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NOTA

Improvement of site productivity for short-rotation plantations in Brazil*

Mejoramiento de la productividad de sitio para plantaciones de corta rotación en Brasil

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RESUMEN

Las plantaciones con especies de rápido crecimiento, manejadas en rotaciones cortas y en sucesivas cosechas, acumulan cantidades considerables de nutrientes, en cortos períodos de tiempo. La baja fertilidad de las tierras brasileñas, principalmente aquellas usadas para las plantaciones forestales, no puede proporcionar a los árboles la cantidad de elementos nutritivos requerida, por lo tanto la aplicación de fertilizantes y otras fuentes de nutrientes es necesaria para obtener una alta productividad. El éxito del futuro manejo de los bosques dependerá de la capacidad de los ingenieros forestales para obtener una alta productividad de madera objetivo, en una manera compatible con el medio ambiente. Las prácticas de manejo de los bosques afectan el ambiente y la calidad de la madera, por lo tanto, las preguntas cruciales que deben enfrentar los investigadores brasileños están relacionadas con las mejores técnicas para compatibilizar la conservación de los recursos y del ambiente con la producción de madera. En esta revisión bibliográfica se discuten algunas estrategias de manejo para conservar y mejorar las condiciones físicas y químicas del suelo sometido a sucesivas cosechas en plantaciones altamente productivas, que aseguren la sustentabilidad del rendimiento.

Palabras claves: plantaciones, *Eucalyptus, Pinus,* fertilización, nutrición mineral.

SUMMARY

Short-rotation plantations of fast-growing species managed in successive crops accumulate large amounts of nutrients in short periods of time. Brazilian soils, mainly those used for forest plantations are not able to supply the nutritional requirements of the trees, thus needing fertiliser application or other nutrient sources to obtain a high productivity. The success of future forest activities will depend on the ability of forest managers to obtain high productivity of wood while maintaining the environment. How forest management practices affect environment and wood qualities, and which are the best techniques to preserve environmental resources and obtain wood are crucial questions that need great efforts from Brazilian researchers. This paper discusses some management strategies to conserve and improve the physical and chemical conditions of soil, exposed to successive harvesting of highly productive forest plantations, maintaining the yields in a sustainable way.

Key words: forest plantation, *Eucalyptus, Pinus,* fertilisation, mineral nutrition.

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I. INTRODUCTION

The growing demand for world-wide and national forest products in the last 50 years, as well as the intense harvesting pressure on Brazilian native forests have stimulated the public and private initiative to establish extensive forest areas with fast growing species. Brazil has now about 6 million reforested hectares with homogeneous plantations, *Eucalyptus* (52%) and *Pinus* (30%) being the prevailing species. Presently, the forest sector plays an important part in the Brazilian economy. On a broad scale, the combination of mean annual temperature and mean annual precipitation favours high rates of forest productivity.

The sustainability of medium and long-term plantations is often questioned, both academically and technically. This is so because most of the plantations were established on soils covered by "cerrado vegetation", which has low nutrient reserves. To increase the productivity rates, the forestry plantation systems used in Brazil are very intensive, including the establishment of fast growing species (provenances, clones) with high nutrient extraction and output capacity.

The area of natural "cerrado" vegetation (Brazilian savannah), where most of the *Eucalyptus* and *Pinus* stands are established as well as where most of the research mentioned in this paper was developed, occupies 1,8 million km^2, i.e., about 20% of the Brazilian territory. It extends mainly in the central-western region, with smaller areas in the north, northeastern and southeastern regions, between 5° to 21° S and 43° to 63° W. Altitudes vary between 500 to 800 m. The Aw type climate (humid tropical climate with dry winters, classification by Köppen). predominates. The annual mean temperature varies between 20° to 26°C. There is a great variation in the mean annual precipitation and its distribution along the year. Most of the area presents a rainy period (November to April) and another dry period (May to October),with 80% of the rainfall concentrated during the rainy period. About 65% of the surface area receives between 1200 and 1800 mm of rain. The period of hydric deficit varies from 4 to 7 months (Adámoli *et al.* 1986).The main soil units in the "cerrado" region are Latosols (Oxisols, 56% of the area), Quartzitic Sands (Entisols/Psamments, 20% of the area), Acrisols (Ultisols, 10% of the area), Lithosols and Cambisols (Inceptisols, 9% of the area) and Podsols (Ultisols, 5% of the area) (Sánchez 1981).

During the last 10 years, the 'minimum soil cultivation' system has been practised in Brazilian plantations. This consists in the retention of slash of the previous harvest in the rows, debarking at the site and distributing barks in between rows, no burning, and restricted soil preparation to the lines or planting holes. Restricted soil preparation and maintenance of vegetal residues on the land produces pronounced effects on the nutrient pools of the ecosystem, and consequently on soil fertility in the long and short-term. Thus, nutrient economy is greatly benefited by the reduction of loss through water and wind erosion, leaching and volatilisation.

Since most of the Brazilian soils are not fertile enough to sustain ideal forest productivity in the commercial sense, fertiliser application and/or other sources of nutrient are necessary to increase or to maintain productivity.

The great expansion of the pulp, paper and steel industry in Brazil in the last two decades has generated large amounts of solid and liquid residues which have become crucial economical and environmental issues. Several forestry companies have used industrial and urban residues as nutrient sources and improvement agents of physical characteristics of the soil. The use of iron slag, dregs and grits, organic sludge, forest wood ash and compost from municipal garbage has become a common practice in eucalyptus and pine forestry plantations.

2. IMPACT OF SUCCESSIVE HARVESTING ON NUTRIENT RESERVES

In forest plantations, nutrient removal through the harvested components represents a considerable drain in the nutrient capital of the ecosystem, since a large proportion of the nutrients is in the biomass. Loss may also occur indirectly through processes such as leaching, erosion, and volatilisation. This loss is enhanced by a faster rate of organic matter decomposition at the exposed sites. Slash burning and intensive soil preparation for planting are also potential factors which influence nutrient loss. The amount of nutrients removed by harvesting depend upon the amount of harvested tree components (figure 1), species, stand development, and site quality. Even if only the stem is harvested, the amount of nutrients removed is very high, especially if the forest is managed in short rotations. Although a close correlation may be expected between yield and nutrient removal, large variations in the rate of nutrient removal may indicate differences in soil nutrient availability, in the nutritional requirements of the species, stand age, climatic conditions, sampling methods and others. The amount of nutrients required for biomass of several species planted in Brazil, is quite variable (table 1). An important difference that can be deduced from table 1 is the rate of removal of each nutrient among genera.

