultural Publishing House, Hanoi.

Nguyen Hoang Nghia and Le Dinh Kha 1998b. Species and provenance trial of acacias. *In* : Results of scientific research on silviculture in Vietnam, 56-59. Agricultural Publishing House, Hanoi.

Nguyen Thi Anh Nguyet 2002. The determination of technical maturation age of *A. auriculiformis* plantation for pulp material in Tri An enterprise. Vietnamese edition. PhD thesis. University of Agriculture and Forestry, Ho Chi Minh City, Vietnam.

Pham The Dung 1996. Intensive techniques of plantation for pulp material in southern Vietnam. Proceedings of BIOREFOR workshop, 25-29 November 1996, Bangkok.

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

Tiarks, A., Nambiar, E.K.S., Cossalter, C. and Ranger, J. 1999. A progress report. *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, 73-76. Center for International Forestry Research, Bogor, Indonesia.

van Reewijk, L.P. (ed.) 1995. Procedures for soil analysis. Technical Paper No 9. International Soil Reference and Information Centre, Wageningen, The Netherlands.

Yamada, M. 2002. Removal of nutrients by harvesting in commercial plantation. *In*: Ecological impact assessment of tropical plantation forest on the environments: proceedings of joint meeting for cooperative research project 26, November 2002. Royal Forest Department, Bangkok.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 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

J.A. Simpson[1], T.E. Smith, P.T. Keay, D.O. Osborne, Z.H. Xu and M.I. Podberscek

Abstract

A long-term field experiment was established in 1996 in southeast Queensland to: (1) examine the impacts of slash management, fertilisation and cover crops on tree growth and nutrient status; (2) quantify the effects on soil properties; and (3) contribute to the CIFOR international network of long-term experiments designed to develop management practices which would aid sustained productivity for forest plantations in tropical environments. This paper reports the major research findings in the first 6.4 years of the experiment.

Retention of slash increased stem volume by 22% at age 6.4 years, compared with the treatment in which the slash was removed. Tree growth was increased further by doubling the quantity of slash and by weed control. Foliar nutrient concentrations generally were above critical concentrations and were not correlated with slash treatments. Soil pH in the surface 10 cm decreased by 0.53 units between planting and age 4.2 years but increased by 0.36 units between ages 4.2 and 6.4 years. Soil pH was lowered significantly in the surface 0-5 cm soil layer at age 4.2 as a result of retaining slash but this difference was not apparent at age 6.4 years. At ages 4.2 and 6.4 years soil organic C, total N, and exchangeable K concentrations were lower in the surface 0-5 cm where residues were removed. No relationship was found between soil and plant nutrient status or between these parameters and tree growth in the first 5 years.

The productivity of the second rotation crop was high. Continued maintenance of the fertility of the soil depends on appropriate site management practices and nutrient additions as required. Retention of slash from the first rotation plantation is recommended as the best management option.

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Introduction

Most of the exotic pine plantations in Queensland, Australia, are grown on infertile, sandy coastal lowland soils in the southeast of the state. This pine resource consists of slash pine (*Pinus elliottii* Engelm. var. *elliottii*) (31%), Honduras Caribbean pine (*P. caribaea* var. *hondurensis* Barr. *et* Golf.) (41%) and the hybrid between these two taxa (25%) (Queensland DPI Forestry 2001). The soils have low P levels and P fertiliser application gave a large increase in production of the first rotation stands (Simpson and Grant 1991, Simpson 1995, Xu *et al.* 1995 a, b).

Adoption of shorter rotations and more intensive silvicultural regimes places increasing pressure on the soil resource and the development and adoption of appropriate inter-rotation management practices will play an important role in the maintenance of productivity of successive crops. In nutrient-poor sites in Louisiana, USA, Haywood (1994) found an 18% reduction in height of 7-year-old second rotation slash pine where all logging residue (slash) was removed compared to the first rotation. Inter-rotation management practices, such as slash management and fertiliser application can have significant impacts on soil organic matter quality, nutrient availability and tree growth of second rotation plantations in subtropical Australia (Bubb *et al.* 1999, Pu *et al.* 2001, Mathers *et al.* 2002).

The objectives of the study were to: (1) examine the impacts of slash management, fertilisation and cover crops on tree growth and nutrient status; (2) quantify the effects on soil properties; and (3) contribute to the CIFOR international network of long-term experiments designed to identify and develop sustainable inter-rotation management practices which would aid sustained productivity for a range of forest plantation types in tropical environments. Early results were reported in Simpson *et al.* (1999) and Simpson *et al.* (2000). This paper reports growth data to age 6.4 years, summarises foliar nutrient data, changes in the quantities of slash remaining on the site and changes in soil chemical properties.

Experimental Details

Site and First Rotation Stand

Details of the experimental site were described by Simpson *et al.* (1999, 2000). The study was carried out at Toolara in Queensland, Australia (26°00'S, 152°49'E and 61 m altitude). The area has a humid subtropical climate. It has a mean annual rainfall of 1354 mm with 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 acid, deep and sandy, and classified as Grey Kandosols (Isbell 1996) or Gleyic Acrisols (FAO 1974). The soils are well-drained in the upper horizons but can waterlog for short periods during the wet season when the watertable rises to within 50 cm of the soil surface.

The first rotation slash pine stand was planted in July 1966 at 1234 stems ha^{-1}. Fertiliser, 310 kg ha^{-1} Nauru rock phosphate (50 kg P ha^{-1}) was broadcast in 1966 and a further application of triple superphosphate (44 kg P ha^{-1}), was applied aerially in 1980. The stand was thinned at age 15.6 years to a stocking of 679 stems ha^{-1}, and clearfelled in November 1995, at age 29.4 years. The site index [average height (m) of the 50 tallest stems ha^{-1} at age 25 yr] of the area was 23.7, compared with a district average of 23.4 for the species. At clearfelling, the stand had a predominant height of 25.2 m, standing basal area of 39.6 m^2 ha^{-1} and standing volume to a 7 cm top end diameter of 325.4 m^3 ha^{-1} (for details see Simpson *et al.* 1999).

Slash Management Trial

Experimental Design and Treatments

Details of the experimental design and treatments have been described by Simpson *et al.* (1999, 2000). A brief account is given below to set the context for this paper. The experiment consists of six treatments laid out as 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). The treatments were:

BL_0	Slash (litter plus logging residue) removed + 50 kg P ha^{-1} added.
BL_2	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 not possible to remove all slash without site disturbance. The < 10 t ha^{-1} of material remaining consisted mainly of fine residues. The BL_2 treatment had 60 t ha^{-1} dry matter (range from 50.8 to 73.8 t ha^{-1}) of which approximately 40% was from the forest floor litter. The BL_3 treatment (140 t ha^{-1}) was included in the design to widen the possible treatment effects on tree growth and soil processes. This treatment simulates the windrowing of logging residues (where the slash is concentrated in windrows) which occurs after mechanised logging.

Trial Establishment

Slash management treatments were applied in February 1996, three months after clearfalling. The trees were planted in May 1996 in individually cultivated spots at 3 m x 3 m spacing (1111 stems ha^{-1}). The stock was container-grown F_1 hybrid seedlings raised from seed collected from six separate orchards with stock identity being retained. Pre- and post-planting herbicides were applied in the first year along the planting rows. Triple superphosphate was applied to supply 45 g P to each seedling in all treatments except for BL_2 – P. A mixture of legume seeds containing lotononis (*Lotononis bainesii*), Wyns cassia (*Chamaecrista rotundifolia* cv Wynn) and Maku lotus (*Lotus pedunculatus* cv Maku) was sown on three occasions in the BL_2+ Legumes treatment. The legumes were slow to develop and in 2001 covered <50% of the area of the treated plots. Further details on experiment establishment are available from Simpson *et al.* (1999, 2000). A thinning, as per operational practice, was carried out at age 3.2 years to reduce the stocking from 1111 to 694 stems ha^{-1}.

Measurements

Tree height and diameter were measured annually. Foliar samples of the most recent fully formed fascicles from the youngest basal spring whorl were collected in August 1998, August 1999, June 2000, May 2001 and July 2002 (ages 2.3, 3.3, 4.2, 5.1 and 6.3 years respectively). Fifty fascicles from each of four average size trees, one from each of four nominated families, were combined to give a composite sample from each plot.

Slash was sampled in February 1996, July 1998, February 2001 and August 2002 (at tree ages 0, 2.5, 5.1 and 6.4 years). The initial samples were taken from five randomly selected 1 m^2 quadrats per plot. For the second sampling, two random 1 m^2 quadrats per plot were collected. The sampling at 5.1 and 6.4 years was undertaken using a 'ranked set' method and 0.25 m^2 quadrats. Three primary points were identified four metres from the plot centre in a predetermined direction. Each point was ranked as light, medium or heavy according to slash loads. Three secondary points were identified one metre from the primary point along predetermined directions and ranked, based on the quantity of slash present at each point. A sample was collected from a 0.25 m^2 quadrat from either the light, medium or heavy ranked secondary points which corresponding to the classification of the primary sample point. The three samples from each plot (one from each light, medium and heavy rankings of the primary points) were combined to give one composite sample per plot. Because different sampling techniques were used errors associated with the treatment means will differ between samplings. The composite slash samples were separated into various fractions. After sorting the material was oven dried, weighed and subsampled for chemical analysis.

Soil samples were collected in January 1996, May 1998, June 2000 and August 2002 (at tree ages of -0.3, 2.4, 4.2 and 6.4 years). For each plot, composite samples from five systematically located 1 m^2 quadrats (10 sub-samples composited per plot, 2 from each of the 5 quadrats) were collected. Samples were collected from 0-10 cm depth at the initial sampling but comprehensive sampling to depth (0-5, 5-10, 10-20 and 20-30 cm) was carried out at the subsequent samplings. Because of different sampling methodologies, comparisons of the initial sample (0-10 cm depth) with subsequent samplings were made by converting the data for 0-5 and 5-10 cm depths to a mean value to represent 0-10 cm depth. Nutrient analysis of plant and soil samples was carried out according to Collins (2000a, b). Soil P concentrations, total P (constant boiling HCl extract) and available P (weak acid extract), were determined but not reported because of large spatial and temporal variability, and no meaningful trends in relation to treatment or time were found. This aspect would be explored further later in the project.

Results

Survival and Growth

At age 1.2 years, 99% of seedlings had survived. Slash management treatments did not influence survival but improved height growth by 11-24% at age 1.4 years (Simpson *et al.* 1999). Results at 3.2 years showed increasing differences as a result of the slash treatments and that there were significant differences in growth between the different hybrid families tested. The aboveground tree biomass and nutrient pools were estimated at age 3.2 years to quantify treatment effects. At age 6.4 years, growth of trees in the BL_0 treatment (slash removed) was poorer than in treatments where slash was retained (BL_2) (Table 1).

The BL_2 treatment improved tree growth over BL_0; height by 0.5 m (5%), diameter by 1.2 cm (8%), basal area by 3.2 m^2 ha^{-1} (18%), and stem volume by 10.6 m^3 ha^{-1} (22%). Doubling the quantity of slash (BL_3) resulted in a further improvement; diameter by 1.2 cm (7 %), basal area by 3.1 m^2 ha^{-1} (15%), and stem volume by 11.4 m^3 ha^{-1} (19%). The legume treatment had no effect on tree growth. Complete weed control (BL_2 – W) markedly improved tree growth when compared to the BL_2 treatment (diameter increased by 1.9 cm (11%), basal area by 6.2 m^2 ha^{-1} (29%) and total volume by 17.9 m^3 ha^{-1} (30%). The BL_2 – P treatment was equivalent to the BL_0 treatment confirming that P was not limiting tree growth.

Response of the BL_2 treatment over the BL_0 treatment was most apparent in mean height increment during the second growing season (i.e. between ages 1.2 and 2.4 years) (Table 2). There was no significant difference in mean height increment between treatments where slash was retained (BL_2 *vs* BL_3). There was a consistent trend for slash retention to improve both basal area and stem volume increment for each increment period between ages 2.4 and 5.1 years. This increment response ceased after age 5.1 years but the cumulative effect on stem volume remained significant. Double slash (BL_3 treatment) improved basal area and volume increment over normal slash (BL_2 treatment) up to age 5.1 years only. The basal area and volume increment patterns for the BL_2+L and BL_2-P treatments were similar to the BL_2 treatment whereas the BL_2 –W treatment has consistently out-yielded the BL_2 treatment (but not the BL_3 treatment) except for basal area increment 5.1 - 6.4 years.

Increment data indicates that the effects of manipulation of slash during the inter-rotation period on stand increment is limited to the first 5 years of growth.

Foliar Nutrient Concentrations

Detailed foliar nutrient data (N, P, K, Ca, Mg, Na, Cu, Zn and B) was collected but is not presented as there were no clear and consistent treatment effects. During the period 2.3 to 6.3 years foliar N concentrations varied markedly - 0.57 to 0.95% between seasons. These concentrations are regarded as low to marginal for healthy growth of the hybrid pine. A very low concentration (0.48% N) was recorded at age 3.3 years in the BL_0 treatment which was significantly different from the plus slash treatments (>0.55% N). However, the slash treatments did not effect foliar N at ages 2.3, 4.2, 5.1 or 6.4 years.

Foliar P concentrations (seasonal range 0.084 - 0.120% P) have remained well above the level regarded as critical throughout with little treatment effect. Foliar K concentrations

Table 1. Effect of slash treatments on stand growth at age 6.4 years

Treatment	Height (m)	DBH (cm)	Basal area (m^2 ha^{-1})	Stem volume (m^3 ha^{-1})
BL$_0$	10.2	15.8	17.9	48.2
BL$_2$	10.7	17.0	21.1	58.8
BL$_3$	11.0	18.2	24.2	70.2
BL$_2$ + L	10.7	17.2	21.2	59.9
BL$_2$ – W	11.1	18.9	27.3	76.7
BL$_2$ – P	10.6	16.4	19.2	53.4
Mean	10.7	17.3	21.8	61.2
LSD p=0.05	0.34	0.83	3.0	7.5

Table 2. Effects of slash treatments on tree growth in each increment period

	Mean height (m)						Basal area (m^2 ha^{-1})				Stem volume (m^3 ha^{-1})			
Age (yr)	0.1-1.2	1.2-2.4	2.4-3.4	3.4-4.4	4.4-5.1	5.1-6.4	2.4-3.4	3.4-4.4	4.4-5.1	5.1-6.4	2.4-3.4	3.4-4.4	4.4-5.1	5.1-6.4
BL$_0$	0.9	1.5	2.5	2.1	1.5	1.2	4.8	6.0	3.4	3.0	8.9	15.9	10.0	15.1
BL$_2$	1.1	1.8	2.6	2.2	1.4	1.2	5.7	7.2	4.2	3.0	11.8	20.7	11.6	16.5
BL$_3$	1.1	1.9	2.6	2.4	1.4	1.2	6.7	8.6	4.9	3.0	14.6	26.0	13.2	18.9
BL$_2$+L	1.0	1.7	2.6	2.3	1.5	1.1	5.6	7.4	4.5	3.1	11.3	21.2	12.6	14.5
BL$_2$-W	1.2	2.0	2.6	2.3	1.5	1.2	7.3	9.5	5.0	3.1	16.7	28.4	15.0	20.9
BL$_2$-P	0.9	1.7	2.5	2.3	1.5	1.3	5.1	6.6	3.9	3.0	10.5	18.3	10.9	16.6
Mean	1.0	1.8	2.6	2.3	1.5	1.2	5.9	7.6	4.3	3.1	12.2	21.7	12.2	17.1
LSD p=0.05	0.2	0.2	NS	NS	NS	NS	0.9	1.2	0.5	NS	2.7	4.1	1.3	4.0

(seasonal range 0.35–0.53%) remained within an acceptable range although declining with age. Within any particular sampling, the highest foliar K concentrations were recorded in the BL$_3$ treatment whilst the BL$_0$ treatment was consistently low. Foliar Ca, Mg and Na concentrations (seasonal ranges 0.13-0.34%, 0.10-0.14% and 0.07–0.14% for Ca, Mg and Na respectively) were largely unaffected by treatments.

Slash Quantities

Table 3 shows that, averaged over all treatments, 64% of the slash present at the time the experiment was planted had decomposed by 2.5 years and 72% by 3.2 years. The half-life of the first rotation slash is ca 2.5 years. However, care must be exercised in the interpretation of these data because of changes in sampling procedures at the different sampling times but the general trend is reliable. The onset of noticeable litter fall from the second rotation crop after age 3.2 years and the thinning at age 3.8 years (slash weights included in the 6.4 year sampling only) must be taken into account in the interpretation of the data. These additions of biomass would have influenced the decomposition both through changing quantities and quality of organic matter. While statistical comparisons within a sampling are valid, the high degree of variability between treatments with similar initial slash loads (e.g. all BL$_2$ treatments) is most likely a reflection of sub-optimal sampling intensity. The reduction in slash quantities was most marked in the <1 mm slash fraction.

Rapid decline in biomass on the soil surface prior to age 2.5 years, resulting from decomposition of the slash, occurred in the BL$_3$ and BL$_2$+L treatments but decomposition was slower in the BL$_2$-W treatment. These differences in decomposition rate are difficult to understand.

Table 3. Biomass on soil surface in slash treatments

Treatment	Slash (including fresh litter) (t ha^{-1})					Living ground vegetation[a] (t ha^{-1})	Total organic matter[b] (t ha^{-1})
	0 yr	2.5 yr	3.2 yr	5.1 yr	6.4 yr	6.4 yr	6.4 yr
BL_0	9.0	4.4	2.8	2.6	9.5	3.6	13.1
BL_2	50.8	30.6	13.9	10.0	12.3	2.6	15.0
BL_3	141.4	44.8	24.9	25.6	29.8	1.7	31.4
BL_2 + L	56.4	18.0	12.3	16.4	11.7	4.5	16.2
BL_2 – W	58.0	45.1	21.2	24.0	18.9	0.1	19.0
BL_2 – P	73.9	37.6	34.0	16.7	19.5	4.3	23.7
Mean	64.9	30.1	18.2	15.9	17.0	2.8	19.8
LSD p=0.05	39.5	24.1	15.9	NS	NS	NS	NS

[a] Includes legumes (in the BL_2 + L treatment the legume component comprised 8.1% of the living vegetation).

[b] Thinning debris (thinned at 3.25 years) included.

Table 4. Soil (0–10 cm) chemical properties at tree ages 0, 2.4, 4.2 and 6.4 years (mean values for all treatments)

Parameter[a]	Sampled (years after planting)				Mean	LSD p=0.05
	0	2.4	4.2	6.4		
pH	5.53	5.19	5.00	5.36	5.27	0.12
EC_{25} (dS m^{-1})	0.030	0.023	0.030	0.031	0.029	0.004
Organic C (%)	1.43	1.55	1.93	2.19	1.77	0.39
Total N (%)	0.037	0.050	0.044	0.057	0.047	0.010
Exch K (cmol kg^{-1})	0.078	0.043	0.036	0.034	0.048	0.012
Exch Ca (cmol kg^{-1})	0.419	0.813	0.419	0.389	0.510	0.099
Exch Mg (cmol kg^{-1})	0.228	0.477	0.231	0.192	0.282	0.041
Exch Na (cmol kg^{-1})	0.062	0.051	0.052	0.073	0.065	0.014

[a] EC_{25} is Electrical conductivity; Exch K, Ca, Mg, Na are exchangeable cation (neutral ammonium acetate extract).

At age 6.4 years weeds (2.8 t ha^{-1}) accounted for only a small portion (14%) of the total biomass on the soil surface. Weed-free conditions were maintained in the BL_2-W treatment. Weed growth was less in the BL_3 treatment compared to the BL_0 treatment because of heavy slash cover initially.

Changes in Soil Chemical Properties

The initial soil samples were collected from the surface 0-10 cm of soil from all treatments at the time of planting. Subsequent samples, collected from all treatments when the trees were aged 2.4, 4.2 and 6.4 years, were more comprehensive and included samples from the 0-5, 5-10, 10-20 and 20-30 cm depths. Nutrient concentrations in the 0-10 cm layer can be compared across sample times if the results from the 0-5 and 5-10 cm samples are averaged. Experimental means for a range of parameters were compared across samplings to examine time trends (Table 4).

Soil pH in the surface 0-10 cm soil layer declined significantly in the 4.2 years since trees were established but increased to near orginal state by age 6.4 years. The decline was greatest prior to age 2.4 years (0.34 pH units) and continued between ages 2.4 and 4.2 years (0.19 pH units)

Table 5. Effect of treatments on chemical properties of the surface 0-5 cm layer of soil at ages 4.2 and 6.4 years

Parameter[a]	Sample No.[b]	Treatment						Mean	LSD p=0.05
		BL_0	BL_2	BL_3	BL_2 + L	BL_2 - W	BL_2 - P		
pH	1	5.18	4.82	4.86	4.76	4.99	4.91	4.92	0.21
	2	5.44	5.16	5.25	5.22	5.46	5.22	5.29	NS
EC_{25} (dS m^{-1})	1	0.026	0.037	0.036	0.037	0.032	0.032	0.033	0.007
	2	0.028	0.034	0.035	0.043	0.028	0.032	0.033	NS
Org C (%)	1	1.79	2.92	2.69	2.66	2.10	2.30	2.41	0.67
	2	1.98	3.37	3.24	3.17	2.40	2.78	2.82	NS
Total N (%)	1	0.033	0.065	0.054	0.064	0.044	0.049	0.052	0.016
	2	0.054	0.080	0.077	0.080	0.064	0.076	0.072	NS
ECEC (cmol kg^{-1})	1	1.68	2.24	2.28	2.24	1.94	1.86	2.04	NS
	2	1.44	1.98	2.02	2.04	1.63	1.84	1.83	NS
Exch K (cmol kg^{-1})	1	0.034	0.049	0.050	0.053	0.042	0.039	0.044	0.009
	2	0.037	0.041	0.049	0.045	0.041	0.041	0.041	NS
Exch Ca (cmol kg^{-1})	1	0.385	0.531	0.658	0.561	0.564	0.447	0.524	NS
	2	0.376	0.463	0.545	0.524	0.544	0.402	0.475	NS
Exch Mg (cmol kg^{-1})	1	0.197	0.284	0.346	0.332	0.273	0.235	0.278	NS
	2	0.169	0.220	0.272	0.279	0.221	0.217	0.230	NS
Exch Na (cmol kg^{-1})	1	0.057	0.057	0.052	0.074	0.063	0.043	0.058	NS
	2	0.068	0.086	0.081	0.100	0.073	0.060	0.078	NS

[a] EC_{25} = Electrical conductivity, Org C = organic C, ECEC = effecctive cation exchange, Exch K, Ca, Mg, Na = exchangeable cation (neutral ammonium acetate extract).

[b] Sample 1 refers to samples collected at age 4.2 years (July 2000) and sample 2 to samples collected at age 6.4 years (August 2002).

before increasing (by 0.36 pH units) at age 6.4 years to be within 0.17 pH units of the initial value. Organic C concentrations have gradually increased with age (from 1.43 to 2.19%) and this effect was also apparent for total N (increasing from 0.037 to 0.057% N). Patterns of seasonal changes in exchangeable cations vary with Na generally showing the reverse patterns to K, Ca and Mg. It is important to note that the age by slash treatment interaction did not attain statistical significance for any of the parameters examined. This suggests that all slash treatments have responded in a similar fashion to seasonal changes.

Chemical properties of the surface soil (0–10 cm) were comparable between the treatments at the establishment of the trial. The only significant difference was for organic C where higher concentrations were recorded in the BL_3 treatment [2.0% organic C compared to 1.3% (range 1.2-1.5%) for all other treatments]. This was possibly a result of incorporation of fine litter and logging residues into the soil surface during the application of the treatments.

Treatment-related changes in soil chemical properties were largely confined to the surface 0-5 cm and for this reason only these data have been presented (Table 5).

Soil pH at age 4.2 years in the surface 0-5 cm was lower (0.31 units) in treatments with retained slash but there was no difference between the single and double quantities of slash (Table 5). However, by age 6.4 years this difference was non significant. An increase in electrical conductivity (0.009 dS m^{-1}) was however detected in the surface 0-5 cm at age 4.2 years as a result of slash retention and whilst this trend was apparent in the 6.4 year data, the difference was not statistically significant. These differences in pH and EC_{25} were not observed at 2.4 years nor were they apparent at soil depths below 5 cm.

Organic C was higher in the surface 0-5 cm soil layer at ages 4.2 and 6.4 years where residues had been retained (Table 5). This difference was not apparent in the 2.4 year sampling nor at soil depths below 5 cm. The treatment effects on total N followed the same trends as organic C with higher N occurring in soil where residues were retained (although not statistically significant for the 6.4 year data).

Soil P (total and available) values were determined but have not been reported because of a high degree of variability, thought to be associated with past fertiliser history.

Cation exchange capacity in the surface 0-5 cm at ages 4.2 and 6.4 years tended to be higher where slash had been retained and this was also reflected by increased Exch K, Ca and Mg (Table 5).

There were few significant treatment effects on any of the soil parameters below 5 cm at 2.4, 4.2 or 6.4 years (data not presented) but for cation concentrations there were consistent trends in the 5-10 cm soil layer for higher concentrations where residues were retained.

Discussion

Site index comparisons between rotations indicate that growth of the second rotation crop is ahead of that of the first rotation. Whilst this may suggest that no major site deterioration has occurred as a result of a single rotation, the reasons behind this improvement are a combination of many other factors including; differences in the genetic quality of stock, improved silvicultural schedules employed in the second rotation and site management practices which conserve organic matter and nutrients.

Retention of slash (logging residues) is a means of maintaining or improving some soil properties (Table 5) and tree growth (Table 1). Total volume production of the F_1 hybrids at age 6.4 years was improved by 22% in the treatments where slash was retained, compared to the BL_0 treatment where the slash was removed. A further 19% improvement in volume was obtained where the slash quantities were doubled. While it is not feasible to increase the net amount of slash on a broad-scale basis, mechanised harvest systems tend to accumulate slash either in windrows or along roads if logs are processed at roadside. These practices will result in less uniform plantations unless logging slash is redistributed.

Legume establishment in plantations to improve the N supply has not been successful to date. Although a small amount of legume now exists in the ground cover (0.37 t ha^{-1} or 8% of the ground cover) there were no benefits in terms of improved tree growth or N status over normal slash retention (BL_2). Complete control of weeds has maximised tree growth (30% improvement in total volume production over slash retention only). Because the maintenance of total weed-free conditions is expensive and can increase soil erosion, the practice has not been recommended for wide-scale adoption in this environment. The maintenance of weed-free conditions along the planting lines would be a good option.

Treatment effects on height were observed before age 2.4 years, but this effect diminished with time. The early response in height growth contrasts with the basal area and volume responses where treatment responses peaked during the fourth growing season (3.4-4.4 years). This persisted to age 5.1 years, although the mass of slash remaining had markedly declined by this age and differences in slash loads between treatments were very small. As the trees aged, up to age 5.1 years, they were apparently responding to improved soil conditions resulting from the decomposition of the slash, rather than possible mulching effects which may have conserved soil water (Simpson *et al.* 2000). Covariance analysis using standing basal area or stem volume at age 4.4 years as the covariate on the 4.4 to 5.1 year increment data to allow partitioning of past effects of treatment and stand development on current increment. The regressions relating either standing basal area or total volume at age 4.4 years to increment between ages 4.4 to 5.1 years were significant, but the treatment effects were also significant (F values 0.025 and 0.080 for basal area and volume respectively). This indicates that the treatments *per se* are still effecting a response. Basal area increment data 5.1 to 6.4 years, whilst following the pattern, highlights a cessation of all treatment responses. The cessation of a continuing response is not so apparent for stem volume where the responses have persisted albeit at a reduced level of statistical significance.

The response to retention of slash in this sandy, infertile site parallels experience elsewhere on broadly similar sites in this network (Bouillet *et al.* 2001, du Toit *et al.* 2001, Gonçalves *et al.* 2001, Hardiyanto *et al.* 2001, O'Connell *et al.* 2001, Tiarks *et al.* 2001 and Xu *et al.* 2001). Tree growth responses to slash retention treatments were less apparent on the more fertile, heavier textured soils (Fan Shaohui *et al.* 2001, O'Connell *et al.* 2001, Sankaran *et al.* 2001).

Soil pH decreased by 0.53 units in the top 10 cm of soil between planting and 4.2 years. The decrease in pH was related to the reduction in the mean quantity of slash for the treatments ($y = 0.1301 \, \mathrm{Ln}(x) + 0.0568$ ($R^2 = 0.89$) where y = pH decline in the surface 10 cm of soil and x = the decrease in slash between ages 0 and 2.5 years). Soil pH remained well within the range to which *Pinus* species are adapted. The increase in pH (0.36 units) between ages 4.2 and 6.4 is a favourable outcome and may be associated with the reduction in rate of decomposition of slash and associated production of organic acids.

At age 4.2 years, an estimated 28% of the organic C lost from the slash was accounted for by increased organic C in the top 10 cm of soil. There were however quite large fluctuations between the treatments. Organic C and N concentrations in the surface 0-5 cm soil layer were increased at age 4.2 years (and 6.4 years) as a result of the retention of residues. There were strong linear relationships between organic C in soil and total N in soil (age 4.2 years R^2 = 0.92 and at age 6.9 years R^2 = 0.89). Mathers *et al.* (2002) have demonstrated using nuclear magnetic resonance (NRM) spectroscopy that the biologically active forms of soil organic C from the surface soil in the BL_3 treatments is higher than for the BL_0 treatment (increased proportions of Alkyl, Methoxyl and O-alkyl fractions).

The relationships between soil and plant nutrient status and between these parameters and tree growth were investigated. No relationships were found. It is important to recognise that the nutrient status of the second rotation sites has not declined to the extent of impacting on stand productivity although the stand growth was increased by slash retention and P application.

Impact on Management

The Queensland Department of Primary Industries Forestry (QDPIF) clear-falls and replants 3700 ha of first rotation exotic pine annually (5-year average). The results of this work have helped provide a scientific basis for management of the important inter-rotation period for these plantations. Retention of slash is now a management policy. With the current harvest systems, logging residue is not evenly distributed over the area and windrowing of the slash is common. The results from this study, coupled with those from supplementary studies estimating distribution patterns for slash after clear-falling under a range of logging systems, now enables impacts on the uniformity of second rotation stands to be estimated.

