

Chapter 2

***EUCALYPTUS GRANDIS* PLANTATIONS IN ARGENTINA IN THE CONTEXT OF SUSTAINABLE SILVICULTURE**

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ABSTRACT

Eucalyptus plantations represent an important forest area in NE Argentina, with 140 000 hectares covered with *Eucalyptus grandis* (Hill ex Maiden). Plantations in this area have high mean annual increments (30-40 m³.ha⁻¹.año⁻¹) and high total productivity (220-370 Mg. ha⁻¹) although they are established on sandy soils. These soils have low organic matter and nutrients contents. Therefore, it is important to analyze if the present high productivity can be sustained along rotations. Sustainability implies to maintain both productivity and nutrient status. Knowledge of nutrients fluxes and nutrient use efficiency is a key issue to understand the way in which plantations use mineral resources in order to evaluate and select the best management practices to sustain productivity.

In this chapter, productivity and nutrient cycling of *Eucalyptus grandis* plantations are analyzed through chronosequences established on sandy soils. The point of view adopted consider that the concept of sustainable silviculture has to be applied and that it has effects on long term forest management. Therefore, nutrient content and nutrient export in different sites and ages are analyzed, as well as litterfall decomposition. These data allow for us to estimate the system yield stability, considering the economic dimension of sustainability. Results highlight that it is necessary to manage the export of nutrients with harvest, tending to their conservation.

Although the soils where *E. grandis* plantations are established have low natural fertility, productivity is high comparing with other regions of similar climate. Thus, nutrient use efficiency and biomass production in the studied sites are high. The highest N demand occurs 3 to 4 years after planting, whereas the highest P demand occurs 6 to 8 years after planting. Shorter rotations increase export of nutrients due to harvest. Harvest residues contain a high amount of nutrients, so their incorporation to the soil after harvest can be a

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good practice to maintain system nutrients pools. Nutrient stability analysis in different harvest scenarios and rotation ages show that N and Ca are the most critical nutrients in this productive system, while P and K are the more stable nutrients. To compensate nutrient losses it is necessary to apply fertilizers, specially N and P. Applications should take into account soil type and the risk of water deficit.

INTRODUCTION

Plantations with exotic species implies a modification in land use. Changes in soil use and decisions taken by foresters to conduct the plantations have to take into account the concept of sustainable forest management (Nambiar, 1996). Sustainable forest management implies the conservation of forest ecosystems, the protection of soil and climate, the production of timber and other products and the provision of recreation and other social amenities (Gamborg and Larsen, 2003). Therefore, one of the main objectives of silviculture is to maintain long term production and site quality specially in intensively managed forest plantations (Merino et al., 2004).

Successive rotations involving the large export of nutrients by removal of wood and logging residues can lead to a reduction in production (Judd, 1996; Merino et al., 2004; Sankaran et al., 2005; Turner and Lambert, 1996). Plantation productivity from second rotation depends on an appropriate management that ensures nutrient availability maintenance (O'Connell et al., 2004). Although no significant evidence of decline in yield over successive rotations was observed, it is necessary that forest industry developed an improved understanding of the ecology of commercial exotic plantations, in order to pay attention to environmental, economic and socio political factors (Louw and Scholes, 2002).

THE STUDY AREA

Forestation with *Eucalyptus grandis* represents an important forest area in Argentina, covering more than 132 000 ha (SAGPYA, 2001). One important region forested with this species is the surrounding of Concordia, Entre Ríos province (38 m.a.s.l.). Annual mean temperature in this region is 18.9 °C, with absolute minimal of -4.8 °C and absolute maximum of 40.5 °C. Mean annual rainfall is around 1300 mm, concentrated in autumn and late spring (Servicio Meteorológico Nacional, Argentina). Most plantations are located along the Uruguay river, on deep sandy soils, with good drainage but low organic matter and fertility (Dalla Tea and Marcó, 1996). This species is also planted on clay soils, although productivity is lower than on sandy soils. The most common stocking is 1100 trees per hectare. Plantations are carried out with low intensive management, short rotations (12 years) and high yield production (220-370 Mg ha⁻¹) (Goya et al., 1997; Goya et al., 1997).

BIOMASS ACCUMULATION IN AN AGE SEQUENCE

Forest plantations are ecosystems that, as they grow and develop, change plant-soil relationship. In fast growing species, water and nutrient use change fast with tree age, and it is necessary to evaluate stand structure along the rotation (Binkley et al., 2002).

One way to analyze biomass accumulation with age are chronosequences studies, in which data from stands of different ages are compared. The different stands represent stages in the sequential development of the ecosystem (Nambiar and Brown, 1997; Turner and Lambert, 2000). In this case, six stands of different ages were chosen, ranging 3, 4, 5, 7, 9 and 14 years old. All of them are installed on deep sandy soil (Fluventic Haplumbrept) and receive similar silvicultural treatments.

The stand structure shows the typical distribution of even age plantations, with the classical progress of the modal to the higher diameters. This pattern guarantees the correct choice of stands to analyze the age sequence.

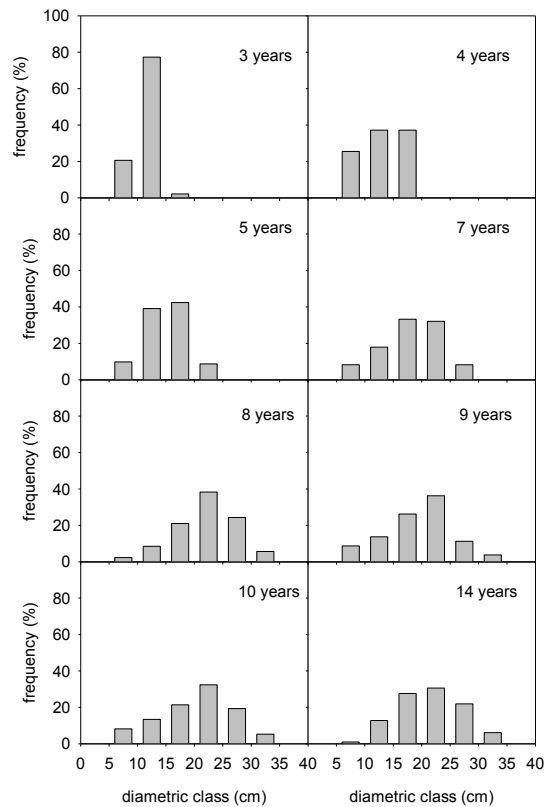


Figure 1. Diametric distribution in the age series in *Eucalyptus grandis* plantations. In each age, trees of three plots of 0,09 ha were measured (10 x 10 trees).

Mean Diameter at Breast High (DBH) increases with age in all the period analyzed (Figure 2), while tree height increases up to 9 years old stands but stays steady in older ages, between 9 and 14 years after planting (Figure 3). As trees growth from maturity to old age, height growth ceases and volume growth is sharply reduced (Ryan et al., 2006; Yoder et al., 1994). The data indicate that in the site analyzed, growth in height slows down 9 years after planting, while growth in stem diameter still increases at a constant rate.

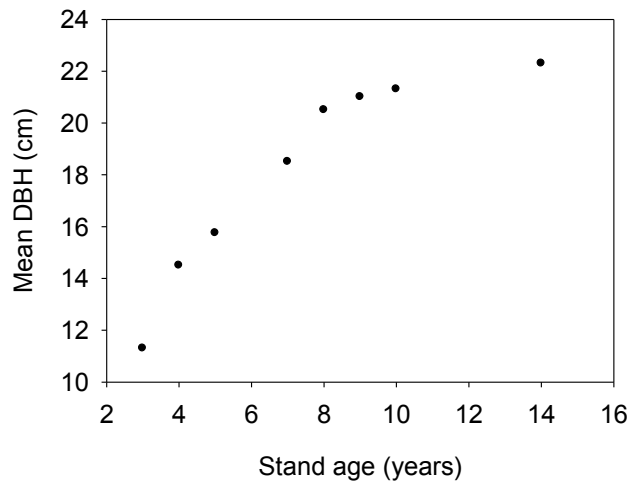


Figure 2. Mean diameter at breast height (DBH) (cm) in each stand age. In each age, trees of three plots of 0,09 ha were measured (10 x 10 trees).

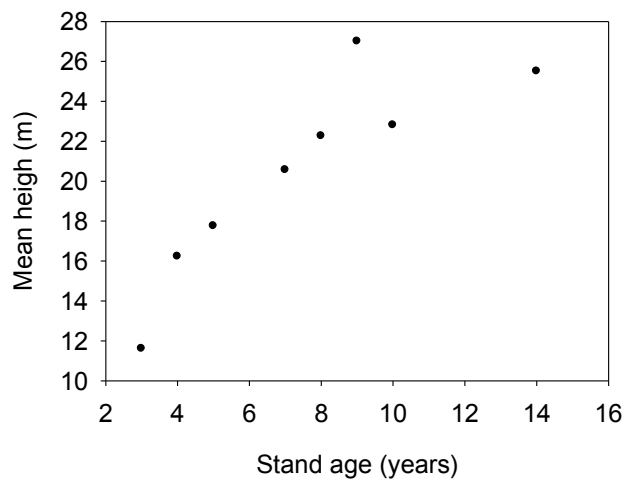


Figure 3. Total tree height (m) in each stand age. In each age, trees of three plots of 0,09 ha were measured (10 x 10 trees).

A unique exponential model was adjusted with all the pair of DBH- total height measured in all the plots, considering all ages together ($H = \exp(3.87 - 14.22 / \text{DBH})$ with $r^2 = 0.85$; $n = 459$). This unique relationship between DBH and height for all ages is useful to compare growth in different sites, because although wood production may be the best direct measurement of site quality, it is difficult to measure, so many studies has focus on the height of dominant trees as the parameter most related to the productivity of a given site (Nord-Larsen, 2006).

As trees grow up, whole plant structure and function change, and appearance and growth are different in young mature trees than in old ones (Bond, 2000). Four developmental phases were determined according to parameters related with productivity, like basal area and foliar biomass. The phase I includes stands of 3 years old, phase II includes stands of 4 and 5 years old, phase III includes stands of 7 and 8 years old and phase IV includes stands of 9, 10 and 14 years old. In every phase, different models relate DBH and total height with the biomass allocated to leaves and branches (Table 1), indicating differences in tree architecture.

Table 1. Regression models selected to estimate each compartment. Equations used are (1) $\ln W = a + b \ln D^2 H$, (2) $W = a + b D^2 H$; (3) $W = a + b D$, (4) $\ln W = a + b \ln D$, where W is the weight in kg, D is diameter at breast height in cm and H is total height in m.