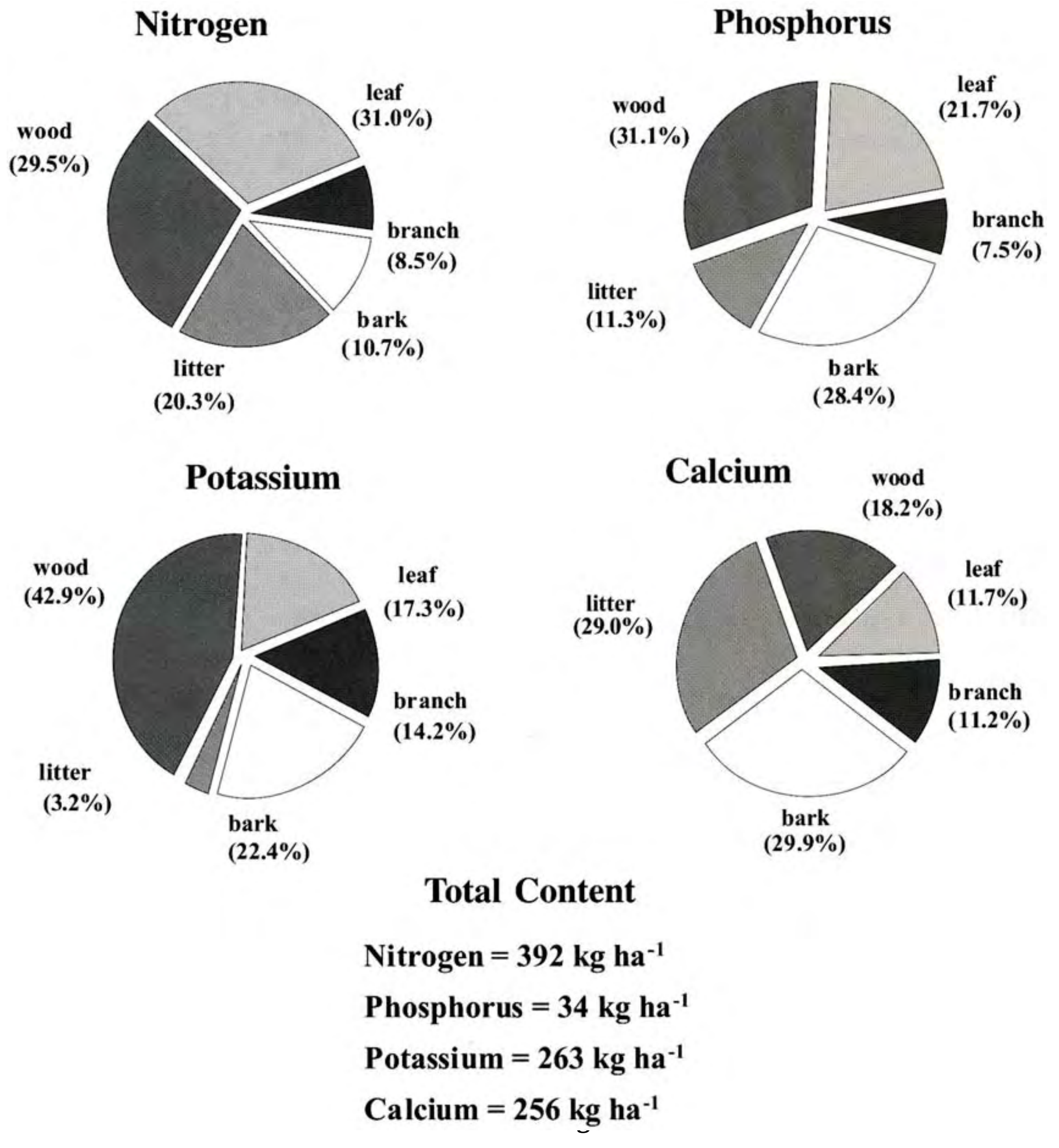

Figure 1. Mean contents of N, P, K and Ca in the leaves, branches, barks, wood and litter of 17 *Eucalyptus grandis* stands, mean age of 5.6 years and productivity range of 54 to 290 m^3 ha^{-1} of debarked wood (Gonçalves 1995).
Cantidades medias de N, P, K y Ca en las hojas, ramas, corteza, madera y "litter" de 17 plantaciones del *Eucalyptus grandis*, con edad media de 5.6 años y rango de productividad de 54 a 290 m^3 ha^{-1} de madera sin corteza (Gonçalves 1995).

TABLE 1

Macronutrients accumulated in wood and bark of different species of *Eucalyptus* and *Pinus*, also in some agricultural crops.

Macronutrientes acumulados en madera y corteza de diferentes especies de *Eucaliptus* y *Pinus*, también en algunas cosechas agrícolas.

Species	Age (years)	Comp.[1]	Biomass ($t\ ha^{-1}$)	Quantity of nutrients ($kg\ t^{-1}$)					Refer.[2]
				N	P	K	Ca	Mg	
E. grandis	10	W	160	0.8	0.02	0.6	1.7	0.5	1
		B	23	3.0	0.27	3.0	3.1	1.0	
E. grandis	6	W	62	2.3	0.11	0.8	0.5	0.2	2
		B	11	3.4	0.76	6.0	7.9	1.4	
E. citriodora	9	W	65	1.8	0.56	1.4	1.1	0.6	3
		B	17	3.1	0.42	4.6	8.5	3.2	
E. grandis	7	W + B	227	1.5	0.13	1.1	2.7	0.5	4
E. saligna	10	W	129	0.9	0.23	0.6	0.8	0.1	5
		B	8	3.1	1.51	6.0	9.5	3.9	
P. oocarpa	8	W	70	1.3	0.12	0.9	0.5	0.2	6
		B	15	3.1	0.17	1.2	1.3	0.2	
	18	W	131	1.1	0.07	0.6	0.6	0.2	
		B	19	2.6	0.17	1.1	0.7	0.3	
P. elliottii	24	W	398	0.9	0.10	0.3	0.1	0.1	7
		B	65	1.7	0.15	0.6	0.1	0.1	
Sugar cane		Stem	100	1.3	0.08	1.1	0.1	0.2	8
Coffee		Pulp	2	16.5	1.50	26.0	3.5	1.5	
Corn		Grain	5	23.0	5.60	7.0	0.4	2.0	
Soy bean		Grain	3	66.7	8.67	19.0	3.3	3.3	

[1] Components of the tree: W = wood; B = bark

[2] References: 1. Silva *et al.* 1983, 2. Reis *et al.* 1987, 3. Pereira *et al.* 1984, 4. Bellote *et al.* 1980, 5. Poggiani 1985, 6. Castro *et al.* 1980, 7. Torraca *et al.* 1984, 8. Malavolta 1976.

Figure 2 shows the mean accumulation rate of N, P, K and Ca in the biomass of the tree above-ground components of eucalyptus plantations in Brazil, including several species, site conditions, silvicultural management and stand ages from 2 to 10 years (Gonçalves *et al.* 1997a). The good fit of the equation indicates the close relation between growth rate, nutrient accumulation and uptake in eucalyptus plantations. The scattering of the points, particularly of P, may be due to differences in the soil P-buffering power, among other reasons such as sampling errors, fertilisation and rainfall regimes. This has been shown to strongly affect P uptake by eucalyptus (Neves *et al.,* 1986),

Since nutrient removal by short rotation is very high, the input of nutrients through fertiliser application, urban and industrial residue recycling as well as alternative site management (minimum soil cultivation) may be necessary to sustain forest productivity. Species with higher nutrient uptake and use efficiency are desirable for poor soils due to their capacity of rapidly taking up and using the nutrients released by site preparation and fertiliser application. In addition, these species are also preferred in order to remove the least possible amount of nutrient per unit of harvested product.