Early results from this work have proved valuable to forest managers and policy makers as will long-term results. It is planned to continue the trial to rotation age (year 2020) but measurement intervals will be extended. As resources become available, further investigation of key soil processes will be undertaken.

Conclusions

On sandy soils low in fertility in coastal south Queensland, retention of slash (harvest residues) has significantly improved growth of second rotation hybrid pines at age 6.4 years. Further improvement in tree growth was obtained by doubling the quantities of slash and by complete control of weeds. Foliar nutrient status of the trees between ages 2.3 and 6.4 years was not affected by the treatments. By 4.2 years after the site was replanted, soil pH and exchangeable

K in the surface 10 cm of soil had declined significantly but pH increased significantly between ages 4.2 and 6.4 years. Organic C and N concentrations increased with time. At ages 4.2 and 6.4 years, treatment effects were confined to the soil surface (0-5 cm).

Based on tree growth and changes in soil nutrients, retention of slash from the first rotation plantation is recommended as the best management option.

Acknowledgments

The field work described forms part of the Queensland Forestry Research Institute's research program funded by Queensland Department of Primary Industries Forestry. We are grateful to the Center for International Forestry Research (CIFOR) for supporting this work and to Dr Sadanandan Nambiar (CSIRO Forestry and Forest Products, Australia) for his valuable comments and suggestions on the manuscript.

References

Bouillet, J.P., Nzila, J.D., Laclau, J.P. and Ranger, J. 2001. Slash management effects on tree growth and nutrient cycling in young *Eucalyptus* replanted sites in the Congo. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 13p.

Bubb, K.A., Xu, Z.H., Simpson, J.A. and Saffigna, P.G. 1999. Growth response to fertilisation and recovery of N-15 labelled fertiliser by young hoop pine plantations of subtropical Australia. Nutrient Cycling in Agroecosystems 54:81-92.

Collins, P. (ed.) 2000a. Plant analysis methods. Queensland Forestry Research Institute, Technical Note No 16. Queensland Department of Primary Industry, Brisbane.

Collins, P. (ed.) 2000b. Soil analysis methods. Queensland Forestry Research Institute, Technical Note No 17. Queensland Department of Primary Industry, Brisbane.

du Toit, B., Dovey, S.B. and Job, R.A. 2001. Effect of site management on early biomass development and allometry in a South African stand of *Eucalyptus grandis*. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 10p.

FAO. 1974. FAO - UNESCO soils map of the world 1:5 000 000. Vol. 1 Legend. UNESCO, Paris. 59p.

Fan Shaohui, He Zongming, He Zhiying, Lin Sizu, Lu Shantu, Ying Jinhua and Yang Xujing. 2001. A study on the influence of site management measures on the growth of four-year-old Chinese fir plantation of second-generation. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 10p.

Gonçalves, L., Gava, L. and Wichert, M.C.P. 2001. Sustainability of wood production in eucalypt plantations of Brazil. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 16p.

Hardiyanto, E.B., Ansori, S. and Sulistyono, D. 2001. Early results of site management in *Acacia mangium* plantations at PT Musi Hutan Persada, South Sumatra, Indonesia. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 12p.

Haywood, J.D. 1994. Early growth reductions in short rotation loblolly and slash pine in central Louisianna. Southern Journal of Applied Forestry 18:35-39.

Isbell, R. 1996. The Australian soil classification. CSIRO, Collingwood, Australia. 143p.

Mathers, N.J., Xu, Z.H., Berners-Price, S., Perera, S.M.C. and Saffigna, P.G. 2002. Hydrofluoric acid pre-treatment for improving ^{13}C CPMAS spectral quality of forest soils in south-east Queensland, Australia. Australian Journal of Soil Research 40:655-674.

O'Connell, A.M., Grove, T.S., Mendham, D.S., Corbeels, M., McMurtrie, R.F., Shammas, K. and Rance, S.J. 2001. Impact of inter-rotation site management on nutrient stores and flux rates and tree growth of eucalypt plantations in south-western Australia. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 13p.

Pu, G., Saffigna, P.G. and Xu, Z.H. 2001. Denitrification, leaching and immobilisation of ^{15}N-labelled nitrate in winter under windrowed harvest residues in hoop pine plantations of 1-3 years old in subtropical Australia. Forest Ecology and Management 152:183-194.

Queensland DPI Forestry. 2001. DPI Forestry Yearbook for the financial year 2000 - 2001. Queensland Government, Department of Primary Industries, Brisbane. 84p.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kallarackal, J. and Kumaraswamy, S. 2001. Improving eucalypt plantation productivity through site management practices in the monsoonal tropics – Kerala, India. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 15p.

Simpson, J.A. 1995. Site-specific fertiliser requirements of exotic pine plantations in Queensland. *In*: Schulte, A. and Ruhiyat, D. (eds.) Proceedings of the International Congress (Third Conference on Forest Soils), Soils of Tropical Forest Ecosystems. Vol. 5: Soil fertility and fertilisation, Balikpapan, Indonesia, 29 October-3 November 1995, 90-106. Mulawarman University Press, Samarinda, Indonesia.

Simpson, J.A. and Grant, M.J. 1991. Exotic pine fertiliser practice and its development in Queensland. Queensland Forest Service Technical Paper No. 49:1-17.

Simpson, J.A., Dart, P. and McCourt, G. 1998. Diagnosis of nutrient status of *Acacia mangium*. *In*: Turnbull, J.W., Crompton, H.R. and Pinyopusarerk, K. (eds.) Recent developments in acacia planting. Proceedings of an international workshop held in Hanoi, Vietnam, 27-30 October 1997, 252-257. ACIAR Proceedings No. 82. Australian Centre for International Agricultural Research, Canberra. 383p.

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. 112p.

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. 112p.

Tiarks, A., Elliott-Smith, M. and Stagg, R. 2001. Effects of logging residue management on the growth and nutrient distribution of a *Pinus taeda* plantation in central Louisiana, USA. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 12p.

Xu, Z.H., Simpson, J.A. and Osborne, D.O. 1995a. Mineral nutrition of slash pine plantations in subtropical Australia. I. Tree growth responses to fertilisation. Forestry Research 41:93-100.

Xu, Z.H., Simpson, J.A. and Osborne, D.O. 1995b. Mineral nutrition of slash pine plantations in subtropical Australia. II. Foliar nutrient responses to fertilisation. Forestry Research 41:101-107.

Xu, D.P., Yang, Z.J. and Dell, B. 2001. Effects of site management on tree growth, soil properties and nutrient availability of a second rotation plantation of *Eucalyptus urophylla* in Guangdong Province, China. Paper presented at the Fourth Workshop, Site management and productivity in tropical plantation forests: impact on soils and options for management over successive rotations. Pointe Noire, Congo 9-12 July 2001. 20p.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Effects of Logging Residue Management on the Growth and Nutrient Distribution of a *Pinus taeda* Plantation in Central Louisiana, USA

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Abstract

A 37-year-old pine plantation was harvested. An experiment was established at the site with three levels of logging residue retention and two levels of weed control. By age 10 years retaining harvest residue increased pine volumes by 10 $m^3 ha^{-1}$ and weed control increased production by another 20 $m^3 ha^{-1}$. Growth differed between genetic family, but there was no genetic family x residue treatment interaction. Retention of logging residue without weed control increased the amount of carbon in the soil at age 5 years, but carbon levels decreased to pre-planting levels by age 10 years.

Introduction

In southern US, most of the original pine forest was cut and the land used for agriculture during the 19th and 20th centuries. These farms were abandoned because of declining crop yields, but periodic fires and lack of seed sources prevented re-establishment of forests. Low natural fertility and water holding capacity combined with farming-induced erosion and soil compaction meant that much of the area fits the criteria of degraded lands (Oldeman and Van Engelen 1993). Subsequent reforestation has restored some of the lost soil organic matter on many of the sites (Van Lear *et al.* 1995), but these coastal plain soils may again lose long-term productivity if forest management practices reduce the amount of organic matter and nutrients in the soil.

To monitor the effects of forest management on public lands, Powers *et al.* (1990) proposed a national study be initiated with treatments that manipulate the amount of logging residue retained, as well as soil compaction. Beginning with the prototype site reported here, more than 60 core installations and another 40 affiliated experiments have been established on both public and private lands in the US and Canada. Goals of the study include developing the scientific basis for sustaining productivity and validating practicable soil-based measures of

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sustainable productivity as encouraged by the international Montreal Process. Results from the first 5 years of replicated installations in Louisiana and Mississippi were reported in the 3rd CIFOR network workshop (Tiarks *et al.* 2000). In this paper, the effects of residue retention and weed control on pine growth and nutrient distributions in a 10-year-old plantation are presented.

Location and Site Description

The study site is on the USDA Forest Service's Palustris Experimental Forest in Rapides Parish, Louisiana approximately 50 km southwest of Alexandria. The site (latitude 31°02'N, longitude 92°38'W, altitude 45 m) is on rolling terrain formed from coastal plain sediments consisting of unconsolidated loams and clays. The soils are Malbis fine sandy loam (Kerr *et al.* 1980) belonging to the Plinthic Paleudults in the USDA Taxonomy classification. These soils are moderately well drained, acidic, and are low in organic matter, available P and exchangeable bases. A water table fluctuates about the 100 cm depth in the winter and spring, but is rarely present in the summer months (Tiarks *et al.* 1995). The soil water holding capacity available during the growing season is about 325 mm for the 2 m deep profile.

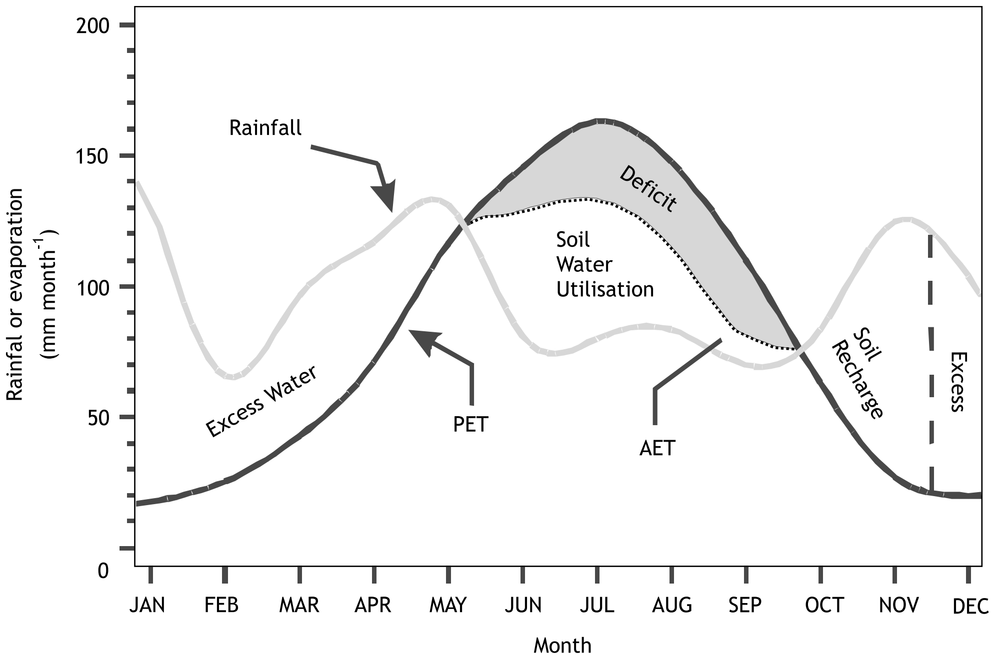
Native vegetation for the area was *Pinus palustris* Mill. forests which were removed in the early 1900s. As no attempt was made to reforest the area and/or control fire, the vegetation developed into an open stand of grass with a scattering of *Quercus marilandica* Muenchh. and *P. palustris* saplings. In 1953, the stand harvested for this study was established by disking strips into the grass and direct seeding. Two years after seeding, the stand consisted of 1032 seedlings ha^{-1}. The stand received management typical to the local area, which included several thinnings and winter prescribed burns about every 3 years, the last being 9 months before harvesting in October 1989. At harvest, the number of trees was 226 ha^{-1} and averaged 20.5 m in height and 30.3 cm dbh. Stem analysis was done on 27 trees selected to represent the diameter classes. Nonlinear regression was used to develop a height-age curve for the previous stand (Baldwin and Feduccia 1982).

The climate type is humid mesothermal without a dry season according to Koppen's system of climatic classification (Kimmins 1987). Data recorded by an automated station on the site beginning in February 1990 showed rainfall averaged 1170 mm yr^{-1} and mean monthly air temperatures ranged from 10-27°C. Based on these measurements, estimates of potential evapotranspiration (PET) and actual evapotranspiration (AET) were calculated (Thornthwaite and Mather 1957). The 10-year averages indicate a water deficit occurs during much of the growing season (Fig. 1) as rainfall declines during the warmer months when PET is increasing. The average water deficit for the 10-year period was 123 mm yr^{-1}, with annual deficits ranging from 7 mm yr^{-1} in 1991 to 213 mm yr^{-1} in 1998. In 1998, plant water available in the profile was depleted to 77 mm, about 25% of the storage capacity of the soil. In the cooler months, increased rainfall and reduced PET combine to allow recharge of the profile by early December. After that excess water drains from the site with a fluctuating water table appearing during periods of high rainfall.

Experimental Details

The study was laid out following the design of a national network of long-term soil productivity research programme (Powers *et al.* 1990). This site was the first location in the network and was used to test the standard protocols and develop detailed methods for installation of other sites. The network plan called for a core set of nine treatments consisting of a factorial of three levels each of organic matter removal and soil compaction, replicated three times in several zones within a forest type. As the first site is not replicated, the compaction treatments are treated as blocks in this report. While this does not fit the exact criteria for experimental design, the use of compaction treatments as blocks allows testing of differences resulting from treatments that conform to the core treatments in the CIFOR 'Site management and productivity in tropical forest plantations' study (Tiarks *et al.* 1998). By age 10 years, the soil compaction had only a minor effect on tree growth on this site.

Figure 1. Ten year average of rainfall and estimated PET and AET for the experimental site



The core treatments consisting of three levels of organic matter removal are:

- **BL_0** All aboveground residue, understorey and litter removed.
- **BL_1** All aboveground parts of pines alone removed during harvest.
- **BL_2** Only merchantable stem removed, with all logging slash retained.

The amount of biomass removed from the BL_2 treated plots was 86 t ha^{-1} of wood and bark. An additional 13 t ha^{-1} of limbs and foliage was removed from the BL_1 plots. On the BL_0 plots, an additional 4 t ha^{-1} of understorey and forest floor was removed for a total of 103 t ha^{-1}.

The main plots are 65 x 65 m and planted at a 2.5 x 2.5 m spacing. Each of the nine 0.4 ha plots are split into two equal parts: weeds were allowed to develop on one half and herbicide was used to control weed growth in the other. Within each vegetation control subplot, there is a 20 x 50 m measurement plot consisting of 160 planting spots. The plots were planted in February 1990 using container grown seedlings raised from seed from 10 half-sib families of genetically improved loblolly pine. The families were planted in a stratified randomised pattern with family identity recorded.

Methods

Tree and Vegetation Measurements

Total tree height was measured annually for the first 10 years except age 8 and, beginning at age 5, dbh measurements were taken when heights were measured. Total volume (under bark), and dry weight of the wood, bark, branches and needles were calculated using equations developed by Baldwin and Feduccia (1982). Nutrient concentrations of wood, bark, needle and branch samples collected at harvest were used to estimate the amount of nutrients in the biomass at age 10 years. At ages 0, 5, and 10 years, forest floor and understorey samples were collected from four sample quadrats on each subplot. They were 1.25 m on each side with one corner anchored to a buffer row tree. The samples were categorised into logging residue or decayed wood, litter, including foliage from harvested pines, grasses and herbs, and hardwood trees and shrubs. Analysis of variance was used to test the statistical significance of differences in growth due to the treatments. Linear regression was used to test for significant relationships between soil bulk density and soil carbon content.

Soil Measurements

Soil samples for bulk density and chemical analysis were collected using core samplers of different diameters for the surface 30 cm and for deeper samples. A hand coring apparatus 60 mm in diameter (Ruark 1985) was used at ages 0, 5 and 10 years to take bulk density samples at the 0-10, 10-20, and 20-30 cm depths. The samples were collected from 10 random locations on each plot. Preliminary measurement of the variability indicated that seven samples are sufficient for determining bulk densities of the surface soil within a range of 0.05 g cm^{-3} at 90% probability. Deeper samples were collected at age 10 years from five locations in each plot using a 19 mm diameter soil sampling tube 1.8 m long (Veihmeyer 1929). These samples were collected in 30 cm increments from 30-180 cm.

Soil samples were air-dried and pulverised by hand to pass through a 2 mm sieve. Roots and rock fragments larger than 2 mm were saved and weighed from the three surface layers, but not from the deeper samples. At ages 0 and 5 years, the samples were bulked by plot and depth. At age 10 years, C, N, and S were determined on individual samples before bulking by plot and depth for other nutrient analysis. The concentrations of organic C, total N and total S were determined by a LECO 2000 elemental analyser in which the samples were combusted at 1350^{o} C. Carbon and S were detected by infrared cells while the N was determined by a conductivity cell after reduction to N_2. Available P was extracted by Mehlich 3 and quantified colormetrically. Potassium and Ca were extracted with $BaCl_2$ and measured by atomic absorption spectroscopy. Carbon, N, and S in plant samples were determined by the elemental analyser. Plant samples were digested in nitric-perchloric acid heated to 190^{o} C for determination of P colormetrically and K and Mg by atomic absorption.

Results and Discussion

Tree Growth

The retention of logging residue (BL_2) and weed control both increased the height of the loblolly pines after the first year (Fig. 2). Without weed control, the height growth difference between leaving all residue (BL_2) and removing all above ground biomass (BL_0) increased from 0.2 m at age 3 years to 0.8 m at age 7 after which the gain was maintained. With weed control, the response to residue retention was 0.4 m at age 3 years, but the largest difference was 0.7 m at age 6 years and then declined to 0.5 m at age 10 years. Compared to the estimate of height at a given age of the previous stand, the new plantation grew slower in the first 5 years but by age 10 years the height of the new stand when all above ground biomass was removed (BL_0) was about the same as the previous stand.

Removing all aboveground biomass improved survival by age 10 years (Table 1) although the difference was statistically significant only when weeds were not controlled. While leaving the forest floor and understorey intact (BL_1) did increase height and diameters by a small amount, the lower survival resulted in no volume difference compared to the total biomass removal. However, leaving all aboveground biomass did increase the volume of the pines by about 10 m^{3} ha^{-1}, a statistically significant improvement. By age 10 years, the weed control treatment increased volume by 20 m^{3} ha^{-1} regardless of the residue management. Together, leaving all the aboveground biomass and controlling the weeds resulted in about a 70% increase in volume compared to removing the logging residue and not controlling weeds.

Half-sib families had a significant effect on individual tree growth and total volume production (Table 2). The families with the largest volume per tree (TX 29 and MS 6) also were the families with the smallest and largest percentage of stem gall disease (*Cronartium quercuum* [Berk.] Miyable ex Shirai f. sp. *fusiforme*) respectively. Thus, in terms of total volume

Figure 2. Effects of residue retention and weed control on the height growth of loblolly pine for the first 10 years. Grey band is the height of the previous rotation estimated from stem analysis

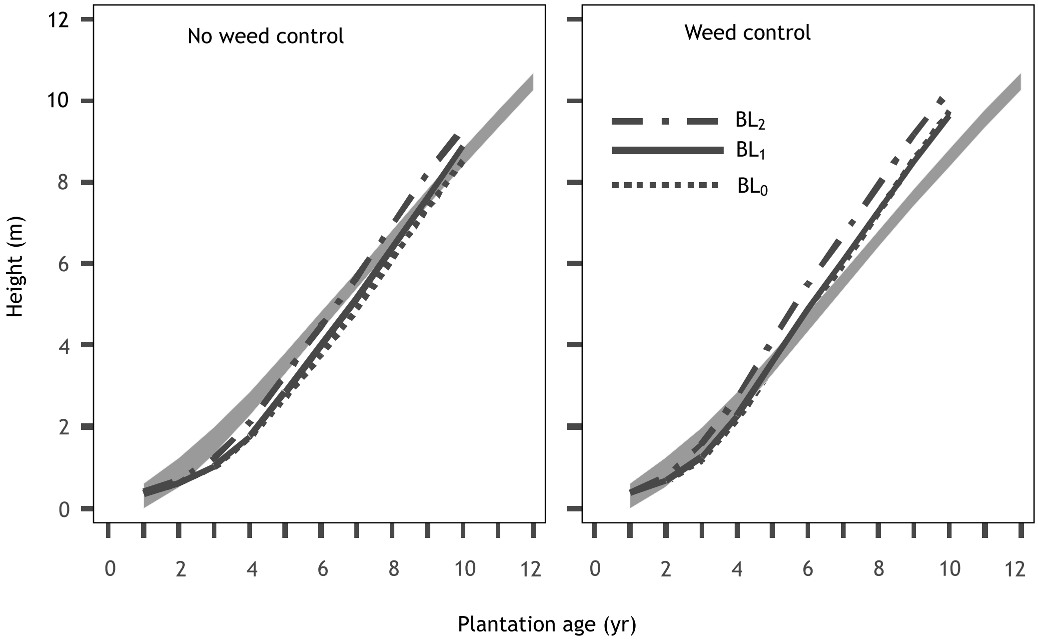


Table 1. Effects of residue management on the survival and growth of loblolly pine at age 10 years

Treatment	Survival	Height	Diameter	Volume (under bark)
	(%)	(m)	(cm)	(m^3 ha^{-1})
No weed control				
BL_0	78a	8.5a	11.7a	44.2a
BL_1	63b	8.9ab	12.5ab	42.0a
BL_2	69b	9.3b	13.1b	53.8b
Complete weed control				
BL_0	77a	9.7a	13.5a	65.7a
BL_1	74a	9.6a	13.6a	64.4a
BL_2	71a	10.2b	14.6b	74.9b

Values within the same column and weed control level followed by the same letter are not significantly different (alpha=0.10).

production, the TX 29 family was significantly better than any of the other selections. The family by residue interaction was not significant for any of the stand attributes and the family by herbicide interaction was significant only for the gall disease impact.

The heights of the pines on all of the plots were at least equal to the estimated height of the harvested stand at age 10 years, indicating that productivity is being maintained. Both the retention of aboveground biomass and weed control increased pine heights above the previous stand, indicating improved site productivity resulting from management activities. However, because of improved planting conditions, survival was better on plots where all residues had been removed. Thus, even though individual tree size

Table 2. Growth of 10 half-sib families at age 10 years averaged over three residue management treatments and two weed control levels

Source and number	Height (m)	Dbh (cm)	Volume (m^3 tree^{-1})	Total volume (m^3 ha^{-1})	Diseased (galls) (%)
LA 14	9.56	13.3	0.051	60.9	14.2
LA 28	9.27	13.0	0.047	52.6	11.8
LA 31	9.07	12.2	0.044	45.2	8.0
LA 33	9.29	12.8	0.046	57.9	4.2
TX 7	9.26	13.4	0.050	58.5	4.9
TX 17	9.27	13.3	0.050	52.3	6.6
TX 29	9.60	13.4	0.053	66.6	3.8
TX 36	9.58	13.2	0.051	62.3	6.9
MS 6	9.49	13.4	0.053	58.1	26.4
MS 26	9.40	13.6	0.052	60.6	12.8
Mean	9.38	13.2	0.050	57.5	10.0
LSD (p=0.05)	0.22	0.5	0.004	8.2	4.4
Interaction[a]	NS	NS	NS	NS	0.006

[a] refers to the significance level of the herbicide by family interaction; NS=not significant.

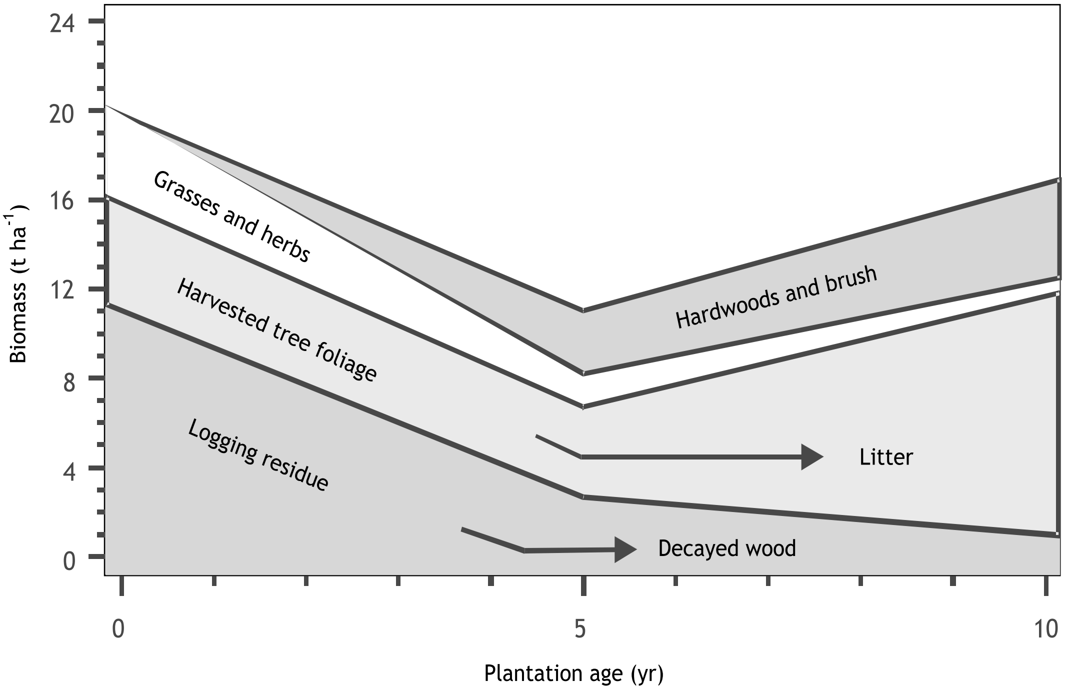
increased when understorey and litter were retained on site, volume production was not affected at age 10 years. The positive effect of retaining logging residues on this site is most likely from the nutrients released rather than water conservation by the mulching effect. The water deficit was high in some years, but pine growth in those years was not noticeably affected. Thus the water storage capacity of the soil profile seems to be sufficient to sustain growth in most years. Large differences in growth and disease impact were measured between families of trees, but genetic source did not interact with treatments in agreement with the results of hybrid pines in Queensland (Simpson 2000).

Understorey Response

Decomposition reduced the woody material in limbs and tops left as logging residue to 0.7 Mg ha^{-1} by age 10 (Fig. 3). The biomass of decaying wood at age 10 was no longer affected by residue treatment because dead limbs falling from the new plantation were beginning to add to the decaying wood component. The amount of litter, including all non-woody material on the forest floor, changed little in the first 5 years, but by age 10 years litter was the primary component of the forest floor and was the only one significantly affected by the residue management treatments. The biomass of the litter ranged from 7.6 Mg ha^{-1} for the BL_0 treatment to 8.0 Mg ha^{-1} for the BL_1 treatment and to 10.9 Mg ha^{-1} for the BL_2 level. As the stand developed and crown closure occurred, the biomass as grasses and herbs declined to 0.8 Mg ha^{-1}. The amount of hardwood and brush had increased significantly by age 10 years, averaging 2.5 Mg ha^{-1} but was not significantly affected by the residue management treatments.

The increase in hardwood and brush resulted from the changing in fire regime from a prescribed burn every 3 years to none in the first 10 years. Because the litter includes the accumulation of fresh and partially decomposed foliage from several years, the amount of litter at age 10 years is larger than the amount of foliage deposited by the harvested stand. As residue retention increased the amount of litter by increasing the size of the pines, the benefit of residue retention might be even larger at the establishment of the next rotation.

Figure 3. Biomass in logging residue and understorey at harvest and in understorey and litter at ages 5 and 10 years for the BL_2 treatment without weed control



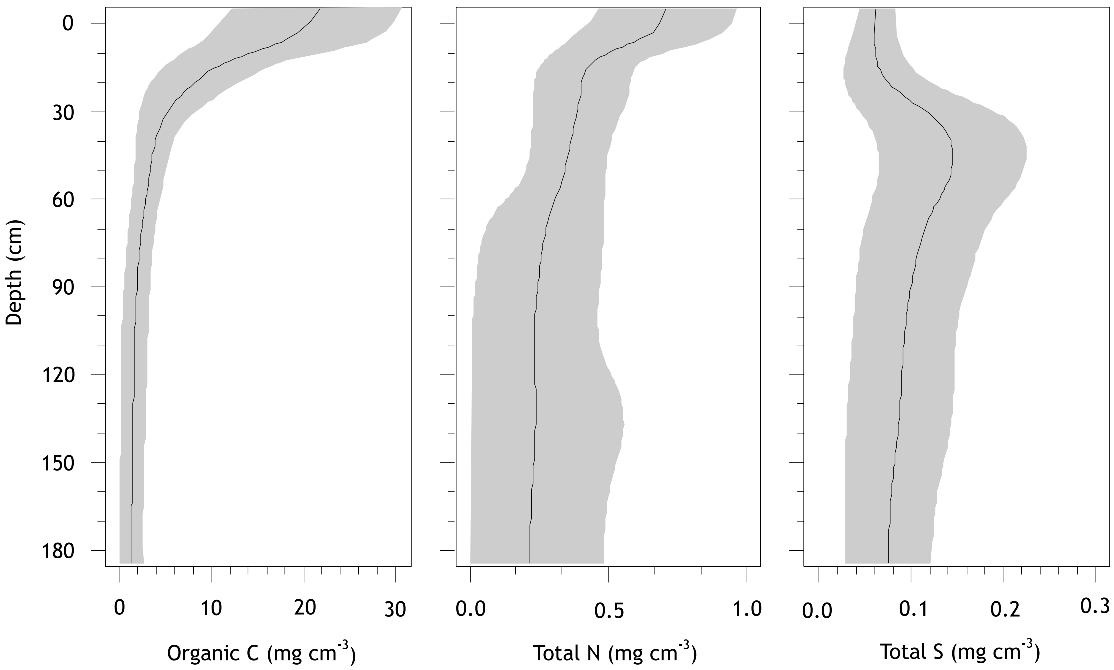
Soil Bulk Density and Organic Carbon Distribution

Ten years after planting, the treatments had little effect on soil bulk density, C or other nutrients. Averaged across all treatments, the soil bulk density increased with depth averaging 1.27 g cm^{-3} at the 0-10 cm depth to 1.80 g cm^{-3} at the 150-180 cm depth. The soil densities also varied widely within a depth with the bulk densities ranging from 0.71 to 1.50 g cm^{-3} in the surface and from 1.43 to 2.09 g cm^{-3} at the 150-180 cm depth. As expected, the concentration of soil organic carbon decreased from 15.0 g kg^{-1} in the surface to 0.7 g kg^{-1}. Because of the increasing bulk density with depth in these soils, the C, N, and S distributions are shown as mass per unit volume (Fig. 4). The amount of C decreases rapidly with depth to about 60 cm but measurable quantities were found at the deepest sampling depth. The C was most variable at the surface but was fairly uniform below 60 cm. The mean N concentration on a volume basis declined rapidly with depth like C, but the N was more variable. Thus at 180 cm, the 90% confidence internal for N ranges from 0 to 0.5 mg cm^{-3}. The large variability in N at the deeper depths may be associated with an accumulation of NH_4^+ on the exchange complex which would have been detected by the methods used.

