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

J.D. Nzila[1], P. Deleporte[1], J.P. Bouillet[2], J.P. Laclau[3], and J. Ranger[4]

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

[1] UR2PI, PO Box 1291, Pointe-Noire, Congo. Tel: +242-943184, Fax: +242-944795, E-mail: cir11@ calva.com or jdnzila@hotmail.com
[2] CIRAD-Forêt, Campus de Baillarguet, Montpellier, France.
[3] CIRAD-Forêt/Universidade de São Paulo/ESALQ, Piracicaba, Brazil.
[4] INRA, Centre de Nancy, Equipe Cycles Biogéochimiques, 54280 Champenoux, France. E-mail: ranger@nancy.inra.fr

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	N	P	K	Ca	Mg
	t ha^{-1}	(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

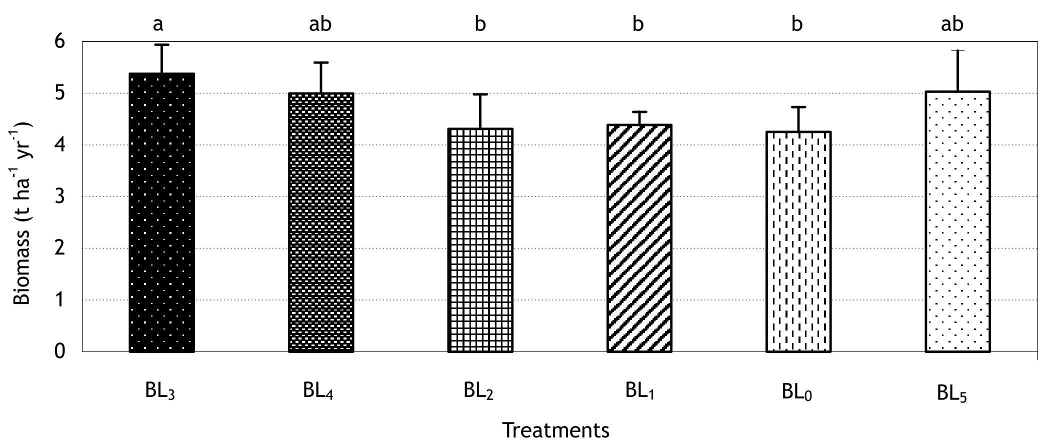
Letters a, b and c indicate significant differences ($p<0.05$) between treatments according to Bonferroni test.

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 (kg ha^{-1})	P	K	Ca	Mg
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 $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ 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	0.34	16.4	0.08	0.05	0.03	0.02	0.26	0.1	0.17	0.45	38.7
		(0.14)	*(0.01)*		*(0.04)*	*(0.03)*	*(0.01)*	*(0.01)*	*(0.04)*	*(0.02)*	*(0.08)*	*(0.06)*	
	1	0.5	0.31	16.2	0.01	0.02	0.02	0.01	0.27	0.08	0.06	0.45	12.3
		(0.11)	*(0.06)*		*(0.01)*	*(0.01)*	*(0.01)*	*(0.004)*	*(0.05)*	*(0.005)*	*(0.01)*	*(0.04)*	
	3	0.5	0.31	16.5	0.01	0.02	0.02	0.01	0.26	0.08	0.06	0.38	16.3
		(0.16)	*(0.09)*		*(0.01)*	*(0.01)*	*0*	*(0.003)*	*(0.07)*	*(0.02)*	*(0.01)*	*(0.12)*	
Changes after 3 years (%)		*-9*	*-10*	*1*	*-88*	*-52*	*-21*	*-58*	*0*	*-23*	*-64*	*-15*	*-58*
BL_1	0	0.55	0.34	16.2	0.07	0.04	0.02	0.01	0.29	0.1	0.15	0.45	32.2
		(0.01)	*(0.01)*		*(0.002)*	*(0.01)*	*(0.005)*	*(0.01)*	*(0.01)*	*(0.002)*	*(0.01)*	*(0.04)*	
	1	0.53	0.34	15.4	0.01	0.04	0.02	0.01	0.26	0.09	0.08	0.44	17.3
		(0.02)	*(0.01)*		*(0.002)*	*(0.01)*	*0*	*(0.01)*	*(0.02)*	*(0.01)*	*(0.02)*	*(0.05)*	
	3	0.55	0.33	16.7	0.01	0.02	0.04	0.01	0.31	0.08	0.08	0.43	17.5
		(0.04)	*(0.03)*		*0*	*0*	*(0.01)*	*(0.01)*	*(0.02)*	*0*	*(0.001)*	*(0.05)*	
Changes after 3 years (%)		*0*	*-3*	*3*	*-86*	*-53*	*64*	*-13*	*6*	*-13*	*-48*	*-5*	*-46*
BL_2	0	0.51	0.35	14.6	0.06	0.03	0.02	0.01	0.28	0.08	0.13	0.43	29.9
		(0.03)	*(0.06)*		*(0.01)*	*(0.01)*	*(0.05)*	*(0.01)*	*(0.01)*	*(0.002)*	*(0.01)*	*(0.03)*	
	1	0.55	0.36	15.1	0.01	0.03	0.04	0.01	0.29	0.1	0.09	0.46	19.5
		(0.05)	*(0.04)*		*(0.01)*	*(0.01)*	*(0.002)*	*(0.00)*	*(0.01)*	*(0.01)*	*(0.01)*	*(0.02)*	
	3	0.52	0.32	16.3	0.01	0.02	0.03	0.01	0.29	0.08	0.06	0.41	15.7
		(0.01)	*(0.01)*		*(0.00)*	*(0.001)*	*(0.01)*	*(0.004)*	*(0.003)*	*(0.01)*	*(0.005)*	*(0.03)*	
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*