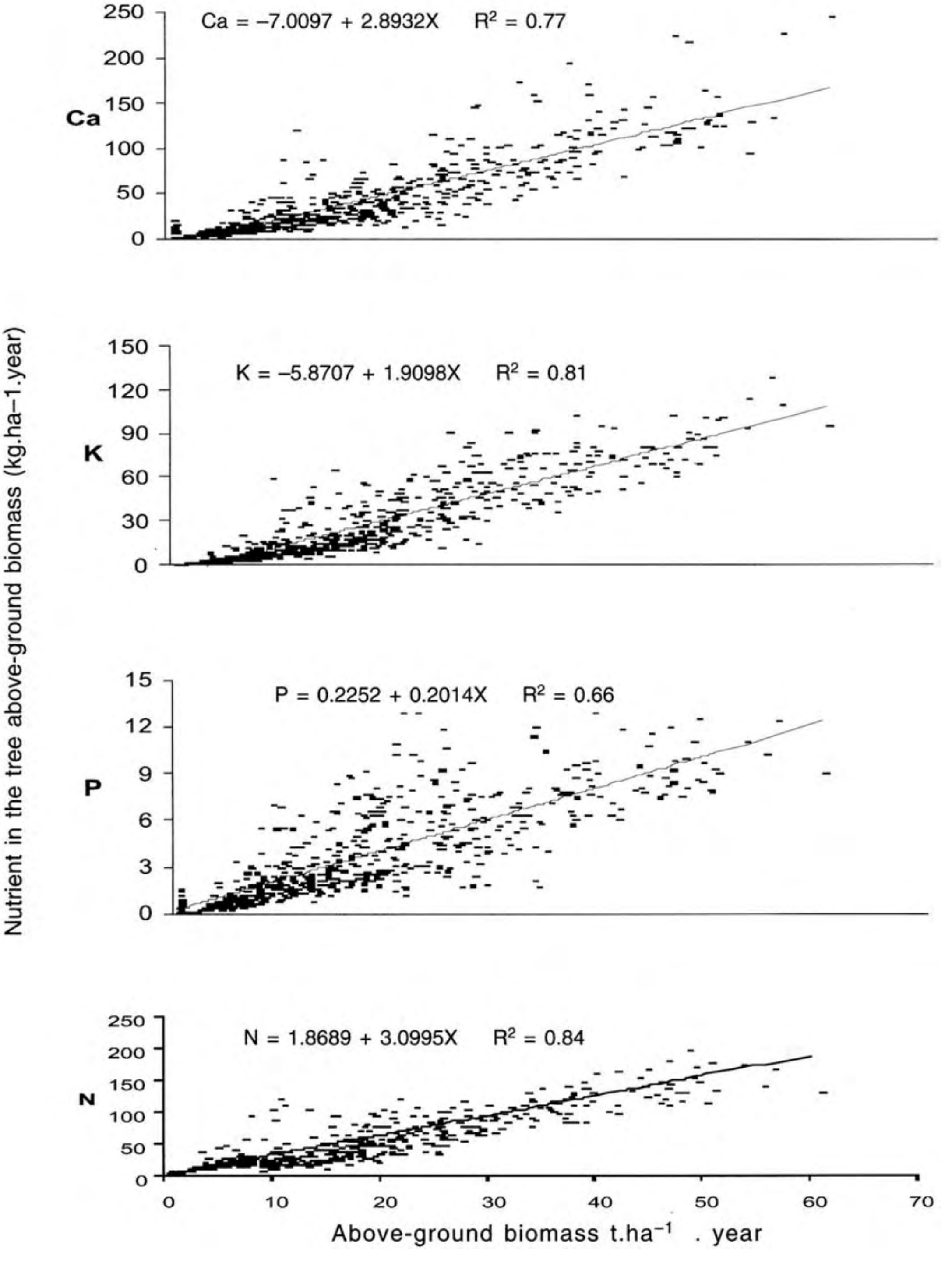

Figure 2. Rates of N, P, K, and Ca accumulated in above-ground biomass of different species and ages of *Eucalyptus* stands of Brazil.

Proporciones de N, P, K y Ca acumuladas en la biomasa de la parte aérea de diferentes especies y edades de plantaciones del *Eucalyptus* en Brasil.

3. MINIMUM SOIL CULTIVATION

The amount of nutrients present in the crown (leaves and branches), bark and litter (main components of the harvest residues) represent a very significant percentage of the nutrient pool of a forest plantation (figure 1, Gonçalves 1995). Figure 1 shows that approximately 51 to 82% of the nutrients of the above-ground biomass are contained in the harvest residues (leaves, branches, litter and bark). Bark removal represents a loss of 10.7, 28.4, 22.4 and 29.8% of N, P, K and Ca, respectively. Maluf (1991) observed that forest residue burning in the Brazilian 'cerrado' region represented a loss of 88% of N, 33% of P, 30% of K, 47% of Ca and 43% of Mg of the total nutrient content present in the residues. The output of these nutrients from the system is carried out by volatilisation and aerial transport of ashes. It is important to note the high loss of nutrients considered as not volatile, for example P, K and Ca. In relation to P, Cotton & Wilkinson (1988) affirm that this nutrient is volatilised when temperatures reach levels superior to 360°C. Raison *et al.* (1988) also verified an accentuated loss of P in eucalyptus residues which rendered values equivalent to 50% of the total amount. Applying the loss percentage observed by Maluf (1991) to the data provided by Gonçalves (1995), it results that residue burning produces a loss of 345 kg of N, 11 kg of P, 79 kg of K and 129 kg of Ca per hectare. A large part of the nutrients can also be removed by wind, runoff and water that percolates into the soil.

From the operational point of view, site preparation and early tending practices in the establishment phase have a major influence on soil and water properties. Minimum soil cultivation has been successfully accepted in Brazil as an alternative method to avoid the detrimental effect of burning and intensive soil preparation, especially in areas to be replanted (Disperati *et al.* 1995). Basically, this method consists in not burning the slash of the previous harvest and laying it in rows without removing the top soil. Seedlings are then planted in hand or machine-made pits or in furrows (about 20 cm wide and 40 cm deep) opened by one-tine ripper. Fertilisers are applied in the pit or furrow. If grass is the main competing weed, pre and post-emergent herbicides are applied on the planting rows at the beginning.

In Brazil it is common to observe higher early growth rates of trees planted in areas where slash burning was used, as compared to unburned areas. This can be attributed to a temporal increase in nutrient availability in the soil of the burnt areas. Zen *et al.* (1994) reported gains of 20% and 10% in the height of *Eucalyptus grandis* in areas with slash burn or slash incorporation to the soil respectively, as compared to where slash was not burned and left on the surface of a Quartzitic Sands soil in southeastern Brazil. However, no difference was observed between treatments 6.6 years later. In another trial, where fertiliser application was combined with soil preparation, a higher volume of *E. grandis* was observed with minimum sod preparation (no-slash burn and ripping with one tine) than with intensive preparation (slash burning plus disk plowing). The differences between the two trials were of 27.5% after two years and of 6.5% after six years. Therefore, in soils with low fertility levels, burning the slash with the associated consequences such as volatilisation, leaching and enhanced mineralisation may lead to the need of increasing the rate of fertiliser application, so as to avoid a decrease in forest productivity (Gonçalves *et al.* 1997b). These authors observed that slash burning notably inhibited the N mineralisation rate in a recently established *Eucalyptus grandis* stand. Only 28 kg ha^{-1} of N were mineralised against 58 kg ha^{-1} of N where minimum soil cultivation was used.

