ABOVE-GROUND BIOMASS, NUTRIENT CONTENT, AND NUTRIENT USE EFFICIENCY OF EUCALYPT PLANTATIONS GROWING IN DIFFERENT SITES IN BRAZIL*

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ABSTRACT

The annual increment in above-ground biomass, and the corresponding nutrient content of eucalypt plantations growing in nine different sites, were evaluated in order to analyse the growth and the nutrient accumulation of *Eucalyptus* spp. in Brazil. The sites represented a wide range of edaphic and climatic conditions, resulting in a large variation in growth increment and tree nutrient content. The highest productivities (approximately 36 t/ha·year) were observed in sites with the lowest water deficits. On average, the stem represents 89% of the above-ground biomass but it can be as low as 78% in the least productive site. The nutrient content in the stem was highest in the most productive sites, showing a close relationship with biomass production. There were two distinct patterns of stem annual nutrient accumulation. At three of the sites, the amount of nutrients in the stem decreased in the order nitrogen > calcium > potassium > magnesium > and phosphorus. However, calcium exceeded nitrogen at the other six sites. Nutrient use efficiency (NUE) for stem and above-ground biomass production was significantly different among sites. On average, the values of NUE for both stem and above-ground biomass decreased in the order phosphorus > magnesium > potassium > nitrogen > calcium. Unlike dry matter, there were appreciable differences among sites in relative nutrient allocation. Although bark constitutes only 10% of the above-ground dry matter, it contains large amounts of nutrients (73% of the calcium in the stem, 65% of the magnesium, 46% of the phosphorus, 41% of the potassium, and 24% of the nitrogen). Debarking in the field can substantially reduce nutrient exportation, which could lead to greater sustainability or less fertiliser use in eucalypt plantation forests of Brazil.

Keywords: biomass; nutrient content; nutrient efficiency; *Eucalyptus* spp.

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INTRODUCTION

The largest areas planted in eucalypts in Brazil are found in the states of Bahia, Espírito Santo, Minas Gerais, Pará, Paraná, Rio Grande do Sul, and São Paulo. These total about 5 million ha (Gonçalves *et al.* 1997). In Brazil, eucalypt plantations occur over wide variations in physiography, climate, and soil (Moreira 1997). The demand for eucalypt timber and fibre is increasing due to (1) an industrial requirement for eucalypts, and (2) the desire to conserve native Brazilian forests.

Several characteristics influence the quantity of nutrients absorbed by trees. These characteristics include total forest stand nutrient demand, growth rate, efficiency of nutrient absorption from the soil, and tree nutrient use efficiency (Gonçalves *et al.* 1997). Climatic factors as well as physical and chemical soil characteristic influence eucalypt biomass production (Barros & Novais 1996). These factors and characteristics cause high variability in eucalypt plantation productivity in Brazil. The volume yield can range from 15 to over 100 m^3/ha·year. Quantifying biomass production, nutrient content, and NUE is important if plantations are to be managed on a sustainable basis.

In eucalypt plantations, nutrients are removed from the site mainly as a result of stem harvesting. If the removed nutrients are not replenished (i.e., by fertiliser, precipitation, and weathering) there should be a reduction in soil nutrient bioavailability which in these tropical, and even some sub-tropical, environments may limit harvesting to just a few rotations. A long-term strategy for sustainable land use requires that plantation managers know the quantitative relationship between the nutrient loss incurred with harvesting and the bioavailable nutrient pool in the soil (Spangenberg *et al.* 1996). For any given species, the amount of nutrient in various tree tissues (foliage, branches, barks, and stems) can differ from one site to another, with climatic conditions being a primary control.

Measurements of the mass, and the nutrient concentration in that mass, provide information on the amount of nutrients immobilised in plant biomass and indicate the amounts required for annual production at a specific production rate. These measurements are also used to calculate NUE, which can be indicative of levels of plant-accessible soil nutrients (Shaver & Melillo 1984). Aerts & Caluwe (1994) commented that a common approach to the study of the adaptive significance of resource use by plants is to determine their resource use efficiency, which is generally defined as the ratio between an output parameter (biomass production, seed production, photosynthetic carbon gain) and a resource input parameter (light absorption, nutrient uptake, water uptake).