Sulfur values were the largest at about the 45 cm depth where the clay concentrations are also the highest.

Soil organic carbon can affect soil bulk densities by two mechanisms. First, increased soil organic carbon will reduce bulk densities in most soils because the particle density of organic carbon is much lower than the particle density of most inorganic soil constituents. Second, increased organic matter may improve soil structure increasing the volume of soil occupied by voids. By assuming particle densities of 1.30 g cm^{-3} for soil organic matter and 2.65 g cm^{-3} for minerals

Figure 4. Distribution of C, N, and S in soil 10 years after plantation was established. Shaded areas are 90 % confidence intervals



(Adams 1973), the soil porosity or portion of soil in voids was calculated for each soil sample. The estimated porosity doubled from about 0.26 to 0.52 as the amount of soil organic matter increased from nil to 30 g kg^{-1} (Fig. 5). Since this analysis is based on all depths, confounding is possible as both porosity and C decrease with depth. However, the interaction term between depth and the C by porosity regression is not significant. Also, the C by porosity fit is significant for each depth individually.

Because soil organic carbon affected porosity, the normal practice of bulking samples that are from the same depth and plot before determining organic carbon may lead to errors. If the relationship is affected by the treatments, the amount of carbon in the profile may be biased if samples are combined before measurements are made. In this study, combining samples before carbon was measured would have underestimated the amount of carbon in the profile for all treatments. The underestimation was largest in both biomass removal and weed control treatments. However, the differences were small, ranging from 0.6% of carbon in the profile in the BL_2 treatment without weed control to 2.9% in the BL_0 treatment with weed control. These differences amount to about a 1.2 Mg ha^{-1} error in the total carbon in the profile. In this study, combining samples before the measurement of carbon was acceptable. However, this potential source of error should be considered if a treatment that may change soil porosity, such as tillage, is part of the experiment.

Carbon and Nutrient Distributions

The only treatment that had an effect on the amount of carbon in the surface 10 cm of soil was weed control and the difference was statistically significant only at age 5 years (Fig. 6). On plots not receiving weed control, the amount of organic carbon increased from 20.8 Mg ha^{-1} at harvest to 22.5 Mg ha^{-1} at age 5. At the same time, controlling weeds reduced the amount of carbon to 17.5 Mg ha^{-1}. By age 10 years,

Figure 5. Effect of soil organic carbon content on soil porosity or fraction of soil occupied by voids

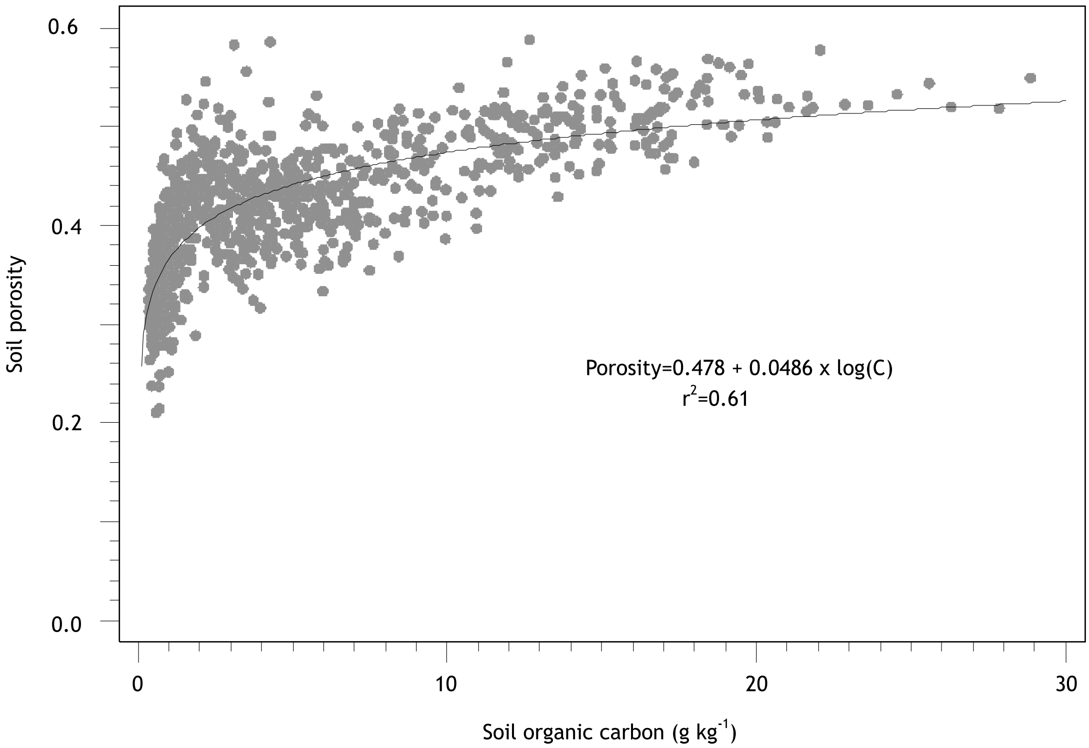
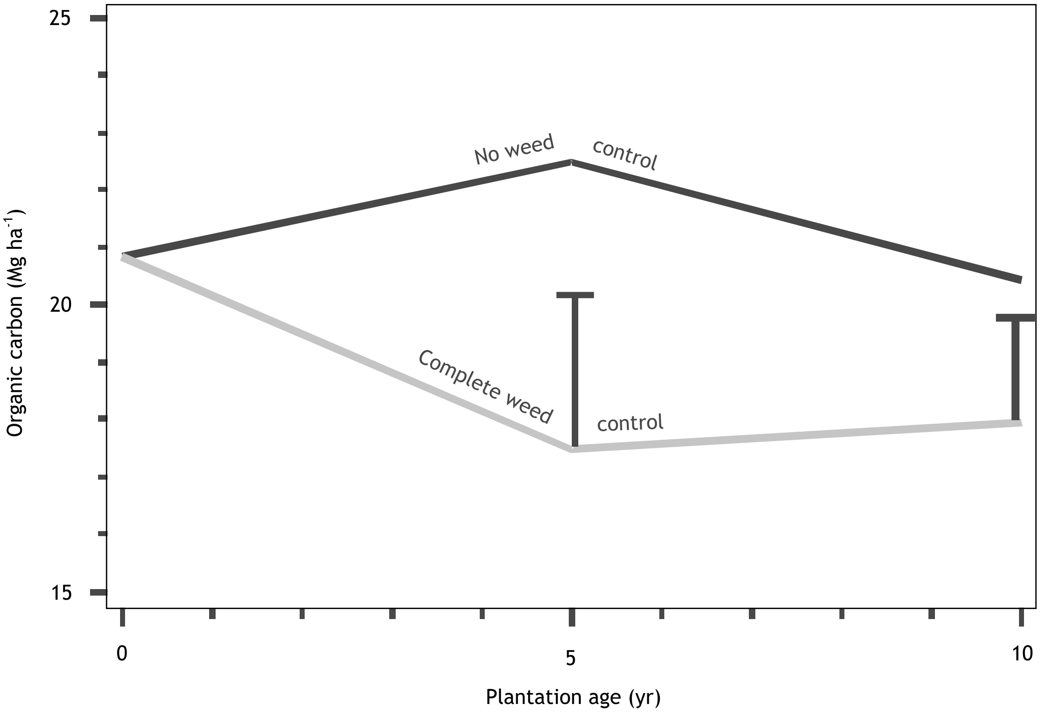


Figure 6. Effects of weed control on soil organic carbon in surface 10 cm of soil. Vertical bars represent LSD for ages 5 and 10 years (p=0.05).



the effects of both treatments had diminished but the amount of organic carbon was still significantly different.

While the weed control had a significant impact on the growth of the pines, the total amount of organic carbon in the system was not affected (Table 3). Weed control increased the fraction of carbon that was in the aboveground portion of the pines from 18.9 to 25.7%. However, when weed control was applied, the fraction in the soil decreased from 75.3 to 68.9%. The same effect of the weed control was noted for the other nutrients. For example, weed control increased the amount of K in the pine biomass by 8.2 kg ha^{-1} while the amount of K in the surface 30 cm of soil was reduced by 7.5 kg ha^{-1}. The overall decrease of 8.1 kg ha^{-1} in all components is only 1.8% of the K in the system, well within measurement error.

The soil is the largest reservoir of the organic carbon and nutrients. More than two thirds of total carbon and more than 95% of the nitrogen on the site is in the soil. Because of this large buffer, management practices may cause only small changes in concentrations in the soil. However, as the availability of nutrients such as P is difficult to measure, these small changes may lead to growth declines if corrective action is not taken. When weeds are controlled, the pine trees are larger. Even if the concentration of nutrients is not affected, harvesting will remove a relatively larger amount of nutrients. For example, weed control reduced the amount of K in the forest floor and understorey but increased the amount of K in pines from 32.8 to 41.0 kg ha^{-1}. As about 11% of the total K on the site is in aboveground biomass, removals during harvest and site preparation may reduce site productivity. As critical limits for nutrients are approached, pine growth will decline rapidly as the reserves

Table 3. Carbon and nutrients in pine biomass, understorey, and soil of 10-year-old loblolly plantation

Component	C		N		P		K		Ca	
	H0[a]	H1[b]	H0	H1	H0	H1	H0	H1	H0	H1
	(Mg ha^{-1})		(kg ha^{-1})							
Needles	3.1	3.9	72.2	93.4	4.86	6.04	21.1	24.4	8.5	11.1
Branches	3.6	4.9	11.0	15.1	1.20	1.64	4.0	5.5	10.0	14.3
Bark	3.1	4.3	8.9	12.4	1.34	1.89	2.6	3.6	13.4	18.8
Wood	8.7	12.8	9.5	14.1	1.70	2.52	5.1	7.5	8.6	12.8
Woody understorey	1.2	0.2	12.3	2.2	0.53	0.12	5.0	1.1	8.9	0.9
Herbaceous understorey	0.4	0.1	5.3	1.0	0.27	0.05	3.2	0.4	3.1	0.5
Litter	3.8	4.7	68.0	62.1	2.62	2.71	6.0	5.6	59.3	48.0
Decaying wood	0.3	0.4	2.6	5.0	0.08	0.12	0.2	0.4	2.4	2.1
Roots 0-30 cm	4.4	4.1	N.D.[c]	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Soil 0-30 cm	38.0	34.2	1546.7	1398.3	N.D.	N.D.	65.1	57.6	791.8	710.3
Soil 30-180 cm	31.4	31.2	3768.9	4197.4	N.D.	N.D.	327.7	330.7	1207.1	1369.3
Total	98.0	100.8	5505.4	5801.0	N.D.	N.D.	440.0	436.8	2113.1	2188.1
% in pines	18.9	25.7	1.8	2.3	N.D.	N.D.	7.5	9.4	1.9	2.6
% in under/ff[d]	5.8	5.4	1.6	1.2	N.D.	N.D.	3.3	1.7	3.5	2.4
% in soil	75.3	68.9	96.6	96.5	N.D.	N.D.	89.2	88.9	94.6	95.0

[a] no weed control; [b] total weed control; [c] not determined; [d] understorey and forest floor.

are depleted. On these nutrient deficient sites, conservation of nutrients and replacement by fertilisation are important management considerations.

Conclusions

At age 10 years, the replanted pines were as tall or taller than the pines in the original stand at a comparable age. While comparisons between rotations are difficult, these results indicate that pine production on this site is sustainable. Leaving all the aboveground logging residue and weed control increased the heights of the pines compared to the previous rotation. Removal of the forest floor resulted in smaller trees, but volume production was not reduced because of better survival. Weed control increased pine growth more than residue retention, and the effects of both management options were additive. Differences in the productivity of half-sib families indicate that some genetic gain is possible. Except for the incidence in stem gall disease, genetic gain was independent of residue retention and weed control.

As the amount of logging residue increased, the amount of litter under the stands at age 10 years increased. However, the increased pine growth and litter accumulation did not affect the amount of organic carbon (OC) in the soil. Weed control reduced the amount of OC in the surface 10 cm of soil at age 5 years, but this difference was smaller and no longer statistically significant by age 10. At low levels of OC, small increases in OC increased the soil porosity. At OC levels greater than about 5 g kg^{-1}, the effect of OC on porosity was small.

At age 10 years, neither residue retention nor weed control affected the amount of nutrients in the ecosystem, including the soil to 180 cm. Weed control did increase the fraction of nutrients that had accumulated in the pines and subject to removal by harvesting. Thus, as the intensity of management increases, the importance of retaining logging residue on the site for supporting long-term productivity will increase.

References

Adams, W.W. 1973. The effect of organic matter on the bulk and true densities of some uncultivated soils. Journal of Soil Science 24:10-17.

Baldwin, V.V. Jr. and Feduccia, D.P. 1982. Loblolly pine growth and yield prediction for managed west gulf plantations. Research Paper SO-236. U.S. Department of Agriculture, Forest Service, Southern Research Station, New Orleans, LA, USA. 27p.

Kerr, A., Jr., Griffis, B.J., Powell, J.W., Edwards, J.P., Venson, R.L., Long, J.K. and Kilpatrick, W.W. 1980. Soil survey of Rapides Parish, Louisiana. U.S. Department of Agriculture, Washington, DC. 86p.

Kimmins, J.P. 1987. Forest ecology. Macmillan, New York, USA. 531p.

Oldeman, L.R. and Van Engelen, V.W.P. 1993. A world soils and terrain digital database (SOTER) - an improved assessment of land resources. Geoderma 60:309-335.

Powers, R.F., Alban, D.H., Miller, R.E., Tiarks, A.E., Wells, C.G., Avers, P.E., Cline, R.G., Loftus, N.S. Jr, and Fitzgerald, R.O. 1990. Sustaining productivity in North American forests: problems and prospects. *In*: Gessel, S.P., Lacate, D.S., Weetman, G.F. and Powers, R.F. (eds.) Proceedings of the 7th North American Forest Soils Conference, 1988 July 24-28, Vancouver, British Columbia, 49-79. University of British Columbia, Vancouver, Canada.

Ruark, G.A. 1985. A refined soil coring system. Soil Science Society of America Journal 49:278-281.

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: a progress report: workshop proceedings 7-11 December 1999, Kerala, India, 73-81. Center for International Forestry Research, Bogor, Indonesia.

Thornthwaite, C.W. and Mather, J.R. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology, Vol X, No. 3. Drexel Institute of Technology, Centerton, N.J.

Tiarks, A.E., Elliott-Smith, M.L. and Stagg, R. 2000. Loblolly pine (*Pinus taeda* L.) plantations in the 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: a progress report: workshop proceedings 7-11 December 1999, Kerala, India, 101-103. Center for International Forestry Research, Bogor, Indonesia.

Tiarks, A.E., Hudnall, W.H., Ragus, J.F. and Patterson, W.B. 1995. Effect of pine plantation harvesting and soil compaction on soil water and temperature regimes in a semitropical environment. *In*: Schulte, A. and Ruhiyat, D. (eds.) Proceedings, International Congress on Soils of Tropical Ecosystems. 3rd Conference on Forest Soils (ISSS-AISS-IBG). Vol. 3, 65-78. Samarinda, Indonesia.

Tiarks, A.E., Nambiar, E.K.S. and Cossalter, C. 1998. Site management and productivity in tropical plantations - impacts on soils and options for management over successive rotations. CIFOR Occasional Paper No. 16. Center for International Forestry Research, Bogor, Indonesia. 11p.

Van Lear, D.H., Kapeluck, P.R. and Parker, M.M. 1995. Distribution of carbon in a Piedmont soil as affected by loblolly pine management. *In*: McFee, W.W. and Kelly, J.M. (eds.) Carbon forms and functions in forest soils. Proceedings 8th North American Forest Soils Conference, Gainesville, Florida. May 1993, 489-501. Soil Science Society of America, Madison, WI.

Veihmeyer, F.J. 1929. An improved soil sampling tube. Soil Science 27:147-152.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Effects of Site Management on the Growth of a Second-rotation Chinese Fir (*Cunninghamia lanceolata*) Plantation Three to Six years after Planting

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Abstract

Study objectives are to measure the influence of various site management treatments on the productivity of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) plantations over a rotation. A second-rotation *C. lanceolata* plantation was established using five site preparation treatments on the cleared area of first-rotation *C. lanceolata*. In the first four years after treatment, trees on the plots treated with double slash (BL_3) grew the best. Five to 6 years after treatment, tree growth in double slash treatment (BL_3) still remained the best, but no significant difference in tree growth was found among different treatments. Two years after treatment, average soil bulk density across all the plots in the 0-10 cm layer was lower compared to preharvest conditions. But 3 years after planting, the bulk density in the surface 10 cm layer had returned to near preharvest levels. Average soil organic matter concentration across all the plots increased a little in the 0-10 cm layer, but decreased in the 10-20 and 20-40 cm layers. Total N, total P, and total K concentrations remain almost the same. The only soil property affected by the residue retention treatments was the pH in the 0-10 cm layer. Three years after planting, soil pH increased as the amount of residue retained increased. The residue of *C. lanceolata* decomposed fastest in the early stages and slowed with time. Leaf residues decomposed the fastest among various residual components, while the branch residues decomposed slowest. After 20 months, 50% of the combined residue was decomposed and only 5% remained after 89 months.

Introduction

Cunninghamia lanceolata (Lamb.) Hook. is one of the most important tree species for producing timber in south China, and plays a crucial role in forestry production in the region. But, along with an enlargement of the area of *C. lanceolata* plantations, replanting is increasing on sites where one or more rotations of *C. lanceolata*

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have been harvested. Concern about the potential of site degradation by *C. lanceolata* plantations is rising. The authors adopted a method of combining time series and spatial series methods to investigate management that will prevent site degradation by successive plantations. The study on the mechanism of site degradation of *C. lanceolata* plantation by spatial series method was reported in other papers (Fan *et al.* 2000, 2001, Fan and Ma 2001 Ma *et al.* 2000a, b).

Here, the time series method is used to study processes affecting site productivity of *C. lanceolata* plantations. In October 1996, a long-term research was initiated to study the influence of retaining different levels of harvest residue on the growth of a second-rotation plantation and as well as the effect on soil properties. The study was established during clearfelling a 29-year-old *C. lanceolata* plantation. The purposes are to look for potential site degradation, and put forward the optimal management measures to maintain or increase the productivity of second-rotation plantations and sustain soil productivity. The effect of different treatments on 1- and 2-year-old *C. lanceolata* plantations was reported by Fan *et al.* (1998, 1999a, b).

Location and Site Description

The experimental plot is on 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 with mean annual precipitation 1817 mm, mean annual temperature 19.4°C, average temperatures in January and July 9.1°C and 28.4°C respectively, and extreme temperature range from -5.8°C to 41°C. Annual sunshine is 1709 hours. The red soil is over 100 cm deep and very fertile, making it suitable for the growth of *C. lanceolata*.

Methods

A randomised complete block design of five plots in each of four blocks was established on a cleared area of first-rotation *C. lanceolata* plantation. Each plot is 600 m^2 in area and was planted with 150 trees. The five residue treatments are:

BL$_0$	No slash. All aboveground organic residue including the crop trees, understorey and litter was removed from the plots.
BL$_1$	Whole-tree harvest. All aboveground parts of the trees removed.
BL$_2$	Stem + bark harvest. Only the main bole and attached bark was removed.
BL$_3$	Double slash. Branches, leaves and other non-commercial components of trees from the BL$_1$ treatment were applied to this treatment.
SB	Stem and bark harvest + burning. Same as BL$_2$ except the residue was burned.

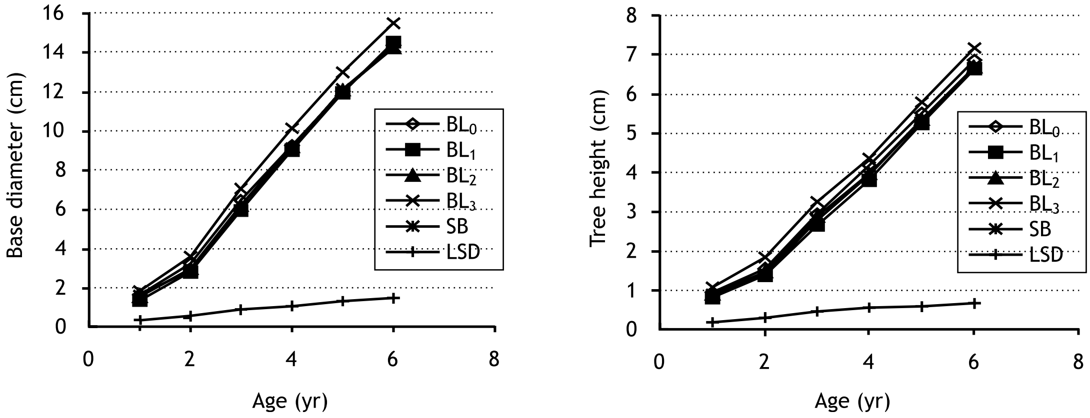
Holes, 50 cm x 50 cm x 40 cm, were hand dug at each planting spot. Seedlings were planted in February 1997. Compound fertiliser (content of N, P, and K were unknown) at a rate of 100 g per seedling was applied in May 1997. Because of poor initial survival associated with weed competition, dead trees 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 *C. lanceolata* growth included height, diameter breast-height (or basal diameter), crown width and the survival rate. Analysis of variance and LSD tests (p=0.05) were used to evaluate the statistical significance of difference between treatments.

Soil samples were collected in October 1996, before planting, for chemical and bulk density analyses, after plots were established and before the first-rotation *C. lanceolata* was harvested. Soil samples for bulk density analyses were collected in January 1999, 2 years after planting. Soil samples for chemical and bulk density analyses were collected in January 2000, 3 years after planting. Mixed soil samples of 5 points in each plot were collected from 3 layers, 0-10,10-20 and 20-40 cm, respectively. For the layer of 20-40 cm, samples were collected from 25-35 cm depth. Each soil sample weighed 1 kg. Samples were air dried for chemical analysis.

Methods for soil analysis were:

- total N, by $K_2Cr_2O_7$ and H_2SO_4 digestion and H_3BO_3 absorption;
- total P, by ignition followed by colorimetric molybdate blue;

Figure 1. Effect of different treatments on the growth of 6-year-old *C. lanceolata* trees



- total K, by ignition method (same as total P) and determined by flame photometer;
- organic matter, the product of organic C and 1.724, by $K_2Cr_2O_7$ and H_2SO_4 digestion; and pH, in 1:2.5 water solution.

Decomposition rate of the logging residue was measured using a nylon mesh bag technique. 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 treated plot in each block. Three bags in each plot were collected 4, 6, 11, 16, 23, 32 and 44 months after harvesting. Soil or organic material (such as living fine roots of plants) adhering to the material inside the bags was carefully brushed away. The oven dry weight of leaf and branch material remaining was compared to the original weight.

Results and Discussion

Growth of *Cunninghamia lanceolata*

Because of poorer soil fertility and other reasons, the difference in growth of *C. lanceolata* between block III and other blocks became obvious by age 3. Thus, block III was excluded from the trial. Tree growth results are reported with the replanted trees included. Preliminary analyses showed that growth differences and treatment effects were not affected by the replanted trees.

In the third year after treatment, *C. lanceolata* grew best on plots treated with double slash (BL_3) and poorest on whole tree harvest plots (BL_1) (Fig. 1). The different treatments had significant effects on basal diameter and height. Four years after treatment, trees on the double slash treated plots (BL_3) were significantly larger than on whole tree harvest plots (BL_1). Five and 6 years after treatment, the double slash treatment (BL_3) still produced the largest tree growth, but differences in tree size, were not statistically significant (Fig. 1, Table 1).

The more residues left on the site, the better the trees grew with the exception of the no slash treatment. Initially the *C. lanceolata* trees on the no slash treatment grew better due to less competition. Slash burning treatment (SB) did not stimulate tree growth (Fan *et al.* 1998, 1999), as it did 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 the discrepancy is probably higher soil fertility in this site compared to the other sites. Residue treatments had significant effects on the growth of the second-rotation Chinese fir stand at 1 to 4 years of age but had no significant effects at age 5 to 6.

Soil Properties

After the first-rotation *C. lanceolata* was cut, dramatic changes occurred in the understorey.

Table 1. Number of stems, basal diameter, diameter at breast-height (DBH) and height (Ht) of *C. lanceolata* treated with different amounts of residue 6 years after planting (including replanted seedlings)

	No. stems (ha^{-1})	Basal diam. (cm)	DBH (cm)	Ht (m)
BL_0	2014	14.4	10.4	6.86
BL_1	1917	14.5	10.5	6.64
BL_2	2132	14.2	10.2	6.69
BL_3	1885	15.5	11.3	7.18
SB	1822	14.3	10.2	6.68
LSD	NS	NS	NS	NS

Table 2. Average soil bulk density, pH and organic matter levels across all the plots before and after planting

Time	Bulk density (g cm^{-3})			pH value (H_2O)			Organic matter (%)		
	Soil depth (cm)			Soil depth (cm)			Soil depth (cm)		
	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40
Before planting	0.94	1.00	1.08	5.07	4.91	4.89	5.35	4.27	2.97
2 years after planting	0.85	1.01	1.09	nd	nd	nd	nd	nd	nd
3 years after planting	0.91	1.02	1.12	5.12	4.94	4.88	5.41	3.81	2.75
LSD p=0.05	0.05	NS	NS	NS	NS	NS	NS	0.41	NS

nd: soil pH and organic matter content was not measured 2 years after planting.

Most of sciophytic vegetation disappeared while heliophytic herbs, with great biomass in the first 2 years, became the dominant understorey vegetation, along with some shrubs. Two years after the test, the average soil bulk density in the 0-10 cm layer of all the 20 plots was lower compared to preharvest conditions (Table 2). This was possibly because of the large biomass of herb roots mostly concentrated in the top 5 cm soil layer under the regular manual weed control. Three years after harvesting the bulk density in the surface 10 cm had returned to near preharvest levels. Bulk density changes in the 10-20 cm and 20-40 cm layers were minor and not statistically significant (Table 2). Three years after planting, the concentration of soil organic matter in the 0-10 cm layer increased slightly compared to preharvest levels but decreased in the 10-20 cm and 20-40 cm layers. When changes in both bulk density and organic matter are considered, the amount of organic matter in the top 0-40 cm of soil decreased from 157.2 t ha^{-1} before harvest to 144.2 t ha^{-1} 3 years after harvest. None of the treatments had a statistically significant effect on soil bulk density or organic matter concentrations.

Soil pH values did not change significantly from before harvesting to 3 years after planting (Table 2). However, the pH of the surface 0-10 cm layer did increase as the amount of logging residue retained on the site increased (Fig. 2). Compared to the preharvest values, removing all aboveground residue decreased the pH, while double slash increased the pH. Changes in pH values in the 10-20 and 20-40 cm layers were not significant but did follow the same trend. The release of exchangeable bases such as calcium from logging residue is probably the main reason for the increase of soil pH values.

Figure 2. Effects of different treatment patterns on the soil pH value at 0-10 cm depth. Means of the treatment with same letter are not significantly different at the level of p=0.05 using LSD test. Bars = standard deviation

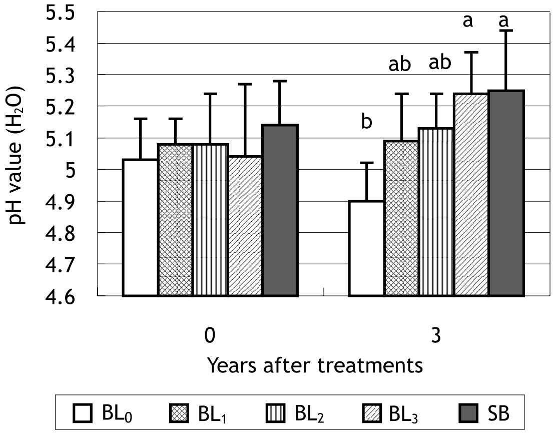


Table 3. The change of soil nutrient levels across all the plots before and after planting

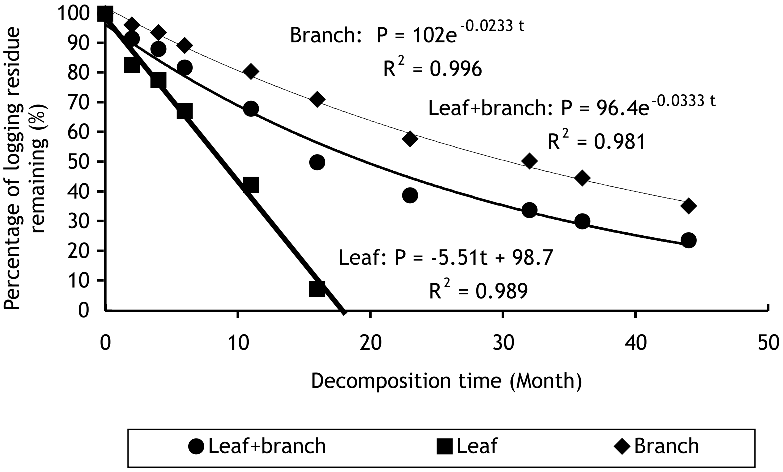
Time	Total N (%)			Total P (mg kg^{-1})			Total K (g kg^{-1})		
	Soil depth (cm)			Soil depth (cm)			Soil depth (cm)		
	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40
Before planting	0.158	0.125	0.093	427	395	390	9.49	9.43	9.88
3 years after planting	0.163	0.124	0.091	437	411	403	9.54	9.75	9.96
LSD p=0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS: not significant at p=0.05.