4. FERTILISER APPLICATION

Fertilisation is needed since soils are not always able to supply all the nutrients required for suitable growth. Even in more fertile soils, the indices of forest growth can be increased with fertilisation, depending on species nutritional requirements, soil moisture and nutrient availability, together with the silvicultural practices.

Before canopy closure. As the nutrient supply to the trees needs to parallel the trees' nutritional demands, it is recommended to split the fertiliser doses in two, adding one part during plantation and the other part during the months before canopy closure. This strategy reduces nutrient loss by volatilisation, leaching, immobilisation and erosion. Usually, the quantity of applied fertiliser has very little effect on the fertility of the soil, but it supplies adequate levels of nutrition to the roots, at a stage when the orientation of root growth and rooting intensity are being determined.

Concerning macronutrients, the visual symptoms of deficiency in eucalyptus and pine plantations, and the response to fertiliser application in order of importance is: P K Ca; among micronutrients: B Zn Cu. N, S and Mg deficiency are usually very rare. The quantity of N, P, and K required varies considerably depending on soil factors, such as organic matter content, parental material and water regime. The applied doses generally range between 30-50, 30-80, 30-100, 1-3 and 1-1.5 kg ha^{-1}, for N, P, K, B and Zn, respectively (Gonçalves *et al.* 1997a). It is recommended to apply 20 to 40% of N and K doses, and a 100% dose of P, at planting time. Alternatively, to avoid high P-fixation mainly in clay soils, it is also suggested to split the P doses, as recommended for N and K. Together with the application of NPK-fertilisers, B and Zn should be applied in a mixture or through individual sources in the planting hole or furrow.

The major response to fertilization at planting is with P, mainly because P content in the forest topsoil is low (Herbert and Schönau, 1989; Barros *et al.*, 1990; Gonçalves, 1995). More recently K (Barros *et al.* 1997, Gava 1997), and Ca responses have increased very much, mainly at sites where several rotations were cultivated. Most of the soils have little or no primary minerals rich in these nutrients. On the other hand, when the soil has some reserves of these minerals, mainly younger soils, part of the nutrients become available through weathering.

B supply is particularly important, mainly in the regions where dieback is common. This is a phenomenon very often found in certain 'cerrado' sites in the centre of Brazil, where water deficit is very high. As for nutrients with low mobility in the soil such as Cu and Zn, they should be applied, as indicated for P, close to the roots at planting time.

Regarding the fertilising methods, a localised application is more adequate for nutrients with low mobility in the soil, depending on fertiliser solubility and soil reaction. Water-soluble P sources should not be mixed with high P-fixing soils; instead they should be placed at the bottom of the furrows or in the planting holes (Barros *et al.* 1990 and Gava *et al.* 1997). In high P-fixing soils, particularly those rich in microorganisms involved in P immobilisation and Fe and Al oxides, it is recommended to apply the medium and low soluble sources of P more localised in the furrows. These P sources can be found as thermophosphates, partially soluble rock phosphate (PSRP) and rock phosphates. Recent field trials with eucalyptus present better growth responses when these phosphates are applied this way. Older techniques recommend the application of thermophosphates and PSRP in bands of 1.0 to 1.5 m of width, mainly under the planting line. Rock phosphate was spread and incorporated into the 10 cm topsoil layer in the whole area, during soil preparation. No more than 30 to 50% of the total P dose should be applied as rock phosphate (Gonçalves, 1995).

Considering that nutrient requirement is higher in the younger stands (table 2), an efficient strategy for P nutrition is to combine the application of a water-soluble source of P in the planting hole or furrows (as a fertilisation starter), with a water-insoluble sources such as phosphate rock, which would supply P to the trees after the establishment phase. This approach was tested by Leal *et al.* (1988) in *E. grandis* plantations in the Brazilian savannah area, with significant gains in productivity. In 5 year old stands, the results showed that after fertilising with a soluble source alone or combined with 2 t ha^{-1} of rock phosphate there was a volume increase of 97 m^3 ha^{-1} and 182 m^3 ha^{-1}, respectively, compared to 67 m^3 ha^{-1} in the unfertilised plots. The application of rock phosphate enriched the Ca and P cycling as indicated by the increased concentration of these nutrients in all the tree components, litter included.

Choosing the fertiliser source has a great importance for the nutritional equilibrium of the trees. The use of primary sources containing secondary nutrients such as Ca, Mg, S and micro-nutrients usually produces higher growth responses than more concentrated fertilisers, poor in these nutrients. When single superphosphate and thermophosphate have been used as a P source, the application of lime as a source of Ca may not be necessary. Experimental results from Brazil (Novais *et al.* 1980 e Gonçalves *et al.* 1986) and South Africa (Schönau 1977, Herbert 1983, Schönau and Herbert 1983) indicate that lime application is not justified to amend soil acidity and to neutralise the excess of exchangeable Al and Mn in stands with acid-tolerant species, such as the majority of *Eucalyptus* and *Pinus* species.

TABLE 2

Estimated critical soil nutrient levels for the growth of *Eucalyptus grandis* managed an 8-yr rotation (Novais *et al.* 1986).

Niveles críticos estimados de nutrientes en los suelos para el crecimiento de *Eucalyptus grandis* manejado en rotaciones de 8 años (Novais *et al.* 1986).

Element[1]	Establishment critical level	Maintenance critical level (1-*i* yr)				
		Mean annual increment ($m^3\ ha^{-1}\ yr^{-1}$)				
	(0-1 yr)	10	20	30	40	50
P ($mg\ dm^{-3}$)						
- Clay soil	60	4.1	4.3	4.3	4.4	4.5
- Sandy soil	80	6.1	6.2	6.3	6.4	6.5
K ($mg\ dm^{-3}$)	10	30	45	60	75	90
Ca ($cmol_c\ dm^{-3}$)	0.20	0.30	0.45	0.60	0.70	0.80
Mg ($cmol_c\ dm^{-3}$)	0.05	0.07	0.10	0.13	0.16	0.19

[1] Soil sampled in the upper 20 cm; P and K extracted by double-acid extractant; Ca and Mg extracted by 1 mol L^{-1} KC1.

Around 60 to 80% of the N and K doses, and optionally part of the P doses, are recommended as an after planting application. Usually, these quantities are split in 2 to 4 applications, preferably during the earlier phases of growth (period of leaf area expansion), before canopy closure. Fertilisers can be applied in semicircles under the crown projection or later in bands between the planting rows.