Studies describing nutrient relationships in tropical plantations, especially those providing information on the amount of nutrient in soils, are limited. Management questions which would benefit from such information include: how should harvesting (wood and bark) and slash be managed to reduce nutrient losses? or, how can nutrient losses be ameliorated? Such issues, pertinent to sustainability of forest production, are of particular significance in the humid tropics because the rates of production are high and many tropical soils are of very low fertility (Fölster & Khanna 1997).

In this paper, we present the results of a study on eucalypt above-ground biomass, nutrient content (nitrogen, phosphorus, potassium, calcium, and magnesium) and NUE for nine representative sites in Brazil. The objectives were to:

(1) Determine a generalised relationship between eucalypt biomass production and soil water availability for Brazil;

(2) Determine the general nutrient accumulation rates and rates of nutrient removal associated with harvesting of eucalypt plantations in Brazil; and

(3) Determine the general effect of water availability on NUE of nitrogen, phosphorus, potassium, calcium, and magnesium content of eucalypt plantations in Brazil.

METHODS

In 1980, the Soil Department of the Federal University of Viçosa, MG, Brazil, initiated a research programme on soil and eucalypt nutrition. During the past 19 years, this programme has established a database on eucalypt growth and production, nutrient accumulation in the biomass, and nutrient partitioning among above-ground components of eucalypts cultivated under varying climatic, topographic, and soil conditions. Soil texture is variable among sites but soil fertility is generally low (Novais *et al.* 1986). Most of the data used in this paper come from that database. The data presented in this paper represent an average condition for each site and were collected in five states spanning the north-south extent of Brazil (Fig. 1). These states contain about 90% of all eucalypt plantations in the country. Site characteristics of each study site are listed in Tables 1 and 2. Both commercial plantations and field experiments were sampled. Matching site and species has been one of the main concerns of eucalypt silviculture in Brazil, and *E. grandis* Hill ex Maiden, *E. saligna* Smith, *E. urophylla* S.T.Blake, *E. camaldulensis* Dehnh., *E. cloesiana* Maiden, and several hybrids are the most planted genetic materials. The species or clones of *Eucalyptus* that were planted represented the best genetic material available at that time for that specific condition. Forest management practices varied from site to site, but represented

FIG. 1–Location of the study states

TABLE 1–Climatic characteristics of the studied sites

Site	Altitude (m)	Climate type	Mean annual temperature (°C)	Rainfall (R) (mm/yr)	Evaporation (E) (m/yr)	Water availability index (R–E) (mm/yr)	Rainfall regime	Water deficit
SP2	700–1000	Sub-montano or temperate, humid	17–19	1300–1500	800–1200	500–300	Uniform	Null
SP3	600–900	Subtropical moderate, humid	18–22	1200–1400	800–1200	400–200	Seasonal	Small to moderate
PA	40–200	Tropical, humid	24–26	2200–2500	800–1200	1400–1300	Seasonal	Small to moderate
ES	00–50	Tropical, sub-humid humid	23–27	1250–1500	800–1200	450–300	Seasonal	Moderate
RS	100–500	Temperate or sub-tropical moderate, humid	16–20	1250–1450	800–1200	450–250	Uniform	Small
MG3	600–1000	Subtropical moderate, humid	18–22	1200–1500	800–1200	400–300	Seasonal	Small to moderate
MG2	300–700	Subtropical, sub-humid, humid	20–23	1000–1200	800–1200	200–000	Seasonal	Moderate
SP1	250–600	Subtropical or tropical, sub-humid, humid	21–24	1100–1500	1200–1600	(–100) – (–100)	Seasonal	Moderate
MG1	800–900	Subtropical or tropical, humid or sub-humid humid	19–25	1100–1400	1200–1600	(–100) – (–200)	Seasonal	Moderate to strong