The concentration of total N increased slightly in the 0-10 cm layer, and slightly decreased in the 10-20 cm and 20-40 cm layers, but the changes were not statistically significant. Total P and total K concentrations slightly increased in all 3 layers, but they were also not statistically significant (Table 3). Total N, total P and total K concentrations were not significantly affected by the harvest and replanting operations (Table 3). The treatments did not have statistically significant effects on the total N, P, K, organic matter concentrations, bulk density or pH value at 10-20 cm and 20-40 cm layer, except for pH value at 0-10 cm layer (Fig. 2).

In the initial 3-year-period of afforestation, full sunshine and fertilisation of the soil stimulated the fast-growing understorey and weeds. The root system of the understorey is mainly concentrated in the 0-10 cm depth, decreasing the soil bulk density and increasing the concentration of organic matter in the surface. However the acceleration of mineralisation of organic matter in deeper layers of soil associated with cultivation led to an overall decrease in the amount of soil organic matter in the surface 40 cm of soil. Three years after planting, the *C. lanceolata* stand was nearly closed and the understorey vegetation declined. These may be the reasons why the bulk density of the soil in the layer of 0-10 cm increased between 2 and 3 years after planting.

Figure 3. Weight loss from mesh bags during decomposition of logging residue fractions over 44 months



Except for pH, soil properties were not affected by the different treatments. While the treatments had a statistically significant effect on pH values in the 0-10 cm layer only, changes at the other depths followed the same trend, with the pH decreasing as more of the harvesting residue was removed. This may indicate that exchangeable bases such as calcium are retained with the logging residue that could have an effect on long-term productivity.

Decomposition Rate of Residues

C. lanceolata harvest residue 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 logging residue are shown in Fig. 3. Calculated with this mathematical model, leaves decomposed faster than branches. It took 9 months and 17 months for the leaves to decompose to 50% and 5% of their original weight. Branch residue took 31 months and 129 months to decompose to similar proportions of its original weight. It took 20 months and 89 months for the total harvest residues to decompose to 50% and 5% of their total weight (Table 5). As reported in many other decomposition studies, the residue decomposes faster in the early stage and slower in the late stage.

Impacts on Operational Management

Burning logging slash was the only site preparation method for the establishment of Chinese fir plantation used by the forest farms in Nanping City. Results of this experiment showed slash burning caused the lowest tree survival rate and no improvement of tree growth. So the managers of Nanping Forestry Committee stopped slash burning in all the state forest farms from 2001. Slash retention is acceptable, although the cost is a little higher, and now practised operationally because it can improve survival rate.

Conclusions

Three and 4 years after treatment, the growth response of the *C. lanceolata* trees followed the same trend as after the first and second year. Trees treated with double slash (BL_3) grew best, followed by the no slash treatment (BL_0). Five and 6 years after treatment, tree growth in double slash treatment (BL_3) still remained the best, but no significant difference in tree growth was found among different treatments.

Table 4. Diameter distribution of branch residue

Branch diameter (cm)	Proportion made up of the branch dry weight (%)	Proportion made up of the residual dry 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 rate of residual components

Component	Half-decomposition time (months)	95% decomposition time (months)
Leaf+branch	20	89
Leaf	9	17
Branch	31	129

Two years after planting, the average soil bulk density of all the 20 plots in the 0-10 cm layer was lower compared to preharvesting conditions. Three years after planting the soil bulk density in the 0-10 cm depth had returned to near preharvest levels. Concentration of soil organic matter increased slightly in the 0-10 cm depth, but decreased at lower depths. When changes in bulk density and soil organic matter contents are combined, the amount of soil organic matter in the top 40 cm decreased somewhat. Soil pH was the only measured soil property that was affected significantly by the treatments. The pH increased as more logging residue was retained on the site. The treatments had no statistically significant effects on soil bulk density, concentration of organic matter, total N, P, and K. But nutrient losses and soil erosion caused by slash burning or slash removal might be primary factors responsible for productivity decline of Chinese fir plantation over successive rotations.

The harvesting residues of *C. lanceolata* decomposed rapidly in the early stages and slowed with time. Decomposition of leaves was the fastest among various residue components, taking 9 months and 17 months for the leaf to decompose to 50% and 5% of the total weight. Branch residue decomposed the slowest, taking 31 months and 129 months to decompose to 50% and 5% of the total weight. It took 20 months and 89 months for the combined harvest residues to decompose to 50% and 5% of the total weight.

Acknowledgements

We thank the network cooperation program of the Center for International Forestry Research for providing essential conditions and funding for the test. We thank C. Cossalter, E. K. S. Nambiar, A. Tiarks and T. Toma for their kind help in test design, data analysis and thesis composition.

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. and Ma, X. 2001. Studies on cultivation nutrition of Chinese fir plantations with multi-generation management. Proceedings of silviculture workshop, 2001, 120-131. Chinese Environment Science Press, Beijing. (in Chinese)

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., 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 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.

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.

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)

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Modelling Nutrient Cycling and Integrating Nutrient Cycling into Growth Models

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Abstract

Models available to predict growth of forest plantations include: process-based, architectural and growth and yield models, each dealing with a particular aspect of the forest production. As a part of plantation sustainability research in Congo, these three approaches are being tested. Among them, the growth and yield model (EUCALYPT-Dendro) aims at: (1) assessing stand production under different silvicultural options, and (2) evaluating the risks of nutrient deficiencies for different harvesting strategies. This chain of models includes three modules: a single tree distance independent model assesses the tree and stand growth; a set of stem taper and biomass equations evaluates wood properties; and the biogeochemical module gives the within-tree content of nutrients (N, P, K). The simulation steps are at monthly intervals but seasonal variations are not yet taken into account. Growth and yield models such as 'EUCALYPT-dendro' are simple and are designed to explicitly take into account silvicultural practices and competition between trees. However, there is no real coupling between them and nutrient cycling models. In these models, 'site fertility' or 'site index' is generally defined as a dominant height at a given age. It is assessed from an inventory and is fixed for the whole simulation. This assumption is valid for forest ecosystems where there are only small changes in soil fertility within one rotation. However, in both temperate and tropical forests, fertility may change dramatically. Integrating nutrient cycles into growth and yield models could be a useful way to take into account such fertility variations, and provide a better basis for improved nutritional management of plantations. A growth and yield model and a procedure to incorporate nutrient cycling in such models is described. This procedure is discussed and compared with other approaches for modelling plantation growth. CIFOR's site management network is well positioned to provide data for evaluating a range of such models. Its structure and the large range of studied ecosystems would allow testing of the generality and robustness of the resulting models. An outcome would be a support decision system providing information on: (1) tree and stand growth, (2) silvicultural practices (thinning and fertilisation regimes), and (3) nutrient cycling. This information could be used by managers to assess volumes, biomass and wood quality of trees, and also for nutrient management decisions

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Introduction

A wide variety of models is available to predict growth of forest plantations. They include process-based, architectural and growth and yield models, each dealing with a particular aspect of forest production.

Process-based models focus on forest ecosystems' functioning (water, carbon, and nutrient fluxes) e.g. Biomass (McMurtrie *et al.* 1990), 3-PG (Landsberg and Waring 1997), CenW (Kirschbaum 1999), G'Day (Dewar and McMurtrie 1996), Triplex (Peng *et al.* 2002). They are mainly used to simulate: (1) the water and CO_2 exchanges between the stand and the atmosphere, and (2) gross and net primary production, using input meteorological data (e.g. rainfall, incident radiation, air temperature) and other information on soil (e.g. soil water and texture), canopy structure and physiological properties.

Architectural models deal with the structure of tree growth focusing on bud growth, branching and mortality. Resulting models are stochastic but can simulate the 3D architecture of plants (Amap, L-Systems). A review is provided by Godin (2000). They are used for different applications such as biomechanics (Fourcaud *et al.* 1996) or landscape studies (Auclair *et al.* 2001).

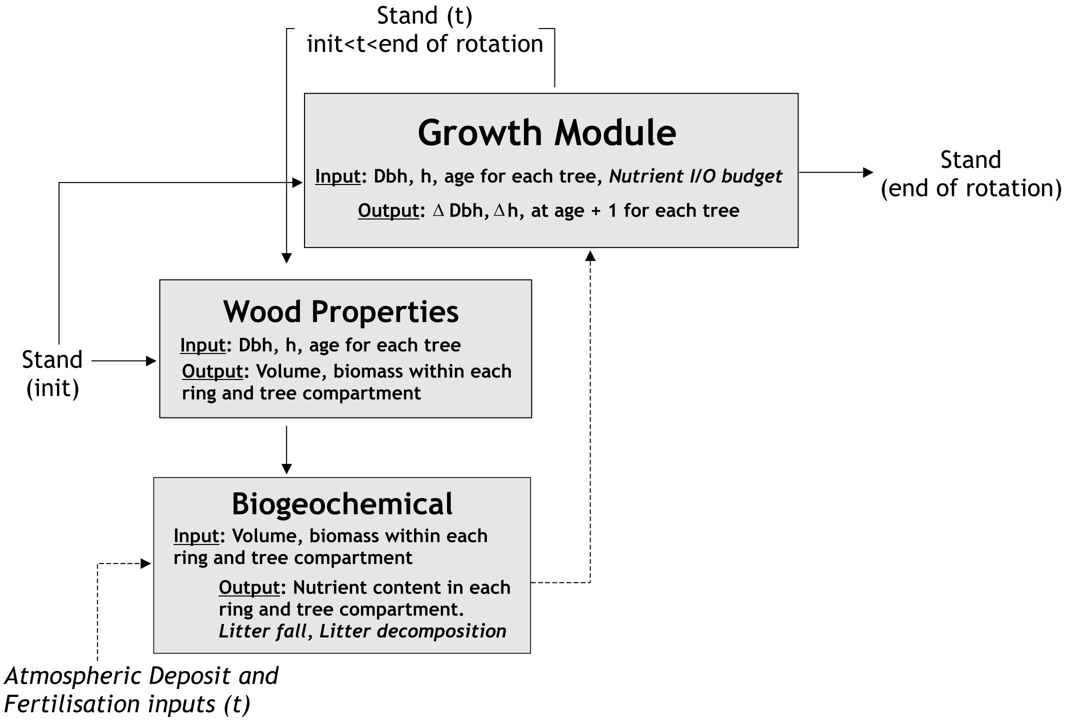
Growth and yield models are designed to simulate the tree and stand growth under different silviculture regimes. They are based upon a series of basic relationships where diameter increments, height growth, and mortality are a function of site potential and silvicultural practices.

Existing nutrient cycling models are mechanistic to varying degrees. They can focus on nitrogen mineralisation, e.g. Snap (Paul *et al.* 2002), nitrogen cycle, e.g. Forsento (Crohn and Haith 1994), both nitrogen and carbon cycle, e.g. Century (Parton *et al.* 1987, Kirshbaum and Paul 2002), or cycling all nutrients including CEC, e.g. NuCm (Liu *et al.* 1991), Min3P (Mayer *et al.* 2002). Although some of these models include a simplified module dealing with ecosystem growth, a natural evolution was their coupling to more detailed forest process-based models. Reviews by Tiktak and van Grinsven (1995) and Homann *et al.* (2000) emphasised: (1) few of the forest-soil-atmosphere models are balanced for both the growth module and the nutrient cycling component, and (2) detailed documentation of all phases of model development, calibration, and evaluation are required due to the numerous parameters used in such models. Despite this, they are well adapted to describe the functioning of the forest ecosystems (see for example applications of G'Day: Medlyn *et al.* 2000, Corbeels *et al.* 2001, McMurtrie *et al.* 2001) although few are used as decision support tools by forest managers (Mäkelä *et al.* 2000).

By contrast, the main interest of growth and yield models lies in their simplicity and because they are designed to explicitly take account of silvicultural practices and competition between trees. Although several studies describe and model the growth responses to silvicultural treatments, e.g. Pienaar and Rheney (1995) and Snowdon (2002), there is no real 'coupling' between them and nutrient cycling models. By 'coupling', we mean simulation of the nutrient input/output budgets and feedback of these budgets into the growth module. In growth and yield models, the site index is often fixed for the whole simulation. This assumption is valid for forest ecosystems where fertility varies only a little over the long-term. However, soil fertility may change dramatically: within one rotation period (60 to 100 years and more for temperate forests) where global changes lead to site index variations (Spiecker 1999, Dhôte and Hervé 2000), or between two rotation cycles for tropical plantations where high amounts of nutrients are exported regularly (e.g. Laclau 2001). Thus, integrating nutrient cycles into growth and yield models may be a useful way to take into account such fertility changes. It may also allow evaluation of management options and provide a basis for improved nutritional management of plantations.

Objectives of this paper are to propose a method to integrate nutrient cycling into growth and yield models and to show how the CIFOR's site management network could be used to facilitate development and testing these models. The paper is divided into: (1) description of a growth

Figure 1. Schematic representation of EUCALYPT dendro – an integrative modelling approach to assess the sustained production of *Eucalyptus* plantations in Congo (Saint-André *et al.* 2002a). Dotted lines and italics indicate that the relationship/model is not yet completed



and yield model, EUCALYPT-Dendro, developed in Congo (Saint-André *et al.* 2002a), (2) description of the possible connection between nutrient cycling and these models, and (3) a proposal for a joint study within the framework of the CIFOR's network.

Description of Growth and Yield Model: EUCALYPT-Dendro

Since 1978, 42 000 ha of clonal *Eucalyptus* plantations have been established in the littoral savannas of Congo, mainly for pulpwood production. They were planted on sandy soils, characterised by low reserves of available nutrients and low water retention capacity (Laclau 2001). Field studies focus on clonal selection, silvicultural practices, stand growth and biogeochemical cycles of nutrients. The extensive data available from these studies, e.g. CIFOR's experiment on the site management (Nzila *et al.* 2002), was used or will be used to develop a chain of models named 'EUCALYPT-Dendro'.

General Description

This chain is calibrated for the most planted eucalypt clone in Congo. It includes three main modules linked into a single chain of models (Fig. 1). The growth module is a single tree distance-independent model, a classical approach in dendrometry, as described below (Dhôte 1990, 1996, Dreyfus 1993, Meredieu 1998, Tomé *et al.* 2001, García and Ruiz 2003). For the tree properties module, a generic stem taper equation was constructed. It explicitly takes into account taper of the bole, butt swell and decrease in diameter within the crown. The equation accurately estimates diameters and volumes along the bole (Deleporte, personal communication). Allometric relationships were developed for estimating the biomass of roots, branches, stem, bark and leaves throughout the rotation (Saint-André *et al.* Submitted). For the biogeochemical module, a model was built to assess the distribution of nutrient concentrations (N, P, K) in individual rings within the bole and their changes with the ring age (Saint-André *et al.*

Figure 2. Simulation of biomass production compared to the measured biomass recorded along an age series. One group of black points correspond to 1.5 growth years for one stand

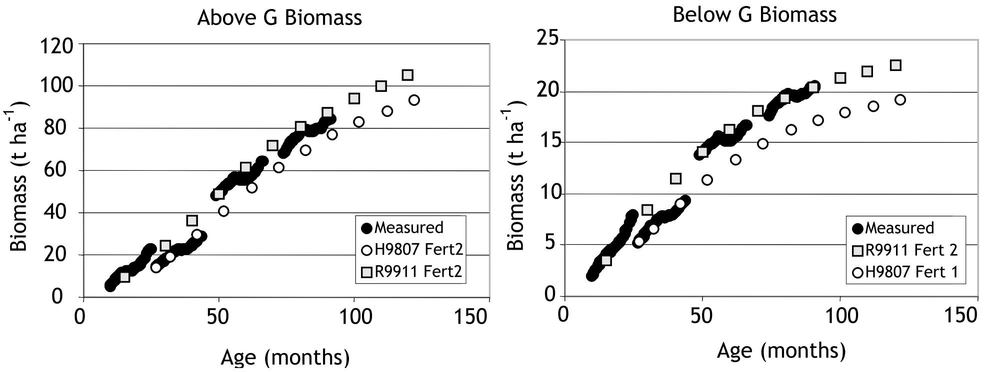
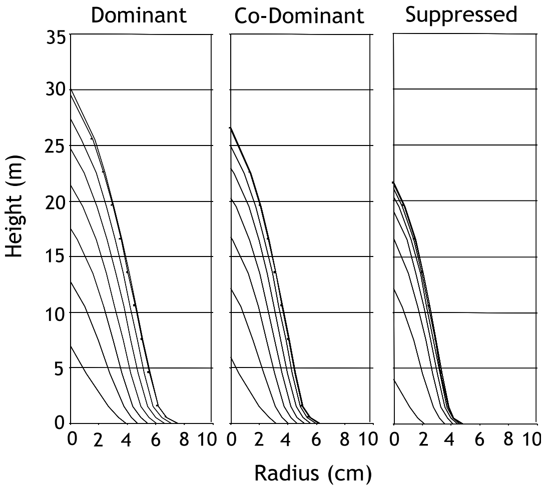


Figure 3. Simulation of ring increments on dominant, co-dominant and suppressed trees



2002b). Furthermore, different allometric relationships estimated the nutrient contents within the branches, roots, leaves and bark (Laclau *et al.* 2000).

The Growth Module

Both stand growth and individual tree growth are modelled. Competition between trees is accounted for through the social position of the tree within the stand and a density index which expresses a competition pressure within the stand, e.g. the number of stems per ha and Stand Density Index (Reineke 1933). The main driver in these models is the dominant height growth model (mean height of the hundred tallest trees in the stand) and 'site fertility' or 'site index', defined as a dominant height at a given age. Our equation is similar to the model developed by Dhôte (1996). However, it incorporates two significant additions: (1) the model was segmented in order to take into account a change in height growth rate during stand rotation, and (2) tree spacing affected the dominant height growth and was introduced as regressor in the equation (Saint-André *et al.* 2002c). Stand basal area increment is a function of the dominant height increment irrespective of stand density. Individual tree basal area is a function of a potential (given by the stand basal area increment) and two reductors (the density index and the social status of the tree). Height of the trees is obtained from a height – girth relationship. Tree mortality, which is, in this case, low due to the short rotation length, is not yet taken into account. Similarly, seasonality of growth (dry and wet seasons) is also not considered but it is under study.

Example of Simulations

The growth module is calibrated for two eucalypt clones, PF1 1-41 and HS2 L2-123, which represent respectively 16% and 6% of the planted area in Congo (first and second rank). The two other modules (wood properties and biogeochemical cycles) are only available for clone PF1 1-41. Two examples of simulation illustrate the capacity of such models for: (1) comparison between biomass estimates and actual values along an age series for the clone PF1 1-41, (2) simulation of stem taper and ring increments for dominant, co-dominant and suppressed trees (clone PF1 1-41).

Biomass estimation

Data were collected from an experiment designed for assessing carbon budget along an age series (Nouvellon *et al.* 2001, Saint-André *et al.* 2002d). Site-dependent parameters of the dominant height growth model were calculated by simulated annealing from the first inventory of stand R9911 (youngest stand of the age series). Using these site parameters and the whole chain of model, biomass of the later inventories (total, aboveground and belowground biomass) were simulated and plotted against the actual values (Fig. 2).

One stand of the age series (H9807) differs from the others, probably because of a lack of maintenance (weed control), and required slightly different site parameters. However, in both cases, simulated values fitted well to the actual values for both belowground and aboveground biomass. Such evaluation will be performed on several other stands covering various situations (fertilities, planting densities etc.) in order to assess the predictive quality of the models.

Stem taper and ring increments

Figure 3 presents the stem profile and the ring increments for a dominant, co-dominant and suppressed tree at age 7 years. This figure shows the capacity of the model (the equation is given by Saint-André *et al.* 2002a) to illustrate differences in stem shape due to stand age and the tree dominance. Further work is required to: (1) improve dominant height growth model, (2) validate each model component and also the integrated model chain, (3) determine confidence interval of estimates, (4) introduce the feed back mechanism such as the effect of nitrogen budget and seasonality on stand growth.

Strength of the Model

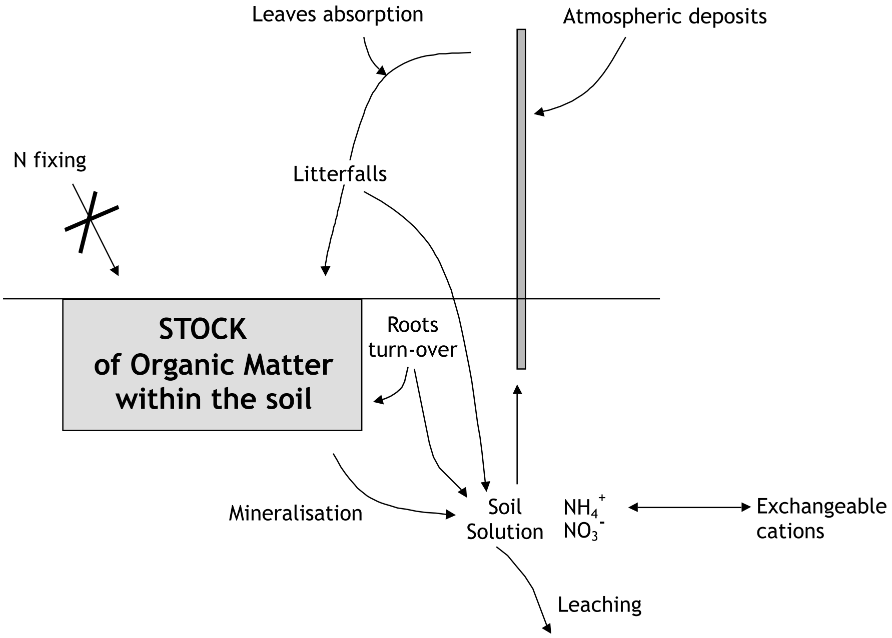
This modelling approach is relatively simple and requires a limited number of parameters and input data (from one stand inventory). Competition between trees and the effects of silvicultural practices are explicitly taken into account in modelling stand and tree growth and the within-trees wood properties (Fig. 1). Although the model must be calibrated for each species or each clone, we have attempted to apply the constraints of generic form (equation remains the same whatever the clone), easy access (parameters should be meaningful for an easier comparison between clones), easy calibration (based upon a limited number of field trials) and easy use (integration within decision tools for the manager).

Weakness of the Model

Our modelling approach does not account for three major issues: (1) long term climate change (CO_2, temperatures), (2) short term climatic effects (seasonality of growth), and (3) feed back of the nutrient input/output on tree and stand growth.

Site index, which reflects nutrient availability and the average climatic conditions of the area, is assessed from an inventory and is fixed for the whole simulation. This assumption is valid for forest ecosystems where site index varies a little within one rotation. However, it has been noticed for both temperate and tropical forests that site index may change between two rotations cycles.

Figure 4. Simplified diagram of the main nutrient fluxes between the soil, the atmosphere and the vegetation



By including the feedback of the nutrient flows on tree and stand growth, we would be able to simulate soil fertility variations and also to integrate the effects of fertilisation practices into the simulation (see 'Incorporating Nutrient Cycling into Growth and Yield Models' below).

In Congo, because rotation period is short (7 years), there is another drawback of the site index estimation from a given inventory. When performing this inventory in the first (or second) growing years, the site index estimation is more sensitive to climatic variations, insect attacks and weed competition. For example, unfavourable climatic conditions may not be balanced by enhanced growth conditions in following years. There are three main solutions for solving such problems: (1) incorporate climatic indices within the growth and yield model (e.g. Snowdon *et al.* 1999, Snowdon 2001), (2) use process-based models (Mummery and Battaglia 2001) or a hybrid between process-based models and growth and yield models (Battaglia *et al.* 1999), or (3) estimate site index from physical, topographical, and plant diversity characteristics of the stand (Louw and Scholes 2002, Ryan *et al.* 2002).

Incorporating Nutrient Cycling into Growth and Yield Models

Scope of Possible Connections

Figure 4 illustrates the main nutrient fluxes between the soil, atmosphere and vegetation. Three types of coupling (empirical, mechanistic, and hybrid of the two) between growth models and nutrient cycling could be drawn.

The empirical approach evaluates the amount and composition of inputs (in litter and fertilisers), their transformation (decomposition and mineralisation) and consequences for tree and stand growth. For these models, the assessment is made at the stand level, the soil is a 'black box', and the measuring time step is about 6 months. Silvicultural trials (such as fertiliser or slash management trials) could be used for calibration. All nutrients (nitrogen but also exchangeable cations) may be considered.

In the process-based approach, the soil is separated into several layers and all related processes are studied: organic matter mineralisation, nutrient losses by leaching, tree nutrient uptake, soil solution composition in relation with CEC. Water fluxes are also taken into account. This approach is particularly adapted for the exchangeable cations (K, Ca, Mg, etc.). Assessment is made at the stand level and the measuring time step is from about one hour to several days. These models require extensive input data which can be collected from well-instrumented experimental sites

Finally, the mixed (hybrid) approach considers only the soil organic matter (no assessment of CEC process). This approach is well suited for the nitrogen. Compared to the empirical approach, the turnover of organic matter in the soil is more mechanistic and the objective is to quantify the fluxes of nitrogen that is available. Assessment is made at the stand level and the time step is from several days to 6 months. This approach also requires well-instrumented sites but may potentially be incorporated into both process-based models and growth and yield models.

Proposed Methodology

We focused on the empirical approach to integrate the growth and yield model with nutrient cycling. Only litter fall and the fertiliser inputs were considered, with the soil regarded as a black box. We quantified: (1) amount and the composition of the inputs, (2) litter decomposition rate, and (3) effect of these inputs on the stand and tree growth models.

There are five main considerations to this approach:

Access to field trials and data

One or more stands with normal practices (to establish primary set of equations), one or more stands with various stand densities (to establish primary set of equations), one or more field trials of slash management, and one or more fertiliser trials (including site variations and time of application).

Litter fall, amount and composition

Amount of litterfall for aboveground compartments can be assessed from litter traps. For the belowground parts (and especially fine roots), litter accessions are more difficult to determine. One solution is to determine a root/shoot ratio (the approach chosen in CenW and Triplex).

Composition of litterfall: subsamples of each compartment (leaves, dead branches, dead roots) are taken for chemical analysis (N, C and lignin contents).

Litter decomposition

Three different methods may be used: confined litter bags, *in situ* nets or litter sandwiches (Binkley 2002). Special attention has to be paid to: (1) the beginning of the experiment (avoiding the dry season), (2) the time span of the experiment to describe as far as possible the entire decomposition curve, (3) the influence of the litter composition on the decay (e.g. Berg and Staaf 1980, 1981, Hyvönen and Agren 2001), and (4) the pattern of litter decomposition which is the sum of two processes: the real decay of the litter (exponential decrease) and nutrient input coming from the microbial activity in the soil (Zeller *et al.* 2000). Dissociating the two processes requires labelled N and may be difficult to perform. However, through some assumptions and using published results (e.g. Zeller *et al.* 2000), it may be possible to fit the two parts of the equation. The result of the litter decay is divided into two fluxes: the first one (mineral N) feeds directly into the soil solution whereas the second (organic N) adds to the pool of organic matter within the soil. However, it will be difficult to measure these two fluxes and we only consider the total amount of N resulting from the decomposition.

Fertiliser inputs

These inputs are known to affect two fluxes: the first feeds directly into the soil solution whereas the second interacts with the microbial community within the soil (Mariotti 1998, Fisk and Fahey 2001, Chen *et al.* 2002). Because dissociating these two fluxes may be difficult, we will only consider the effect of fertiliser on the tree and stand growth.

Impacts on tree and stand growth

All these nutrient inputs have some consequences for tree and stand growth. The objective of this part is to quantify how the models, calibrated for normal silvicultural practice, are modified by these inputs. Response curves have to be established according to the amount and the composition of these inputs and the time of application. Snowdon and Waring (1981, 1984 in Snowdon 2002) identified two basic patterns of growth responses: Type 1 responses are characterised by a temporary increase in growth rate whereas Type 2 are characterised by a sustained change in stand productivity (improved site quality).

The models studied will be: (1) dominant height growth model and the stand basal area growth (stand growth), (2) individual tree basal area increment and the relationship height/girth (tree growth), (3) stem taper, biomass equations and nutrient content allometric relationships (matter allocation and nutrient content within the trees), and (4) litterfall (amount and composition).

Three methods could be investigated: the first one fits these models for each of the considered nutrient inputs and tests the parameter variations with the amount, the type, the composition and the date of application of the fertiliser or the litter addition. The second method, proposed by Pienaar and Rheney (1995), incorporates an additive submodel component to the initial model to take the treatments effects into account. The third method, proposed by Snowdon (2002), models growth responses as a change in the stage of stand development combined (or not) with a change in site quality.

These five approaches will be used to incorporate aspects of nutrient cycling into EUCALYPT-Dendro. Field trials are available in Congo. The set of primary equations is yet to be constructed (see EUCALYPT-dendro's equations). A majority of suggested measurements have already been made but additional studies are needed (e.g. biomass and nutrient content within the trees for the fertiliser trials, accurate estimation of the fine roots turn-over, carbon and lignin content within litterfall etc.).

Model Development in the CIFOR Network

The CIFOR Network covers a wide range of ecosystems (e.g. *Eucalyptus* plantations in Australia, Brazil, China, Congo, India, South Africa; *Acacia* plantations in Indonesia and Vietnam; and *Pinus* plantations in Australia). It offers the opportunity to: (1) test the growth and yield model (or a part of it), (2) define the pattern of litter decomposition, and (3) study effects of mineral inputs on the allometric relationship. These experiments are now 5-6 years old and some analyses could be performed on the existing data.