Since nutrient demand varies with the stand's nutritional development, Novais *et al.* (1986) proposed two sets of critical nutrient levels in the soil for eucalyptus (table 2). The first set (critical levels at forest planting) refers to levels that allow seedling establishment in the field, from planting time up to 6-12 months later, depending on site quality. The second set of critical levels, known as maintenance level, is supposed to be high enough to sustain eucalyptus growth through the whole rotation age, which in Brazil is of 8 years. As can be observed in table 2, the critical levels of maintenance increase with site quality, being highest for sites where the growth rate is high. The critical levels were determined based on information for *E. grandis*.

The nutrient requirements of species with the same genus do not appear to vary greatly, and an interpolation of results from studies of species within a genus across a range of sites has proved meaningful. Knowledge concerning the nutrient absorption curve is of great value in defining the time, frequency and need for splitting fertiliser applications. If information about these variables is available, a computer model to help the operational fertilisation of fast-growing plantations can be developed. A preliminary model called NUTRICALC has been developed to estimate nutrient balance and to make fertilising recommendations for eucalyptus plantations in highly weathered soils in Brazil (Barros *et al.* 1992).

Gonçalves *et al.* (1996) proposed interpretation tables of soil analysis, as well as fertilising recommendation for eucalyptus and pine plantations. The conclusions of this work are based on a wide analysis of several fertiliser trials carried out in Brazil, and on the fertilising experience of Brazilian forest companies in these genera. The interpretation and recommendation of N fertilisation takes into account the organic matter content of the soil and the main source of N (table 3). For P and K (tables 4 and 5), the available content of these nutrients and the texture of the soil is considered. One of the basic aspects of these tables is that the organic matter and clay contents of the majority of Brazilian soils have a close relationship with the growth rates. Larger doses, mainly of K (up to 120 Kg ha-1 of K), have been used by some forest companies with high technology (Gava 1997), at sites established with very productive genetic materials and used previously with several rotations. The same author proposed a formula (little modified in this paper) to calculate the amounts of dolomitic lime that should be applied to obtain appropriate Ca and Mg contents in the soils:

$$NL = \frac{(20 - (Ca + Mg))}{10}$$

where,
NL = needs of dolomitic lime (t ha-1).
Ca + Mg = exchangeable contents in the soil.

TABLE 3

N fertilizer recommendation for Eucalyptus and Pinus species based on organic matter content of the soil (Gonçalves *et al.* 1996).
Recomendación de fertilizantes nitrogenados para especies de Eucalyptus y Pinus basadas en el volumen de la materia orgánico del suelo (Gonçalves *et al.* 1996)

Genus	Soil organic matter (g dm^{-3})		
	0-15	16-40	> 40
	kg ha^{-1} de N		
Eucalyptus	60	40	20
Pinus	30	20	0

TABLE 4

P fertilizer recommendation for *Eucalyptus* and *Pinus* species based on clay and available P content in the soil (Gonçalves *et al.* 1996).
Dosis de fertilizantes fosfatados para especies de *Eucalyptus* y *Pinus* basadas en el contenido de arcilla y el P disponible en el suelo (Gonçalves *et al.* 1996)

Clay content	Genus	P-resin content (mg dm^{-3})			
		0-2	3-5	6-8	> 8
(%)		— Rate of P_2O_5 (kg ha^{-1}) —			
< 15	*Eucalyptus*	60	40	20	0
	Pinus	30	20	0	0
15-35	*Eucalyptus*	90	70	50	20
	Pinus	45	35	0	0
> 35	*Eucalyptus*	120	100	60	30
	Pinus	60	50	0	0

TABLE 5

K fertilizer recommendation for *Eucalyptus* and *Pinus* species based on clay and exchangeable K content in the soil (Gonçalves *et al.* 1996).
Recomendación de fertilizantes potásicos para especies de *Eucalyptus* y *Pinus* basados en el contenido de arcilla y el K intercambiable en el suelo (Gonçalves *et al.* 1996).

Clay content	Genus	Exchangeable K ($mmol_3$ dm^{-3})		
		0-0.7	0.8-1.5	> 1.5
(%)		— Rates of K_20 (kg ha^{-1}) —		
< 15	*Eucalyptus*	50	30	0
	Pinus	30	20	0
15-35	*Eucalyptus*	60	40	0
	Pinus	40	30	0
> 35	*Eucalyptus*	80	50	0
	Pinus	50	40	0

After canopy closure. After canopy closure, nutrients arc also recycled in the soil following mineralisation of litter. Re-translocation and mineralisation of litter are likely to be the most important sources of nutrients for growth of new tissues, than the nutrients derived directly from the mineral soil pool. However, in sites with a low nutrient capital, particularly N, the slow down and decline in the mineralisation of the humus and litter below the level required, with litter accumulation, can lead to response to fertiliser application. The enhancement of tree-growth by N fertilisation is in agreement with the assumptions made by Smethurst and Nambiar (1990a). These authors, after analysing the N supply to young radiata pines, showed that there is a surplus of mineral N during the first 3 years of growth, and that responses to N fertilisation are likely to occur right after this age on all except low productivity sites. This is so because the rates of N uptake by fast-growing radiata pines increase almost exponentially between planting and canopy closure. Values range from 7 kg N ha^{-1} in the first year to 80 kg N ha^{-1} in the fifth year (Cellier *et al* 1985, Nambiar and Bowen 1986). These values contrast deeply with the decline in rates of N mineralisation, approximately 45 kg N ha^{-1} in the first year to 20 kg N ha^{-1} in the third year (Smethurst and Nambiar 1990 b).

According to Miller (1981) the response to silvicultural practices, such as fertiliser application which enhances the growth rates, should be understood as mechanisms of growth acceleration through time. This implies that after the stage of accelerated growth by fertiliser application, the treated trees must eventually revert to the growth curve that characterises the site. Yet, major responses to fertilisation at the establishment phase of the stand are usually followed by a slow and progressive decline, being minimum or non-existent by harvest time. This effect has been often observed in Brazilian stands, and its magnitude depends on the rotation length. For eucalyptus stands, if the trees are suffering from a deficiency of the applied element, they will show a growth response that generally lasts from three to seven years, depending on site quality. In this sense, fertiliser application could be considered as a way to reduce rotation length.

Bellote *et al.* (1980) and Reis *et al.* (1987) showed that most of the biomass and nutrient accumulation by *E. grandis,* planted in three sites of the Brazilian savannah region, occurred between two and four years after planting. In pine plantations, the most intense period of nutrient accumulation occurs later than in eucalyptus, because of the slower growth rate of the former. After canopy closure, a stage with small nutrient fluctuations in the living biomass follows (Bellote *et al.* 1980, Castro *et al.* 1980, Reis *et al.* 1987). Usually, these fluctuations occur because of seasonal climatic variations. Leaf shedding may increase during long dry periods as a mechanism to reduce water loss, or at the beginning of the rain season when older senescent leaves are detached from the trees by the wind (Reis and Barros 1990). When the process of canopy formation stabilises, nutrient accumulation is relatively much higher in the stem; the litter biomass accumulated in the ground reaches its maximum. At this stage, most of the tree's nutrient demand is supplied by the biochemical and biogeochemical cycles. Under 'cerrado' conditions the re-translocation rates of N and P from leaves of *E. grandis* were higher than 60% (Gonçalves *et al.* 1997b, table 6).