Compartment	Equation (*)	a	b	R ²	P
Total	(1)	5.295	0.931	0.97	< 0.05
Stem with bark	(1)	5.061	1.060	0.99	< 0.05
Leaves (Phase I y II)	(2)	-0.258	19.117	0.97	< 0.05
Leaves (Phase III)	(4)	-7.720	3.128	0.97	< 0.05
Leaves (Phase IV)	(4)	-5.324	2.189	0.86	< 0.05
Branches < 5 cm	(4)	-2.047	1.508	0.78	
Branches of the year					
Phase I	(4)	-6.975	2.934	0.97	< 0.05
Phase II	(4)	-7.759	3.141	0.97	< 0.05
Phase III	(3)	-1.498	0.241	0.77	< 0.05
Phase IV	(2)	0.223	0.822	0.80	< 0.05

With the functions adjusted for each compartment, the biomass of each compartment per hectare was calculated, as well as the total biomass (Table 2). As stand develop, total biomass follow a typical logistic function, characterized by higher growth rate in juvenile plants and a later reduction of growth rate up to 9 years old (Figure 4). Thereafter, growth continue but at decreasing rate. When growth rate culminate, it correspond to the maximum mean annual increment (MAI) (Figure 5) and this moment is highly dependent of site quality and is a site quality index (Andersson et al., 2000).

The architecture of the trees change with age, and so their allometric relationship (Medhurst et al., 1999). The percentage of stem biomass increases with age, while the percentage of leaves is higher in the first phases. Foliar biomass and leaf area have a typical pattern, with an important rate of increment at the juvenile phases and constant values before total biomass level off (Gonçalves et al., 2004; Laclau et al., 2000).

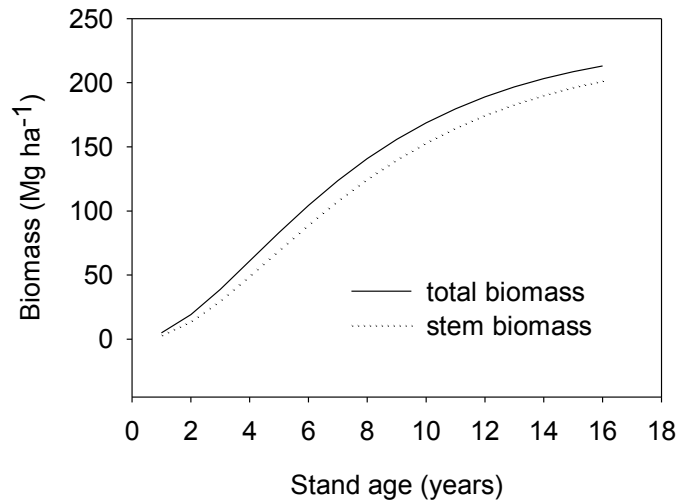


Figure 4. Models for total and stem biomass prediction with age. The equation adjusted is $B = a(1 - \exp(-bE))^c$ where B is total or stem biomass and E is the age of the stand. Parameters of the equation are: $a = 234$, $b = 0.20$, $c = 2.25$ for totals biomass ($r^2 = 0.85$) and $a = 227$, $b = 0.19$, $c = 2.41$ for stem biomass ($r^2 = 0.82$).

Table 2. Mean values for the biomass of each compartment along development phases in *Eucalyptus grandis*.

Phase	Biomass in each compartment (Mg.ha ⁻¹)					Harvest index (%)
	leaves	branches of the year	branches <5cm	stem with bark	total	
I	2.8 a	1.3 a	5.1 a	22.4 a	31.5 a	68
II	7.7 b	2.0 a	7.3 ab	64.1 ab	81.1 ab	76
III	4.6 a	2.7 a	9.6 bc	125.6 bc	142.4 bc	84
IV	3.2 a	2.2 a	10.1 c	155.8 c	171.4 c	86

In this chronosequence, foliar biomass smoothes between 6 and 8 years after planting. Changes in biomass allocation have consequences in harvest index, i.e. the proportion of commercial material comparing with total harvest biomass. If rotation is shortened, stem biomass decreases, but further the proportion of residues increases (Table 2).

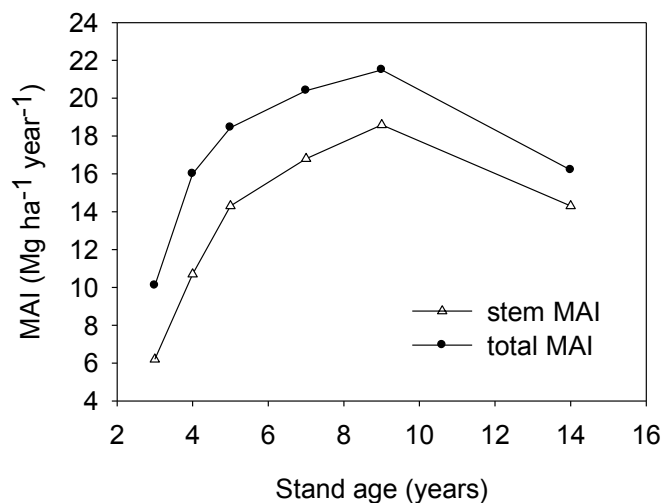


Figure 5. Mean annual increments for total aboveground biomass and for stem biomass (Mg.ha⁻¹ year⁻¹) in the ages of the chronosequence of *Eucalyptus grandis*.

LEAF AREA INDEX (LAI)

Stand productivity depends strongly on leaf production (Whitehead and Beadle, 2004), which relates directly with leaf area and leaf area index (LAI) (Binkley et al., 1995; Cromer and Jarvis, 1990). Tree leaf area has an allometric relationship with DBH and tree basal area. This allometric relationship is site, age and density dependent (Long et al., 2004). Maximum leaf area index is reached in phase III. Figures are high comparing with plantations of this species in Brazil and South Africa (Whitehead and Beadle, 2004). After this phase, trees modify leaf turnover and growth efficiency decreases. Stand leaf area declines in most forest at a relative early point in stand development (Binkley et al., 2002). Reduction in leaf area can be the cause or the consequence of the decreasing growth increments observed after phase III. Relationship between LAI and MAI is straightforward (Figure 6).

NET PRIMARY PRODUCTION

Net primary production is the organic matter produced by a stand in one year. Then, it is necessary to evaluate litterfall in order to add it to annual tree growth. Litterfall has the same annual pattern in all the phases analyzed. It is higher during summer and lower in winter. Higher litterfall in summer may be due to temperatures above to optimal (22 °C) and prolonged dry periods (Whitehead and Beadle, 2004). Annual litterfall represents around 60% of total productivity (Table 3). In the plantations analyzed, productivity is high even in the first phases, which demonstrate their capacity to rapidly acquire resources from the site. Productivity is high comparing with plantation of this and other species in the South Hemisphere (Birk and Turner, 1992; Herbert, 1992; Lugo et al., 1988).

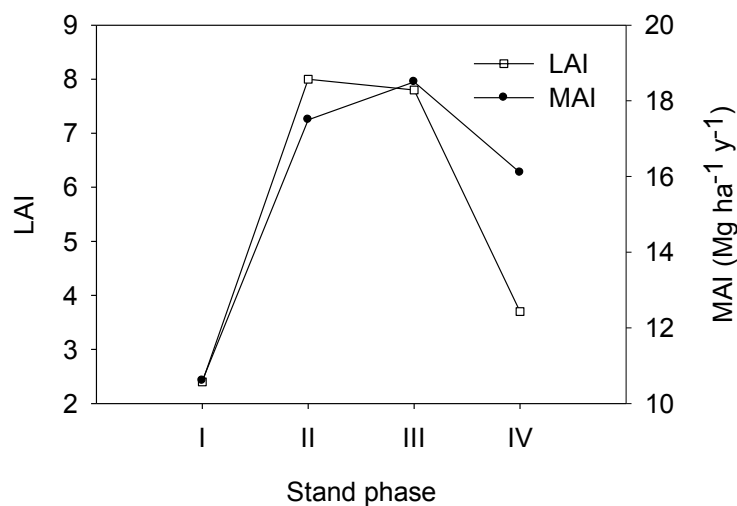


Figure 6. Mean annual increment (MAI) and leaf area index (LAI) for the phases of the *Eucalyptus grandis* chronosequence.

Table 3. Components of the above ground productivity in *Eucalyptus grandis* chronosequence.

Phase	Total biomass (Mg.ha ⁻¹)	Growth (Mg.ha ⁻¹ .year ⁻¹)	Total litterfall (Mg.ha ⁻¹ .year ⁻¹)	Productivity (Mg.ha ⁻¹ .year ⁻¹)	Return time (years)
I	31.5	10.6	6.6	17.2	1.9
II	81.1	17.5	8.7	26.2	3.2
III	142.4	18.5	7.2	25.7	5.9
IV	171.4	16.1	7.0	23.1	7.8

The turnover time is a parameter that represents biomass renovation, and it describes stand dynamic. In the different phases analyzed, the turnover time varies between 2 to 8 years (Table 3), representing high figures comparing with the most productive plantations in the world (Attiwill and Leeper, 1987).

In phase IV, net primary productivity is lower than in the previous phase. The decrease of stand productivity with age is well documented, although its causes are not well established (Binkley et al., 2002). To explain the decrease in growth with age many explanations are possible: change balance between photosynthesis and respiration, increased hydraulic resistance to water path from soil to leaves, decreased in nutrient supply as they accumulate in tree biomass, reduced leaf area due to crown abrasion, increased mortality in older trees, increased reproductive efforts and genetic changes with meristem age (Ryan et al., 1997).

BELOWGROUND BIOMASS

Roots are a very important component of the system, but it is difficult to estimate it. In the age sequence analyzed, the proportion of biomass allocated to roots is higher in phase I,

and decreases with age. Root system increases soon after planting to access nutrients and water. Once water and nutrient are adequate to shoot demand, plants allocate more photosynthates and nutrients to the development of leaves in order to maximize light capture and carbon fixation (Gonçalves et al., 2004). Coarse roots biomass (more than 10 mm) in the upper 50 cm of soil is the part of the root system that increases more with age (Table 4). On the other hand, fine roots biomass stays in similar magnitude along the phases. Fine roots (< 2 mm) are responsible of absorbing nutrients more actively, whereas coarse roots play an important role in mechanical support and in taking water from deep soil (Bouillet et al., 2002).

Table 4. Biomass of fine and coarse roots (Mg.ha⁻¹), above ground and total biomass (Mg.ha⁻¹) and proportion of above ground biomass respect to total biomass in the developmental phases of the *Eucalyptus grandis* chronosequence.

Phase	Fine roots (<5mm) (Mg.ha ⁻¹)	Coarse roots (> 5mm) (Mg.ha ⁻¹)	Above ground biomass (Mg.ha ⁻¹)	% Above ground biomass	Total biomass (Mg.ha ⁻¹)
I	2.49	3.11	32.8	85.4	38.4
II	2.06	5.63	84.9	91.7	92.6
III	2.58	4.55	150.0	95.5	157.1
IV	2.96	7.01	180.7	94.8	190.7

The analysis of root density (number of roots per dm² of soil in vertical planes) make evident that 76,3 % of fine roots are located in the upper 30 cm of soil. Fine root (<5mm) density varies between 10 to 13 roots per dm² in the upper 50 cm of soil. Coarse roots (> 5mm) appear below 10 cm depth, and the peak density of coarse roots is deeper in older stands. These data reflect the tendency to explore deeper soil in older trees. In 3 m depth soil profiles analyzed in 1, 2 and 9 years old *Eucalyptus* clone plantations in Congo, fine root density decreased sharply with depth, being most roots concentrated in the upper 25 cm of soil (Bouillet et al., 2002).