TABLE 2–Site topographic conditions and soil characteristics

Site	Topographic conditions	Clay content (%)	Soil classification
SP2	Plateau	50–90	Tropepts/Tropulduts
SP3	Hilly mountainous	60–70	Orthox/Tropepts
PA	Plateau	9–82	Orthox/Uldults/Psamments
ES	Coastal plains	10–30	Tropulduts/Aquults
RS	Hilly mountainous	15–70	Uldults/Udalfs
MG3	Hilly mountainous	40–80	Tropepts/Tropulduts
MG2	Hilly mountainous	40–80	Tropepts/Tropulduts
SP1	Plateau	10–23	Ustox
MG1	Central plateau	10–15	Ustox

the best management practices recommended at that time. In general, site preparation consisted of bedding or disking of the planting row; fertiliser application at planting hole or furrow, and again in bands 6 to 18 months later; weeding; and control of cutting ants.

Tree biomass and nutrient content were assessed in stands representative of each site. Biomass sampling plots (600 m^2) were randomly selected. For commercial plantations, at least one sampling plot was used for each 20 ha where sites were homogeneous in terms of soil and topography. However, in experiments, three to four plots were sampled. A random block design was used. All trees were measured for diameter (dbh) and height. In each plot, trees corresponding to the mean-sized tree were felled, and their components (leaves, branches, stem-bark, stem-wood) separated, weighed in the field, and sub-sampled for dry weight determination (oven-dried at 65°C) and nutrient analysis. Plant tissue was wet digested with hot nitric acid and perchloric acid (3:1) and analysed for phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). Nitrogen was analysed by the micro-Kjeldahl procedure. From these data, tree biomass and nutrient concentrations were calculated. The nutrient content in each tree component was estimated by multiplying biomass by nutrient concentration, and for the whole tree and stem by summing the amount in tree or stem components. The ratio between mean biomass and mean nutrient content was used as an index of nutrient NUE.

Average values, as well as maximum and minimum values, were calculated for each parameter and regressed against environmental characteristics. Multivariate clustering methods were used for site grouping. The sites and mean above-ground biomass were subjected to single linkage and Euclidean distances to site grouping by using Statistica (Statsoft Inc. 1999).

A water availability index (WAI) was estimated by subtracting total annual evaporation from annual rainfall. Annual evaporation and annual rainfall represent an average of a 59-year assessment (from 1931 to 1990).

RESULTS AND DISCUSSION

Biomass and Water Availability

The sites can be divided in three groups according to their above-ground and stem biomass productivity when a linkage distance of 2.7 is arbitrarily adopted (Fig. 2). The highest productivity group is represented by SP2, 27 t/ha·year, which was 1.15 times higher than that of the second best site (SP3) (Table 3). The intermediate productivity group (SP3, PA, ES,

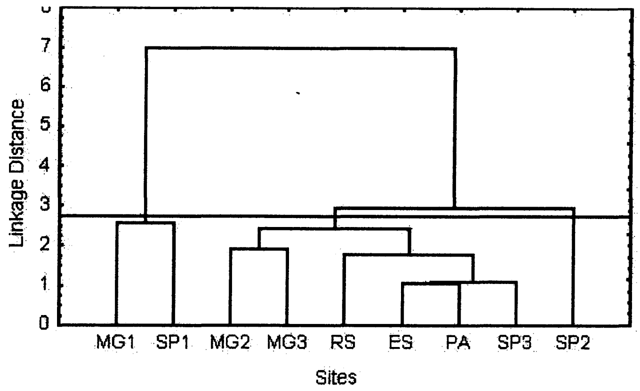

FIG. 2–Dendrogram for hierarchical cluster analysis using Single Linkage and Euclidian Distance between sites and mean above-ground biomass

TABLE 3–Stem and above-ground biomass increment of eucalypt plantations at different sites in Brazil