5. RECYCLING OF INDUSTRIAL, AND URBAN RESIDUES

Several types of industrial residues have been used and/or tested in eucalyptus and pine plantations. Those residues that show a proven efficiency as improvement agents of physical, chemical, and biological characteristics of soil (resulting in considerable productivity gains) are discussed in this paper. Depending on the site quality, and the chemical and physical attributes of the residues, the following doses are used: 2-4 t ha^{-1} of iron slag, 1-2 t ha^{-1} of dregs plus grit, 10-20 t ha^{-1} of organic sludge, 5-10 t ha^{-1} of forest wood ash and 15-20 t ha^{-1} of municipal garbage compost. These residues enhance forest productivity from 20 to 50%, depending on site quality. The use of mineral fertilisers as a complementary source is inevitable because of the residue nutrient unbalance.

Iron slag. This residue is originated from iron processing. Together with limestone and coke or charcoal, this mineral is submitted to blast furnace at very high temperatures (1900° C), thus promoting iron decrease. Slag is the residue of the process, resulting from the combination of silicates and other impurities with Ca and Mg contained in

TABLE 6

Mean nutrient concentration in deciduous and normal leaves and branches, and re-translocation rates of nutrients (Gonçalves *et al.* 1997b).

Concentración media de nutrientes en hojas y ramas caducas y normales, y proporciones de re-translocation de los nutrientes (Gonçalves *et al.* 1997b).

Nutrient	Mean concentration				Mean re-translocation before depposition			
	Deciduous leaves	Normal leaves	Deciduous branches	Normal branches	Leaves		Branches	
	——— $g\ kg^{-1}$ ———				%	$kg\ ha^{-1}\ yr^{-1}$	%	$kg\ ha^{-1}\ yr^{-1}$
N	6.2	17.9	2.9	5.0	61	50	23	4
P	0.3	1.6	0.2	0.8	79	6	67	2
K	2.9	6.5	1.8	2.6	50	15	8	1
Ca	6.9	7.8	4.3	5.7	-	-	-	-
Mg	2.2	2.7	0.9	0.9	8	1	0	0

the limestone (table 7). These behave similarly to limestone and can be used to balance the soil acidity and nutrient sources. Considering that Brazil is one of the world's greatest iron and steel producers, the production of slag is very high. Information provided by Piau (1991) shows that the production of this residue grows annually, being currently higher than 9 million t year. There is a wide range of types of slag concerning nutrient and heavy metal availability. For instance, hearth slag provides the soil with higher amounts of Ca and Mg, while blast furnace slag releases more K (Oliveira, *et al.* 1994).

Oliveira *et al.* (1994) analysed several field experiments to study slag effects on eucalyptus growths. In the first one, the application of 600 kg ha^{-1} of slag enhanced with 1% P into planting furrows of *Eucalyptus camaldulensis* was compared with several phosphate fertilisers at 110 kg/ha P_2O_5, applied in two sandy soils (67 and 83% sand). After 7 years, the results show a good response of Eucalyptus to slag, specially in sandy soil. In another experiment, the authors compared increasing rates of the same slag mixture enhanced with P, with two types of limestone and mineral fertilisation (band application of 600 kg ha^{-1} Araxá rock phosphate and 100 g single superphosphate/ planting hole), also in 7 year-old *Eucalyptus camaldulensis* stands, planted in sandy soil with 83% sand. The treatments that used slag plus fertilisation were, on average, 35% superior compared to the trials using fertilisation alone, and equivalent to the treatments with limestone application. As to the contamination of the soil by heavy metals, Amaral Sobrinho *et al.* (1995) showed that the annual application of up to 25 t ha^{-1} slag during 10 years did not contaminate the soil. Nevertheless, one recommends annual monitoring of heavy metal contents, both in the soil and water table, in order to detect possible increases in the initial figures and to prevent future problems.

TABLE 7

Chemical composition of blast furnace slags.

Composición química de escorias de horno de explosión de la industria siderurgica.

NP[1]	69.0%	Mo	26 $mg\ kg^{-1}$
Ca	270.0 $g\ kg^{-1}$	Co	20 $mg\ kg^{-1}$
Mg	37.0 $g\ kg^{-1}$	Zn	545 $mg\ kg^{-1}$
K	7.8 $g\ kg^{-1}$	Cu	358 $mg\ kg^{-1}$
P	0.5 $g\ kg^{-1}$	B	84 $mg\ kg^{-1}$
S	0.36 $g\ kg^{-1}$	Pb	205 $mg\ kg^{-1}$
Fe	35.2 $g\ kg^{-1}$	Cr	975 $mg\ kg^{-1}$
Al	34.8 $g\ kg^{-1}$	Ba	341 $mg\ kg^{-1}$
Ti	2.0 $g\ kg^{-1}$	Cd	16 $mg\ kg^{-1}$
Mn	14.0 $g\ kg^{-1}$	Sr	1279 $mg\ kg^{-1}$

[1] NP = neutralization power.
Source: Adapted from Piau (1991).

Dregs and Grits. These residues result from the " Kraft" process used in the pulp and paper industry. Dregs are dark-coloured solid materials with a very peculiar odour, decanted and removed during green liquor clarification. Grits are yellowish-odourless solid and granulated residues from calcined green liquor, composed of sintered and vitrified lime during the combustion of seashells and extinct lime from lime kilns (Waldemar & Herrera 1986). Both materials are separately collected from the industry. However, they are usually mixed and taken to a warehouse or sanitary landfill.

The mean chemical composition of the dregs-grits mixture is shown in table 8. This mixture can be used to balance soil acidity and also as a plant nutrient supplier. The neutralising power of grits is equivalent to that of $CaCO_3$ (approximately 100%), while for dregs it is around 72% (Waldemar & Herrera 1986); the mean dregs-grits mixture ranges from 82-83% (Waldemar & Herrera 1986, Bergamin *et al.* 1994). Studies in the use of dregs and grits as nutrient suppliers for trees are scarce. In the agricultural area, a study by Tedesco & Zanotto (1978) and those reported by Waldemar & Herrera (1986) are very important. In forestry, Valle *et al.* (1995) applied dregs and grits products separately to *Eucalyptus grandis* stands established in sandy soils. The residues were distributed and incorporated with disk plowing; planting was performed 30 days after the residue incorporation. At 4.2 years of age, the stands which had received the application of the residues had increased their productivity (table 9). In the case where only dregs were applied, the results were inferior to that with grits, probably due to its higher effect on soil acidity.

These results evidence the potential use of dregs and grits as a forest fertilisation supplement. The materials have a high moisture content as they leave the mill, so they need a period of sun exposure to eliminate the moisture before being transported and applied in the fields. Periodic follow-up of certain soil-toxic elements, specially sodium, is recommended.

Organic sludge. It is an effluent produced by the pulp and paper industry. As it leaves the mill -receiving only neutralization and decantation processes- it is called Primary Sludge. In a second stage, its biological activity is intensified through an increased population of aerobic microorganisms achieved by N and P addition and oxygen injec-

TABLE 8

Chemical composition of the dregs plus grits mixture (dry base).

Composición química de "dregs" más "grits" (base seca).