Due to different root diameter and soil depth considered, it is difficult to compare root biomass reported by other authors. Nevertheless, root biomass estimated in this age sequence is much lower than fine root and total root biomass reported for *Eucalyptus globulus* plantations (11 and 23 Mg.ha⁻¹ in fine and total root biomass respectively in a 12 years old plantation) (Fabiao et al., 1987). This plantation was over a sandy soil, too and it had similar leaf biomass (190 Mg.ha⁻¹), but the sampling was performed more deeply than in our chronosequence (70 cm depth). The same authors reported fine and total biomass for an 18 years old plantation in a silt sandy soil. In this older plantation, fine root biomass and total biomass was lower than in the 12 years old plantation (6 and 12 Mg.ha⁻¹ respectively). Differences may be due to both different soil quality as well as for different age. In the same way, figures for fine root and total root biomass reported for other 7 years old *Eucalyptus* plantations in Brazil are much higher although they have lower aboveground biomass (Ladeira et al., 1997). The low root biomass estimated in the chronosequence cannot be explained only by the difference in sampling depth. Age and soil nutrient and water availability are some of the factors that affect allocation to roots (Hacke et al., 2000; Sperry et

al., 1998). Allocation to roots tends to be minor in sites with good availability of nutrients and water, while the scarce of both factors increases root system size.

GROWTH OF COPPICED TREES

Coppicing of harvest trees (i.e. regeneration of shoots from the stump) is a common practice in *Eucalyptus* forest management. In the region under study, it is common to coppice trees four times. Advantages of managing the regrowth of trees is that survival is higher because trees are more resistant to biotic and abiotic stresses and that root system explores greater volume of soil with the subsequent greater uptake of nutrients and water (Forrester et al., 2003). Some disadvantages are that stand density decreases after each rotation due to tree mortality in the previous rotation and some stumps that not resprout, and that it is not possible to improve genetic material (Proe et al., 2002). So the decision of coppicing or replanting depends on the balance between the genetic gain that is possible to obtain with selected material and the decrease in density in the coppiced plantation (Whitlock et al., 2004).

Coppiced trees growth faster than recent planted seedlings (Graciano, Goya, Arturi, Pérez and Frangi, unpublished data). The higher growth of coppiced trees compared with intact trees is not well understood, but the larger root system, the smaller leaf:root ratio, reserves of lipids and carbohydrates and some internal balance of hormones may be the main causes (Philippot, 1996). Coppiced trees are higher than planted trees still two years after plantation establishment (Figure 7) and DBH in the second year is significantly higher in coppiced trees than in replanted trees (5 to 8 cm, respectively). Higher growth is associated with lower leaf nitrogen and phosphorus content and also lower specific leaf area. A positive relationship between specific leaf area and leaf nitrogen content has been observed in many species (Afas et al., 2004), but this leaf characteristic are typical of older trees. In the chronosequence, specific leaf area decreases from 126 cm².g⁻¹ at the first phase of stand development, to 81 cm².g⁻¹ in the last phase analyzed. One year after planting, specific leaf area in replanted trees is 120 cm².g⁻¹ while in coppiced trees it is 90 cm².g⁻¹. Leaf nitrogen and phosphorus concentrations also decrease in the chronosequence. In coppiced trees leaf nitrogen concentration equals 24 mg.g⁻¹ while in replanted trees it is 32 mg.g⁻¹ and leaf phosphorus concentration is 1.0 mg.g⁻¹ in coppiced trees and 1.4 mg.g⁻¹ in replanted trees. These data reflect that leaf morphology and physiology is different in coppiced trees and replanted trees, and that the difference is sustain at least for two years. In the same way, growth in height and in stem diameter is higher in coppiced trees than in planted ones, so the former occupy the site faster than the latter.

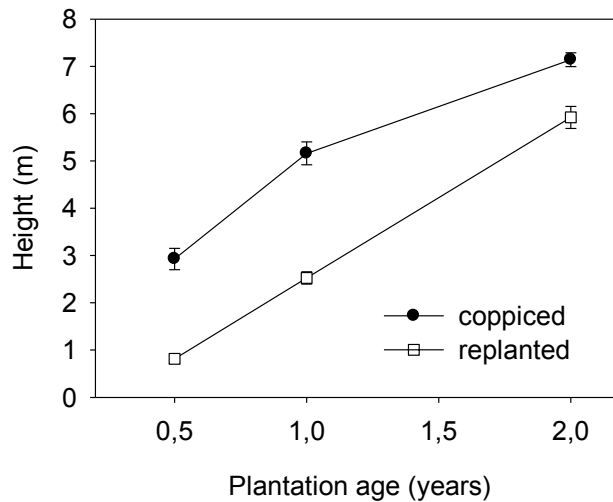


Figure 7. Total height (m) of coppiced and replanted *Eucalyptus grandis* in a plantation 0.5, 1 and 2 years after establishment. Bars indicate standard deviation.

NUTRIENTS ACCUMULATION IN AN AGE SEQUENCE

The main factors considered by foresters to choose sites to plant *Eucalyptus* are, by one hand adequate rainfalls and temperatures and, on the other hand, the availability of inexpensive land and the accessibility to the customers. Although nutritional deficiencies have appeared in many sites, the expectation is that they can be easily managed. A deeper understanding of nutritional conditions in forest ecosystem make possible to identify conditions and to calculate and prescribe compensatory actions (Andersson et al., 2000). Intense global competition demands to increase yield per unit area, reduce the cost of wood produced and reduced rotation length but also to ensure greater environmental care in land use (Louw and Scholes, 2002).

Thus, it is important to know how the most important nutrients are distributed in the system at different plantation age. Nutrient concentration and then nutrient content of the soil and tree compartments (leaves, bark, stems, branches and fruits) change as stand develop (Laclau et al., 2000). The litter layer is an important pool of nutrients, and it is closely related with tree's nutrient content (as it is fed by litterfall) and with soil nutrient content (through decomposition). Extraction of nutrients with timber harvest can be reduced if rotation length and slash are adequately managed.

CHANGES WITH AGE IN TREE NUTRIENT CONTENT

Nutrients in plants are analyzed through two parameters: nutrient concentration and nutrient content. Nutrient concentration indicates the richness of the material, and it is related with the physiology of the organ. Therefore, leaves have the higher nutrient concentration while stems have the lower (Table 5).

Table 5. Nutrient concentration (mg.g⁻¹) in tissues of *Eucalyptus grandis* chronosequence.

	Phase	Nutrient concentration (mg.g ⁻¹)				
		N	P	K	Ca	Mg
leaves	I	28.5 a	1.3 a	6.5 a	9.1 a	3.0 a
	II	23.0 b	0.9 b	5.8 a	11.1 a	2.3 b
	III	18.7 c	1.2 b	7.1 a	14.6 b	2.7 ab
	IV	14.8 c	1.2 b	7.9 a	14.4 b	3.3 b
stem without bark	I	2.09 a	0.06 a	1.03 a	1.03 a	0.16 a
	II	2.25 a	0.05 a	0.84 a	1.49 a	0.14 a
	III	1.94 a	0.13 b	0.96 a	0.96 a	0.16 a
	IV	0.95 a	0.18 c	0.20 b	1.54 a	0.18 a
bark	I	4.74 a	0.32 a	6.31 a	19.99 a	2.39 a
	II	4.69 a	0.32 a	5.14 b	22.95 a	1.85 a
	III	4.35 a	0.96 b	5.30 b	22.00 a	1.45 a
	IV	3.05 b	0.66 c	5.04 b	29.58 a	1.90 a
branches (d=1-5 cm)	I	3.11 a	0.15 a	1.94 a	4.28 a	0.66 a
	II	3.00 a	0.14 a	1.61 b	2.56 a	0.50 a
	III	2.68 a	0.34 b	2.17 ac	5.09 ab	0.86 ab
	IV	0.95 a	0.08 c	1.56 ab	1.07 a	0.29 ac
branches (d<1 cm)	I	6.66 a	0.40 a	3.75 a	6.09 a	0.66 a
	II	5.21 ab	0.35 ab	3.74 a	8.31 a	0.81 ab
	III	4.00 b	0.65 ac	4.13 a	8.58 a	1.17 b
	IV	3.60 b	0.44 a	3.49 a	9.17 a	1.24 b
fruits	I	9.00 a	1.04 a	5.49 a	5.41 a	2.04 a
	II	7.61 a	0.61 b	5.72 a	8.25 a	1.48 ab
	III	5.85 a	0.47 b	6.99 a	8.88 a	2.02 ac
	IV	4.50 a	0.69 b	7.37 a	7.96 a	2.74 d
fine roots	II	6.05	0.28	3.62	10.18	0.86
	III	7.42	0.46	2.97	6.07	0.92
	IV	7.49	0.39	3.10	10.67	1.39
coarse roots	II	4.57	0.25	3.46	8.05	0.37
	III	4.24	0.40	3.41	5.80	0.44
	IV	2.58	0.31	3.88	7.45	0.67

An interesting variable to analyze is the nitrogen concentration. As stand develops, nitrogen richness in leaves, bark and stem decreases. On the other hand, calcium concentration in leaves increases with age, while phosphorus and potassium concentration have not clear tendency. Decrease of nitrogen concentration on leaves of older trees is well documented (Harrison et al., 2000; Misra et al., 1998; Ryan et al., 1997). The decrease of nitrogen concentration in leaves is associated with a lower SLA as trees develops, reflecting changes in leaf structure. Changes in leaf structure are a combination of factors that limit tree growth (Medhurst et al., 1999). In young trees, if nutrient and water are enough, light is the limiting factor, so interception is maximized with leaves of high SLA (Whitehead and Beadle, 2004). As trees grow up, nitrogen or water can be the limiting factors. When the limiting

factor is nitrogen, photosynthesis is limited by the small photosynthetic apparatus, so leaves are “cheap”, with low nitrogen concentration and relative high calcium concentration. A much higher proportion of nitrogen remain in senescence leaves (litterfall), probably in structural molecules. This explain also why calcium concentration in leaves increase with age, as it is an immobile nutrient (Grove et al., 1996). When water is the limiting factor, SLA decreases, because cells do not reach full turgor so full expansion is not possible (Ryan et al., 2006).

In the case of leaves, nitrogen lower concentration is associated with a lower foliar biomass, so nitrogen content in leaves decreases with age. Foliar nitrogen concentration relates directly with soil nitrogen concentration in all ages. In general, foliar nutrient concentration has been reported to be related with growth, although the relationship is not straightforward (Cromer, 1996; Judd et al., 1996). Interactions between nutrients are important to improve growth (Herbert, 1996). For example, the optimum N:P ratio for *Eucalyptus grandis* is around 13 (Judd et al., 1996). In our age sequence, the evolution of this ratio indicates that in the first three phases, nitrogen is not limiting growth. But in phase IV nitrogen concentration is lower than needed according to P concentration, because N:P ratio drops below 13. This nitrogen limitation is reflect by the relation between total biomass accumulation and nitrogen and phosphorus accumulation between phase I and phase IV: biomass increases 7 folds, phosphorus content increases 6 fold and nitrogen content increases only 1.5 folds.