Site	Species*	Number of plots	Stem biomass (t/ha·yr) Min.	Stem biomass (t/ha·yr) Av.	Stem biomass (t/ha·yr) Max.	Above-ground biomass (t/ha·yr) Min.	Above-ground biomass (t/ha·yr) Av.	Above-ground biomass (t/ha·yr) Max.
SP2	1, 2	30	19.86 (89)†	24.91 (92)	32.97 (92)	22.25	27.12	36.01
SP3	1, 2	85	17.10 (91)	21.75 (89)	28.57 (89)	18.83	24.35	32.14
PA	3	9	15.39 (81)	19.77 (83)	24.79 (84)	19.03	23.89	29.49
ES	1, 3	72	15.66 (81)	21.30 (91)	27.14 (95)	19.34	23.51	28.57
RS	2	24	13.57 (92)	20.62 (93)	26.00 (94)	14.82	22.06	27.55
MG3	1, 5	31	11.21 (81)	18.04 (91)	25.56 (94)	13.85	19.86	27.10
MG2	1, 4, 10	46	10.72 (87)	16.42 (90)	23.60 (94)	12.29	18.23	25.03
SP1	1, 2, 5	160	6.12 (78)	9.65 (85)	12.88 (86)	7.85	11.32	15.02
MG1	3, 4, 5, 6, 7, 8, 9	161	5.72 (74)	6.95 (78)	8.41 (82)	7.71	8.96	10.21
Average		68.7	12.8 (85)	17.7 (89)	23.3 (91)	15.1	19.9	25.7

* 1 – *Eucalyptus grandis*; 2 – *E. saligna*; 3 – *E. grandis* × *E. urophylla*; 4 – *E. cloeziana*; 5 – *E. urophylla*; 6 – *E. camaldulensis*; 7 – *E. citriodora*; 8 – *E. tereticornis*; 9 – *E. pellita*; 10 – hybrids.

† Values in parentheses represent percentage of the above-ground biomass.

RS, MG3, and MG2) ranges from 18 to 24 t/ha·year, while SP1 and MG1 comprise the lowest productivity group at less than 12 t/ha·year. When compared with the poorest site (MG1) the difference in yield was 3.58 and 3.03 times greater at SP2 for stem biomass and above-ground biomass, respectively.

Climatic conditions are determinants of forest dry-matter production. The availability of stored water for forest growth will depend largely on inputs of water through rainfall, on the water storage properties of the soil profile, and on the level of transpiration (Beadle 1997). These sites represented a wide range of climatic conditions (Table 1), which appeared to be the primary reason for the substantial variation in stand growth. The above-ground and stem biomass showed a large and positive linear dependence on the WAI (Fig. 3), when site PA is excluded. This site can be considered a leverage when those two variables are related. As defined by Hair *et al.* (1998), leverage points are substantially different in one or more independent variables, so that affects the estimation of one or more regression coefficients for PA site. It appears that other factors are limiting biomass accumulation. Even if the highest productivity (29.5 t/ha·year) is considered, eucalypt growth at this site would not be correctly predicted by that equation (Fig. 3). The SP2 site has a humid climate and uniform rainfall distribution, and lacks a soil water deficit. At the MG1 and SP1 sites, the yearly water deficit restricts growth for 4 to 6 months (Golfari *et al.* 1978). Furthermore, the soil has small nutrient reserves, low CEC, and a sandy texture (Table 2), which is responsible for low water retention capacity and high plant water deficit. The plant water deficit is probably aggravated by low potassium content (5–7 mg K/dm^3 soil) (Ladeira 1999; Santana 1994) of these sites. Teixeira *et al.* (1995) reported that eucalypt species, which are suited to dry soil conditions, have higher transpiration losses and lower water use efficiency under low potassium supply. Deficiencies in the supply of water and nutrients slow photosynthetic rates and creation of new tissues. When water becomes unavailable, photosynthesis ceases (Smith *et al.* 1997).