Moisture (%)	52.1
pH	12.0
Organic matter (g kg^{-1})	256.0
N (g kg^{-1})	0.5
P_2O_5 (g kg^{-1})	4.2
K_2O (g kg^{-1})	8.3
CaO (g kg^{-1})	327.8
MgO (g kg^{-1})	19.4
Mn (g kg^{-1})	2.4
Fe (g kg^{-1})	3.1
Na (g kg^{-1})	43.2
Cu (g kg^{-1})	82.0
Zn (g kg^{-1})	220.0
Ni (g kg^{-1})	75.0

Source: Valle *et al,* 1995.

TABLE 9

Growth of *Eucalyptus grandis* 4.2 years old stands in function of the application of dregs, grits, and dolomitic limestone.

Crecimiento de *Eucalyptus grandis* en plantaciones de 4.2 años de edad en función de la aplicación de "dregs", "grits" y caliza dolomítica.

Treatments	M.A.I. m^3 ha^{-1} yr^{-1}
Control (chemical fertilization)	44
2t/ha grits	53
4 t/ha grits	54
2 t/ha dregs	50
4 t/ha dregs	48
1 t/ha dregs + 1 t/ha Cal. Dol.	54
2 t/ha dregs + 2 t/ha Cal. Dol.	57

Source: Valle *et al.* 1995.

TABLE 10

Chemical composition of primary and secondary sludge of a pulp and paper industry.
Composición química media del lodo primario y secundario de una industria de celulosa y papel.

Characteristic	Primary sludge	Secondary sludge
Organic matter - g kg^{-1}	234.0	239
pH	7.2	7.7
Total C - g kg^{-1}	-	-
Total N - g kg^{-1}	3.1	2.1
C/N ratio	-	-
Total P_2O_5 - g kg^{-1}	0.01	3.7
Total K_2O - g kg^{-1}	0.5	0.3
Total CaO - g kg^{-1}	17.6	33.1
Total MgO - g kg^{-1}	0.5	2.1
S - g kg^{-1}	1.5	-
B - mg kg^{-1}	5.0	-
Cu - mg kg^{-1}	-	24.0
Fe - g kg^{-1}	1.3	5.4
Zn - g kg^{-1}	0.5	0.7
Mn - g kg^{-1}	0.1	1.3
Mo - mg kg^{-1}	-	-
Al - g kg^{-1}	4.3	0
Na - g kg^{-1}	1.0	3.3
Co - mg kg^{-1}	-	-
Ni - mg kg^{-1}	-	16.0
Moisture - %	79.7	59.5

Source: Valle *et al.* (1995).

tion; it is then called Activated or Secondary Sludge (table 10). The activated sludge is flocculated, after an aluminum sulfate treatment. Next, it is decanted and is pH-corrected with limestone before its transference to a deposit area.

The amount of organic sludge varies greatly, usually ranging from 80 to 160 t day^{-1} of activated sludge for 1000 t/day of pulp production, being the main residue in pulp industry. Some companies compost the activated sludge by means of aerobic and anaerobic processes, thus producing the composted organic sludge, commercialised as an organic fertiliser. In an *Eucalyptus grandis* stand, planted in red-yellow podzolic soil (Ultisol), Fabres & Conceiçao (1996) tested the application of activated sludge (89% moisture) in the total area using high-pressure sprinkling pumps mounted on water trucks. At 48 months of age, the necessary rate to provide 90% maximum production was 38 m^3 ha^{-1}. This rate has been enhanced with K chloride at the ratio of 1 kg KC1 / m^3 of activated sludge (40 kg KC1 ha^{-1}) and has been applied at a large scale in *Eucalyptus* stands to replace mineral fertilisation.

In an experiment dealing with secondary sludge just off the mill (raw), Valle *et al.* (1995) evaluated several application methods and rates of the material in *Eucalyptus grandis* stands planted in sandy soil (table 11). After 2.2 years they verified significant responses to the application of the residue which was highly dependable on the application method. Applications performed directly into the planting hole affected negatively the growth of the trees, probably because of the immobilisation of nutrients by non-decomposed material. In that sense, Harrison *et al.* (1996) pointed out the negative influence of the increased C/N ratio on plant development. The type of organic sludge applied and, specially, its degree of decomposition, are very important issues which must be considered for their use as organic fertilisers.

Forest biomass ash. Forest biomass ash, also known as ash coal, is obtained from the burning of wood (usually 3-6 cm in diameter) and bark for the production of thermal energy by steam generation. Such material is composed of small pieces of charcoal and 'ash'. Plants with production capacity of 1000 t day^{-1} pulp, generate approximately, 80 t day^{-1} of ash, with moisture contents ranging between 40-50%. The 'burnt ash' is obtained by re-burning the ash and finally carbonising the charcoal particles, resulting in a very fine yellow powder. The aim of re-burning is to increase nutrient concentrations available for plants, and specially to reduce the volume of residues to be transported and applied (table 12). According to Moro (1994) this process reduces the ashes form 10 to 3.5 t ha^{-1} to be applied in *Eucalyptus* plantations, thus reducing the application costs in 2.8 times.

The use of ash has a strong influence on the pH, P, K, Ca and Mg contents, and soil CTC, so reducing the exchangeable Al content (Naylor & Schmidt 1989, Sahm *et al.* 1993, Bellote *et al.* 1994, Guerrini *et al.* 1994, Guerrini & Moro 1994, Gonçalves & Moro 1995, Kahal *et al.* 1996). Because of its characteristics, ash is recommended for balancing soil acidity, with a neutralising power ranging from 30 to 100% in relation to limestone

TABLE 11

Growth of 2.2 years old *Eucalyptus grandis,* in function of the application of activated sludge (Valle *et al.* 1995).

Crecimiento de *Eucalyptus grandis* a 2.2 años de edad en función de la aplicación de lodo activado (Valle et al. 1995).

Treatments[1]	M.A.I. $m^3\ ha^{-1}\ yr^{-1}$
1.87 kg secondary sludge into planting hole	33
3.75 kg secondary sludge into planting hole	30
5 t ha^{-1} secondary sludge incorporated between rows	34
10 t ha^{-1} secondary sludge incorporated between rows	36
20 t ha^{-1} secondary sludge incorporated between rows	36
5 t ha^{-1} secondary sludge without incorporation	33
10 t ha^{-1} secondary sludge without incorporation	32
20 t ha^{-1} secondary sludge without incorporation	40
Chemical fertilization (without sludge)	31

[1] All treatments received chemical fertilization 230 kg ha^{-1} of 6-28-6 + 10% FTE BR 12 at planting and 115 kg ha^{-1} of 20-05-20 + 10% FTE BR 12 at 6, 12, and 24 months of age FTE BR 12 = micronutnent-contained fertilizer (18 g kg^{-1} B, 8 g kg^{-1} Cu, 30 g kg^{-1} Fe, 20 g kg^{-1} Mn, 1,0 g kg^{-1} Mo, and 90 g kg^{-1} Zn).

TABLE 12

Chemical analysis of forest biomass ash and reburnt forest biomass ash.

Análisis químico de ceniza de biomasa de bosque (CBB) y de CBB requemada.