Nutrient content in the components of trees is an important parameter to know the pools of nutrients in the system and also to estimate nutrient export with different types of harvest and nutrients content in the residues.

Nutrient content changes with stand age. This parameter change both with nutrient concentration and biomass of each tree component. Nitrogen content in debarked stems increases with age although concentration of nitrogen decreases, because the weight of stems increases in higher proportion. But nitrogen content in leaves decreases with age, because nitrogen concentration as well as foliar mass decrease with age. This is an important point to be considered when defining rotation length. If harvest includes total tree extraction or if residues are burnt, the reduction of rotation age would impact negatively on nitrogen cycle.

If total above ground biomass is harvest in phase IV, the export of nutrient reaches to 234 kg.ha⁻¹ of N, 38 kg.ha⁻¹ of P, 119 kg.ha⁻¹ of K and 576 kg.ha⁻¹ of Ca. If harvest is done in phase III, the amount of N and K exported increases, although the weight of wood is lower. To evaluate the cost in nutrients of each tree component, nutrient content of each compartment is divided by the mass of each compartment (Table 7). The most expensive compartment are leaves, specially in young trees. As stand develop, the nitrogen costs of all components decrease. The cheaper component is the steam. According with this data, it is clear that harvest of hole trees should be avoid, and only the stems should be removed from the site.

Tabla 6. Nutrient (kg. ha⁻¹) content in biomass of *Eucalyptus grandis* chronosequence.

	Phase	Content of nutrients (kg. ha ⁻¹)				
		N	P	K	Ca	Mg
leaves	I	78.2 a	3.6 a	17.9 a	25.1 a	8.2 a
	II	175.9 b	6.6 a	44.1 b	84.7 b	17.3 ab
	III	86.7 a	5.5 ab	32.9 ab	67.6 ab	12.4 a
	IV	47.6 a	3.9 ac	25.6 a	46.3 a	10.5 ac
stem without bark	I	46.7 a	1.3 a	22.9 a	23.1 a	3.6 a
	II	144.4 a	3.4 a	60.9 a	95.4 ab	9.0 a
	III	243.7 b	16.4 b	120.5 b	120.6 b	20.4 b
	IV	148.0 a	27.3 c	31.7 a	239.4 c	28.3 b
bark	I	18.3 a	0.9 a	18.3 a	58.1 a	6.9 a
	II	33.1 a	2.3 a	36.3 ac	161.8 a	13.0 a
	III	38.3 b	8.5 b	46.6 bc	193.4 a	12.8 a
	IV	33.3 a	7.2 b	54.9 b	322.6 b	20.8 b
branches (d= 1-5 cm)	I	15.7 ac	0.8 a	9.8 ab	21.6 a	3.4 a
	II	21.8 ab	1.0 a	11.7 a	18.6 a	3.6 a
	III	25.6 b	3.2 b	20.7 c	48.7 b	8.2 b
	IV	9.6 c	0.8 a	14.5 ab	10.8 c	2.9 a
total aboveground	I	159.1 a	11.6 a	77.1 a	128.7 a	22.1 a
	II	386.3 a	21.2 a	163.5 ab	362.2 ab	43.0 ab
	III	404.7 b	44.3 b	243.1 b	433.4 bc	53.7 b
	IV	246.5 a	47.3 b	148.5 a	622.0 c	62.4 b
Fine roots	II	13.9	0.54	5.59	18.51	1.77
	III	20.31	1.23	7.99	14.79	2.55
	IV	20.51	0.94	7.15	26.96	3.88
Coarse roots	II	28.43	1.43	20.59	48.02	2.18
	III	21.95	2.10	17.70	30.10	2.23
	IV	15.32	1.72	21.53	41.29	3.72

CHANGES WITH AGE IN LITTERFALL NUTRIENT CONTENT

Nutrient content in litterfall changes along the year. In all ages, nutrient concentration is higher when the mass of litterfall is lower, suggesting that in this period the senescing process is not complete, and leaves fall for other reasons. But the mass of leaves that falls makes that 60% of nutrient content in litterfall occurs in summer, when mass of litterfall is higher. Changes in nutrient concentration in litterfall demonstrate that nutrient absorption and nutrient use efficiency varies along the year (Vitousek et al., 1982). Litterfall is greater in months with high evaporative demands, in order to reduce transpiring area. In this period, retanslocation of nitrogen and phosphorus is higher. Hence, concentration of this nutrients in litterfall are least when the rate of litterfall is greatest (Attiwill et al., 1996).

In all phases, concentration of nitrogen and phosphorus in litterfall is similar, although concentration of these nutrients in full expanded leaves change a lot between phases. This implies that although the capacity of nutrient withdrawal never is complete, the same level is

achieved in spite of the concentration of the full expanded leave. Therefore, the proportion of nitrogen retranslocated is much higher in young trees than in older ones.

Table 7. Cost of each organ with the extraction of hole trees in different phases of stand development in *Eucalyptus grandis*.

Nutrient cost of each organ (1/kg. g ⁻¹)						
	Phase	N	P	K	Ca	Mg
leaves	I	28.45	1.31	6.51	9.11	2.98
	II	22.99	0.86	5.76	11.07	2.26
	III	18.74	1.20	7.12	14.61	2.67
	IV	14.76	1.21	7.94	14.36	3.25
Stem without bark	I	2.09	0.06	1.03	1.03	0.16
	II	2.25	0.05	0.84	1.49	0.14
	III	1.94	0.13	0.96	0.96	0.16
	IV	0.95	0.18	0.20	1.54	0.18
bark	I	4.74	0.32	6.31	19.99	2.39
	II	4.69	0.32	5.14	22.95	1.85
	III	4.35	0.96	5.30	22.00	1.45
	IV	3.05	0.66	5.04	29.58	1.90
Branches (d=1-5 cm)	I	3.11	0.15	1.94	4.28	0.66
	II	3.00	0.14	1.61	2.56	0.50
	III	2.68	0.34	2.17	5.09	0.86
	IV	0.95	0.08	1.44	1.37	0.29
Total	I	4.6 a	0.34 a	2.24 a	3.7 a	0.64 a
	II	4.2 a	0.26 b	1.85 a	3.9 ab	0.47 b
	III	2.3 b	0.29 b	1.41 b	3.0 ac	0.35 c
	IV	1.4 b	0.26 b	0.82 c	3.4 a	0.34 c

CHANGES WITH AGE IN LITTER LAYER NUTRIENT CONTENT

Litter layer increases with age (Table 8). The superficial soil organic matter increase reflects that the rate of decomposition in this plantation is low. Decomposition has high rates at the beginning of the process, but thereafter it slows down (Fisher and Binkley, 2000). Decomposition rates during the first year are similar for all the stand phases analyzed. Figures are low comparing with decay rates of sites with similar environmental conditions (Attiwill et al., 1996; Keith, 1997). Therefore, organic matter incorporates slowly to the soil. This has implications in post harvest forest management, indicating that slash burning should be avoided.

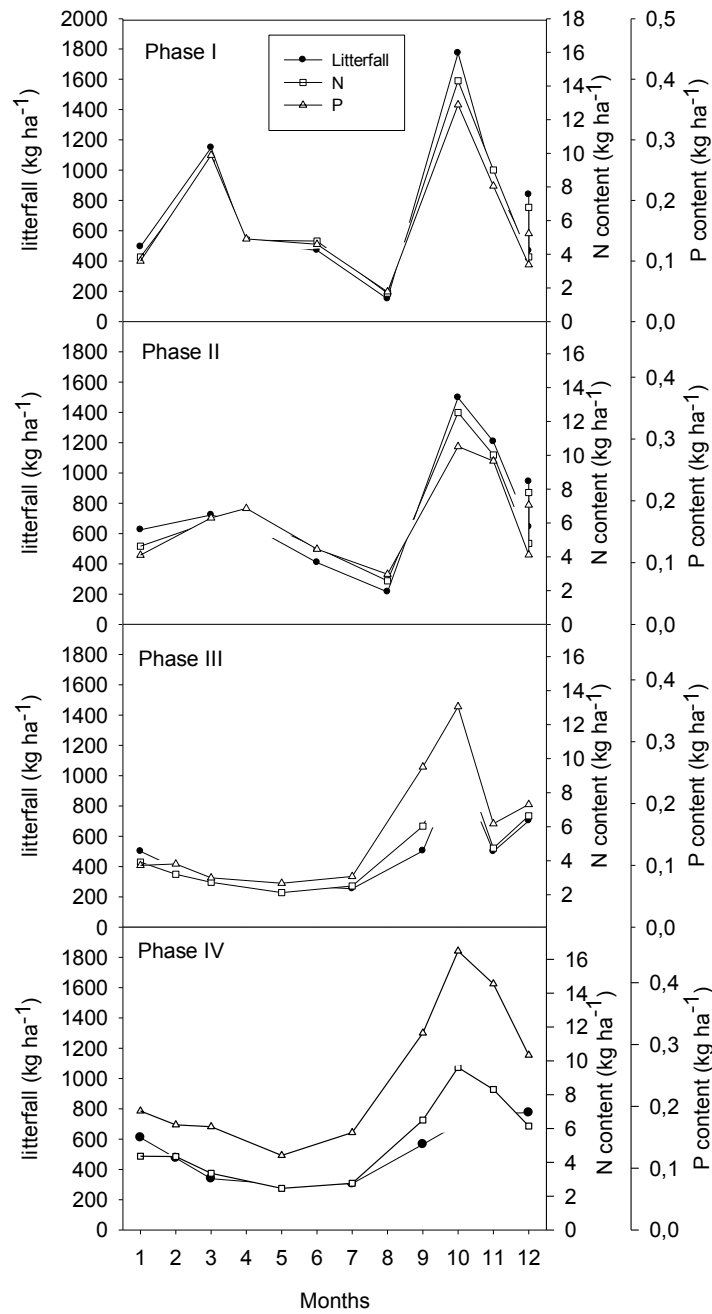


Figure 8. Content of nitrogen and phosphorus in litterfall (kg ha⁻¹) and mass of litterfall (kg ha⁻¹) along the year in different phases of an *Eucalyptus grandis* chronosequence.

Table 8. Mass of components of litter layer in different ages of the chronosequence of *Eucalyptus grandis*.