Water stress appears to be the major constraint to eucalypt growth at the MG1 and SP1 sites (Tables 1 and 2; Fig. 4). The water content and the rate of water movement in soils

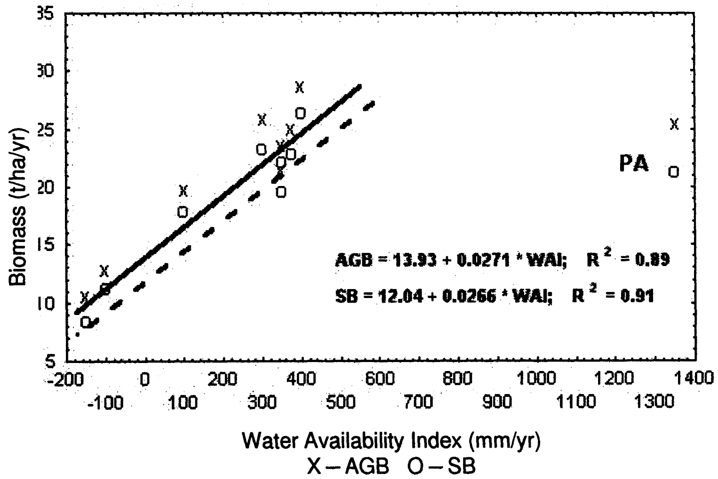

FIG. 3–Above-ground biomass (AGB) and stem biomass (SB) *versus* water availability index (WAI)

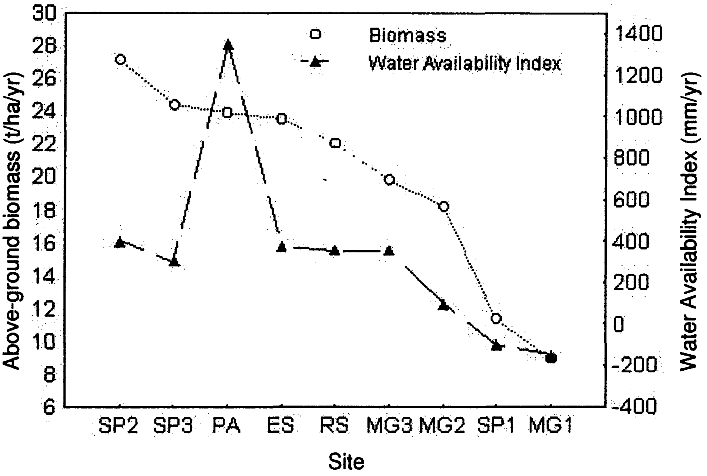

FIG. 4—Above-ground biomass and water availability index for the studied sites

depend to a large extent on soil type and soil structure, which is reflected in soil moisture-holding capacity (Taiz & Zeiger 1998). At both locations, the soil is sandier (Table 2) and the distribution of annual precipitation permits little recharge of soil water, thus influencing growth during a substantial part of the rotation. At sites such as MG1 and SP1, where high vapour saturation deficit, combined with soil water deficit, can be expected for long periods of the day during the winter, considerable reduction in tree growth rate is expected. Sands & Mulligan (1990) have reported similar behavior for *Pinus radiata* D.Don during the Australian summer.

Trees growing under water stress, such as at sites MG1 and SP1, tended to allocate more carbon to the canopy than to the stem (Table 3). Reis *et al.* (1987) reported that, under similar conditions, a considerable portion of carbon is allocated to the root system, which represents about 40% of the total tree biomass. As reported by Santantonio (1989), as site conditions became less favorable there was a consistent, strong, negative relationship ($r^2 = -0.94$) in partitioning between fine roots and stems in a close canopy stands. These findings lead to the conclusion that selecting sites with favourable growth condition for eucalypt plantations will produce more usable wood, both in absolute and in relative terms.