Chemical characteristics	Ash	Reburnt ash
pH ($CaCl_2$ 0.01 M)	8.8	10.0
Total C (org. and min.) - g kg^{-1}	119.4	48.1
Organic C - g kg^{-1}	44.7	0.6
Total organic matter - g kg^{-1}	215.0	86.6
compostable organic matter - g kg^{-1}	80.5	0.0
Total N - g kg^{-1}	1.5	0.3
Total P_2O_5 - g kg^{-1}	2.6	14.3
Total K_2O - g kg^{-1}	5.4	32.6
Total Ca - g kg^{-1}	18.4	163.7
Total Mg - g kg^{-1}	1.6	15.4
Total S - g kg^{-1}	0.05	2.1
B - mg kg^{-1}	51	–
Cu - mg kg^{-1}	50	–
Mn - mg kg^{-1}	3125	–
Zn - mg kg^{-1}	46	–
Fe - mg kg^{-1}	1725	–
C/N ratio (total C and total N)	80/1	160/1
C/N ratio (org. C and total N)	30/1	2/1

Source: Guernni & Moro (1994).

(Magdoff *et al.* 1986, Lerner & Utzinger 1986, Hansen *et al.* 1986, Butler & Mays 1993). Several authors also pointed out the effects of this material on apparent density (Guerrini & Moro 1994), water-holding capacity, microporosity, electrical conductivity, and soil microbial biomass.

Studies by Bellote *et al.* (1994) indicate that ash application together with pulp sludge in a sandy Red-Yellow Latosol (Oxisol) increased the undergrowth decomposition speed at least three times, compared to the one obtained in the treatments receiving mineral fertilisation alone. For N, P, and K, plots receiving ash plus pulp sludge released approximately 40, 2, and 7 kg/ha, respectively, against 12, 0.6, and 1.2 kg/ha in the plots receiving only chemical manure, in a 10-month evaluation. Such accelerated undergrowth decomposition provoked by ash application raises the soil fertility level and nutrient absorption by trees, specially K and Ca, as also verified by Gonçalves & Moro (1995). These authors observed that this effect on soil fertility lasted for 2 to 3 years in medium textured soils. Moro & Gonçalves (1995) observed high responses to the ash application in *Eucalyptus grandis* stands. The productivity gains were 48% superior compared to those of the control. They verified that the ideal amount of ash for a 300 km-economic range was up to 20 t ha^{-1} for each harvesting cycle.

TABLE 13

Stem volume (cyclindric) of *Eucalyptus grandis,* in the first rotation (IR) and in the second rotation (coppices - 2R), four years after the application of different rates of compost from municipal garbage broadcast on a Quartizitic Sands soil.

Volumen del tronco (cilindrico) de *Eucalyptus grandis* en la primera rotación (IR) y en la segunda rotación (brotación - 2R), cuatro años después de la aplicación de diferentes dosis de compuesto orgánico de basura urbana desparramada sobre un suelo arenoso (Psamment).

Compost rates[1]	Compost rates[1]	
	IR	2R
t ha^{-1}	- m^3	ha^{-1}
0	233	271
7	246	316
14	237	296
21	304	368
28	310	428
56	266	388

Source: Adapted from Zen *et al.* (1994).

[1] 210 kg ha^{-1} of NPK 10-20-10 plus 100 g of a partially acidulated phosphate rock were combined with the compost rates in 1R. The compost was incorporated in the surface soil by discing between tree rows in 2R.

Organic compost from municipal garbage. Zen *et al.* (1994) reported increases from 32 to 58% in stem volume of *Eucalyptus grandis* cultivated on a poor (less than 9% of base saturation and CEC of 1.8 $cmol_c kg^{-1}$) Quartzitic sand soil (96% sand) (table 13), as a result of the application of increasing rates of compost obtained from municipal garbage. Under such conditions, the use of organic matter may affect tree growth by improving soil moisture retention, nutrient availability (the composition of the compost was N = 1.8%, P = 0.23%, K = 0.89%, Ca = 2.11%, Mg = 0.30%, and C/N = 16: 1) and microbial activity (soil organic matter = 0.9%). The authors isolated the effect of the compost in the first rotation, including plots where no-fertiliser and no-compost (117 m^3 ha^{-1}) were added, and where 21 t ha^{-1} of compost was applied but not fertilised (266 m^3 ha^{-1}). The difference between these two treatments was 84% in productivity. An additional gain of 14% was obtained if the NPK fertiliser was applied (see Table 4 for the volume with fertiliser application). In the trial involving eucalyptus coppices, the compost was scattered and incorporated into the surface soil by disk plowing.

6. WEED MANAGEMENT

Many fast-growing species planted in the tropics are very sensitive to weed competition in the earlier stages of growth. A reduction in plant survival and growth may result from competition by water and nutrients, because weeds use up larger volumes of soil than the young tree seedlings (Nambiar 1990). However, depending on site conditions and soil cultivation methods, complete weed elimination may not be desirable until tree roots can effectively capture soil resources, especially nutrients. Lowery *et al.* (1993) compiled part of the information on weed control in tropical forest plantations, and reported that although in most cases, complete weeding resulted in better tree growth and survival, partial weeding in strips within the tree rows could represent a good compromise between tree soil resource use and nutrient conservation in the site. A critical point is to define how long can tree seedlings and weeds grow together before the survival and the growth of the tree are reduced In an area infested by *Panicum maximum,* in southeastern Brazil, Marchi *et al.* (1995) found an almost continuous decrease in survival and volume growth of *E. grandis* as the period of competition increased.

Generally, on dystrophic soils with seasonal variations in water supply, high levels of weed infestation in stands with open canopies will reduce the effects of fertilisation mainly by reducing water availability to the trees However, Sands and Nambiar (1984) observed that the effect of weeds on tree water status diminished during successive summer periods, as tree roots increased their access to water stored deeper in the soil profile. Woods *et al.* (1992) showed that weeds increased the uptake of fertiliser N by plant biomass, so improving its retention on site and reducing N leaching, in a two to three year old *Pinus radiata* plantation. They also demonstrated that when N supply is high, intense weed control was unnecessary in plantations of more than two years of age, and *vice-versa* when the N soil levels were low. The continuous increase of crown cover, mainly in the first 12 months, as a result of fertilisation (Cromer and Willians 1982, Cromer *et al.* 1993) helps to shade out and suppress competition from weeds.

Silva *et al.* (1997) studied the effects of soil cultivation on weed proliferation and evaluated its importance on nutrient uptake and accumulation in an *Eucalyptus grandis* stand, three and six months after establishment Minimum cultivation of the soil considerably reduced weed proliferation, mainly herbaceous Intensive site preparation and burning enhanced weed growth, mainly herbaceous. Site harrowing increased proliferation of weeds propagated by vegetative form. The herbaceous weeds accumulated great amounts of nutrients in biomass, showing that the weeds can reduce the nutrient loses of the system, mainly in the periods where soil is more exposed.

Generally, the eucalyptus stands in Brazil have been maintained free or with low weed competition for about 200 days, and the pine stands for about 600 to 800 days The strip weed control has become a common practice in several forestry companies, resulting in a great herbicide economy and good protection of the soil Considerable cost reduction has been obtained with this kind of weed management without decreasing growth rates.

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