Phase	Mass of litter layer compartments (Mg/ha)					Total
	Leaves	Branches	Bark	Fruits	Miscellaneous	
I	2.8 (6.4)	1.0 (20.5)	0.30 (33.6)	0.02 (31.8)	0.33 (17.2)	4.5 (15.6)
II	3.9 (7.0)	6.3 (9.1)	0.87 (11.3)	0.39 (17.5)	0.63 (9.6)	12.1 (9.4)
III	4.7 (8.7)	10.8 (10.3)	3.29 (11.7)	0.57 (14.3)	0.50 (14.1)	19.8 (10.2)
IV	6.5 (10.5)	14.3 (13.5)	4.09 (10.1)	1.34 (14.9)	1.64 (20.6)	27.9 (10.9)

Table 9. Decomposition parameters of leaves of *Eucalyptus grandis* in different ages of the chronosequence. Equation is fitted with data of 2 years, with periodical sampling of 5 bags per site.

Phase	K (year ⁻¹)	1/k (years)	Mean life (years)	Exponential equation (*)			days	k ₁
				a	b	r ²		
I	0.42	2.38	1.65	4.53	-0.0010	0.86	360	1.5
II	0.49	2.06	1.43	4.52	-0.0010	0.89	360	0.7
III	0.57	1.74	1.21	4.57	-0.0020	0.96	360	0.4
IV	0.41	2.45	1.70	4.54	-0.0010	0.88	360	0.3

Rate of decomposition depends on chemical composition of the litter material and its interaction with soil and climate (Attiwill et al., 1996). In litter layer, nitrogen concentration decreases with stand age, while carbon concentration tends to increase (Table 10). These changes result in an increase of carbon/nitrogen ratio, relationship that decrease decomposition rate. This low decomposition rate can explain the accumulation of litter as stand develop, although litter fall maintain in similar magnitude in all ages (Table 3). The accumulation of litter takes together the accumulation of nutrients in the litter layer (Table 10). Litter layer has a close relation with soil nutrient content, as will be analyzed in next section.

CHANGES WITH AGE IN SOIL NUTRIENT CONTENT

Changes in land use modify soil fertility and soil structure. Plantations analyzed are situated over sandy soils (Fluventic Haplumbrept) and all of them have received similar cultural treatments. These soils have very low clay content, as well as organic matter concentration (1.1 to 0.4 %) and carbon concentration (0.9 to 0.2 %), so it is expected that the change in land use can alter its properties. Organic matter associated with sand and silt is more sensitive to changes in land use and management compared with organic matter associated with clay (Ashagrie et al., 2005).

Table 10. Nutrient concentration (mg.g⁻¹) and nutrient content (kg.ha⁻¹) in litter layer of *Eucalyptus grandis* chronosequence.

Nutrient concentration in leaves of the litter layer (mg.g ⁻¹)						
Phase	N	P	K	Ca	Mg	C/N
I	11.0 (0.1)	0.2 (0.01)	2.2 (0.03)	21.8 (0.4)	1.5 (0.03)	51
II	10.5 (0.1)	0.3 (0.02)	2.5 (0.2)	23.8 (2.2)	2.1 (0.3)	54
III	10.3 (0.05)	0.4 (0.01)	2.0 (0.3)	17.6 (2.3)	1.7 (0.2)	56
IV	7.9 (0.4)	0.3 (0.1)	2.7 (0.1)	14.0 (0.2)	1.6 (0.04)	72
Nutrient content in the litter layer (kg.ha ⁻¹)						
Phase	N	P	K	Ca	Mg	
I	34.4	0.8	7.8	74.0	5.7	
II	72.1	2.1	16.1	133.3	15.9	
III	85.0	3.7	24.9	197.5	21.3	
IV	119.2	6.0	48.2	247.7	32.1	

Concentration of calcium, magnesium, manganese and nitrogen drop as stand develop. Nevertheless, concentration of phosphorous and potassium maintain in similar magnitude in all ages. Carbon concentration is higher in phase II, and decreases suddenly in the last phase (Table 11). So the second rotation would start with lower soil carbon concentration than the first rotation, as was observed in an *Eucalyptus grandis* plantation in Australia (Turner and Lambert, 2000).

Table 11. Soil chemical characteristics at different depths and phases of stand development in an *Eucalyptus grandis* chronosequence.

Phase	Ca	Na	Mg	P	Fe	Mn	K	CEC	C	N	C/N	pH(1:1)
	(mg.g ⁻¹)							(meq%)	(%)	(%)		(H ₂ O)
Depth = 0-20 cm												
I	0.53	0.02	0.10	0.02	0.27	5.32	0.09	4.78	0.66	0.07	10	5.0
II	0.85	0.02	0.12	0.01	0.19	6.18	0.09	7.26	0.90	0.08	12	4.8
III	0.02	0.01	0.06	0.02	0.16	0.08	0.13	2.28	0.80	0.05	16	4.6
IV	0.03	0.00	0.02	0.01	0.06	0.03	0.06	1.29	0.27	0.01	27	4.8
Depth = 20-40 cm												
I	0.75	0.02	0.10	0.01	0.20	3.08	0.08	5.67	0.58	0.06	10	5.09
II	1.20	0.02	0.12	0.01	0.19	3.34	0.10	8.42	0.84	0.07	12	4.78
III	0.04	0.01	0.07	0.01	0.11	0.05	0.08	1.42	0.70	0.03	23	4.90
IV	0.03	0.00	0.01	0.01	0.05	0.03	0.06	1.30	0.22	0.01	22	4.52
Depth = 40-60 cm												
I	0.73	0.02	0.11	0.01	0.22	2.87	0.08	5.68	0.51	0.05	10	5.21
II	1.64	0.02	0.14	0.01	0.17	1.59	0.11	10.48	0.78	0.06	12	4.90
III	0.07	0.01	0.10	0.01	0.11	0.05	0.10	1.75	0.70	0.01	70	4.96
IV	0.08	0.00	0.02	0.01	0.05	0.03	0.05	1.14	0.12	0.04	3	4.57

Nutrient content considering the upper 60 cm in phase IV was much lower than in phase I for all nutrients (Table 12). But in intermediate phases, some nutrient contents increase (i.e. nitrogen, calcium, potassium), some of them maintain similar contents (i.e. sodium) and

others decrease (i.e. phosphorus, ferrous). Nutrient contents in this soil are low and similar to those found in Brazilian sandy soils (Reis and Barros, 1990). In the juvenile phases nitrogen content correspond to soils of medium fertility, but in the older phase, this parameter corresponds to soils of low fertility. On the other hand, phosphorus content presents values of very low fertility in all phases (Fölster and Khanna, 1997).

Table 12. Nutrient content in the upper 60 cm of soil in different phases of an *Eucalyptus grandis* chronosequence.

Phase	Nutrient content (kg.ha ⁻¹) in the upper 60 cm of soil								
	Ca	Na	Mg	P	Fe	Mn	K	N	C
I	6792	210	1045	117	2316	37385	833	5974	58762
II	12368	201	1281	79	1813	35440	998	6955	82802
III	327	43	566	90	1057	509	826	2699	60310
IV	210	9	74	49	232	126	259	898	9298

It is important to remark that as stand develop, nutrient content in soil decreases while nutrient content in litter layer increases. So the system deplete soil nutrients and accumulates nutrients in the litter layer.

ESTIMATION OF NUTRIENT CYCLE PARAMETERS

Nutrient circulation and nutrient use efficiency are analyzed through the following parameters (Cole and Rapp, 1981; Vitousek, 1982):

- *Requirements*: total content of nutrients in annual increment (leaves, wood and fruits)
- *Return*: soil annual return of nutrient to the soil through litterfall
- *Redistribution*: difference between nutrient content in full expanded leaves and annual organs and recent fallen leaves, fruits and twigs.
- *Uptake*: estimated through requirements minus redistribution

The only nutrient that reduces its requirement as stand develops is nitrogen. Other nutrients requirements stay steady with age (Table 13). Nitrogen redistribution decays sharply with age. So as stand develops, nitrogen requirements decay, but also the importance of redistribution in satisfying this demand, so requirement is supply mainly by uptake. This pattern is expected because soil nitrogen content decays with age, too. It is well known that redistribution of nitrogen is lower in low-nutrient sites. Plants growing under luxuriant nitrogen regimes accumulate more mobile nitrogen compounds, whereas nitrogen-stressed plants have a larger proportion in structural, insoluble forms (Fisher and Binkley, 2000).

Nitrogen cycle follows the typical stages of the function and evolution of a stand (Grove et al., 1996; Miller, 1984). In a first stage of stand evolution, the demand of nutrients is high and production of leaves and dimensional changes occur fast. The site is not completely occupied but there is net accumulation of nutrients in the canopy. This stage corresponds to phase I and II of the chronosequence, characterized by high nitrogen requirement and high net

extraction of this nutrient from the litter-soil complex (21 and 25 kg.ha⁻¹.year⁻¹ in phase I and II respectively). As stand develops, immobilization continues principally in woody tissues, and although absorption is still high, the turnover of nitrogen represents a higher proportion of nitrogen taken up (82%) and therefore net extraction is lower (14 kg.ha⁻¹.year⁻¹ in phase III).

Table 13. Nutrient cycle parameters in different phases of the *Eucalyptus grandis* chronosequence.

	N	P	K	Ca	Mg
	(kg. ha ⁻¹ . year ⁻¹)				
	Phase I				
Requirements	185.2	8.5	48.2	64.0	19.3
Redistribution	113.1	6.3	24.4		
Return	51.3	1.4	15.9	84.2	9.8
Uptake	72.2	2.2	23.8	91.1	11.2
(Return/uptake)*100	71	66	67	92	88
Return-uptake	-20.9	-0.7	-7.9	-6.9	-1.4
(Redistribution/requirement)*100	61.0	74.5	50.6		
	Phase II				
Requirements	178.8	6.7	57.4	104.9	17.5
Redistribution	81.1	3.7	23.4		
Return	72.6	1.7	16.9	110.3	12.5
Uptake	97.8	3.0	34.0	122.7	13.7
(Return/uptake)*100	74	56	50	90	91
Return-uptake	-25.1	-1.3	-17.1	-12.4	-1.3
(Redistribution/requirement)*100	45.3	54.7	40.8		
	Phase III				
Requirements	106.8	8.0	54.1	91.1	15.6
Redistribution	31.9	4.0	15.1		
Return	61.1	2.1	30.8	105.5	12.9
Uptake	74.9	4.0	38.9	68.8	12.5
(Return/uptake)*100	82	53	79	153	103
Return-uptake	-13.8	-1.9	-8.2	36.7	0.4
(Redistribution/requirement)*100	29.9	49.7	28.0		
	Phase IV				
Requirements	76.1	8.1	41.3	94.1	17.9
Redistribution	18.0	3.3	19.3		
Return	58.4	2.8	25.6	72.6	14.7
Uptake	58.2	4.8	22.0	58.6	13.7
(Return/uptake)*100	100	59	116	124	107
Return-uptake	0.2	-2.0	3.6	14.0	0.9
(Redistribution/requirement)*100	23.6	41.1	46.7		

In the last stage of stand development growth rate diminishes and the age of its beginning depends on site fertility. In this phase, nitrogen requirement is lower and return of nitrogen to litter-soil system equals nitrogen absorption, so there is no more net accumulation of nitrogen in plant tissues.