Nutrient Accumulation

The rate of nutrient accumulation in the stem and total above-ground biomass is given in Table 4. There were two distinct patterns of annual nutrient accumulation in the stem biomass. At MG1, MG2, and MG3 the amount of nutrient in the stem decreased in the following order: nitrogen > calcium > potassium > magnesium > and phosphorus. However, calcium showed the highest accumulation at the other six sites: calcium > nitrogen > potassium > magnesium > and phosphorus. The SP2 site showed the highest amount of all nutrients in stem and above-ground biomass. On the other hand, MG1 and SP1 sites showed the lowest amounts of all nutrients in stem and above-ground biomass and the MG1 site showed the highest allocation of all nutrients in the canopy (Table 4). These results can be

TABLE 4—Annual rate of nutrient accumulation in the stem and above ground in eucalypt plantations at different sites in Brazil

Site	Stem (kg/ha·yr)						Above ground (kg/ha·yr)					
	N	P	K	Ca	Mg	*Total*	N	P	K	Ca	Mg	*Total*
SP2	40.6	3.1	41.9	91.7	12.7	190.0	60.5	4.5	53.7	107.3	16.9	242.9
	(67)	(68)	(78)	(85)	(75)							
SP3	36.4	2.2	30.8	48.8	7.0	125.2	64.3	3.6	42.6	61.0	10.9	182.4
	(57)	(61)	(72)	(80)	(65)							
PA	34.7	1.9	21.8	50.5	7.1	116.0	53.8	3.4	36.7	69.6	11.2	174.7
	(64)	(56)	(59)	(73)	(63)							
ES	27.3	2.9	18.6	85.6	10.9	145.3	48.2	4.6	28.2	101.1	15.2	197.3
	(57)	(63)	(66)	(85)	(71)							
RS	36.1	3.9	26.9	62.4	11.3	140.6	47.2	5.3	35.0	71.7	14.0	173.2
	(76)	(74)	(77)	(87)	(81)							
MG3	34.5	1.8	17.9	22.9	5.2	82.3	54.3	3.6	32.4	35.0	8.8	134.1
	(64)	(50)	(55)	(65)	(59)							
MG2	31.5	2.3	21.5	25.3	5.6	86.2	58.6	4.0	35.2	35.4	8.9	142.1
	(54)	(57)	(61)	(72)	(63)							
SP1	14.6	1.6	14.2	16.6	3.8	50.8	30.4	2.4	20.5	23.0	5.7	82.0
	(48)	(65)	(69)	(72)	(67)							
MG1	15.0	1.3	8.4	7.6	1.9	34.2	39.1	2.9	19.1	15.6	5.0	81.7
	(38)	(45)	(44)	(49)	(37)							
Av.	30.1	2.3	22.4	45.7	7.3	107.8	50.7	3.8	33.7	57.7	10.7	156.7
	(59)	(61)	(67)	(79)	(68)							

Values in parentheses represent percentage of the above-ground biomass

attributed to site conditions as discussed above. There is a close relationship (r = 0.94 for stem biomass and r = 0.96 for above-ground biomass) between the accumulation of biomass and nutrient content. Similar relations for other species (Miller 1984) and for eucalypts (Gonçalves *et al.* 1997) have been reported. Hence, silvicultural practices, which target increased productivity generally, lead to higher nutrient removal from the site. When nutrients are removed from a stand during harvesting, their replenishment comes from weathering, atmospheric deposition, and fertiliser application. Since eucalypts in Brazil are generally cultivated on sites with low soil fertility (Novais *et al.* 1986) nutrient removed by harvesting must be replaced by fertiliser.

From an ecological point of view, decreasing biomass removal during harvesting has a positive effect on soil nutrient pools and water conservation. However, debarking in the field has little effect on the harvested biomass, while it has an important effect on nutrient conservation. It decreases harvested biomass by only about 10% (2 t/ha·year), yet it represents a significant reduction in nutrient export (Table 5). On average, the bark contains 73% of the calcium, 65% of the magnesium, 46% of the phosphorus, 41% of the potassium, and 24% of the nitrogen in the stem. Debarking in the field, besides conserving nutrients, protects the soil. Leaving slash on the soil surface results in increased microbial mineralisation of organically-bound nutrients, causing an increase in cation and anion concentrations in the soil solution (Fölster & Khanna 1997). Increased nutrient availability should lead to greater sustainability of eucalypt plantations in Brazil.