A short review of the literature shows that the effect of silviculture on the biomass equations is not very clear. Fownes and Harrington (1992) reported woody biomass and leaf area allometric equations did not differ over a wide range of stand densities (from 2500 to 10 000 stems ha^{-1}) for two tropical species (*Acacia auriculiformis* and *Leucaena diversifolia*). Harrington and Fownes (1993) compared the allometry of planted *vs* coppice stands of four tropical species *(Acacia auriculiformis, Eucalyptus camaldulensis, Gliricidia sepium and Leucaena diversifolia*, for several stand ages ranging from 6 to 24 months of age). The stem biomass relationship with the stem basal diameter did not differ between planted and coppiced stands for the four species. With the exception of *Gliricidia sepium*, the same result was found for the leaf area index. In contrast, it was also reported in the literature that leaf biomass allometry varied with site (Adams and Lockaby 1988, Canadell *et al.* 1988) or nutrient status (Cromer and Williams 1982, Snowdon 1985). Existing data from the CIFOR network provides the opportunity to clarify some of the inconsistencies and to better understand factors affecting variations of biomass allometries.

Table 1 shows the type of data and parameters required to perform such studies, and the related models to be tested. The section below illustrates what could be done on the height growth model.

Table 1. Type of data and parameters required within the CIFOR network

Data to by used	Model to be tested
Dominant height every year	Dominant height = f(age, site index)
Stand basal area every year	Basal area increment = f(dominant height increment)
Tree basal area every year	Tree basal area increment = f(tree basal area)
Tree height and girth every year	Tree height = f(tree girth)
Aboveground biomass at 1, 3 years, end of rotation	Biomass = f(D^2H, age, …)
Aboveground nutrient content at 1, 3 years, end of rotation	Nutrient content = f(D^2H, age, …)
Litterfall every year	Biomass = f(time, litter type, ….)
Litter decomposition every year	Weight loss = f(time, litter type, ….)

Table 2. Evolution of mean height with stand age. CIFOR's slash management trial in *Eucalyptus grandis* stands in São Paulo State, Brazil. BL_0 = all residues removed, BL_2 = only understorey and litter retained, SLB = all residues burnt (from Gonçalves *et al.* these proceedings)

	H_m (Mean height)		
Age (yr)	BL_0	SLB	BL_2
0.5	2.3	3.4	2.5
1.3	4.6	7.5	5.5
2.4	9.2	13.6	11.2
3.3	13.3	17.9	15.2
4.2	15.8	20.0	17.5
5.3	18.0	22.0	19.5
6.4	19.6	23.3	21.0

An Example of Application

This network has shown site management has consequences for tree and stand growth. These analyses were performed annually through ANOVA or Generalised Linear Models (GLM). A strong limitation of these analyses is that all the dynamic aspects of the tree and stand growth are not included. The objective of this example is to consider the whole trend (and not only a single year). Data used are detailed in Gonçalves *et al.* (these proceedings). We selected three contrasting treatments among the six presented in their study to illustrate what could be achieved (Table 2).

We analysed the effect of slash management on the height growth curve. A Richard's equation (Richard 1959) was fitted for each treatment (Eq. 1 and Fig. 5). Three main parameters were to be estimated: the asymptote (parameter a), the speed to reach this asymptote (parameter b), and the curve shape (parameter c). The objective was to test the effect of slash management on the curve parameters rather than on the height itself.

$$h_m = a(1-e^{-b\cdot age})^c \qquad \text{(Eq.1)}$$

Table 3a gives the values of each parameter (first fit). The sum of square error (SCE) and the root mean square error (RMSE) give an indication on the error's spread. The highest is the RMSE compared to the mean height values, the lowest is the model. In this case, results are consistent : RMSE ranges from 0.5 to 0.6 m which represent respectively 3% and 5% of the average height.

Parameter variation was given by the ratio (maximum-minimum)/average. Parameter *b* varied most (25%). Therefore, the model was fitted again with parameters *a* and *c* common to all treatments and parameter *b* varying across treatments (Table 3b). A standard statistical test

Figure 5. Meaning of the parameters in the Richard's equation. Points are the measured height for the all-residues-burnt treatment (SBL) (Gonçalves *et al.* 2004). The curve is the fitted model

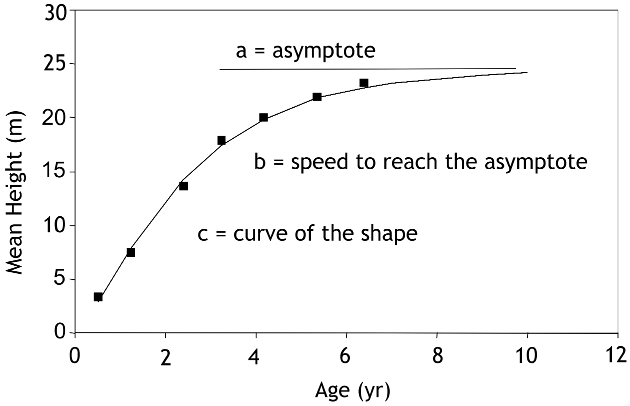


Table 3. Alternative model fits: (a) parameters *a*, *b* and *c* fitted to all treatments, (b) parameters *a* and *c* are common to all treatments; parameter *b* dependent on individual treatments

	(a)				(b)		
	BL_0	SLB	BL_2	Variation	BL_0 T2	SLB T2	BL_2T2
a	24.07	25.72	23.83	8%	24.49	24.49	24.49
b	0.32	0.41	0.39	25%	0.3	0.47	0.36
c	1.44	1.31	1.47	11%	1.38	1.38	1.38
SCE	1.38	0.96	1.03		1.39	1.46	1.08
RMSE	0.59	0.49	0.51		0.69	0.7	0.65

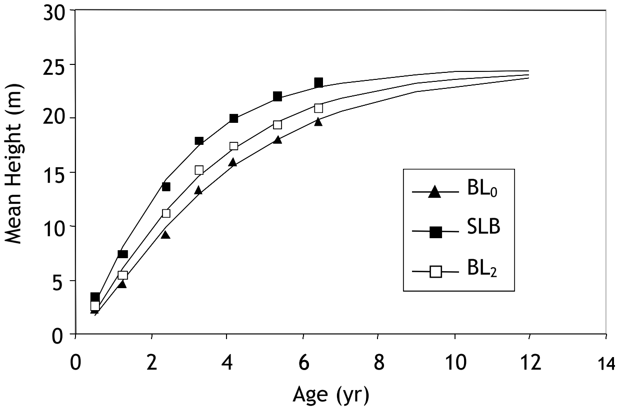
F (Brown and Rothery 1994) was used to compare the two fits. This test is based upon the sum of square of errors and the total number of parameters involved in the models. In the first fit, with 9 parameters (3 parameters x 3 treatments) the total sum of square was 3.36 m^2. In the second case, with 5 parameters (1 parameter x 3 treatments + two common parameters) the sum of square error was 3.93 m^2. The difference between these sum of squares was not significant (Fobs = 0.51 << Ftab = 3.26) indicating that parameters *a* and *c* can be common to all treatments.

These results indicate slash management has no effect on the asymptote and the curve shape, the only difference lies in the speed to reach this common asymptote. An illustration of this result is shown in Fig. 6 where the three curves have the same asymptote but the time required to reach it is different from one treatment to another. This result is common in many other cases where nutrition is the variable. The growth response is clearly of type 1 (Snowdon 2002), indicating that the slash management regime can reduce the time required for the stand to reach a given stage of maturity. For practical purposes we used the mean height, but it would have been better to work on the dominant height which better reflects the site index or site fertility. If this result is confirmed, we could conclude that the tree response to slash management is similar to that found in fertiliser trials. It would be illuminating to do the same study on other ecosystems of the CIFOR network where both growth rates and nutrient supply are different.

Conclusion

This paper has presented a method to integrate nutrient cycling into growth and yield models. It is based upon silvicultural field trials with complementary experiments on litter composition and decay. The CIFOR's network offers an excellent opportunity for testing this approach. A first step

Figure 6. Results of the second fit: parameters *a* and *c* are common to all treatments whereas parameter b varies with treatments. The asymptote is reached at about 9 years, 12 years and 14 years for treatments SLB, BL_2 and BL_0 respectively



could consist in analysing the current experiments on slash management and identifying parameter variations of several allometric relationships among the tested treatments. The example in this study showed promising results. Further work would contribute to better understand factors affecting variations of tree and stand growth. A major outcome would be a support decision system providing information on: (1) tree and stand growth, (2) silvicultural practices (thinning and fertilisation regimes), and (3) nutrient cycling. This information could be used by managers to assess volumes, biomass and wood quality of trees, and also for nutrient management decisions.

Acknowledgements

The authors wish to thank reviewers M. Battaglia, E.K.S. Nambiar, and A.M. O'Connell, for their comments and suggestions that improved this paper. We also acknowledge CIFOR and the UR2PI (Congo) for their financial and technical support.

References

Adams, J.C. and Lockaby, B.G. 1988. Variability of understorey sweetgum biomass relationships. Southern Journal of Applied Forestry 12:5-7.

Auclair, D., Barczi, J-F., Borne, F. and Etienne, M. 2001. Visualisation software as a forest management decision support system. *In:* Criteria and indicators for sustainable forest management at the forest management unit level, IUFRO Task Force on Sustainable Forest Management, 22-25 March 2000, Nancy, France, 207-214. European Forest Institute-Proceedings No.38.

Berg, B. and Staaf, H. 1980. Decomposition rate and chemical changes of Scots pine needle litter. II. Influence of chemical composition. *In:* Perssor, T. (ed.) Structure and function of northern coniferous forests – an ecosystem study. Ecological Bulletin (Stockholm) 32:373-390.

Berg, B. and Staaf, H. 1981. Leaching, accumulation and release of nitrogen in decomposing forest litter. *In:* Clark, F.E. and Rosswall, T. (eds.) Terrestrial nitrogen cycles. Ecological Bulletin (Stockholm) 33:163-178.

Battaglia, M., Sands, P.J. and Candy, S.G. 1999. Hybrid growth model to predict height and volume growth in young *Eucalyptus globulus* plantations. Forest Ecology and Management 120:193-201.

Binkley, D. 2002. Ten-year decomposition in a loblolly pine forest. Canadian Journal of Forest Research 32:2231-2235.

Bossel, H. 1996. TreeDyn3 forest simulation model. Ecological Modelling 90:187-227.

Brown, D. and Rothery, P. 1994. Models in biology: mathematics, statistics and computing. Wiley, Chichester, England. 688p.

Canadell, J., Riba, M. and Andres, P. 1988. Biomass equation for *Quercus ilex* L. in the

Mont-seny Massif, north-eastern Spain. Forestry 61:137-148.

Cavero, J., Plant, R.E., Shennan, C., Friedman, D.B., Williams, J.R., Kiniry, J.R. and Benson, V.W. 1999. Modeling nitrogen cycling in tomato-safflower and tomato-wheat rotations. Agricultural Systems 60(2):123-135.

Chen, C.R., Xu, Z.H. and Hughes, J.M. 2002. Effects of nitrogen fertilization on soil nitrogen pools and microbial properties in a hoop pine (*Araucaria cunninghamii*) plantation in southeast Queensland, Australia. Biology and Fertility of Soils 36:276-283.

Corbeels, M., McMurtrie, R.E. and O'Connell, A.M. 2001. Modelling the effects of harvest residue management on soil nitrogen supply in short rotation eucalyptus plantations in southwestern Australia. *In:* Carnus, J.-M., Dewar, R., Loustau, D., Tomé, M. and Orazio, C. (eds.) Models for the sustainable management of temperate plantations forests, 71-80. European Forest Institute Proceedings No 41.

Crohn, D.M.and Haith, D.A. 1994. A forest site nitrogen dynamics model for land application of sludge. Transactions of the American Society of Agricultural Engineers 37:1135-1144.

Cromer, R.N. and Williams, E.R. 1982. Biomass and nutrient accumulation in a planted *E. globulus* (Labill.) fertilizer trial. Australian Journal of Botany 30:265-278.

Dewar, R.C. and McMurtrie, R.E. 1996. Sustainable stem wood yield in relation to the nitrogen balance of forest plantations: a model analysis. Tree Physiology 16:173-182.

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. PhD Thesis, Université Claude Bernard – Lyon 1 – No. 131-90. 256p.

Dhôte, J-F. 1996. A model of even-aged beech stands productivity with process-based interpretations. Annales des Sciences Forestières 53:1-20.

Dhôte, J-F. and Hervé, J-C. 2000. Productivity changes in four sessile oak forests since 1930: a stand-level approach. Annals of Forest Science 57:651-680.

Dreyfus, P. 1993. Modelling Austrian black pine response to silvicultural practices in the south east of France. *In:* Modelling stand response to silvicultural practices. Proceedings of IUFRO S4.01 Conference, 5-18. September 27-October 1 1993, Blacksburg, Virginia, USA.

Fisk, M.C. and Fahey, T.J. 2001. Microbial biomass and nitrogen cycling responses to fertilization and litter removal in young northern hardwood forests. Biogeochemistry 53:201-223.

Fourcaud, T., Blaise, F., Barthelemy, D., Houllier, F., de Reffye, Ph.and Nepveu, G. 1996. A physiological approach for tree growth modelling in the software AMAPpara. *In:* Nepveu, G. (ed.) Proceedings of the Second Workshop, 'Connection between silviculture and wood quality through modelling approaches and simulation software', Kruger National Park, South Africa, 26-31 August, 1996, 321-334. INRA, Nancy, France.

Fownes, J.H. and Harrington, R.A. 1992. Allometry of woody biomass and leaf area in five tropical multipurpose trees. Journal of Tropical Forest Science 4:317-330.

Godin, C. 2000. Representing and encoding plant architecture: a review. Annals of Forest Science. 57(5-6):413-438.

García, O. and Ruiz, F. 2003. A growth model for eucalypt in Galicia, Spain. Forest Ecology and Management 173:49-62.

Harrington, R.A. and Fownes, J.H. 1993. Allometry and growth of planted versus coppice stands of four fast-growing tropical species. Forest Ecology and Management 56:315-327.

Homann, P.S., McKane, R.B. and Sollins, P. 2000. Belowground processes in forest-ecosystem biogeochemical simulation models. Forest Ecology and Management 138:3-18.

Hyvönen, R. and Agren, G.I. 2001. Decomposer invasion rate, decomposer growth rate, and substrate chemical quality: how they influence soil organic matter turnover. Canadian Journal of Forest Research 31:1594-1601.

Kirschbaum, M.U.F. 1999. CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. Ecological Modelling 118:17-59.

Kirschbaum, M.U.F. and Paul, K.I. 2002. Modelling C and N dynamics if forest soils with a modified version of the CENTURY model. Soil Biology and Biochemistry 34:341-354.

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. PhD Thesis. 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.

Landsberg, J.J. and Waring, R.H. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95:209-228.

Liu, S., Munson, R., Johson, D., Gherini, S., Summers, K., Hudson, R., Wilkinson, K. and Pitelka, L. 1991. Application of nutrient cycling model (NuCM) to a northern mixed hardwood and a southern coniferous forest. Tree Physiology 9:173-194.

Louw, J.H. and Scholes, M. 2002. Forest site classification and evaluation: a South African perspective. Forest Ecology and Management 171:153-168.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Agren, G.I., Oliver, C.D. and Puttonen, P. 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiology 20:289-298.

Mariotti, A. 1998. Nitrate: un polluant de longue durée. Pour La Science No.249:60-65.

Mayer, K.U., Frind, E.O. and Blowes, D.W. 2002. Multicomponent reactive transport modelling in variably saturated porous media using a generalized formulation for kinetically controlled reactions. Water Resources Research 38:1174-1195.

McMurtrie, R.E. 1991. Relationship of forest productivity to nutrient and carbon supply - a modeling analysis. Tree Physiology 9:87-99.

McMurtrie, R.E., Halliday, J.C., Dewar, R.C., Tate, K.R., Corbeels, M. and Scott, N.A. 2001. Modelling long-term changes in forest productivity and soil nitrogen supply following conversion of pasture to *Pinus radiata* plantation. *In:* Carnus, J.-M., Dewar, R., Loustau, D., Tomé, M. and Orazio, C. (eds.) Models for the sustainable management of temperate plantations forests, 59-70. European Forest Institute Proceedings No. 41.

McMurtrie, R.E., Rook, D.A. and Kelliher, F.M. 1990. Modelling the yield of *Pinus radiata* on a site limited by water and nitrogen. Forest Ecology and Management 30:415-423.

Medlyn, B.E., McMurtrie, R.E., Dewar, R.C. and Jeffreys, M.P. 2000. Soil processes dominate the long-term response of forest net primary productivity to increased temperature and atmospheric CO_2 concentration. Canadian Journal of Forest Research 30:873-888.

Meredieu, C. 1998. Croissance et branchaison du pin laricio (*Pinus nigra* Arnold ssp. *laricio* (Poiret) Maire): élaboration et évaluation d'un système de modèles pour la prévision des caractéristiques des arbres et du bois. PhD Thesis. Université Claude Bernard – Lyon 1 – No. 242-98. 250p.

Mummery, D. and Battaglia, M. 2001. Applying ProMod spatially across Tasmania with sensitivity analysis to screen for prospective *Eucalyptus globulus* plantation sites. Forest Ecology and Management 140:51-63.

Nouvellon, Y. *et al.* 2001. Séquestration du carbone par des plantations d'*Eucalyptus* au Congo. Rapport intermédiaire du projet ATP-Carbone, Novembre 2001. Cirad Internal Report. 16p.

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

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Division S-3-Soil microbiology and biochemistry. Soil Science Society of America Journal 51:1173-1179.

Paul, K.I., Polglase, P.J., O'Connell, A.M., Carlyle, J.C., Smethurst, P.J. and Khanna, P.K. 2002. Soil Nitrogen Availability Predictor (SNAP): a simple model for predicting mineralisation of nitrogen in forest soils. Australian Journal of Soil Research 40:1011-1026.

Peng, C., Liu, J., Dang, Q., Apps, M.J. and Jiang, H. 2002. Triplex: a generic hybrid model for predicting forest growth and carbon nitrogen dynamics. Ecological Modelling 153:109-130.

Pienaar, L.V. and Rheney, J.W. 1995. Modeling stand level growth and yield response to silvicultural treatments. Forest Science 41:629-638.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research 46:627-638.

Richard, F.J. 1959. A flexible growth function for empirical use. Journal of Experimental Botany 10:29, 290-300.

Ryan, P.J., Harper, R.J., Laffan, M., Booth, T.H. and McKenzie, N.J. 2002. Site assessment for farm forestry in Australia and its relationship to scale, productivity and sustainability. Forest Ecology and Management 171:133-152.

Saint-André, L., Laclau, J-P., Bouillet, J.-P., Deleporte, P., Miabala, A., Ognouabi, N., Baillères, H. and Nouvellon, Y. 2002a. Integrative modelling approach to assess the sustainability of the *Eucalyptus* plantations in Congo. Paper to Fourth Workshop, Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software, IUFRO Working Party S5.01.04, Harrison Hot Springs Resort, British Columbia, Canada, 8-15 September, 2002. 10p.

Saint-André, L., Laclau, J.-P., Deleporte, Ph., Ranger, J., Gouma, R., Saya, A. and Joffre, R. 2002b. A generic model for the dynamics of nutrients concentration within the stem wood over the whole stand rotation. Annals of Botany 90:65-76.

Saint-André, L., Mabiala, A., N'Thongo, A., Mouvondy, W., Nouvellon, Y., Jourdan, C., Roupsard, O., Deleporte, P., Bouillet, J.-P. and Marien, J.-N. 2002d. Evolution de la biomasse sur une chronoséquence d'*Eucalyptus*. Rapport Final – ATPCarbone. Cirad Internal Report.

Saint-André, L., Mabiala, A., N'Thongo, A., Nouvellon, Y., Jourdan, C., Roupsard, O., Deleporte, Ph. and Hamel, O. (Submitted). A complete set of weighted equations for belowground and aboveground biomass of a natural *Eucalyptus* hybrid in Congo. Submitted to Annals of Botany (December 2003).

Saint-André, L., Safou-Matondo, R., Bouillet, J.-P. and Deleporte, Ph. 2002c. A tree-spacing driven dominant height growth model in the *Eucalyptus* plantations in Congo. Paper to International Conference on Eucalypt Productivity: a Synthesis of the Physiological, Environmental, Genetic and Silvicultural Determinants of Growth, Hobart, Tasmania. 10-15 November 2002.

Snowdon, P. 1985. Effects of fertilizer and family on the homogeneity of biomass regressions for young *Pinus radiata*. Australian Forest Research 15:135-140.

Snowdon, P. 2001. Short-term predictions of growth of *Pinus radiata* with models incorporating indices of annual climatic variation. Forest Ecology and Management 152:1-11.

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., Jovanovic, T. and Booth, T.H. 1999. Incorporation of indices of annual climatic variations into growth models for *Pinus radiata*. Forest Ecology and Management 117:187-197.

Spiecker, H. 1999. Growth trends in European forests – do we have sufficient knowledge?, *In*: Karjalainen T., Spiecker H. and Laroussinie, O. (eds.) Causes and consequences of accelerating tree growth in Europe, 157-170. European Forest Institute-Proceedings No. 27.

Tiktak, A. and van Grinsven, H.J.M. 1995. Review of sixteen forest-soil-atmosphere models. Ecological Modelling 83:35-53.

Tomé, M., Borges, J.G. and Falcão, A.O. 2001. The use of management-oriented growth and yield models to assess and model forest wood sustainability. A case study for *Eucalyptus* plantations in Portugal. *In:* Carnus, J.-M., Dewar, R., Loustau, D., Tomé, M. and Orazio, C. (eds.) Models for the sustainable management of temperate plantations forests, 81-94. European Forest Institute Proceedings No. 41.

Zeller, B., Colin-Belgrand, M., Dambrine, E., Martin, F. and Bottner, P. 2000. Decomposition of 15N-labelled beech litter and fate of nitrogen derived from litter in a beech forest. Oecologia 123:550-559.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Summary of Progress

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Introduction

Plantations in the tropics and subtropics with fast-growing species are intensively managed over short rotation cycles with the expectation of high yield. While their potential growth rates are high they also increase demand on soil resources. The greatest impact from management inputs occurs during operations associated with harvesting, site preparation, planting and silviculture. This CIFOR partnership project was initiated to address some of those issues.

The original governing concept of the project is that inter-rotation management phase of plantation is a period of great risks (damage and depletion of resources) but also a period of great opportunity (to conserve and enhance nutrient supply, use the best genotypes, and apply best silviculture management). The project therefore focuses on the critical inter-rotational phase of management: harvesting, site preparation, and early stand development. A core principle in planning this project is that the study at each location is a self-contained experiment which will produce scientifically valid results on its own merit and make significant contributions to improved management locally in addition to contributing to the overall outcomes from the network.

The research has three main objectives:

- evaluate the impact of soil and site management practices on the productivity of successive rotations of plantations,
- develop management options for maintaining or increasing productivity, and
- where it is appropriate strengthen local institutional capacity to respond to new problems and opportunities (Tiarks *et al.* 1998).

Each site includes: (1) a common set of core treatments, and (2) optional treatments tailored to the special interest and experience of local researchers and managers. The core treatments are based on several levels of harvest residue removal, which create a range of impacts on organic matter levels and nutrient supply. Optional treatments are based on local management needs, and soil and stand considerations.

In this summary, we present an overview of the general trend in results and key outcomes achieved so far, based on the contributions which have been presented in detail in the papers in these and earlier proceedings. A detailed interpretation of results across sites is premature at this stage partly because of the varying degrees of milestones and progress achieved by individual

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partners. To the extent possible, these are presented in individual papers in the proceedings. It will be some years before firm interpretations based on the data across the sites and general conclusions can be drawn.

Location and Environment of Sites

At present, the network includes 16 sites in 8 countries (Table 1). Most of the sites in the tropics are located in a broad band around the equator. Others are in the subtropics apart from those in Western Australia that are in a Mediterranean environment. Accordingly there is a large range in temperatures, and mean annual rainfall ranges from 825 to 3000 mm year^{-1}. Rainfall data are based on long-term averages of regional data. All sites were selected based on their representativeness of the region and a major soil type.

Eucalyptus and *Acacia* species were planted with planned rotation lengths of 10 years or less. Chinese fir (*Cunninghamia lanceolata*) at the Fujian and, the pine hybrid site in Queensland are managed on a crop cycle of about 30 years. Some sites are nearing completion of the first experimental rotation, others, such as the Vietnam site that was established in 2002, are in the early stages of the first experimental rotation. This is because partners established sites as their resources permitted and because of the varying rotation lengths (Table 1).

Biomass and Nutrient Contents of Original Stand

In a network, good measures of the biomass and nutrients in the original stand and initial soil properties including fertility levels are necessary to:

- compare results among the different sites,
- measure effects of plantation management on soil properties, especially possible nutrient depletion, and
- predict response to management options including residue retention and fertilisation.

The amount of aboveground biomass of the stands harvested for the study installations varied considerably by site (Table 2). The biomass in understorey shrubs and litter is included for five sites where the investigators have indicated that the understorey and associated nutrients is usually subject to removal during harvest. The aboveground biomass on the best site at Manjimup in southwestern Australia was 275 t ha^{-1} or about 6 times the biomass on the site in Guangdong, China. As expected, the two sites with rotation lengths of nearly 30 years had higher total biomass, but the rates of production were about 8 t ha^{-1} yr^{-1} which is comparable to the annual production on the poorest sites with rotation lengths less than 10 years. The amount of N in the aboveground biomass was relatively high in the four *Acacia* sp. sites, as these species can fix N. The amount of P in the biomass varied from 8 to 62 kg ha^{-1} with the lowest amounts found on sites with the lowest biomass production. Correlation coefficients between biomass and amount of nutrients in the biomass are 0.59 for N, 0.28 for P and 0.28 for K. Given the diverse environments of sites in the study, definitive interpretations are not yet possible. However, the relatively good relationship between biomass and N indicates that the potential importance of N supply on productivity of sites carrying non-N-fixing species (eucalypts and pines). In some sites which had a long history of N-fixing pasture before conversion to eucalypts (e.g. some sites in Western Australia) there may be adequate soil nutrient reserves to support plantations for one rotation. The wide dispersion for P and K in the biomass across sites probably results from the use of these nutrients in fertilisers on some sites. Correlations between biomass and Ca, and Mg are 0.46 and 0.54 respectively. These values suggest that removal of wood and residue from the site would lead to significant depletion of these cations in some sites and over several crop cycles may limit productivity. Partners need to continue monitoring the status of cations in the soil. Sites in Indonesia and Vietnam have already included Ca fertilisation as optional treatments and other sites with low values of soil cations need to consider this approach.

Table 1. Location and rainfall of sites with species planted and year of establishment

Country-site	Species	Location	Rainfall[a] (mm yr^{-1})	Rotation (yr)	Year of planting
Congo					
Pointe-Noire	*Eucalyptus* hybrid	4°48’S, 11°54’E	1200	8	1998
South Africa					
Natal	*E. grandis*	29°24’S, 30°12’E	950	7	1999
P.R. China					
Guangdong	*E. urophylla*	21°43’N, 111°35’E	2178	6	1997
India					
Kayampoovam	*E. tereticornis*	10°41’N, 76°23’E	2700	7	1998
Punalla	*E. tereticornis*	9°06’N, 76°54’E	2000	7	1998
Surianelli	*E. grandis*	10°02’N, 77°10’E	3000	7	1998
Vattavada	*E. grandis*	10°08’N, 77°15’E	1800	7	1998
Australia					
Western Australia					
Manjimup	*E. globulus*	34°20’S, 116°00’E	1023	10	1995
Busselton	*E. globulus*	33°45’S, 115°07’E	825	10	1995
Brazil					
Itatinga	*E. grandis*	23°00’S, 48°52’W	1580	7	1995
Indonesia					
Toman	*Acacia mangium*	4°05’S, 103°45’E	2610	9	2000
Sodong	*A. mangium*	4°05’S, 103°45’E	2610	10	2000
Riau	*A. mangium*	0°20’S, 101°48’E	2700	6	2001
Vietnam					
Binh Duong	*A. auriculiformis*	11°18’N, 106°52’E	2686	7	2002
Australia					
Queensland	*Pinus elliottii x P. caribaea*	26°00’S, 152°49’E	1354	30	1996
P.R. China					
Fujian	*Cunninghamia lanceolata*	26°45’N, 118°10’E	1817	29	1997

[a] Mean annual rainfall figures are generally from the nearest representative meteorological station and may differ from actual rainfall at the site.

Response to Harvest Residue Treatments

On eight of the 15 sites where data are available, growth on at least one of the residue retention treatments was statistically greater than removing all aboveground biomass (Table 3). The increase in stand volume ranged from 16% in Guangdong, China to more than 90% in Congo confirming the strong effects of organic matter on production on some sites. In general, tree growth increased as more residue was retained, but differences between single slash (BL$_2$) and

Table 2. Total aboveground biomass and the amount of nutrients in the biomass which is potentially subject to loss by residue removal

Country/site	Biomass (t ha^{-1})	N	P	K	Ca	Mg	Reference
		(kg ha^{-1})					
Congo							
Pointe-Noire	118[a]	315	48	119	74	48	Bouillet *et al.* (1999)
South Africa							
Natal	135[a]	311	27	220	315	105	du Toit *et al.*(2004)
P.R. China							
Guangdong	44[a]	106	8	48	55	16	Xu *et al.* (1999)
India							
Kayampoovam	82[b]	358	56	334	627	89	Sankaran *et al.*[d]
Punalla	51[b]	247	20	175	349	72	Sankaran *et al.*[d]
Surianelli	67[b]	344	39	205	674	116	Sankaran *et al.*[d]
Vattavada	155[b]	338	38	358	882	102	Sankaran *et al.*[d]
Australia							
Western Australia							
Manjimup	275[a]	521	56	NR(c)	1211	NR	O'Connell and Grove (1999)
Busselton	98[a]	NR	NR	NR	NR	NR	O'Connell *et al.* 2000
Brazil							
Itatinga	140[a]	332	38	183	248	43	Goncalves *et al.* (1999)
Indonesia							
Toman	190[a]	661	14	191	416	42	Hardiyanto *et al.* (2000)
Sodong	241[a]	1020	21	241	619	80	Hardiyanto *et al.*[d]
Riau	151[a]	593	16	347	254	42	Nurwahyudi and Tarigan[d]
Vietnam							
Binh Duong	51[a]	198	7	144	70	12	Vu Dinh Huong *et al.*[d]
Australia							
Queensland	265[a]	292	18	53	267	151	Simpson *et al.* (2000)
P.R. China							
Fujian	233[b]	391	62	501	472	146	Fan *et al.* (2000)

[a] Biomass and nutrients in aboveground tree components only.