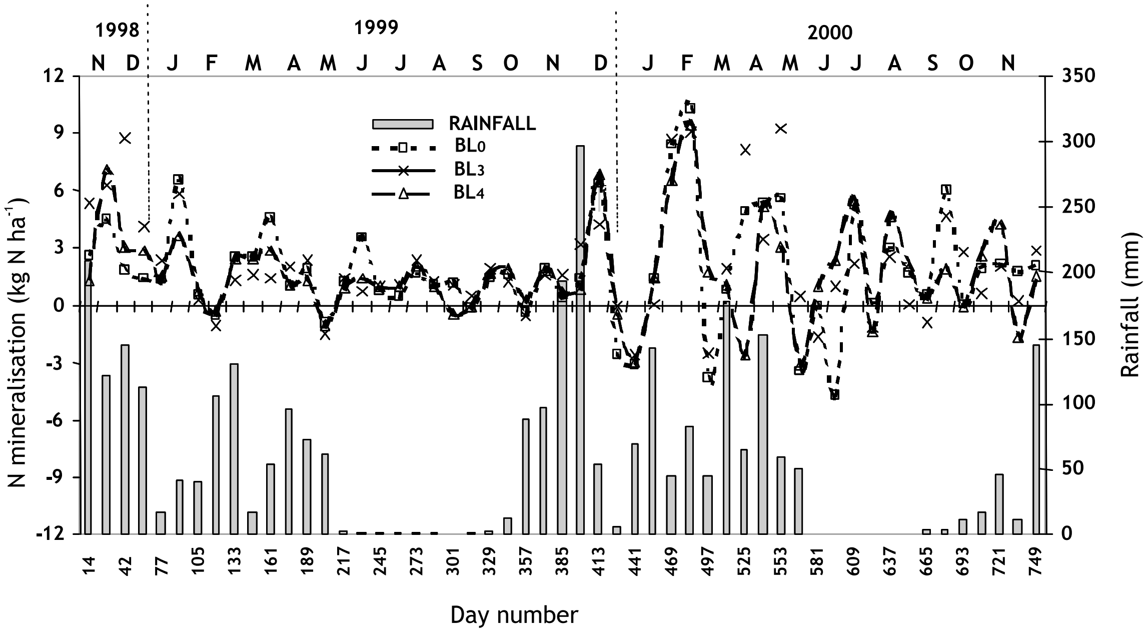
S/T= base cation saturation, with S = exchangeable cations sum (Ca+Mg+K+Na), and T = Cation Exchange Capacity (CEC).
Differences between treatments according to Bonferroni test are not presented to keep the table readable.

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.

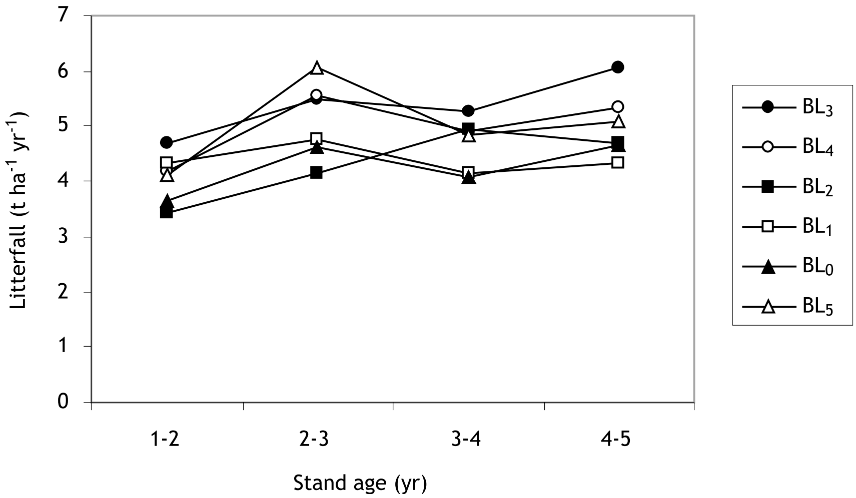
This result was consistent with the stand's increased need for N observed throughout successive rotations (Bouillet *et al.* 2001b). Therefore, N released during slash and litter decomposition might partly explain the growth differences observed among treatments.

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.

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