TABLE 5–Stem bark as a percentage of above-ground biomass, and stem-bark nutrient content as a percentage of stem biomass for eucalypt plantations in Brazil.

Site	Bark	N	P	K	Ca	Mg
SP2	10	19	28	29	74	61
SP3	9	26	48	37	69	71
PA	11	22	61	48	85	67
ES	9	23	44	46	72	76
RS	8	18	48	38	73	67
MG3	9	20	39	38	68	62
MG2	10	26	44	41	71	61
SP1	12	33	55	44	64	63
MG1	13	29	42	48	78	61
Average	10	24	46	41	73	65

Nutrient Use Efficiency

The efficiency with which a plant obtains or uses a unit of nutrient to produce biomass should be related to the ability of an individual plant to respond to fluctuating resource availability. For a variety of species, NUE increases as nutrient availability decreases (Birk & Vitousek 1986; Lajtha & Klein 1988; Shaver & Melillo 1984). The trees at the sites evaluated in this paper exhibited differences in NUE for stem and above-ground biomass production. The NUEs ranged from 10405 (for phosphorus in stem biomass) to 272 (calcium in stem biomass) (Table 6). On average, the NUE was in the following order: phosphorus > magnesium > potassium > nitrogen ≅ calcium.

Water availability was significantly correlated to nitrogen, phosphorus, and calcium NUE. The correlation between WAI and nitrogen was 0.79 ($p = 0.021$), it was 0.65 ($p = 0.082$) for phosphorus, and –0.68 ($p = 0.063$) for calcium, when the leverage site PA was not

TABLE 6–Nutrient utilisation efficiency of stem and above-ground biomass of eucalypt plantations at different sites in Brazil

Site	Stem biomass					Above-ground biomass				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
	kg dry matter / kg nutrient									
SP2	614	8 035	595	272	2135	448	6027	505	253	1605
SP3	598	9 886	706	446	3479	379	6764	572	399	2234
PA	570	10 405	907	391	3365	444	7026	651	343	2133
ES	780	7 345	1145	249	2157	488	5111	834	233	1547
RS	571	5 287	767	330	1952	467	4162	630	308	1576
MG3	523	10 022	1008	788	3819	366	5517	613	567	2257
MG2	521	7 139	764	649	3255	311	4558	518	515	2048
SP1	661	6 031	680	581	2979	372	4717	552	492	1986
MG1	463	5 346	827	914	4716	229	3090	469	574	1792
Average	589	7 722	822	513	3095	389	5219	594	409	1909

considered. For potassium and magnesium these values were 0.53 ($p = 0.175$) and –0.18 ($p = 0.658$). The positive correlation between WAI and NUE values for nitrogen and phosphorus may indicate a possible restriction on the availability of these nutrients for tree growth, as growth rate and WAI are positively related. Therefore, under limiting nutrient supply nutrient remobilisation in the tree would be more intense, increasing the ratio between biomass and nutrient amount in the tree. These results are in line with those reported by other authors (Birk & Vitousek 1986; Lajtha & Klein 1988; Shaver & Melillo 1984). Calcium is a nutrient whose uptake is largely dependent on the transpiration flux (Taiz & Zeiger 1998). The negative correlation between WAI and calcium-NUE is expected, because this nutrient is not retranslocated in the tree. This leads to a relatively higher removal of calcium with harvesting, particularly if debarking at the site is not adopted, with a possible negative impact on forest sustainability if calcium is not applied as fertiliser or lime.

Plant phosphorus utilisation efficiency is strongly influenced by the soil phosphorus capacity factor, which is affected by soil properties such as clay content (Muniz *et al.* 1985; Novais *et al.* 1993). Our results show that on sites where soil is sandier, such as MG1 (Table 2), phosphorus-NUE is lower than for sites where soil has higher clay content, such as SP2 (Table 6). Therefore, for the same soil phosphorus content, we would expect faster soil phosphorus exhaustion in MG1 than in SP2.

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