Phosphorus cycle has a different pattern. Requirements maintain similar in all phases. But redistribution is more important at the beginning of stand development, representing the 74%

in phase I and 41% in phase IV. Net extraction of phosphorus increases from 0.7 kg.ha⁻¹.year⁻¹ in phase I to 2 kg.ha⁻¹.year⁻¹ in phase IV. So depletion of phosphorus from litter-soil complex continues still in older stages.

In the case of calcium and potassium, maximum requirement and net extraction from the soil occur in phase II. In the case of calcium, return is higher than absorption in phase III and IV, so net extraction from the litter-soil complex occur only in the first two phases. On the other hand, potassium has a net return to litter-soil complex only in phase IV.

NUTRIENT USE INDICES

Nutrient use efficiency is a measure of productivity per unit of nutrient available (Ewel and Hiremath, 1998). It is useful not only to explain patterns and processes in natural ecosystems, but also it is a useful tool in managed forest systems (Hiremath et al., 2002). Nutrient use indices permit to evaluate and manage stands in order to maximize production of goods per unit of nutrient used. Use efficiency of nitrogen, phosphorus, potassium, calcium and magnesium increase as stand develops. The same pattern was observed in a clonal *Eucalyptus* plantation in Congo (Laclau et al., 2000). Stem dry matter produced per unit of each nutrient taken up increases with age for all nutrients analyzed (Table 14). In phase I, each gram of nitrogen taken up produces 0.33 Mg of stem wood. In phase IV, the same amount of nitrogen yields 2.84 Mg of wood.

Table 14. Nutrient use efficiency in a chronosequence of *Eucalyptus grandis* expressed as Mg of stem dry mass produced per each gram of nutrient taken up.

Phase	Nutrient use efficiency (Mg of wood. g of nutrient ⁻¹)				
	N	P	K	Ca	Mg
I	0.33	10.77	0.99	0.26	2.11
II	0.69	22.65	2.00	0.55	4.96
III	1.78	33.29	3.42	1.93	10.65
IV	2.84	34.41	7.51	2.82	12.05

Other statistic that is useful to analyze nutrient use efficiency is the ratio between total dry mass annual production and annual uptake of each nutrient (Table 15). In later phases, dry mass production is higher per unit of nitrogen taken up. The main factor that determines this high efficiency is that nitrogen requirement slows down as stand develops. But phosphorus efficiency has the opposite pattern. This is because, as stand develops, requirement of phosphorus is similar but redistribution becomes less important, so growth is sustain mainly by phosphorus uptake.

Comparing nutrient efficiency of *Eucalyptus grandis* with that of 20 years old *Pinus taeda* plantation, it is noticeable that nitrogen and phosphorus use efficiencies are higher in the former species. One of the causes of higher nutrient use efficiency in *Eucalyptus* is the higher nutrient redistribution (Beadle and White, 1968; Grove et al., 1996). Nevertheless, efficiency of calcium and magnesium is lower in *Eucalyptus* than in *Pinus* (Table 15). It is well known that eucalypts have high calcium requirements (Turner and Lambert, 1983).

Table 15. Nutrient use efficiency estimated as annual dry mass production ($\text{kg. ha}^{-1} \text{ year}^{-1}$) per annual nutrient uptake ($\text{kg. ha}^{-1} \text{ year}^{-1}$) for different phases of an *Eucalyptus grandis* chronosequence. Data of a 20 years old plantation of *Pinus taeda* are presented .

Phase	Nutrient use efficiency (annual productivity. annual nutrient uptake $^{-1}$)				
	N	P	K	Ca	Mg
I	238	7818	723	189	1536
II	268	8733	771	214	1912
III	343	6425	661	374	2056
IV	397	4813	1050	394	1686
<i>Pinus taeda</i>	168	4153	824	771	2458

PREDICTION OF FOREST SYSTEM STABILITY

Forest use in subsequent rotations can reduce site quality and diminish productivity, specially in low fertile sites, due to nutrient export with harvest and rotation length shorter than ecology rotation (Louw and Scholes, 2002; Sankaran et al., 2005). Then, sustainable silviculture should pay attention to nutrient destiny and nutrient cost of harvest (Mendham et al., 2003; Nzila et al., 2002). On the other hand, commercial plantations are in general guide only by financial indexes. High costs can change enterprise decisions, so maintaining productivity in the ecological dimension can elevate costs to levels that any commercial company can afford (Mackensen and Folster, 2000).

In order to analyze how different harvest scenarios affect the nutrient stability of plantations in the loamy sand soil, some indexes are calculated. Then, it is possible to predict which alternative has the higher present financial value and, moreover, if this present value can be maintain whether ecological sustainability is considered trough the cost of export nutrients.

Three harvest scenarios are considered: 1) harvest of commercial stems (diameter higher than 5 cm) and slash conservation in site, 2) extraction of whole trees and commercialization of stems with diameter higher than 5 cm and 3) extraction of commercial stems and slash burning in site. In the last scenario, it is considered a volatilization of nutrients by slash burning equal to 88% of nitrogen, 33% of phosphorus, 30% of potassium, 47% of calcium and 43% of magnesium (Maluf, 1991). Litter layer is considered part of the harvest slash, so they have the same destiny in each scenario. Each scenario is evaluated in two ages in which is possible to harvest: at 8 and 11 years old plantation (phases III and IV, respectively).

Nutrient export differs between scenarios and between rotation length (Goya, Frangi, Denegri and Larocca, unpublished data). If rotation is shorter, nitrogen and potassium extraction is higher in all harvest scenarios, but calcium extraction is lower (Table 16). In both rotation lengths, if harvest residues are burnt, losses of nitrogen and potassium are higher, even respect to total tree extraction. So for these nutrients, the better scenario consists in longer rotation and extraction of only commercial stem, while the worst scenario consists in shorter rotation, extraction of commercial stems and slash burning. Phosphorus extraction

is not significantly altered by rotation length and harvest scenario. Calcium and magnesium extractions are higher in the longer rotation, especially if residues are burnt. The negative effects of slash burning in nutrient extraction are due to the impact of this practice in litter layer, where large amounts of organic matter and nutrients are accumulated (Gonçalves et al., 2004). Reduction of nitrogen export in longer rotation results from the balance of higher amount of biomass extracted but with lower nitrogen concentration in tissues (see Table 5 and 6).

Table 16. Export of nutrients in each harvest scenario and rotation length in *Eucalyptus grandis* plantations. Extraction of only the commercial stem, extraction of complete tree (stem + bole) and extraction of the stem and burning the bole in site are the harvest scenarios considered for each rotation length.

Rotation	Harvest scenario	Nutrient export (kg.ha ⁻¹)				
		N	P	K	Ca	Mg
8 years	Stem	286,4	24,8	167,1	314,1	33,2
	Complete tree	409,2	38,0	233,5	458,4	62,8
	Stem + slash burning	491,1	39,6	243,9	63,2	79,5
11 years	Stem	181,3	34,6	86,6	562,1	49,0
	Complete tree	251,4	41,7	143,8	703,6	68,9
	Stem + slash burning	368,9	46,2	175,4	911,8	97,2

Consequences of each harvest scenario are evaluated comparing the amount of nutrients exported with harvest respect to nutrient pool in soil. So, plantation stability ratio (PSR) is calculated as the ratio between export nutrients and nutrient content in soil up to 100 cm deepness, excluding litter layer (Fölster and Khanna, 1997). Higher values of this ratio represent less nutrient stability of the plantation in the long term. For all nutrients analyzed and both rotation lengths, the higher values of PSR are in the scenario in which residues are burnt (Table 17). Nitrogen is the more instable nutrient, but it is also the only nutrient that becomes more stable at longer rotation. If an PSR higher than 0.5 is consider instable (Gerdin and Schlatter, 1999), nitrogen and calcium are the only nutrients that affect the plantation stability, while the other nutrients analyzed have values below that threshold. So attending nitrogen stability, it is better a longer rotation length with the extraction of only commercial stem and leaving the residues on site.

Table 17. Plantation stability ratio (PSR) calculated as the ratio between the amount of each nutrient exported and nutrient content in the upper 100 cm of soil. Data are presented for two ages *Eucalyptus grandis* plantations and for three harvest scenarios.

Rotation	Scenario	Plantation Stability Ratio				
		N	P	K	Ca	Mg
8 years	Stem	1,60	0,17	0,10	0,34	0,02
	Complete tree	2,28	0,27	0,14	0,49	0,04
	Stem + slash burning	2,74	0,28	0,15	0,68	0,06
11 years	Stem	0,87	0,34	0,14	0,70	0,23
	Complete tree	1,21	0,41	0,23	0,88	0,32
	Stem + slash burning	1,77	0,46	0,28	1,14	0,45

To analyze the rent of different forest managements, two rotation lengths (8 and 11 years) are analyzed through the difference in the financial indexes (Dasgupta and Pearce, 1972; Whittock et al., 2004). For each scenario, a cash flow is built, considering local practices (site preparation, planting, silvicultural practices and harvest) in the region under study. Mean costs for the region are considered. In order to evaluate the export of nitrogen with harvest, its reposition cost is analyzed considering fertilization with urea, with 70% of effective absorption. A criterion to accept a rotation length consists in higher internal return rate (IRR).

IRR is maximum in the shorter rotation without nitrogen reposition (fertilization). But if fertilization is applied, the longer rotation is preferable considering IRR as financial criteria. When nitrogen is added by fertilization, establishment cost increases, so a longer rotation is much more convenient.

Table 18. Internal rate of return (IRR) (%) for 8 years and 11 years for two rotation length in *Eucalyptus grandis* plantations, with and without reposition of nitrogen export with harvest.

Rotation length	With fertilization	Without fertilization
8 years	4.5	13.0
11 years	8.5	12.7

Doses applied by foresters in the region are of 50 kg ha⁻¹ of nitrogen (Dalla Tea and Marcó, 1996). This amount is not enough to return nitrogen extraction with wood in any harvest scenario. But costs of fertilization to compensate nutrient extraction alter substantially financial profitability of the system, as is indicated by the analysis of IRR. Therefore, as adding nutrients through fertilization has high economic cost, it is necessary to diminish nutrient extraction and to implement silvicultural practices tending to conserve nutrients in the system (Mackensen and Folster, 2000).

BIOMASS AND NUTRIENT ACCUMULATION AT HARVEST IN DIFFERENT SOIL TYPES

Forest productivity is regulated by many environmental factors, of which nutrient availability is one of the most important and easy to be managed by forest managers. Maintaining nutrient supply of forest soils is crucial for sustaining productivity (Louw and Scholes, 2002). In order to quantify nutrient extraction with harvest it is necessary to know biomass partitioning and nutrient content in each compartment. The adequate manage of the plantation should minimize nutrient extraction and ensure nutrients for future rotations.

Biomass estimation has been used to estimate growth, productivity and nutrient cycle, although it has not commonly been used for practical purposes in nutrient management (Goya et al., 1997). Changes in allocation pattern alter the harvest index and nutrient extraction. On the other hand, knowing nutrient content in not harvestable compartments makes possible to estimate nutrient turnover with slash. Site quality defines the productivity of plantations, but moreover, it changes biomass and nutrient allocations (Grove et al., 1996; Madeira et al., 2002; Xu et al., 2002). Biomass, productivity and nutrient content at harvest in 14 years old *Eucalyptus grandis* plantation over three different soils are evaluated. Soils used have different fertility and physical properties (Table 19).