[b] Biomass and nutrients in all aboveground components including trees, shrubs, and litter.

[c] Data not reported.

[d] These proceedings.

double slash (BL_3) were often small and not statistically significant. The only negative effect of retaining residue was noted in South Africa, where frost pockets in the double slash treatment reduced survival. At one of the sites in Sumatra the effectiveness of application of herbicide was diminished by the presence of heavy slash. On seven of the 15 sites, the residue treatments did not have a statistically significant effect on tree growth at the latest measurement. These sites probably have higher levels of soil fertility, but interpretations must be made on a site-by-site

Table 3. Tree growth response to residue retention and optional treatments at the early stages of growth

Country-site	Age at measurement (yr)	Percent of rotation length	Response to residue retention	Growth response to optional treatments
Congo				
Pointe-Noire	4	50	Positive	Burning negative, not significant
South Africa				
Natal	3	43	Positive	Burning negative, not significant
P.R. China Guangdong	6	100	Positive	Positive response to fertiliser and coppice
Australia				
Western Australia				
Manjimup	7	87	None	No effect of burning
Busselton	7	87	Positive	Positive effect of burning
Brazil				
Itatinga	5	71	Positive	No effect of burning
India				
Kayampoovam	4	30	None	Positive for weed control
Punalla	4	30	None	Positive for weed control; N&P fertiliser
Surianelli	4	30	None	None
Vattavada	4	30	None	Positive for N fertiliser
Indonesia				
Toman	2	22	None	None
Sodong	1.5	15	Positive	Positive response to P
Riau	1.5	25	Positive	
Vietnam				
Binh Duong	First measurement after planting not completed			
Australia				
Queensland	6	20	Positive	Positive for weed control
P.R. China				
Fujian	6	21	None	Burning negative, not significant

basis. Also, only five sites have completed at least half of the rotation and final interpretations should wait until the stands are nearer harvest age. Meanwhile, in light of the rapid and strong effect of residue retention, and the amount of nutrients held by slash, this practice should be encouraged, especially on sites with low nutrient reserves. Removal of slash for fuel by the local community is a common practice in some regions. While this may be an unavoidable social issue, the results of this project provide a basis for the quantitative assessment of the impact of such practices on site resources.

Responses to Optional Treatments

On sites where slash was burned as a site preparation practice, the treatment increased growth on only one site, Busselton in southwestern

Australia (Table 3). On the other sites, burning had no statistically significant effect on tree growth when compared to plots that had the same level of residue retention, but not burned. Since tree growth has not been affected to date and because of the potential loss of organic matter and nutrients by burning, the results indicate this practice should be discouraged as a site preparation method. We note that by working with managers some partners have already incorporated this knowledge in their local prescriptions.

Weed control increased stand volume on the two low productivity sites in Kerala, India, but was not significant by age 4 years on the two sites with higher productivity. This was attributed to the open canopy of *E. tereticornis* compared to the denser canopy of *E. grandis*. Weed control also increased tree volume in the pine plantation in Queensland by 30%. In plantation forestry, weed control is widely practised as an essential management operation in several of our partner organisations, especially where sites are managed by large companies, but the practice is less well developed in cases where intensive plantation forestry is still in its infancy. Because of the high economic costs of weed control, the changes in the land base in which plantations are being expanded and the potential environmental impacts, more studies are needed to evaluate the timing and intensity of vegetation management necessary for successful plantation establishment and high production. This is an issue being studied at the Vietnam site.

Tree growth responded to applications of fertiliser in southern China, two locations in Indonesia and two of four locations in India. The positive responses to fertiliser, especially N and P, were not necessarily related to the biomass production of the original stand, indicating other factors are limiting productivity on some of the sites. While stand management such as poor weed control and unsuitable genetic selections may have reduced productivity of the harvested stand, soil properties including fertility levels and water holding capacity were probably important causal factors of stand development and their responsiveness to fertiliser application.

In general the results from optional treatments are becoming critical for interpretation of the results and also for guiding key issues of concern for the local management. The original purpose of the optional treatments was to build flexibility for accommodating local experience into the project.

Network Effectiveness

The successful co-operation by partners has resulted in an international network project, pioneering in its approach on sustainable management of plantations in subtropics and tropics. The study has common goals, a common set of core treatments, uniform protocol for treatment application and measurements, and excellent sharing of information. This is rare, considering the wide geographical range, research background of partners and ownership of plantations.

As the project has matured, the original rationale, concept of treatments, network arrangements, and mutual obligations of the partners have been maintained. Key objectives and accomplishments are described in the following sections.

Evaluate the Impact of Soil and Site Management Practices on the Productivity of Successive Rotations of Plantations.

Results so far have validated the original concept that the inter-rotational management phase is a period when site productivity is at risk, but also offers opportunities to sustain productivity of the soil and enhance productivity with appropriate management. Residue treatments have shown the value of retaining logging slash and associated nutrients, especially on sites where fertility is already low. In some locations, such as the Congo, there was a high loss of cations when all residue was removed, but no similar change was noted in tree growth at this stage, suggesting the need for longer term studies for developing reliable management practices.

The network continues to gather data to establish the relationships between residue retention, soil nutrient capital and nutrient uptake rates by trees. Such relationships will help better definition of nutrient supply in relation to productivity objectives and how and at what cost refined management can be applied operationally. As the sites complete rotations and the treatments are repeated over the next rotation, the importance of good management and ways to sustain production will become clearer.

Develop Nutrient Management Options for Maintaining or Increasing Productivity

There are two key aspects directly addressed in this project to assist sound management for commercial wood production. One is to understand and practise techniques which minimise the losses of site resources and the other is to develop a basis for judicious application of nutrients to match nutrient supply levels required for projected growth rates. For both approaches, first we need to identify those nutrients which are most likely to be limiting in a given ecosystem and understand their dynamics.

This project has already provided quantitative information on the amounts of the nutrients in different components and how they may be affected by management practices. One clear example is in the management of bark. Strong evidence is presented to show that debarking at stump followed by redistribution of the bark on the site will contribute substantially to conservation of nutrients especially those which are not easy to replace, such as Ca. Some partners have already advocated this effectively in their organisations. Once site-specific critical limits to production are established, managers can use the site-specific information to develop harvesting techniques to maximise nutrient conservation.

Most partners are developing a database to build robust relationship between growth rates and nutrient uptake rates. These are important for matching supply with production goals. In several cases, fertiliser application is required to avoid loss in production and this will become even more important in subsequent rotations. Plantations in China, India and Indonesia have shown large responses to fertiliser, but local scientists need to use data from the network to refine the recommendations on which sites will respond to specific nutrients and the quantities required.

Strengthen Local Institutional Capacity to Respond to New Problems and Opportunities

In a research network like ours it is likely that the resource base and the skill base of partners will vary between institutions and the value of the partnership is in strengthening each other. During the establishment of each site, local scientists were trained (where necessary) to establish the study with rigorous protocols, including collecting and analysing plant and soil samples to give results that can be used with confidence. The teams have developed the ability to interpret results and produce findings that can be reported to the scientific community. These teams include the principal investigators who author the reports, and also research management and research support including laboratory and field staff. Their organisations can apply methods developed in this study to other locations in response to change in land base, and management goals to identify and correct site-specific critical limits to production.

Establish Close Participation with Local Managers and Foster Appropriate Mechanisms for Technology Transfer

In all cases, the project has been implemented with support of local forest management. The support and facilities required for implementing large experimental work would not have been possible without such participation. Experimental sites have become valuable demonstrations of impacts of management on production. In several cases the overall production in the experiment has been substantially greater than those achieved in the broader plantations immediately adjacent to the experiment. This has increased the awareness of the value of scientifically-based management practices. Careful communication of the ideas and results from the study and follow up economic evaluation of the various management options will pave the way for continuous improvement.

In some locations, results from the network have been used to change plantation management. For example, in Australia (Queensland), Brazil, Congo and China, retention of harvest residues is a recommended policy and burning slash is discouraged. As more interpretations are made, the findings can be used to develop local best management practices and provide a foundation for instituting more formal codes of forestry practices.

Future Plans

While this project has made a number of achievements, we recognise many challenges lay ahead. These are being considered and are commented on the following sections.

Integration of Results across Sites

So far the interpretation of results has been largely focused within sites. Interpretation including all sites has been confined to somewhat broader considerations only. There are two contributing factors: (1) it was important to make local impacts first through application of local results as opposed to developing general principles; (2) the progress of experimental work varied greatly across sites and the available database was insufficient for making sensible comparisons and integrations. This is being addressed to some extent by a new initiative using modelling.

A database of the pre-harvest biomass and nutrient capital, the soils information and post-establishment tree data is being developed. This will enable greater integration of results, access to all partners on a mutually agreed basis, and validation of models simulating the effects of management practices on production. Initially we plan to undertake modelling with selected eucalypts sites and later extend to other sites and genera.

Impacts of Management on Soil Properties

As individual contributions show, we are accumulating important information on the potential impact of various management activities on the soil resource. This information is strong in description of nutrient stock in the ecosystem at the start of the study. It is less so in the dynamics of nutrient in relation to treatments, stand growth and uptake. There are also questions to be addressed during the next phase of the project. A review in progress shows important issues include:

- Use of a sampling strategy to ensure that the measured values reflect the variations in actual soil properties.
- Soil depth sampled should be sufficiently deep to account for rooting depth and to provide an accurate estimation of soil reserves available for tree growth.
- Bulk density should be measured at sufficient points and depths such that spatial variability can be considered in the calculations of nutrient reserves.
- Large numbers of samples need to be taken to detect small changes in a relatively large pool such as soil organic carbon or nitrogen.
- Indices of nutrient availability, such as P, may be below the range where the analysis can detect difference. Other measures of available nutrients may be needed in some situations
- Analytical methods employed must be robust and well calibrated, and as far as possible comparable across sites.
- When partners are dependent on outsourcing analytical work, attention is required to ensure quality control of the data.

Review of soil information and arrangements for ongoing soil measurements as the stands develop to harvesting age are important aspects of future work.

Long-term Research and Application

Because of the rapid expansion of short-rotation plantations, the management system is still new in many areas of the tropics. The network has made a valuable contribution to developing scientifically valid data on the sustainability of the production of the plantations. Two sites are close to harvesting age and their detailed assessment at the end of the rotation will provide valuable leads to future investment by other partners. To fulfil the objectives of the network, the study sites need to be harvested and replanted as the initial rotation is completed. Efforts will be made to maintain the core objectives. Maintenance of the core treatment structure needs to be reviewed recognising the rapid turnover of organic matter and the large effect of residue retention on some sites. Optional treatments need to be tailored to address site-specific problems demonstrated by results from the first study, emerging issues of forest management and knowledge of critical ecosystem constraints.

It is essential to recognise the importance of sustaining this program over long-term and beyond the current rotation of experimental stands to obtain sound information for supporting sustainable management. It is equally important to translate research results into operational prescriptions in close partnership with local managers.

References

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.

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: Sao 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.

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

O'Connell, A.M. and Grove, T.S. 1999. Eucalypt plantations in southwestern 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.

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., Cossalter, C., Tiarks, A. 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.

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. 2000. *In*: Nambiar, E.K.S., Cossalter, C., Tiarks, A. and Ranger, J. (eds.) Site management and productivity in tropical plantation forests: a progress report: workshop proceedings, 7-11 December 1999, Kerala, India, 83-82. Center for International Forestry Research, Bogor, Indonesia.

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.

Xu, D., Yang, Z., Chen, M. and Chen, Q. 1999. Plantations 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.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Dynamics of Nutrient Retranslocation in Stemwood of a *Eucalyptus* Clone in the Congo

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Introduction

Since 1978, 42 000 ha of clonal *Eucalyptus* plantations have been established around Pointe-Noire. The dynamics of the biogeochemical cycles of nutrients after afforestation of native savannas have been studied for a few years to assess the influence of *Eucalyptus* plantations on soil nutrient capitals. The work presented here is a part of this general investigation (Laclau 2001). The objective was to quantify nutrient retranslocations in the stemwood of a *Eucalyptus* clone throughout the whole rotation. Stemwood was studied because it represents the major sink of nutrients for this clone.

Methods

Sampling occurred in 1-, 2-, 3-, 4-, 5-, 6- and 7-year-old planted crops of the same clone (Laclau *et al.* 2001). The continuous nature of growth of *Eucalyptus* hybrids in Congo prevented distinguishing annual rings in stemwood. Therefore the first step was to model the position of 'virtual' annual rings in the stem, namely to rebuild the cambial growth of a tree from stem profiles. Taper functions were used for estimating stem profiles underbark throughout stand development. The stands in the age series had been inventoried (circumference at breast height and height) at the end of the rainy season each year after planting, which made it possible to establish growth curves for the stand. Disks of wood were taken at the level of the ground and every 4 m for four trees selected in each stand. Sampling occurred in April in all the stands to avoid seasonal effects in the comparison of the nutrient distribution between the stands.

The wood of each annual ring was separated in all the disks, dried at 65°C, ground and homogenised. Chemical analyses were performed individually for each ring per level and per tree sampled. The mean nutrient concentration of each growth sheath for each tree sampled was calculated by weighting concentrations with the cross sectional area of the ring at each level sampled in the stem. The nutrient content ha^{-1} at each age was calculated from the mean concentrations of the four trees sampled and

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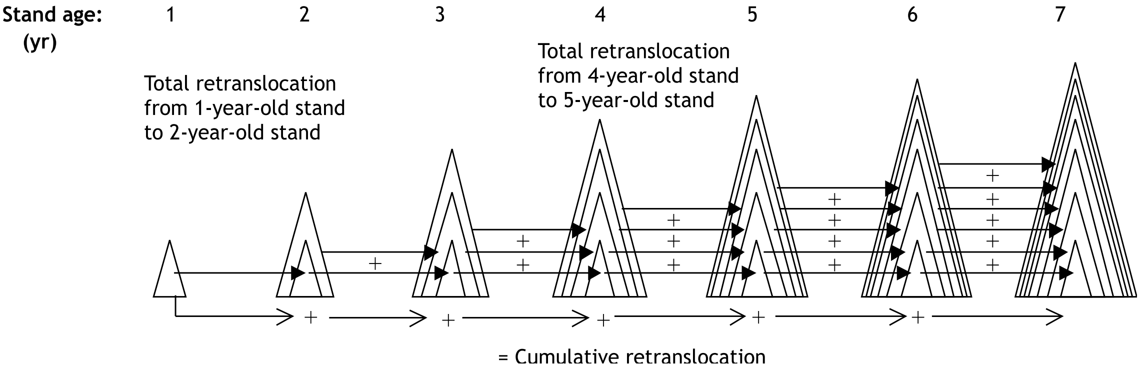
Figure 1. Method for calculating different nutrient retranslocations in stemwood. The + sign indicates that retranslocation in individual rings is added to calculate total and cumulative retranslocations.



tables of biomass. Retranslocations were calculated stepwise between two successive ages in the age series. Thus the summation of retranslocation during the stand life corresponded to the cumulative retranslocation in stemwood. Total retranslocation in stemwood between the successive ages *n* and *n*+1 was calculated by adding the nutrient retranslocations in all the rings initiated before age *n* (Fig. 1). Cumulative retranslocation was inferred by adding total retranslocations in stemwood during the whole rotation.

Results and Discussion

The rates of retranslocation differed markedly among nutrients and among rings (Table 1):

- Whatever the stage of development, over 80% of N retranslocations and 50% of K retranslocations occurred the first year after ring formation. The quantities involved decreased with ageing of the ring. They amounted to 2-12 kg ha^{-1} year^{-1} of K and 1-8 kg ha^{-1} year^{-1} of N. Highest values were observed between ages 3 and 6 years, when the wood production was maximum. Potassium was more mobile than N and was retranslocated fastest and in largest amount relative to the initial content. The rate of retranslocation clearly decreased in the last year of the rotation. Negative values of retranslocation indicated a net accumulation of N in the inner rings between the 6- and 7-year-old stages.
- Although the behaviour of P in stemwood differed according to stand age, an overall retranslocation was observed up to age 6 years. The rate of retranslocation was maximum between the ages 3 and 4 years. Most P retranslocations occurred the first year after ring initiation. A net accumulation of P in all the rings was observed between 6 and 7 years.
- Changes in concentration of Ca and Mg noticed from age 1 to age 2 years in individual rings (Laclau *et al.* 2001) showed clearly that retranslocation occurred, but the nutrient amount involved remained low (about 0.5 kg ha^{-1} Ca and 1.1 kg ha^{-1} Mg). The behaviour of these elements in stemwood was not regular from age 2 years onward. The main trends were: (1) low retranslocation in the external ring up to age 6 years; and (2) a net accumulation in most of the rings between the 6- and 7-year-old stages. However the extent of variation in mineral content of the rings between ages was low.

The cumulative nutrient retranslocations in stemwood from the age 1 year to 6-year-old stage amounted to 18.5 kg ha^{-1} N, 4.2 kg ha^{-1} P, 38.8 kg ha^{-1} K, 1.5 kg ha^{-1} Ca and 3.2 kg ha^{-1} Mg. They represented respectively 11, 18, 121, 6 and 15% of the amounts of N, P, K, Ca and Mg incorporated in stemwood at the 7-year-old stage. Net accumulation in stemwood between 6 and 7 years found for N, P, Ca and Mg led to lower cumulative

Table 1. Nutrient retranslocations from each ring throughout the rotation. The values indicated are the amounts that have moved out from a given ring during the corresponding period

Age: (yr)	1-2	2-3	3-4	4-5	5-6	6-7	Net retranslocation
	Retranslocation (kg ha^{-1} yr^{-1})						
N							
Ring 1	1.3	0.1	0.0	0.3	-0.3	-0.5	0.9
2		2.4	1.7	-1.0	0.4	-2.0	1.5
3			6.4	-0.3	0.6	-4.0	2.7
4				4.3	-0.5	-1.5	2.3
5					3.1	-0.1	3.0
6						1.1	1.1
Total retranslocations	1.3	2.5	8.1	3.3	3.3	-7.0	11.5
P							
Ring 1	0.4	-0.1	0.1	0.0	0.0	0.0	0.4
2		-0.2	1.0	0.3	-0.3	-0.1	0.7
3			2.1	-0.7	0.0	-0.7	0.7
4				0.1	0.2	-1.0	-0.7
5					1.3	-0.9	0.4
6						-0.2	-0.2
Total retranslocations	0.4	-0.3	3.2	-0.3	1.2	-2.9	1.3
K							
Ring 1	2.1	0.9	0.6	0.2	0.2	-0.1	3.9
2		7.0	1.0	2.2	2.2	0.0	12.4
3			2.9	3.4	2.1	1.0	9.4
4				6.8	1.3	0.3	8.4
5					5.9	0.8	6.7
6					2.0	2.0	
Total retranslocations	2.1	7.9	4.5	12.6	11.7	4.0	42.8
Ca							
Ring 1	0.3	-0.1	-0.1	0.2	-0.1	-0.2	0.0
2		-0.1	-1.1	1.2	-0.1	-1.4	-1.5
3			0.0	-0.2	0.1	-1.2	-1.3
4				0.6	0.5	-1.4	-0.3
5					0.5	0.3	0.8
6						-0.3	-0.3
Total retranslocations	0.3	-0.2	-1.2	1.8	0.9	-4.2	-2.6
Mg							
Ring 1	1.1	-0.2	0.1	0.1	0.0	0.1	1.2
2		-0.4	-0.6	0.8	0.2	0.0	0.0
3			0.1	0.5	-0.1	-0.5	0.0
4				1.8	-0.4	-0.8	0.6
5					0.2	-0.7	-0.5
6						0.3	0.3
Total retranslocations	1.1	-0.6	-0.4	3.2	-0.1	-1.6	1.6

Ring i was the ring initiated from age (i-1) years to age i years.

retranslocations during the whole rotation. They amounted to 11.5 kg ha^{-1} N, 1.3 kg ha^{-1} P, 43.8 kg ha^{-1} K, -2.7 kg ha^{-1} Ca and 1.5 kg ha^{-1} Mg. These results demonstrated that K retranslocations from the wood of this clone have an important role in supplying current requirements throughout stand rotation. In contrast, retranslocations from stemwood of other elements were low compared to the amounts incorporated in the trees and most of requirements for wood production throughout the stand development were supplied by the soil.

References

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. PhD thesis. Institut National Agronomique Paris Grignon, France. 146p.

Laclau, J.-P., Bouillet, J.-P., Ranger, J., Joffre, R., Gouma, R. and Saya, A. 2001. Dynamics of nutrient translocation in stemwood across an age series of *Eucalyptus* hybrid. Annals of Botany 88:1079-1092.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Measuring Carbon and Water Fluxes from *Eucalyptus* Stands in the Congo

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Introduction

In recent years, there has been a growing interest in developing methods to estimate carbon fluxes and sequestration from ecosystems. Following the Kyoto Protocol, carbon sequestration from growing forests may be accounted to help countries to meet their CO_2 emissions targets. Studies on the role of forests in the sequestration of carbon have been facilitated by developments in micrometeorological methods such as eddy covariance (EC), that allows continuous and long-term measurements of water and CO_2 fluxes between the forest and the atmosphere (e.g. Aubinet *et al.* 2000, Berbigier *et al.* 2001). These measurements provide valuable information to assess the functional responses of the forests to environmental factors such as water stress, and to develop and validate forest process-based models.

In the Congo, about 42 000 ha of clonal eucalypt plantations have been established on native savannas around Pointe-Noire. A study has been established to measure and model carbon, water and energy exchanges, primary production, stand growth and carbon sequestration from these plantations. The experiment is intended to: (1) estimate carbon stocks (soil and trees) in a clonal chronosequence of eucalypts; and (2) measure water and CO_2 fluxes by an eddy correlation system, meteorological variables, water balance, soil respiration, litter decomposition and tree growth in one stand from the chronosequence, over a two year-period. An overview of this experiment is given in this paper, together with some preliminary results.

Materials and Methods

Experimental Area

The plantations around Pointe-Noire (4°S 12°E; altitude 50-100 m) are based on two natural hybrids (*Eucalyptus* PF1, and *E. tereticornis* x *E. grandis*), and the artificial hybrid *E. urophylla* x *E. grandis*. They have been established on cleared

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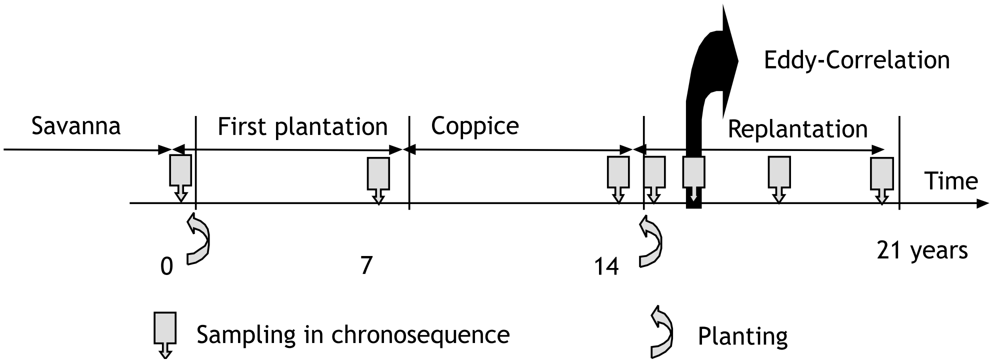
Figure 1. Diagram of the sampling strategy in the chronosequence



native savannas, on sandy, ferralitic, and low fertility soils. The climate is characterised by annual rainfall of about 1200 mm, with a dry season between May and September, mean annual temperature of about 25ºC, and high relative humidity (85% on average), with low seasonal variations (2%). The clone selected for this experiment is the clone *E.* PF1 1-41, the most productive clone of the hybrid *E.* PF1. This clone covers more than 7000 ha in the planted area.

Estimation of Carbon Stocks in a Chronosequence

Carbon sequestration by trees and soils is being estimated in a diachronic chronosequence of 21 years (Fig. 1), that is representative of the silviculture applied in these plantations: a first plantation on native savannas followed by a coppice crop and then a new plantation. A 'replantation' chronosequence approach offers several advantages: (1) the age effect over productivity can be accounted for, and (2) regarding carbon sequestration in the soils, chronosequences can be used for cross-validation between estimates obtained from continuous fluxes measurements and estimates obtained from stocks measurements. On the other hand, chronosequence approach may also present disadvantages such as possible soil variation within the sequence and climate variation during the rotation. Six stands have been selected for carbon storage and soil respiration measurements (Fig. 1): (1) a plantation forest at the end of the first rotation; (2) 7-year-old coppice (end of the second rotation); and (3) 1-, 3-, 4-, and 6-year-old stands in third rotation (replantations).

In each of these stands, aboveground, belowground and litter biomass, and carbon stocks in the soils are estimated annually. Tree growth is monitored every 15 days. Soil respiration is periodically measured with a portable closed-path Licor 6200. Root production, lifespan and turnover are estimated from ingrowth cores and rhizotrons.

Measurements of Water and CO_2 Fluxes in the 3-year-old Stand

The 3-year-old stand of the third rotation has been selected for continuous measurements of CO_2, H_2O and sensible heat fluxes using an Eddy correlation system. These measurements started on September 2000. In this stand (42 ha), tree density is 567 trees ha^{-1}. Between January 2001 and October 2001, mean height and basal area increased from 11.2 to 14.9 m, and from 4.4 to

Table 1. Parameters monitored in eddy-correlation stand

Parameters	Measurement	Reference
Energy, H_2O, CO_2 fluxes	Eddy-correlation: closed path: Li-6262 + Sonic Young 8100	Aubinet *et al.* (2000)
Climate	Campbell: Rn (NR-lite, Kipp&Zonen), Rg, PAR,T, H, Wind	
Water availability	TDR (Trase: 0-5m) + leaf water potential (PMS)	
Heat storage	Thermocouples in soil, trunks, air	
Sapflow	Thermal dissipation	Granier (1985)
Rhizospheric/non rhizospheric soil respiration	Portable closed path (Li-6200) + soil temp. + soil humidity (Thetaprobe). Trenched plots + CENTURY model	Epron *et al.* (1999), Parton *et al.* (1987)
Water-use efficiency	Sapflow + dendrometers + eddy-correlation	
Stem growth	Dendrometers, stem profile, biomass	
Root growth and turn-over	Rhizotrons, ingrowth cores, biomass	Jourdan (1995)
LAI and litterfall	LAI-2000+Litter-traps+SLA and biomass	
Litter mass remaining	Litter-bags + NIRS	Gillon *et al.* (1999)

5.8 m^2, respectively. Leaf area index (LAI) of the stand exhibited important seasonal variations, with maximum value (1.6) at the end of the rainy season, and minimum value (0.98) at the end of the dry season.

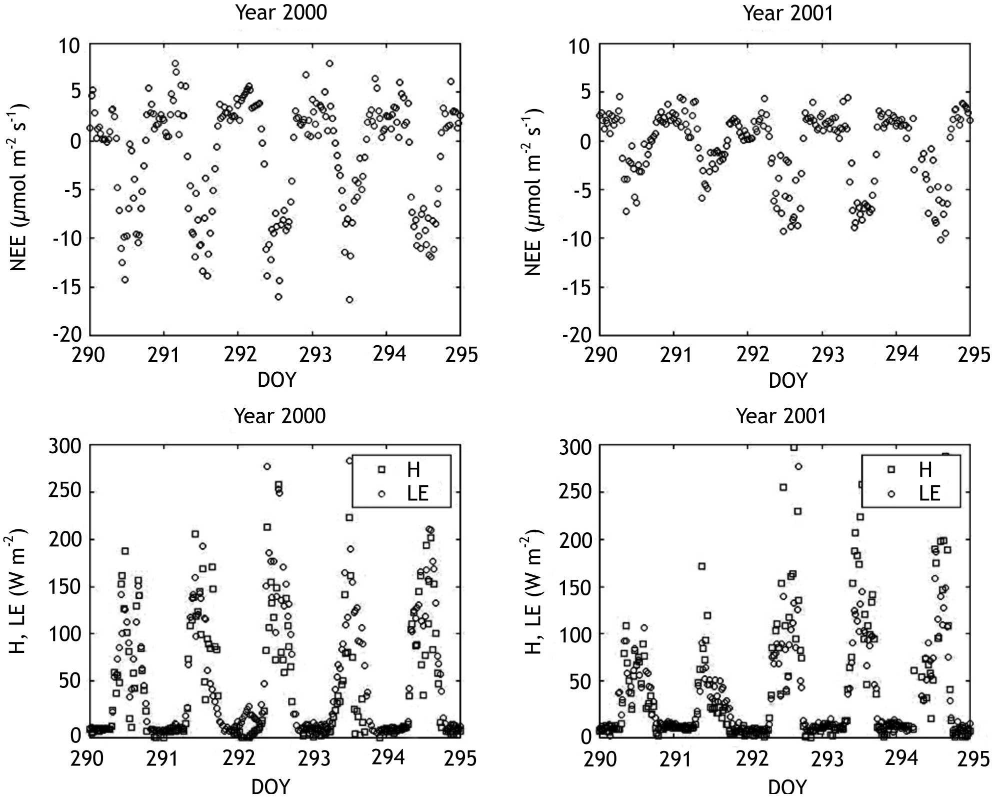
Flux measurements are obtained from a three-dimensional sonic anemometer (Sonic Young 8100) and a closed path Licor 6262 CO_2/H_2O analyser, positioned at 22 m above ground level, on a tower erected in the middle of the stand. Meteorological variables (precipitation, air temperature and relative humidity, net and global radiation, wind speed) are also measured (Table 1). Other measurements on this stand include sap flow measurements (8 trees), soil temperature and water content profiles, litter fall, litter decomposition and soil respiration profiles (Table 1). The parameters obtained on this stand will be used to estimate carbon sequestration, and to validate process-based model of water and CO_2 exchanges, tree growth and soil respiration.

Results

Some early results are presented below.

Eddy correlation measurements started at the end of the dry season of year 2000 (end of September 2000). Daily minima of Net Ecosystem Exchanges (NEE) reached values around -20 mmol m^{-2} s^{-1} during the rainy season, and -10 mmol m^{-2} s^{-1} during the dry season. Due to an unusual prolongation of the dry season, CO_2 fluxes in October 2001 were lower than in October 2000 (Fig. 2). Most of the diurnal variations in NEE were explained by those of incoming photosynthetic active radiation (PAR). Daily values of NEE varied from around 0 g C m^{-2} day^{-1} at the end of the dry season down to around -4 g C m^{-2} day^{-1} during the rainy season, and were strongly correlated with both the daily incoming PAR, and the daily evapotranspiration estimated from eddy correlation measurements of latent heat flux (LE).

Figure 2. Net carbon ecosystem exchange (NEE), sensible heat fluxes (H), and latent heat fluxes (LE), measured by eddy correlation at the 'Hinda' site from day of year (DOY) 290 to DOY 295 in 2000 and 2001

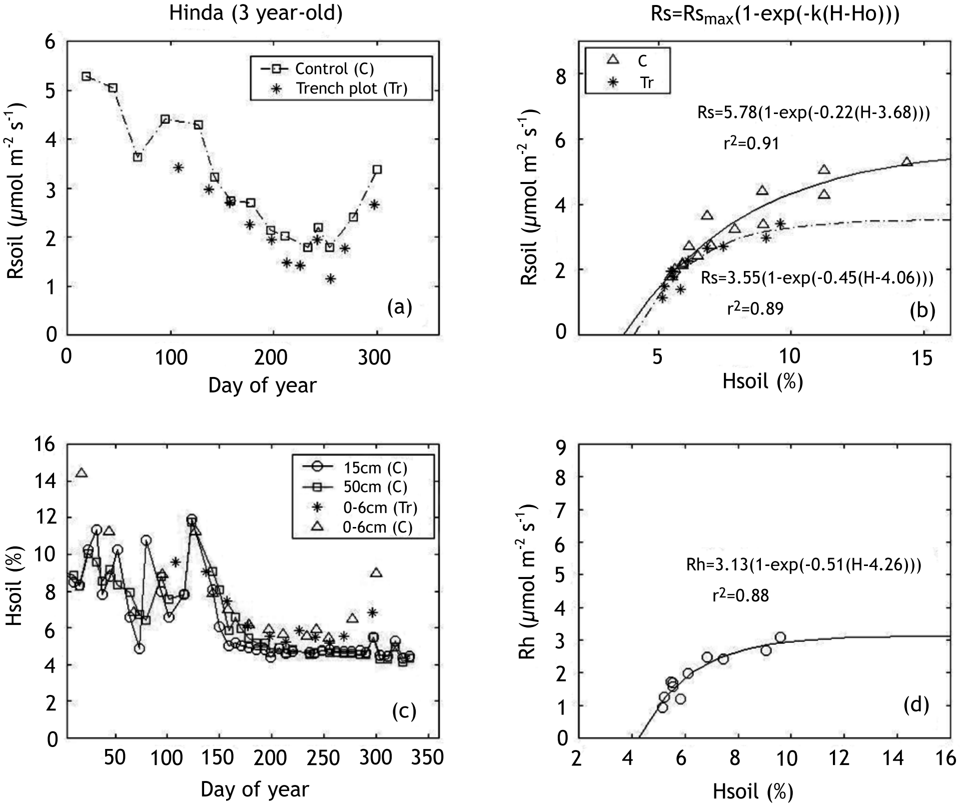


Soil respiration showed a marked seasonal pattern, with maximum values (around 5.3 mmol m^{-2} s^{-1}) during the wet season, and minimum values (around 1.5 mmol m^{-2} s^{-1}) at the end of the dry season. (Fig. 3a): this pattern was mostly explained by the strong correlations obtained between surface (0-5 cm) soil water content and soil CO_2 effluxes (Fig. 3b,d). This soil moisture effect on soil respiration is easily described by a 3-parameter equation:

$$R_s = R_{smax}\{1-\exp[-k(H-H_0)]\}$$

where R_{smax} is the soil respiration for high soil water content, and H_0 is the soil moisture for which soil respiration tends to zero. The contribution of root respiration to total soil respiration was estimated by comparing soil CO_2 effluxes obtained from trenched plots to effluxes obtained from the main plot (Fig. 3a). On average, root respiration accounted for 27% of total soil CO_2 efflux, while the heterotrophic component (Rh) accounted for 73% of total soil respiration. For nights with low wind speed, ecosystem respiration could not be directly estimated from EC measurements of NEE, due to CO_2 storage in the air layer from the soil surface to the height at which EC measurements are obtained. As for soil respiration, ecosystem respiration obtained for night with sufficient wind speed showed a marked seasonal pattern, with maximum values obtained during the wet season, and minimum values obtained at the end of the dry season.

Figure 3. The seasonal dynamic of soil CO_2 efflux on trenched plots (Tr), and on the control plot (C) (a), and of soil volumetric water content (c), at the Hinda site; Relationship between soil CO_2 effluxes and soil water content (b), and between heterotrophic soil respiration (Rh) and soil volumetric water content (d)



Discussion and Conclusions

Carbon sequestration in clonal eucalypt stands in the Congo is being estimated using: (1) carbon stocks measurements over a chronosequence; and (2) continuous, multi-year measurements of carbon exchanges with an eddy correlation system. The first results obtained in a 3-year-old stand have confirmed the major role played by ecosystem respiration in the annual carbon balance of these plantations: more than half of the gross carbon gain (GPP=NEE+Re) was lost through ecosystem respiration. On this 3-year-old stand daily EC estimates of carbon sequestration varied between 0 to 4 g C day^{-1}, depending on soil water status and daily incoming PAR. Fine root production data are being processed to estimate litter production by roots (L_R). This information, together with measurements of above- and belowground living biomass increments (G_A, G_B), and litter production by aerial compartment (L_A), will be used to estimate NPP ($NPP=G_A+G_B+L_A+L_R$), and net carbon gain (NEP=NPP-Rh), that will be compared to the annual net carbon gain estimated by eddy correlation. Other results obtained in this experiment (water and energy fluxes, LAI measurements, etc.) are being used to develop and validate models that simulate the carbon, water and energy budgets of these plantations.

References

Aubinet, A. *et al.* 2000. Estimates of the annual net carbon and water exchange of forests: the Euroflux methodology. Advances in Ecological Research 30:113-175.

Berbigier, P., Bonnefond, J-M. and P. Mellmann. 2001. CO_2 and water vapour fluxes for 2 years above Euroflux forest site. Agriculture and Forestry Meteorology 108:183-197.

Epron, D., Farque, L., Lucot, E. and P-M. Badot. 1999. Soil CO_2 efflux in a beech forest: the contribution of root respiration. Annales Science Forestière 56:289-295.

Gillon, D., Joffre, R. and A. Ibrahima. 1999. Can litter decomposability be predicted by near infrared reflectance spectroscopy? Ecology 80:175-186.

Granier, A. 1985. Une nouvelle méthode pour la mesure du flux de sève dans les troncs des arbres. Annales Science Forestière 42:193-200.

Jourdan, C. 1995. Modélisation de l'architecture et du développement du système racinaire du palmier à huile (*Elaeis guineensis* Jacq.). Académie de Montpellier, Université Montpellier II, Montpellier, France. 241p.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Journal of Soil Science Society of America 51:1173-1179.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Mineralogy and Weathering of Soils under Eucalypt Plantations in Pointe-Noire Region, the Congo

J.D. Nzila[1], M.P. Turpault[2], J.P. Laclau[1] and J. Ranger[2]

Nutrient release by weathering of soil minerals is one of the major fluxes for calculating nutrient accurate budgets for forest soils. In extensively managed sites, atmospheric deposits and weathering determine the resilience of the ecosystem, in terms of soil capacity for forest growth. In more intensively managed plantations, weathering remains an input difficult to quantify. For sustainability purposes, it is ecologically and economically necessary to optimise the soil nutrients and supply additional nutrients when necessary for production.

Unfortunately, this flux cannot be measured directly. For years, soil scientists used controlled experimental approaches for estimating weathering. It is now generally recognised that this methodology is only useful for identification of mechanisms, and not for flux quantification.

Estimates of the weathering flux were developed by *in situ* approaches, by several authors, using observations, measurements and modelling. Even though accuracy needs to be improved, this methodology is beginning to bring relevant data for ecosystem function and to calculate nutrient budgets (Fichter *et al.* 1998, Ezzaïm *et al.* 1999a, b). This rather complex methodology was used to determine weathering in the soils used for afforestation by eucalypts in the Pointe-Noire area in Congo.

The main steps of this methodology are:

- quantification of atmospheric deposits, nutrient uptake by vegetation, soil solid phase and solution characteristics;
- quantitative soil mineralogy, localisation of nutrients in minerals, and hypothesis on current soil mineral evolution (mainly from theoretical studies); and
- weathering flux modelling using the geochemical PROFILE model developed by Sverdrup and Warvfinge (1993) at the University of Lund (Sweden).

The main results are concerned with the soil mineralogy and the first quantification of the weathering flux by the Profile model.

Soils developed on the coastal plain of Pointe-Noire were very sandy (>80% of sand) and extremely poor as revealed by the total chemistry

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of fine earth (>90% of SiO_2; about 0.02% of MgO, CaO and K_2O). Available nutrient pool is limited, except for P.

Soil mineralogy was characterised by the dominance of quartz and kaolinite. The coarse fractions (>200 µm) were essentially constituted of quartz (98%), while the fine fractions (<2 µm) were dominated by kaolinite (75-80%). All other minerals could be considered as 'accessory' minerals in this soil, but they were the nutrient bearing minerals and particularly concentrated in some fractions (Table 1).

- White mica containing 10.4% K_2O and 1.6% of MgO and secondary mineral from illite: illite/vermiculite and vermiculite minerals. These minerals were present mainly in clay and silt fractions (about 1-5%).
- Ilmenite, ulvöspinelle and secondary rutile. These minerals were particularly concentrated in silt fractions where TiO_2 concentration raised to 5.5%.
- Two types of dravite (tourmaline) were analysed (Fe dravite and Mg dravite) containing between 0.3 and 0.6% of CaO and between 2.1 and 7.4% of MgO.
- Ubiquitous minerals such as SiAl minerals of metamorphic origin (staurolite, sillimanite) and accessory minerals of crystalline or metamorphic rocks (ilmenite and rutile containing respectively 56 and 11.5% of TiO_2).

Table 1. Main characteristics of identified minerals

Minerals	Main nutrients analysed	Main picks observed in X-ray analyses	Approximate percentage in fractions	Localisation
White mica	Si > Al > K >> Fe ≈ Mg	10 Å …	≈ 1	clay, silt
Dravite Fe	Si ≈ Al > Fe >> Mg ≈ Na >> Ca	3.99 Å; 3.48 Å; 3.38 Å; 2.49 Å …		silt, fine sand
Dravite Mg	Si > Al > Mg > Fe > Na >> Ca	3.99 Å; 3.48 Å; 3.38 Å; 2.49 Å ...		silt, fine sand
Staurolite	Al > Si > Fe >> Mg	4.15 Å ; 1.98 Å; 1.54 Å ; 1.48 Å ...	< 0.1	silt, fine silt
Sillimanite	Al > Si			coarse silt, fine sand
Zircon	*n.d.*	4.4 Å ...		sand
Kaolinite	Si > Al > Fe >> Ti	7.16 Å ...	30-80	clay, silt
Iron oxides	Fe >> Al > Si	2.69 Å ...		clay, silt
Ilmenite	Fe ≈ Ti	3.78 Å; 2.74 Å ...	<10	coarse silt, fine sand
Ulvöspinelle	Fe >> Ti			coarse silt, fine sand
Quartz	Si	4.26 Å; 3.34 Å ...	30-100	sand, silt

n.d. not determined.

Apart from the crystalline mineral phase, there was an amorphous mineral phase quantified by DCB extraction. It contained between 0.1 and 0.2% Al and between 0.5 and 1% Fe, indicating that Fe was dominantly located in this amorphous phase. These amorphous compounds were able to retain some specific nutrients like P. This had to be verified because no P-bearing mineral was identified, and it is unlikely that all P was organically bound.

Nutrient bearing minerals were scarce in the soil but most were concentrated in the fine particles (clay and silt) and so represented a substantial area. *Eucalyptus* roots penetrated deep layers of soil. Thus, to a depth of 2 m, the total nutrients reserves in eucalypt plantations were about 2000 kg ha^{-1}, 4000 kg ha^{-1} and 6000 kg ha^{-1} respectively for Ca, Mg and K.

The first modelling exercise confirmed the extremely low flux of nutrients potentially liberated by current weathering. Improvements are being made, especially for parametrisation of dissolution rate coefficients of the identified minerals. These data were integrated in the nutrient budget calculations (Laclau 2001).

These results confirm that sustainable soil management must fully recognise the very limited available reserves of soils. Part of soil fertility is associated with the organic matter pool, management of which was confirmed as critical in these particular soil conditions (Nzila 2001).

References

Ezzaïm, A., Turpault, M.-P. and Ranger, J. 1999a. Quantification of weathering processes in an acid brown soil developed from tuff (Beaujolais, France). Part I. Formation of weathered ring. Geoderma 87:137-154.

Ezzaïm, A., Turpault, M.-P. and Ranger, J. 1999b. Quantification of weathering processes in an acid brown soil developed from tuff (Beaujolais, France). Part II. Soil formation. Geoderma 87:155-177.

Fichter, J., Bonnaud, P., Turpault, M.-P. and Ranger J., 1998. Quantitative determination of minerals in acid forest soils of granite. Z. Pflanzenernähr. Bodenk. 161:129-139.

Laclau, J.P. 2001. Dynamique du fonctionnement minéral d'une plantation d'*Eucalyptus*: impact du reboisement sur un sol de savane au Congo. PhD thesis, INA-PG, in preparation.

Nzila, J.D. 2001. Caractérisation minéralogique des sols ferrallitiques sableux sous plantations d'*Eucalyptus* et sous savane naturelle de la région de Pointe-Noire (Congo). URP2PI Report. 51p.

Sverdrup, H. and Warvfinge, P. 1993. Calculating field weathering rates using a mechanistic geochemical model PROFILE. Applied Biochemistry 8:273-283.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Impact of the Replacement of Natural Hybrids by a More Productive Hybrid (*Eucalyptus urophylla x E. grandis*) on Nutrient Accumulation in Eucalypt Stands in the Congo

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Introduction

More than 40 000 ha of *Eucalyptus* have been planted on the savannas around Pointe-Noire (Congo). In order to improve the productivity of these plantations, breeders have developed genetically improved planting stock that is more productive. For some years, the clones of natural hybrids (*E.* PF1 and *E. tereticornis* x *E. grandis*) originally planted, have been replaced by the clones of artificial hybrid *E. urophylla* x *E. grandis* (UG). Some UG clones achieve a MAI 50% higher than *E.* PF1 1-41, the most productive clone of natural hybrids. This increase in biomass production may lead to a higher nutrient uptake and greater nutrient removal at harvesting (7-8 years old). Forest managers must take care of the nutrient requirements to achieve sustainable production of plantations in these sandy and very poor soils. The objective of this study was to compare *E.* PF1 1-41 and 3 UG clones according to nutrient accumulation at harvesting.

Material and Methods

The plantations were established on the coastal plain around 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 and -5°C. The soils are Ferralic Arenosols according to FAO classification.

The UG clones were harvested at 8 years, in a clonal experiment testing 23 UG clones and *E.* PF1 clone 1-41, among which 3 UG clones were sampled. Two of the UG clones (18-50 and 18-52) were full sibs. The clones 1-41 were sampled from a monoclonal plantation located 1 km from the main clonal trial. Both stands are on similar soil type and were managed under the same silvicultural regime.

Twelve trees per clone, representing six basal area classes, were harvested, and the major components separated: stembark and stemwood gathered to diameters of 7 cm (limit for pulpwood) and 2 cm (limit for firewood), living branches, dead branches and leaves.

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Samples were dried at 65°C, ground and homogenised. Total N was analysed by acid-base volumetry after Kjeldahl mineralisation. Phosphorus was determined by colorimetry using the Murphy and Riley reagent. Calcium, K and Mg were analysed by atomic absorption spectrophotometry.

Biomass and nutrient content predictive models were developed using GLM procedure of SYSTAT 9.0 software. The models obtained were then applied to the inventory of the stands to evaluate the biomass and nutrient content for each component on a per hectare basis.

Results

Marked differences in growth and production were observed among clones. Although clones 18-52 and 18-50 were full sibs, the former, which was the most productive, produced a MAI 18% higher than clone 18-50, as observed in clonal tests (Saya *et al.* 2001). As expected, UG clones produced better MAIs than *E.* PF1.

Large differences in total biomass were observed between the two hybrids and among UG clones, even between the full sibs 18-50 and 18-52. The best clone (18-52) produced 20%, 25% and 43% more than clones 18-50, 18-65 and 1-41, respectively. Stemwood represented the main part of the aboveground biomass. Its proportion of total biomass was similar between hybrids: 86.8% for the clone 1-41 *vs* a mean of 86.6% for UG clones. By contrast, marked differences between hybrids were observed for bark and leaves: the percentage of bark was 50% higher in the clone 1-41 than in UG clones, but the percentage of leaves was 36% lower in the clone 1-41 than in UG clones. The clone 1-41 exhibited the lowest percentage of living branches but there were great variations among UG clones.

The accumulation of P and Ca was generally lower in UG clones than in the clone 1-41: on average 27% and 17%, less respectively. The opposite pattern was found for N (+19%), K (+18%) and Mg (+13%). Nitrogen accumulation increased with clone production, but not proportionally. The nutrient content was always lower in the stemwood of UG clones than in the clone 1-41 for P (-71%) and Ca (-50%). UG also exhibited systematically lower content of Mg (-38%), Ca (-29%), N (-22%), P (-17%) and K (-13%) in the bark, but much higher accumulation of all nutrients in the living branches and the leaves.

Nitrogen removal (in stemwood and bark up to stem diameters of 7 and 2 cm) increased with biomass production and corresponded, on average, to 70% of the total aboveground N content. The nutrient removal by UG clones was much lower (vs clone 1-41) for P (-66%), Ca (-45%) and K (-26%). Differences were observed among UG clones. In particular, the nutrient content removed with clone 18-65 was the lowest for P but the greatest for K.

The contents of Ca in slash (leaves, branches and bark up to stem diameter of 7 cm) were of the same order of magnitude for both hybrids. By contrast they were higher for K (+102%), P (+70%) N (+33%) and Mg (+31%) in UG clones. Nevertheless, variability was observed among UG clones. In particular the clone 18-52 was characterised by the highest amounts of nutrients in slash, except for K.

Discussion and Conclusion

This study showed a marked inter-clonal variability in biomass and nutrient content. Key points are:

- The biomass of stemwood ranged from 109-139 t ha^{-1} in the UG clones sampled at 8-years-old compared to 97 t ha^{-1} for the clone 1-41.
- Biomass allocation differed between clones UG and 1-41. Whereas the proportion of bark was higher for the clone 1-41, the dry matter of leaves and living branches represented a greater part of the aboveground biomass for UG clones.
- Phosphorus and Ca content in aboveground biomass of UG clones were lower than in 1-41, even for clones 18-50 and 18-52, whose wood production was much higher. Differences in nutrient content between both hybrids were large in bark but rather low in wood. The amount of nutrients in the canopy was higher in UG clones than in clone 1-41.

Clones of the natural hybrid *E*. PF1 are progressively replaced by UG clones in the industrial plantations around Pointe-Noire. This study emphasises that, although the production of wood with the best UG clones was much higher than with the *E*. PF1 clones, the accumulation of P and Ca in the biomass was lower and only slightly higher for N, K and Mg. Moreover, the amount of nutrients returning to the soil in slash was higher for UG clones than for the clone 1-41. Although no data have been collected yet, the higher biomass of leaves suggests that the amount of litter produced during the rotation was likely to be higher for UG clones than for the clone 1-41. This feature might be positive for the maintenance of soil fertility through the effect of soil organic matter. However, effect on sustainability of the more productive UG clones will be closely related to the mineralisation of organic matter (litter and slash) and to nutrient losses by drainage after stand harvest (Nzila *et al*. 2001). Moreover, the long-term availability of N in soils is a matter of concern since the input-output budget during the first rotation after afforestation is clearly unbalanced for the clone 1-41 (Laclau *et al*. 2001). The N deficit will therefore increase over successive rotations (Bouillet *et al*. 2001) and this will have to be remedied through higher nitrogen inputs in these plantations in order to maintain their high productivity.

References

Bouillet, J.P., Safou-Matondo, R., Laclau, J.P., Nzila, J.D. and Ranger J. 2001. Changes over successive rotations in NPK fertiliser needs of Congolese clonal eucalyptus plantations. Relationships with changes in soil fertility. *In*: Proceedings of the IUFRO symposium 'Developing the eucalypt of the future', 10-15 September 2001, Valdivia, Chile. Compact Disk.

Laclau, J.P., Ranger, J., Nzila, J.D., Bouillet, J.P. and Deleporte, P. 2001. Nutrient cycling in *Eucalyptus* plantations in Congo. Consequences for the management of the stands. *In*: Proceedings of the IUFRO symposium 'Developing the eucalypt of the future', 10-15 September 2001, Valdivia, Chile. Compact Disk.

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*: Proceedings of the IUFRO symposium 'Developing the eucalypt of the future', 10-15 September 2001, Valdivia, Chile. Compact Disk.

Saya, A., Vigneron, P., Bouvet, J.M., Cornillon, P.A. and Gouma, R. 2001. Effect of plot size and spacing on assessment of *Eucalyptus* hybrids clonal value. *In*: Proceedings of the IUFRO symposium'Developing the eucalypt of the future', 10-15 September 2001, Valdivia, Chile. Compact Disk.

Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Biomass and Potential Nutrient Removal by Harvesting in Short-rotation Plantations

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Abstract

Data on standing biomass, mean annual increment of carbon stock, and nutrient accumulation in 40 industrial plantations at 21 sites in 11 countries are summarised. Aboveground biomass and mean annual increment of carbon near the harvest age, of these plantations ranged from 44 to 324 t ha^{-1} and from 3.1 to 22.9 tC ha^{-1} yr^{-1}, respectively. Plantations managed on a short rotation are expected to accumulate carbon rapidly. However, there are large variations of biomass accumulation depending on site conditions. There is concern about the potential decrease of productivity caused by nutrient loss by intensive and repeated harvesting. It is important to determine the nutrients removed and conserve them as much as possible to prevent productivity loss and for sustainable management of industrial plantations. Careful management of the nutrient cycle through residue retention and fertiliser application is necessary to maintain high productivity.

Introduction

The forest plantation area of the world in 2000 was 187 million ha and occupied about 5% of the total forest area. World industrial roundwood consumption has been rising annually, reaching 1580 million m^3 in 2000 (FAO 2003). The area of short-rotation industrial plantations for pulpwood has been increasing rapidly to secure a stable supply of wood chips with high quality for the pulp and paper industry. To cope with the growing demand for paper, the Japanese pulp and paper industry has been active in afforestation and recycling waste paper. Its afforestation efforts have extended from Japan to other countries since the 1990s and in 2003 it co-operated about 320 000 ha of industrial plantations outside Japan, primarily in the southern hemisphere. The principle behind these plantation activities is 'to plant the trees we consume'.

The carbon-sink roles of afforestation and reforestation activities meeting certain specific criteria were considered for inclusion in Clean Development Mechanism (CDM) of Kyoto protocol

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Table 1. The range of aboveground biomass and mean annual increment of carbon (MAIC) by five species extensively planted for pulpwood

Species	Age (yr)	Aboveground biomass (t ha^{-1})	MAIC (tC ha^{-1} yr^{-1})
A. auriculiformis	6 – 7	96 – 136	8.0 – 9.7
A. mangium	6 – 9	109 – 190	7.8 – 10.5
E. globulus	6 – 8	69 – 275	5.7 – 17.2
E. grandis	7 – 12	44 – 324	3.1 – 22.9
E. nitens	7 – 11	122 – 195	8.4 – 8.77

leading to interest in the plantations related to CDM in some countries. Information on biomass of industrial plantations as carbon stock is important for planning and managing operating industrial plantations related to CDM. The Japan Overseas Plantation Center for Pulpwood (JOPP) and the Japan International Forestry Promotion and Cooperation Center (JIFPRO) have examined biomass of the industrial plantations operated by the Japanese industry in Australia, Southeast Asia, South America and South Africa (JIFPRO 2002, JOPP 1999, 2000, Morikawa *et al.* 2002).

Most Japanese overseas industrial plantations will soon go into their second rotation and managers are concerned about nutrient management of their plantations. Repeated harvesting in short-rotation cycles removes large amounts of nutrients from the site and possibly causes decreased productivity by nutrient depletion, but it is essential that the productivity of the sites is sustained for the continuous operation of industrial plantations.

The objective of this paper is to summarise data on biomass, mean annual increment of carbon and nutrient distribution in the plantations of *Acacia* and *Eucalyptus,* which are the dominant fast-growing species in industrial plantations. Biomass and nutrient contents of 40 plantations at 21 sites in 11 countries (Appendix 1), which was accumulated by JOPP and CIFOR's Site Management Network (Nambiar *et al.* 1999, 2000), has been compiled.

Aboveground Biomass and Mean Annual Increment of Carbon

Standing aboveground biomass excluding litter (AGB) and mean annual increment of carbon (MAIC) of 40 plantations in 11 countries are in Appendix 2. AGB and MAIC of 31 industrial plantations ranged from 34 to 324 t ha^{-1} and from 2.4 to 22.9 tC ha^{-1} yr^{-1}, respectively. The range of AGB and MAIC by species, *A. auriculiformis*, *A. mangium*, *E. globulus*, *E. grandis* and *E. nitens*, which most industrial pulpwood plantations use are summarised in Table 1 (Bouillet *et al.* 1999, Gonçalves *et al.* 1999, JOPP 1999, 2000, 2002, O'Connell and Grove 1999, Sabar *et al.* 1999, Sankaran 1999, Shaohui *et al.* 1999, Simpson *et al.* 1999, Xu *et al.* 1999, Yamada *et al.* 1999, 2000a, 2000b, 2000c, du Toit *et al.* 2000, Hardiyanto *et al.* 2000, Laclau *et al.* 2000, Sankaran *et al.* 2000, Bellote *et al.* 2001, JIFPRO 2002, Morikawa *et al.* 2002).

The highest value of MAIC (22.9 tC ha^{-1} yr^{-1}) was observed at a 7-year-old *E. grandis* plantation in Sao Miguel Arcanjo, Brazil (Bellote *et al.* 2001). This value of MAIC was more than the double of the other *E. grandis* plantations at similar age (MAIC 3-10 tC ha^{-1} yr^{-1}; Yamada *et al.* 2000b, Gonçalves *et al.* 1999, Sankaran 1999, Sankaran *et al.* 2000, du Toit *et al.* 2000). The total AGB at this site in Brazil (321 t ha^{-1}) would not be achievable in other sites even within the same region. Among *E. globulus* plantations, the higher MAIC (> 16 tC ha^{-1} yr^{-1}) were observed in Manjimup, Western Australia (O'Connell and Grove

Table 2 Nutrient distribution in short-rotation plantations of *A. mangium*, *E. globulus* and *E. grandis* near harvest age (site no. 4, 6, 7, 12, 13, 14, 17 and 21 in Appendix 1)

		A. mangium			*E. globulus*			*E. grandis*	
		PNG (4)	Indonesia (6)	Indonesia (7)	Chile (12)	Australia (13)	Australia (14)	Brazil (17)	South Africa (21)
AGB (t ha^{-1})	Bark	8.0	14.2	12.9	13.1	26.9	24.0	8.9	12.8
	Stem	84.5	124.7	105.1	104.1	186.9	170.0	125.1	107.4
	AGB	109.2	189.5	145.4	148.1	256.9	275.0	140.3	133.8
N (t ha^{-1})	Bark	95.0	139.0	41.4	37.1	51.1	45.0	35.7	42.6
	Stem	187.0	236.0	161.9	74.9	114.0	95.0	223.9	77.3
	AGB	452.0	661.0	290.2	466.5	465.8	521.0	332.4	249.2
P (kg ha^{-1})	Bark	2.1	1.5	7.6	5.4	3.4	5.8	11.8	6.3
	Stem	7.4	7.8	38.9	23.5	49.0	22.2	18.8	4.1
	AGB	19.2	14.3	58.4	52.4	68.7	55.9	38.2	17.8
K (kg ha^{-1})	Bark	19.9	35.6	23.9	50.7	50.6	n/a	47.4	52.9
	Stem	49.1	37.4	216.6	129.0	104.7	n/a	106.3	81.6
	AGB	133.3	191.2	288.4	339.3	309.5	n/a	182.7	189.0
Ca (kg ha^{-1})	Bark	65.2	163.7	n/a	234.7	582.9	423.0	95.0	101.0
	Stem	54.0	103.5	n/a	72.0	214.9	104.0	110.1	80.8
	AGB	189.0	415.8	n/a	505.6	1167.5	1211.0	247.8	248.1

1999, Yamada *et al.* 1999). The lowest MAIC (6 tC ha^{-1} yr^{-1}) of *E. globulus* plantations was in Albany, also in Western Australia (JOPP 1999). Relatively small variation in MAIC (8-11 tC ha^{-1} yr^{-1}) was observed in *Acacia* plantations in Southeast Asia (JOPP 1999, 2002, Sabar *et al.* 1999, Hardiyanto *et al.* 2000, JIFPRO 2002, Yamada *et al.* 2000c and Morikawa *et al.* 2002).

MAICs were smaller than 5 tC ha yr^{-1} in Fujian, China (*Cunninghamia lanceolata*; Shaohui *et al.* 2000), in Guangdong, China (*E. urophylla*; Xu *et al.* 1999), and in Queensland, Australia (*Pinus elliottii*; Simpson *et al.* 1999). In Fujian and Queensland, despite of the smaller MAIC, a longer rotation period resulted in a high AGB (about 200 t ha^{-1}).

Industrial plantations are managed to accumulate biomass rapidly. Large variation in biomass and therefore carbon pool was observed from site to site even within a species emphasising that site conditions are important determinants of productivity.