Table 19. Soil characteristics of the three soil on which the 14 years old plantations of *Eucalyptus grandis* are established.

Characteristic	Red sand		Loamy sand			Black soil		
Type	Deep red sand		Dark brown sand			Black soil		
Taxonomy	Oxic Quartzipsamment		Fluventic Haplumbrept			Argiudolic Pelludert		
	Entisol		Entisol			Vertisol		
Description	Sand on reddish clay loam at > 150 cm		Sandy loam epipedon on sandy clay loam at 70 cm, grayish with inclusions of reddish materials			Deep hydromorphic soil. Silty clay loam mollic epipedon (30-35 cm), argilic B2, calcium carbonate concretions below 75-90 cm		
Horizon	Ap	AC	Ap	A	C	A1	B21t	B22t
OM (%)	0.42	0.21	1.50	1.30	1.40	4.50	1.97	1.63
pH (H ₂ O)	5.4		5.4			5.8		
ECEC (meq./100g)	1.22	1.02	5.80	7.70	21.70	28.40	39.80	42.00
Humidity Equivalent (%)	1.90	1.70	9.20	10.50	22.80	26.20	40.50	42.60
Base Saturation (%)	26	30	30	33	66	78	85	96

BIOMASS ACCUMULATION

Diametric distribution in each site follows the normal distribution typical of evenage stands, with modal in a higher class in loamy sand site (Figure 9). Nevertheless, the modal of biomass distribution is in the same class in all sites. But loamy sand site has higher modal and an important fraction of the total biomass in higher classes. So trees in this site reach higher dimensions than in red sand and black soil sites.

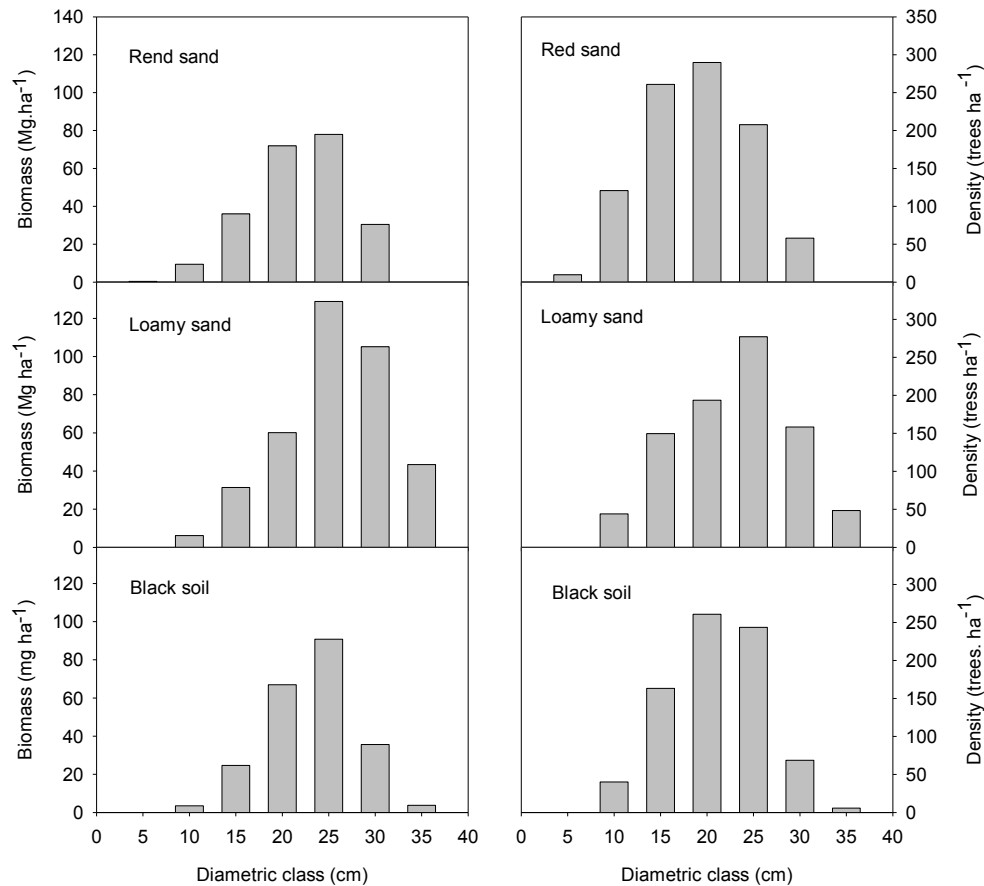


Figure 9. Biomass accumulation (Mg ha^{-1}) and tree frequency (trees ha^{-1}) in diametric classes of 5 cm in the *Eucalyptus grandis* plantations on three different soils.

Stand parameters change in each site (Table 20). Plantation on loamy sand has a 20-30% more DBH, 35-29 more height and 31-33 % more basal area than red sand and black soil sites respectively. Moreover, volume and MAI are 73% higher in loamy sand site (Table 21). So higher biomass in loamy sand site is due to higher mean height as well as to higher proportion of trees in upper DBH classes. Nevertheless, biomass and MAI of three sites are high, comparable with *Eucalyptus grandis* plantations in the most productive sites of Brazil, South Africa and Australia (Goya et al., 1997).

Table 20. Total height (m), diameter at breast height (cm), stem weight (kg) and leaf biomass to stem biomass ratio in 14-years old *Eucalyptus grandis* plantation on three different soils.

Site	Height (m)	DBH (cm)	Stem weight (kg)	Leaf: stem mass ratio
Red sand	24.3 ± 0.58	20.60 ± 0.76	187.51 ± 17.02	0.023
Loamy sand	33.9 ± 0.56	25.89 ± 0.91	406.06 ± 31.86	0.017
Black soil	25.6 ± 0.40	22.87 ± 0.73	237.07 ± 16.91	0.021

Table 21. Dry mass of each compartment per hectare (biomass) (Mg ha⁻¹), mean annual increment (MAI) of total trees and main stem (Mg ha⁻¹ year⁻¹), basal area (m² ha⁻¹), volume of wood per hectare (m³ ha⁻¹), mean annual increment expressed as changes in volume (m³ ha⁻¹ year⁻¹) and harvest index (mass of stems with diameter higher than 5 cm respect to total mass) (%) of 14 years old plantations of *Eucalyptus grandis* over three different type of soils.

	Red sand	Loamy sand	Black soil
biomass (Mg ha ⁻¹)	4.13	5.59	4.12
leaves	1.06	1.88	1.08
fruits	1.22	1.95	1.19
current year branches	2.72	3.42	2.63
branches < 1 cm	9.00	11.35	8.73
branches < 5 cm	0.45	0.57	0.44
branch's bark	199.97	351.00	201.93
stem	13.45	23.64	13.59
stem's bark	226.14	375.06	225.23
total MAI (Mg ha ⁻¹ y ⁻¹)	16.15	26.80	15.02
stem MAI (Mg ha ⁻¹ y ⁻¹)	14.28	25.10	13.46
basal area (m ² ha ⁻¹)	36.60	48.00	36.00
volume (m ³ ha ⁻¹)	418.30	721.00	417.30
MAI (m ³ ha ⁻¹ y ⁻¹)	29.80	51.50	29.80
Harvest Index (%)	88.00	94.00	90.00

Trees in loamy sand site have higher proportion of biomass in stem and lower proportion of biomass in leaves. Therefore, leaf: stem biomass ratio is lower for loamy sand site. This ratio indicates higher efficiency because plants accumulate more biomass in stems with less mass of leaves. In better site quality it is reported that *Eucalyptus* increment stem growth in absolute and relative way (Cromer and Jarvis, 1990; Herbert and Robertson, 1991). The efficiency of leaves to accumulate stem dry mass depends on nutrient partitioning to compounds involved in photosynthesis, partitioning of nutrients within the organs and total respiration rate (Sheriff and Nambiar, 1991). So better nutrition can improve leaf photosynthetic rate (Sands et al., 1992). But dry mass partitioning is also important in defining stem growth. For example, in sites with low nutrient or water availability in soil, root system is larger and therefore it demands more fixed carbon and reduces carbon allocation to stem (Sperry et al., 1998).

In order to analyze the impact of harvest in the three sites, it is important to remark that in the loamy sand site productivity is higher but the proportion of leaves is shorter than in the other two sites. So it is necessary to evaluate nutrient content of each compartment in order to estimate nutrient extraction.

NUTRIENT ACCUMULATION IN BIOMASS

The compartment that accumulates more nutrients per hectare in all sites is the stem, followed by leaves (Table 22). Nevertheless, nitrogen accumulation in the black soil site was higher in leaves than in debarked stems. On this soil, leaf nitrogen concentration reaches 21.6 mg.g⁻¹, two folds foliar concentration in the red sand and loamy sand sites (14.7 and 14.9 mg.g⁻¹ respectively).

Table 22. Nutrient content (kg.ha⁻¹) in each compartment of 14 years old Eucalyptus grandis plantations over three different type of soils.

	Nutrient content (kg ha ⁻¹)				
	N	P	K	Ca	Mg
<i>Red sand</i>					
leaves	61.7	5.0	32.8	59.3	13.4
fruits	6.0	0.7	7.8	8.4	2.9
current year branches	2.7	1.1	7.7	16.2	2.4
branches < 1 cm	10.7	1.2	9.5	24.9	3.4
branches < 5 cm	8.0	0.7	12.9	12.3	2.6
branch's bark	1.5	0.3	1.9	13.2	1.5
stem	189.5	10.0	74.6	17.5	19.6
stem's bark	32.6	9.0	67.7	397.9	25.6
total	312.8	27.6	215.1	707.0	71.4
<i>Loamy sand</i>					
leaves	83.3	5.4	40.8	65.8	14.9
fruits	9.0	0.9	14.3	14.9	4.4
current year branches	10.1	1.4	8.1	24.5	3.3
branches < 1 cm	11.6	1.2	10.0	30.3	5.2
branches < 5 cm	12.5	1.4	15.1	11.9	6.6
branch's bark	2.0	0.5	2.5	14.7	2.2
stem	196.4	8.5	106.1	247.8	23.9
stem's bark	70.9	18.0	111.5	699.7	47.7
Total	378.9	37.3	308.4	1109.6	108.2
<i>Black soil</i>					
leaves	88.8	67.0	34.5	49.3	9.7
fruits	5.3	0.9	7.0	8.3	1.8
current year branches	9.4	1.5	10.3	17.6	2.2
branches < 1 cm	13.4	1.6	9.9	27.6	4.3
branches < 5 cm	9.5	2.8	20.8	11.7	2.4
branch's bark	2.0	0.5	2.8	9.4	1.2
stem	47.7	17.3	107.7	99.4	15.7
stem's bark	48.4	25.8	85.7	857.5	31.9
Total	224.4	57.0	278.8	1080.9	69.1

Nutrient content in each compartment is a key information in order to determine nutrient export in different harvest scenarios.