Nutrient Distribution in Biomass and Potential Nutrient Removal by Harvesting

Nutrient (N, P, K, Ca and Mg) distribution in 24 sites is shown in Appendix 3. AGB and nutrient distribution (N, P, K, and Ca) in stem and bark of *A. mangium*, *E. globulus* and *E. grandis* near the harvest age are summarised in Table 2 (Gonçalves *et al.* 1999, O'Connell and Grove 1999, Yamada *et al.* 1999, 2000a, 2000b, Hadiyanto *et al.* 2002, Sabar *et al.* 1999, JOPP 2000).

Removing stem wood with bark on from a plantation site is a common practice when harvesting industrial plantations. Stem wood biomass accounted for 62-89% of AGB while the nutrient content in stem wood was much lower. However, bark accounted for only about 10% of AGB but contained high levels of nutrients, especially Ca in these three species (40-57% of total Ca content in aboveground biomass). Leaving bark on the site as residue at harvesting would be effective for nutrient conservation in short-rotation plantations and aid sustainable production. Nutrients released by mineralisation of the residues would be transferred to the soil and taken up by roots but may be leached, particularly if very mobile nutrients, such as N are involved.

Even if residues are left in the plantation, nutrient removal will occur when the stem wood is harvested and taken away. Some estimates of nutrient removal by stem wood harvesting in eucalypts and acacia are: 75-236 kg N ha^{-1}, 4-49 kg P ha^{-1}, 37-217 kg K ha^{-1}, and 54-215 kg Ca ha^{-1} (Table 2). These estimates suggest that stem removal alone in short-rotation plantations can have a significant impact on soil nutrient budgets.

In principle, to evaluate the nutrient sustainability of plantations, the input and output fluxes, such as weathering, atmospheric deposition and N fixation for the input, and leaching, erosion and harvesting for the output, should all be determined. However, the contribution by weathering and atmospheric deposition are unlikely be a significant source of supply of nutrients in short-rotation crops. It seems that in most cases additional fertiliser applications will be required to maintain productivity. Information summarised in this paper may indicate the required amount of fertilisation to compensate for losses during a rotation.

Conclusion

When plantations are established for carbon sequestration, one must consider not only the rate of carbon accumulation but also the rate of nutrient loss through harvesting and site management. Residue management in the plantations is important for nutrient conservation since the nutrients are highly concentrated in bark, branches and leaves. Retention of residues will reduce nutrient loss and help conserve site productivity. However, nutrient removal in stem wood alone is substantial and considering the poor plant-available nutrient pool in the soil, the application of fertiliser is likely to be necessary in the industrial plantations where continuous high productivity is expected.

Acknowledgements

This research was conducted as a part of the project ‘Ecological impact assessment of tropical plantation forests on the environment’ funded by the Forestry Agency of Japan and as a part of the CIFOR/Japan research project ‘Rehabilitation of degraded tropical forest ecosystems phase 2’. We acknowledge the member companies of JOPP for their support. We are indebted to JIFPRO for the cooperation and technical advice. We also appreciated the valuable comments during the workshop and by editors of these proceedings.

References

Bellote, A.F.J., Dedecek, R.A., da Silva, H., Gava, J.L. and Menegol, O. 2001. Nutrient export by clear cutting *Eucalyptus grandis* of different ages on two sites in Brazil. *In:* Kobayashi, S., Turnbull, J.W., Toma, T., Mori, T. and Majid, N.M.N.A. (eds.) Rehabilitation of degraded tropical forest ecosystems, 173-177. Center for International Forestry Research, Bogor, Indonesia.

Bouillet, J.P., Nzila, J.D., Ranger, J., Laclau, J.P. and Nizinski, G. 1999. *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.

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.

FAO 2003. State of the world’s forests 2003. FAO, Rome (available at FAO’s web site, www.fao org).

Gonçalves, J.L.M., Poggiani, F., Stape, J.L., Serrano, M.I.P., 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.

Hardiyanto, E.B., Ryantoko, A. and Anshori, S. 2000. Effects of site management in *Acacia mangium* plantations at PT Musi Hutan Persada, South 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, 41-49. Center for International Forestry Research, Bogor, Indonesia.

JIFPRO (Japan International Forestry Promotion & Cooperation Center) 2002. Annual Report 2001. Technical report for CDM plantation. 85 p. (in Japanese).

JOPP (Japan Overseas Plantation Center for Pulpwood) 1999. Annual report 1998. Carbon sink in industrial plantation. (in Japanese).

JOPP 2000. Annual report 1999. Carbon sink in industrial plantation. (in Japanese).

JOPP 2002. Annual report 2001. Ecological impact assesment of tropical plantation forests on the environment. (in Japanese).

Laclau, J.P., Ranger, J., Nzila J. de D. and Bouillet, J. P. 2000. Nutrient cycling in a short rotation *Eucalyptus* plantation and an adjacent savanna in 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, 95-99. Center for International Forestry Research, Bogor, Indonesia.

Morikawa Y., Inoue H., Yamada M., Hardiyanto D., Diana R., Marjenah, Fatawi M., JIFPRO and JOPP. 2002. Carbon accumulation of man-made forests in monsoon Asia in relation to CDM. *In:* Proceedings of Tokyo Workshop, Oct. 7-11, 2001. BIO-REFOR-Suitable forest management system and biodiversity, 43-51. BIO-REFOR and IUFRO-SPDC.

Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) 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.

Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) 2000. Site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India. 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, 53-60. Center for International Forestry Research, Bogor, Indonesia.

Sabar, S.T.H., Hardiyanto, E.B. and Gales, K. 1999. *Acacia mangium* plantations in PT Musi Hutan Persada, South Sumatra, Indonesia. *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, 39-44. Center for International Forestry Research, Bogor, Indonesia.

Sankaran, K.V. 1999. Eucalypt plantations in monsoonal tropics - Kerala, India. *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, 45-51. Center for International Forestry Research, Bogor, Indonesia.

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.) Effects of site management and productivity in tropical plantation forests: workshop proceedings, 7-11 December 1999, Kerala, India, 51-60. Center for International Forestry Research, Bogor, Indonesia.

Shaohui, F., Chendong, Y., Zongming, H., Zhiying, H., Sizu, L. Shantu, L. Jinhua, Y. and Xujing, Y. 2000. 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.

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.

Xu, D.P., Yang, Z.J., Chen, Q.D. and Chen, M.H. 1999. Plantations 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.

Yamada, M., Hanamizu, K., Kawazoe, T., Tange, K. and Morikawa, Y. 1999. Carbon stock in fast-growing tree species. (1) *Eucalyptus globulus* man-made forest in Manjimup, Western Australia. Tropical Forestry 46:23-30. (in Japanese).

Yamada, M., Tsurumi, K., Haraguchi, N., Kawazoe, T., Yamanoshita, T., Tange T. and Morikawa, Y. 2000a. Carbon stock in fast-growing tree species. (2) *Acacia mangium*, *A. auriculiformis* and *Eucalyptus camaldulensis* man-made forest in Sonbe, Vietnam. Tropical Forestry 47:33-39. (in Japanese).

Yamada, M., Matsuda, M., Tange, K. and Morikawa, Y. 2000b. Carbon stock in fast-growing tree species. (3) *Eucalyptus grandis* man-made forest in Melmoth, South Africa. Tropical Forestry 48:18-24. (in Japanese).

Yamada, M., Hanamizu, K., Daido, T., Tange, K. and Morikawa, Y. 2000c. Carbon stock in fast-growing tree species. (4) *Acacia mangium* man-made forest in Madang, Papua New Guinea and general discussion. Tropical Forestry 49:20-33. (in Japanese).

Appendix 1. Planted species, location, climate and rotation length (RL) of the study sites of JOPP, JIFPRO and the CIFOR's Site Management network.

Site No	Species	Country	Site	Latitude	Longitude	Alt(m)	Temp. (°C) mean (min/max)	Rainfall (mm yr^{-1})	RL(yr)	Age	Reference
1	*Acacia auriculiformis*	Vietnam	Sonbe	-	-	-	21/35	1900	-	6	JOPP 1999
2	*Acacia auriculiformis*	Vietnam	Vung Tau	10°37'N	107°29'E	90	27	1872	7	7	JOPP 2002
3	*Acacia mangium*	Vietnam	Sonbe	-	-	-	21/35	1900	-	6	JOPP 1999
4	*Acacia mangium*	Papua New Guinea	Madang	5°12' S	145°12' E	80	25/30	2500	10	7	Yamada *et al*. 2000a
5	*Acacia mangium*	Indonesia	Benakat	3°05'-5°28'S	103°10'-104°25'E	60-200	29 (22/33)	1890-3330	-	9	JIFPRO 2002
6	*Acacia mangium*	Indonesia	Subanjeriji	3°05'-5°28'S	103°10'-104°25'E	60-200	29 (22/33)	1890-3330	9	9	Hardiyanto *et al*. 2000
7	*Acacia mangium*	Indonesia	Subanjeriji	3°05'-5°28'S	104°25'E		29	2000-3000	7	9	Sabar *et al*. 1999
8	*Cunninghamia lanceolata*	China	Fujian	26°45'N	118°10'E	-	19.4 (-5.8/41)	1817	29	29	Shaohui *et al*. 2000
9	*Eucalyptus globulus*	Australia	Manjimup	34°11'-13'S	116°01'-05'E	-	27,6	1024	7-8	5	JOPP 1999
10	*Eucalyptus globulus*	Chile	Canente	38°3'S	73°21'E	100-500	3/26	1056	8	5	JOPP 2000
11	*Eucalyptus globulus*	Australia	Albany	-	-	-	7/26.5	687	8	6	JOPP 1999
12	*Eucalyptus globulus*	Chile	Canente	38°3'S	73°21'E	100-500	3/26	1056	8	7	JOPP 2000
13	*Eucalyptus globulus*	Australia	Manjimup	34°11'-13'S	116°01'-05'E	-	27.6	1024	7-8	8	Yamada *et al*. 1999
14	*Eucalyptus globulus*	Australia	Manjimup	-	-	-	9/25	1000-1100	8	8	O'Connell & Grove 1999
15	*Eucalyptus grandis*	South Africa	Kwazullu	28°35' S	31°35' E	-	19.2 (9.2/21.9)	1155	10-12	5	JOPP 1999
16	*Eucalyptus grandis*	Brazil	Sao Miguel Arcanjo	23°51'S	47°46'W	715	-	-	-	7	Bellote *et al*. 2001
17	*Eucalyptus grandis*	Brazil	Sao Paulo	23°00'S	48°52'W	750	18/22	1580	7	7	Goncalves *et al*. 1999
18	*Eucalyptus grandis*	India	Kerala	10°02'N	77°10'E	1280	27 (20/42)	3000	7	7	Sankaran 1999, 2000
19	*Eucalyptus grandis*	India	Kerala	10°08'N	77°15'E	1800	27 (20/42)	1800	7	7	Sankaran 1999, 2000
20	*Eucalyptus grandis*	South Africa	Kwazullu	29°24'S	30°12'E	1260	15,2	950	7	7	du Toit *et al*. 2000
21	*Eucalyptus grandis*	South Africa	Kwazullu	28°35' S	31°35' E	-	19.2 (9.2/21.9)	1155	10-12	8	Yamada *et al*. 2000b
22	*Eucalyptus grandis*	Brazil	Mogi Guacu	22°04'S	47°03'W	680	-	-	-	12	Bellote *et al*. 2001
23	*Eucalyptus. natural hybrids*	Congo	Pointe-Noir	4°48'S	11°54'E	90-110	25 (22/27)	1200	8	8	Bouillet *et al*. 1999
24	*Eucalyptus nitens*	Chile	Canente	38°3'S	73°21'E	100-500	3/26	1056	10-12	7	JOPP 2000
25	*Eucalyptus nitens*	Chile	Canente	38°3'S	73°21'E	100-500	3/26	1056	10-12	8	JOPP 2000
26	*Eucalyptus nitens*	Chile	Canente	38°3'S	73°21'E	100-500	3/26	1056	10-12	11	JOPP 2000
27	*Eucalyptus spp.*	Congo	Pointe-Noir	4°48'S	11°54'E	90-110	25 (22/27)	1200	8	6	Laclau *et al*. 2000
28	*Eucalyptus tereticornis*	India	Kerala	10°41'N	76°23'E	120	27 (20/42)	2700	7	7	Sankaran 1999, 2000
29	*Eucalyptus tereticornis*	India	Kerala	9°6'N	76°54'E	150	27 (20/42)	2000	7	7	Sankaran 1999, 2000
30	*Eucalyptus urophylla*	China	Guandong	2°143'N	111°35'E	20-50	22 (37/2.1)	2178	6	7	Xu *et al*. 1999

Appendix 1. *Continued*

Site No	Species	Country	Site	Latitude	Longitude	Alt(m)	Temp. (ºC) mean (min/max)	Rainfall (mm yr^{-1})	RL(yr)	Age	Reference
31	*Pinus elliottii*	Australia	Queensland	26°00'S	152°49'E	61	14/25	1354	30	29	Simpson *et al*. 1999
32	*Azadirachta indica*	Indonesia	Lombok	8°42'S	116°47'E	-	-	700-1000	-	3	Morikawa *et al*. 2002
33	*Cassia siamea*	Indonesia	Lombok	8°42'S	116°47'E	-	-	700-1000	-	3	Morikawa *et al*. 2002
34	*Dalbergia cochinchinensis*	Thailand	Sakaerat	14°12'N	101°50'E	-	26,5	1030	-	15	JOPP 2002
35	*Dalbergia latifolia*	Indonesia	Lombok	8°42'S	116°47'E	-	-	700-1000	-	3	Morikawa *et al*. 2002
36	*Eucalyptus camaldulensis*	Thailand	Sakaerat	14°12'N	101°50'E	-	26,5	1030	-	15	JOPP 2002
37	*Eucalyptus camaldulensis*	Vietnam	Sonbe	-	-	-	21/35	1900	-	6	JOPP 1999
38	*Eucalyptus camaldulensis*	Thailand	Ladkrating	-	-	-	-	-	-	6	JOPP 2002
39	*Peronema canescens*	Indonesia	Benakat	3°05-5°28S	103°10'-104°25'E	60-200	29 (22/33)	1890-3330	-	10	JIFPRO 2002
40	*Swietenia macrophylla*	Indonesia	Benakat	3°05'-5°28'S	103°10'-104°25'E	60-200	29 (22/33)	1890-3330	-	20	JIFPRO 2002

Appendix 2. Biomass and mean annual increment of carbon (MAIC) in the plantations studied by JOPP, JIFPRO and the CIFOR's Site Management Network.

Stand No	Species	Site	Age (yr)	MAIC[a] (tC yr^{-1})	Biomass (t ha^{-1})					
					Above Ground	Stem	Bark	Branch	Leaf	Root
Industrial plantation										
1	*Acacia auriculiformis*	Sonbe	6	8.0	95.7	67.8	10.1	12.6	5.3	
2	*Acacia auriculiformis*	Vung Tau	7	9.7	136.1	92.8	18.0	20.2	5.1	15.6
3	*Acacia mangium*	Sonbe	6	10.1	121.2	92.5	15.5	9.8	3.3	
4	*Acacia mangium*	Madang	7	7.8	109.2	42.3	4.0	6.1	2.3	
5	*Acacia mangium*	Benakat	9	9.6	172.2	114.7	18.4	32.7	6.5	26.3
6	*Acacia mangium*	Subanjeriji	9	10.5	189.5	124.7	14.2	46.6	4.1	
7	*Acacia mangium*	Subanjeriji	9	8.1	145.4	105.1	12.9	23.4	4.0	
8	*Cunninghamia lanceolata*	Fujian	29	3.4	197.0					
9	*Eucalyptus globulus*	Manjimup	5	16.3	163.0	110.5	18.6	17.0	16.9	14.4
10	*Eucalyptus globulus*	Canente	5	8.6	86.1	58.2	7.7	10.2	10.0	14.5
11	*Eucalyptus globulus*	Albany	6	5.7	68.8	42.6	8.8	8.4	9.0	18.2
12	*Eucalyptus globulus*	Canente	7	10.6	148.0	104.1	13.1	16.3	14.6	24.9
13	*Eucalyptus globulus*	Manjimup	8	16.1	256.9	186.9	26.9	22.7	20.3	37.0
14	*Eucalyptus globulus*	Manjimup	8	17.2	275.0	170.0	24.0	59.6	21.5	
15	*Eucalyptus grandis*	Kwazullu	5	7.9	78.7	61.5	8.2	5.9	3.2	11.5
16	*Eucalyptus grandis*	Sao Miguel Arcanjo	7	22.9	320.7	274.6	20.2	16.1	9.8	
17	*Eucalyptus grandis*	Sao Paulo	7	10.0	140.3	125.1	8.9	3.1	3.2	24.2
18	*Eucalyptus grandis*	Kerala	7	3.1	43.5					
19	*Eucalyptus grandis*	Kerala	7	10.1	141.9					
20	*Eucalyptus grandis*	Kwazullu	7	8.6	120.6	83.2	9.0	23.7	4.7	63.2
21	*Eucalyptus grandis*	Kwazullu	8	8.4	133.7	107.4	12.8	9.3	4.3	17.8
22	*Eucalyptus grandis*	Mogi Guacu	12	13.5	324.3	281.1	16.4	19.7	7.1	
23	*Eucalyptus natural hybrids*	Pointe-Noir	8	7.1	114.3	96.3	5.9	9.4	2.6	
24	*Eucalyptus nitens*	Canente	7	8.7	122.1	83.2	10.5	13.3	15.2	20.1
25	*Eucalyptus nitens*	Canente	8	8.4	135.0	91.8	11.6	14.8	16.8	22.2
26	*Eucalyptus nitens*	Canente	11	8.9	195.1	137.1	15.3	21.2	21.6	31.0
27	*Eucalyptus spp.*	Pointe-Noir	6	11.2	134.7	95.6	6.5	23.0	9.6	
28	*Eucalyptus tereticornis*	Kerala	7	4.6	64.0	46.8	7.9	7.2	2.1	
29	*Eucalyptus tereticornis*	Kerala	7	2.4	33.7					
30	*Eucalyptus urophylla*	Guandong	7	3.1	44.0	32.6	5.6	3.4	2.4	
31	*Pinus elliottii*	Queensland	29	3.9	227.8	176.3	31.0	18.5	2.0	30.9
Rehabilitation sites										
32	*Azadirachta indica*	Lombok	3	7.6	45.5	22.5	4.1	14.3	4.6	
33	*Cassia siamea*	Lombok	3	8.6	51.6	24.7	3.3	19.5	4.1	
34	*Dalbergia cochinchinensis*	Sakaerat	15	3.5	104.0	73.5	10.1	17.1	3.4	28.8
35	*Dalbergia latifolia*	Lombok	3	5.9	35.3	14.6	4.1	15.6	1.0	

[a] Carbon content in aboveground biomass is supposed to be 50%.

Appendix 2. *Continued*

Stand No	Species	Site	Age (yr)	MAIC[a] (tC yr^{-1})	Biomass (t ha^{-1}) Above Ground	Stem	Bark	Branch	Leaf	Root
36	*Eucalyptus camaldulensis*	Ladkrating	15	2.6	78.9	61.7	7.6	7.2	2.4	20.2
37	*Eucalyptus camaldulensis*	Sonbe	6	5.1	61.1	40.1	9.3	9.9	1.7	
38	*Eucalyptus camaldulensis*	Sakaerat	6	7.9	94.7	67.1	12.4	13.7	1.5	24.2
39	*Peronema canescens*	Benakat	10	1.4	28.6	15.1	2.9	8.9	1.8	6.1
40	*Swietenia macrophylla*	Benakat	20	6.5	258.6	163.0	24.1	63.5	8.1	73.2

[a] Carbon content in aboveground biomass is supposed to be 50%.

Appendix 3. Biomass and nutrient allocation of the study sites of JOPP, JIFPRO and CIFOR's Site Management network.

Site no	Species	Site	Country	Age(yr)	Organ	Biomass (t ha^{-1})	N	P	K	Ca	Mg
							(kg ha^{-1})				
2	*A. auriculiformis*	Vung Tau	Vietnam	7	Leaf	5.1	123	2.8	35.0	18.0	5.7
					Branch	20.2	104	5.4	61.4	42.0	13.5
					Bark	18.0	183	5.0	54.7	91.0	17.4
					Stem	92.8	156	20.2	79.3	82.0	43.2
					Aboveground	136.1	566.0	33.4	230.4	233.0	79.8
4	*A. mangium*	Madang	Papua New Guinea	7	Leaf	4.6	113.3	4.4	48.1	34.2	10.8
					Branch	12.2	57.1	5.3	16.2	34.9	4.4
					Bark	8.0	95.0	2.1	19.9	65.2	1.0
					Stem	84.5	187.0	7.4	49.1	54.0	5.1
					Aboveground	109.2	452.0	19.2	133.3	189.0	21.3
6	*A. mangium*	Subanjeriji	Indonesia	9	Leaf	4.1	113	3.5	58.3	20.5	6.4
					Branch	46.6	173	1.5	59.9	128.1	17.5
					Bark	14.2	139	1.5	35.6	163.7	5.5
					Stem	124.7	236	7.8	37.4	103.5	12.5
					Aboveground	189.5	661	14.3	191.2	415.8	41.9
7	*A. mangium*	Subanjeriji	Indonesia	9	Leaf	4.0	22.8	2.8	11.2	n/a	n/a
					Branch	23.4	64.2	9.1	36.7	n/a	n/a
					Bark	12.9	41.4	7.6	23.9	n/a	n/a
					Stem	105.1	161.9	38.9	216.6	n/a	n/a
					Aboveground	145.4	290.2	58.4	288.4	n/a	n/a
8	*Cunninghamia lanceolata*	Fujian	China	29	Aboveground	197.0	195.0	39.8	241.0	246.0	76.7
12	*E. globulus*	Canete	Chile	7	Leaf	14.6	302.2	16.9	90.4	100.0	26.7
					Branch	16.3	52.3	6.6	69.2	98.9	19.6
					Bark	13.1	37.1	5.4	50.7	234.7	43.8
					Stem	104.1	74.9	23.5	129.0	72.0	32.6
					Aboveground	148.1	466.5	52.4	339.3	505.6	122.7
13	*E. globulus*	Manjimup	Australia	8	Leaf	20.4	246.8	11.4	97.3	208.5	47.5
					Branch	22.7	53.8	4.9	57.0	161.2	33.0
					Bark	26.9	51.1	3.4	50.6	582.9	51.6
					Stem	186.9	114.0	49.0	104.7	214.9	55.1
					Aboveground	256.9	465.8	68.7	309.5	1167.5	187.3
14	*E. globulus*	Manjimup	Australia	8	Leaf	21.5	259.0	14.6	n/a	315.0	n/a
					Branch	59.6	122.0	13.3	n/a	369.0	n/a
					Bark	24.0	45.0	5.8	n/a	423.0	n/a
					Stem	170.0	95.0	22.2	n/a	104.0	n/a
					Aboveground	275.0	521.0	55.9	n/a	1211.0	n/a
16	*E. grandis*	Sao Miguel Arcanjo	Brazil	7	Crown	25.9	253.5	13.2	77.5	53.8	36.0
					Bark	20.2	59.3	3.8	55.2	97.6	39.2
					Stem	274.6	204.8	9.0	140.9	59.9	30.5
					Aboveground	320.7	517.6	26.0	273.6	211.3	105.7

n/a = data not available.

Appendix 3. *Continued*

Site						Biomass	N	P	K	Ca	Mg
no	Species	Site	Country	Age(yr)	Organ	(t ha^{-1})	(kg ha^{-1})				
17	*E. grandis*	Sao Paulo	Brazil	7	Leaf	3.2	57.3	5.1	20.9	25.0	8.6
					Branch	3.1	15.5	2.5	8.1	17.7	3.1
					Bark	8.9	35.7	11.8	47.4	95.0	14.9
					Stem	125.1	223.9	18.8	106.3	110.1	16.3
					Aboveground	140.3	332.4	38.2	182.7	247.8	42.9
18	*E. grandis*	Kerala	India	7	Leaf	n/a	58.1	4.2	16.9	n/a	n/a
					Branch	n/a	15.3	2.5	16.1	n/a	n/a
					Bark	n/a	9.0	3.7	16.5	n/a	n/a
					Stem	n/a	23.5	11.9	39.9	n/a	n/a
					Aboveground	n/a	106.0	22.3	89.0	n/a	n/a
19	*E. grandis*	Kerala	India	7	Leaf	n/a	82.0	5.4	42.0	n/a	n/a
					Branch	n/a	36.7	4.7	52.7	n/a	n/a
					Bark	n/a	34.9	5.2	67.1	n/a	n/a
					Stem	n/a	78.8	12.8	109.1	n/a	n/a
					Aboveground	n/a	232.0	28.1	271.0	n/a	n/a
21	*E. grandis*	Melmoth	South Africa	8	Leaf	4.3	115.8	4.5	24.5	30.3	13.1
					Branch	9.3	13.5	2.9	30.0	35.9	8.6
					Bark	12.8	42.6	6.3	52.9	101.0	58.9
					Stem	107.4	77.3	4.1	81.6	80.8	19.3
					Aboveground	133.8	249.2	17.8	189.0	248.1	99.9
22	*E. grandis*	Mogi Guacu	Brazil	12	Crown	26.8	211.3	15.8	126.4	79.0	23.6
					Bark	16.4	53.3	14.0	37.8	98.0	14.3
					Stem	281.1	198.6	16.6	69.4	37.1	16.0
					Aboveground	324.3	463.2	46.4	233.6	214.1	53.9
23	*E.* natural hybrids	Pointe-Noire	Congo	8	Leaf	2.6	65.1	4.3	14.6	7.4	6.0
					Branch	9.4	39.5	7.4	15.9	7.9	5.8
					Bark	5.9	31.0	10.9	23.1	25.7	16.4
					Stem	96.3	158.2	22.2	57.1	27.7	16.5
					Aboveground	114.3	293.8	44.8	110.7	68.7	44.7
26	*E. nitens*	Canete	Chile	11	Leaf	21.6	338.8	19.8	113.0	81.9	22.2
					Branch	21.2	99.0	9.2	28.1	60.5	7.7
					Bark	15.3	49.1	4.7	73.6	208.7	15.7
					Stem	137.1	76.8	17.9	113.8	9.8	8.3
					Aboveground	195.2	563.7	51.7	328.5	360.8	53.7
27	*E.* spp.	Pointe-Noire	Congo	6	Leaf	3.8	56.3	3.9	11.9	6.7	7.7
					Branch	9.6	21.5	5.0	6.3	6.5	5.1
					Bark	6.5	20.7	9.8	12.6	23.8	17.6
					Stem	95.6	115.6	16.0	34.2	15.4	11.5
					Aboveground	115.5	214.1	34.7	65.0	52.4	41.9
28	*E. tereticornis*	Kerala	India	7	Leaf	2.1	38.9	2.4	23.0	20.7	5.2
					Branch	7.2	32.6	8.2	45.9	126.4	10.6
					Bark	7.9	32.5	11.0	70.7	170.8	16.4
					Stem	46.8	74.6	20.7	90.3	91.2	12.9
					Aboveground	64.0	178.6	42.4	229.9	409.1	45.1

n/a = data not available.

Cont.

Appendix 3. *Continued*

Site no	Species	Site	Country	Age(yr)	Organ	Biomass (t ha^{-1})	N (kg ha^{-1})	P	K	Ca	Mg
29	*E. tereticornis*	Kerala	India	7	Leaf	n/a	20.7	1.3	14.5	n/a	n/a
					Branch	n/a	8.1	1.5	12.3	n/a	n/a
					Bark	n/a	20.1	2.6	24.3	n/a	n/a
					Stem	n/a	42.7	2.9	33.3	n/a	n/a
					Aboveground	n/a	92.0	8.3	85.0	n/a	n/a
30	*E. urophylla*	Guangdong	China	7	Aboveground	44.0	106.0	8.0	48.0	55.0	16.0
31	*P. elliottii*	Queensland	Australia	29.4	Leaf	2.0	16.0	1.3	4.1	7.8	4.0
					Branch	18.5	41.8	3.6	15.7	58.0	15.4
					Bark	31.0	61.2	5.4	26.6	66.1	20.3
					Stem	176.3	129.4	5.4	37.1	105.4	44.7
					Aboveground	227.8	248.4	15.7	83.5	237.3	84.4
34	*Dalbergia cochinchinensis*	Sakaerat	Thailand	15	Leaf	3.4	76.0	2.7	33.0	21.0	10.0
					Branch	17.1	128.0	3.0	66.0	93.0	19.0
					Bark	10.1	134.0	1.8	65.0	88.0	8.0
					Stem	73.5	187.0	1.7	114.0	45.0	2.3
					Aboveground	104.0	525.0	9.2	278.0	247.0	39.3
36	*E. camaldulensis*	Sakaerat	Thailand	15	Leaf	1.5	27.0	1.7	16.0	15.0	3.0
					Branch	13.7	39.0	1.6	33.0	82.0	8.0
					Bark	12.4	29.0	1.9	54.0	332.0	24.0
					Stem	67.1	123.0	0.7	49.0	19.0	0.7
					Aboveground	94.7	218.0	5.9	152.0	448.0	35.7
38	*E. camaldulensis*	Ladkrating	Thailand	6	Leaf	2.4	48.0	2.0	29.0	22.0	5.0
					Branch	7.2	43.0	1.9	42.0	39.0	4.0
					Bark	7.6	30.0	1.5	57.0	290.0	14.0
					Stem	61.7	183.0	0.8	193.0	27.0	14.0
					Aboveground	78.9	304.0	6.2	321.0	378.0	37.0

n/a = data not available.

These proceedings present results from research in progress in the CIFOR project *Site Management and Productivity in Tropical Plantations*. They include papers presented at workshops in Pointe-Noire, Congo in July 2001 and at Guangzhou and Haikou, China in February 2003. These papers complement those presented at workshops in Pietermaritzburg, South Africa in 1998 and Kerala, India in 1999, which described the experimental basis for the research and presented preliminary results. 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 management. Good management of this phase, between harvesting and tree establishment in the next rotation, is critical for the future outcome of plantations. There is potential for physical and chemical soil degradation, but also to introduce sound new technologies to improve long-term soil management. Although the species and the soil problems vary according to local conditions, all the experiments are designed to provide knowledge that will benefit both the specific sites and our understanding of underlying processes influencing plantation productivity.