EXPORTATION OF NUTRIENTS WITH HARVEST

Clearfelling in each type of soil represents different nutrient export (Table 23). Nitrogen, phosphorus and potassium export in red sand and loamy sand is similar, although biomass harvest in loamy sand is higher.

Table 23. Export of nutrients in different harvest scenarios in the three sites analyzed in 14-years old *Eucalyptus grandis* plantations.

	Nutrient extraction (kg ha ⁻¹)				
	N	P	K	Ca	Mg
Red sand					
Debarked stem	190	10	75	175	20
Stem with bark	222	19	142	573	45
Bole extraction	91	9	73	59	26
Loamy sand					
Debarked stem	196	9	106	248	24
Stem with bark	267	26	218	948	72
Bole extraction	129	11	91	162	37
Black soil					
Debarked stem	48	17	108	99	16
Stem with bark	96	43	194	957	48
Bole extraction	128	14	85	124	22

Each kg of debarked stem has a different nutrient cost in each type of soil. For nitrogen and calcium, the cost is higher in red sand site and lower in black soil. For phosphorus and potassium, cost is higher in black soil and lower in loamy sand. In all sites, nutrient cost increases much if stem is harvest with bark. In the black soil, the cost in nitrogen, phosphorus, potassium and magnesium extracted by kg of stem produced is the double if stem is harvest with bark respected to harvest it debarked. In the other two sites, extraction of stems with bark doubles the cost of all nutrients analyzed except for nitrogen and calcium. Nitrogen cost in this two sandy soils increase only around 20% if it is extracted with bark. However, in all soils calcium cost raises more than three folds if stems are not debarked in site, due to the high calcium concentration in bark. This highlight the importance of debarking stems on site and not to burn it (Gonçalves et al., 2004).

Nutrient extraction enlarges still more if crowns are removed. This is explained because leaves are the richest compartment of trees. If hole trees are removed, nitrogen cost of each kg of debarked stem in black soil raises to figures similar to cost in loamy sand site. This sharply increase in nitrogen cost is due to the high nitrogen concentration in leaves that do not represent larger stem growth. In conclusion, wood extraction should limit to debarked stems, and bark and crown should stay in site in order to reduce as much as possible nutrient costs (Judd et al., 1996).

LITTERFALL AND LITTERFALL DECOMPOSITION

Considering that nutrient accumulation in compartments that can be left in site is high, it is important to consider nutrient return to litter-soil system in order to evaluate system stability. Litter layer is the major precursor of soil organic carbon and its assessment and characterization are important for a better understanding of soil carbon dynamic (Zinn et al., 2002). Soil organic carbon plays an important role in all edaphological processes, from aggregation to plant nutrient supply, specially in less fertile and coarse textured soils. In the long term, losses of soil organic carbon may affect crop yields by the reduction of nutrient supply (Zinn et al., 2002). Different tendencies have been reported in soil organic carbon in *Eucalyptus* plantations in the tropics, including losses, no alterations and even increases. These different results can be explained by soil type and species, as well as by different silvicultural practices and environmental conditions that makes impossible to found general tendencies (Zinn et al., 2002).

In the three sites studied, litterfall is higher in sites with higher MAI, so differences between sites in total aboveground productivity enlarge. So it is greatest in the loamy sand site, is intermediate in the red sand and lower in the black soil (Table 24). In all sites, leaves are the larger compartment. Return time is 9.1, 8.7 and 11.75 years for red sand, loamy sand and black soil. This figures indicate that in the most productive site, the biomass cycle is more dynamic, and return to carbon and nutrients to the soil occur at higher rates. In the black soil site, that has lower MAI but higher availability of nutrients in soil, return time is longer, so carbon and nutrients are retained in tree biomass more time.

Table 24. Components of annual litterfall ($\text{Mg ha}^{-1} \text{ year}^{-1}$) in the three sites with 14 years old *Eucalyptus grandis* plantations.

litterfall compartment ($\text{Mg ha}^{-1} \text{ y}^{-1}$)	red sand	loamy sand	black soil
leaves	6.07	8.42	1.78
bark	0.61	1.72	0.80
branches	1.21	4.01	0.60
fruits	0.96	2.23	0.95
total	8.76	16.38	4.14

Litterfall returns to soil large amounts of nutrients, and the most productive forests have the most nutrient rich litter (Attiwill et al., 1996). Return of nutrients is higher in the loamy sand site, because the lower nitrogen concentration in recent fallen leaves is counteracted by the higher mass of litterfall (Tables 24 and 25). Nitrogen return in litterfall represents the 80% of foliar nitrogen content in the sandy soil sites, while in the black soil nitrogen return in litter layer represents only the 40% of foliar nitrogen content. This implies a longer retention of nutrients in tree biomass in the black soil.

Litterfall feeds litter layer. However, litter layer thickness depends also on decomposition rate. The litter layer is thicker in the loamy sands (3.2 Mg ha^{-1}), while it is thinner in the red sand (2.8 Mg ha^{-1}) and in the black soil (2.2 Mg ha^{-1}). Litterfall is decomposed at different speeds in each site. Decay rate of dry matter is similar in both sandy soils ($k=0.30$) and lower than in black soil ($k=0.44$), so mean litter residence is of 3.3 years in sandy soils and 2.3 years in black soil (Goya, Frangi, Dalla Tea and Pérez, unpublished data).

Table 25. Nutrient concentration (mg.g⁻¹) in recent fallen leaves of *Eucalyptus grandis* at the three different sites. In parentheses standard deviations.

	Nutrient concentration (mg g ⁻¹)				
	N	P	K	Ca	Mg
Red sand	5.8 (1.04)	0.4 (0.03)	2.2 (0.16)	15.0 (1.34)	2.4 (0.17)
Loamy sand	6.0 (0.61)	0.4 (0.05)	2.0 (0.28)	14.5 (0.41)	2.0 (0.07)
Black soil	7.4 (0.92)	0.5 (0.04)	1.8 (0.46)	12.7 (0.68)	1.7 (0.37)

Organic matter content, inorganic colloids and nutrient and water availability in the soil are the main factors that modulate decay rate. During decomposition, nitrogen and phosphorus can be immobilized or released. The retention of nitrogen and phosphorus is characteristic of decomposition of litter in *Eucalyptus* plantations (Attiwill et al., 1996; Corbeels et al., 2003). Nitrogen increment in litter is associated with higher microbial biomass (Aerts and De Caluwe, 1997). There is a theoretical detritus C:N ratio (30:1) above which decomposers are nitrogen limited and below which they are carbon limited (Kaye and Hart, 1997). In all sites analyzed, nitrogen in litter layer increases with time at the beginning of decomposition period, with higher immobilization in the black soil. But although their lower decaying rate, sandy soils release during the first year relative more nitrogen (48 and 36 % for red sand and loamy sand respectively) than black soil, that only released 6% of its initial content. Phosphorus is released during the first year in the red sand, while it is immobilized in the loamy sand and in the black soil. Then, despite not significant differences in chemical quality of leaves at initial phase, the C:N and C:P ratios are lower in the black soil. So nitrogen concentration in substrate, together with better conditions in soil (nutrient concentration, water retention, organic matter), accelerate decay rate in the black soil. So in the nutrient richest soil, decomposition rate is faster and immobilization of nitrogen and phosphorus in litter is higher too.

The lower decomposition rate, specially in sandy soils, together with the higher nutrient return in litterfall, highlights the importance of avoiding slash burning after harvest in order to reduce nutritive cost of wood production and to ensure nutrients for future cycles.

REPLENISHING OF NUTRIENTS: FERTILIZATION

As we analyzed in previous sections, nutrient extraction depends on rotation length and soil type. In order to maintain the pool of nutrients in the system, one possibility is to add fertilizers. The amount of fertilized in each type of soil and rotation length should be different if the objective is to maintain the pool of nutrients. However, it is not easy to predict the effect of the addition of nutrients in a system. Soil type affects many aspects related to tree nutrition: nutrient availability in soil, decomposition rate of the litter layer, nutrient uptake, tree growth and biomass partitioning. Therefore, fertilization can alter all these pools and fluxes that are soil dependent. Moreover, it is well known that nutrients interact in soil and in

plants. Therefore, predictions of effects of fertilization are difficult and local experiments are needed.

In young *Eucalyptus grandis* fertilized with nitrogen or phosphorus growth increases more with the application of phosphorus than nitrogen, still in the red sand and loamy sand that have very low availability of nitrogen (Graciano et al., 2006). Moreover, nitrogen content in plants fertilized with phosphorus is higher, due to both higher nitrogen concentration in tissues and higher biomass. Therefore, the application of a single fertilizer (phosphorus) alters the uptake of other important nutrients, like nitrogen.

Different soil types differ in nutrient concentration, but also in physical properties, for example water retention capacity (Arya et al., 1999). Water availability affects also decomposition of litter layer, nutrient uptake and tree growth and partitioning. High availability of nutrients produces changes in biomass allocation, for example reduction of biomass allocated to roots (Misra et al., 1998; Sands et al., 1992). But this change in allocation is also affected by water availability. When trees are subject to water shortage, the root system tends to be wider (Hacke et al., 2000; Snowdon, 2000). Therefore, trees are exposed constantly to forces that modulate their dry mass partitioning, their growth rate and nutrient use efficiency in directions that not always follow the same direction. The result of all the forces is difficult to predict (Gonçalves et al., 2004), but it is clear that the result is not easy to be calculated knowing only soil nutrient availability. At least water availability should be also considered.

In young plants of *Eucalyptus grandis* in the three soils analyzed, fertilization with nitrogen or with phosphorus increases tree growth but it reduces allocation to roots (Graciano et al., 2006). But fertilization with the same nutrients in the red sand and loamy sand does not increase growth when plants are exposed to moderate water shortage (Graciano et al., 2005; Graciano et al., 2006). In these soils, the reduction in root:shoot ratio due to fertilization is not revert in conditions of water shortage. On the other hand, in the black soil, root:shoot ratio does not diminish if fertilization is applied in conditions of water shortage, and so growth increases in fertilized plants still with low water availability. Therefore, prescription of fertilization should take into account the soil type and the possibility of water deficit, specially in coarse soils (Sánchez Rodríguez et al., 2002). Sandy soils have low water retention capacity, so short periods in summer without rainfall diminish suddenly water availability for plants, and in this soil fertilization has negative effects in tree growth under water shortage conditions.

CONCLUSION

Plantations of *Eucalyptus grandis* are high nutrient demanders. With harvest, high amounts of nutrients are exported from the system. However, the extraction of only the debarked stems contribute to nutrient system stability. The most critical nutrient is nitrogen. Replenishing the system with the nitrogen extracted with harvest has a high impact in financial profitability, so nutrient extraction has to be minimized by taking out the system only debarked stems. Slash burning has to be avoided because a high quantity of nutrients are accumulated in litter layers as stands develops, specially in coarse textured soils.

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