

## Site evaluation and productivity of a 3-year old stand of *Eucalyptus urograndis* in São Paulo, Brazil

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**Abstract** - Plantation forests in Brazil cover 7 million hectares, which represents 1% of the country (68% of *Eucalyptus* and 25% of *Pinus* plantations). The aim of this study was to evaluate a *Eucalyptus urograndis* plantation. High levels of Ca and Mg in the soil suggest that limestone had leached into the soil profile. The soil resistance down to 60 cm depth in the row of planting was lower than the inter-row space, indicating that deep tillage had been effective. Soil resistance, down to 20 cm depth at an inter-row distance of 1 m from the planting row, was higher, likely by the increase in soil compaction during the site preparation. The canopy biomass differed amongst the DBH classes, justifying the use of an allometric equation based on a basal area for assessing the canopy biomass. The observed variation in DBH did not correlate with variation in wood density. The wood density of 0.37 g cm<sup>-3</sup> was lower than those reported for 7-year-old plantation. The *in situ* removal of the bark increased nutrient availability by 8-11%. Harvesting of tree bole in 3-year old plantation didn't result in a large nutrient export, indicating that proper plantation management can contribute to plantation forest sustainability.

## Avaliações de sítio e produtividade em plantios de *Eucalyptus urograndis* com 3 anos de idade em São Paulo, Brasil

**Resumo** - No Brasil os plantios florestais ocupam 7 milhões de hectares que correspondem a 1% do território (68% com plantações de *Eucalyptus* e 25% com *Pinus*). O objetivo desse trabalho foi avaliar plantios de *Eucalyptus urograndis*. Estoques elevados de Ca e Mg no solo, sugerem uma lixiviação do calcário. A resistência do solo até os 60 cm de profundidade na linha de plantio foi menor do que na entrelinha, indicando que a subsolagem foi eficiente. Os valores de resistência do solo foram mais altos na entrelinha, distante 1 m da linha de plantio, até os 20 cm de profundidade, provavelmente pelo aumento da compactação na preparação da área. A biomassa da copa das árvores diferiu entre as classes de DAP, justificando o uso de equação para a sua estimativa. A variação observada para área basal não refletiu em diferenças de densidade da madeira. A densidade da madeira de 0,37 g cm<sup>-3</sup> foi menor do que a de plantios com 7 anos. A remoção da casca no campo aumentou o suprimento de nutrientes entre 8% e 11%. A colheita da madeira aos 3 anos não resultou numa exportação significativa, indicando que o manejo apropriado dos plantios, pode contribuir para a sustentabilidade florestal.

## Introduction

Forest plantations cover about 7 million ha and represent approximately 1% of Brazilian territory, with 4.75 million ha of *Eucalyptus* (68%), 1.76 million ha of *Pinus* (25%) and 0.46 million ha of other species (ANUÁRIO..., 2011).

In recent decades there has been a significant increase in productivity of forest plantations. However, the demand for forest products is also increasing, which implies that there is a need for increasing the forest plantation area in Brazil. A strategy for the establishment of new plantations can be to afforest pastures with low productivity. These pastures provide an attractive opportunity for establishing new plantation forests.

In Brazil, charcoal production from forestry has increased steadily since 2002. From 2006 to 2007, charcoal production from plantation forests increased by 46%, which represents about 3.8 million tonnes, whereas charcoal production from natural forest had a growth of only 1% with a production of 2.5 million tonnes (SBS, 2008).

There is a current policy in Brazil to conduct research to develop alternative energy sources. The hybrid *Eucalyptus urograndis* is planted widely in different regions of Brazil and is considered a viable option for energy purposes (Tonini et al., 2006). Within this context, novel research concerning forest biomass development are technological innovations in biofuel production using chemical and physical processes. The specifications of the source material for biofuel (charcoal, biodiesel) production may well be different from that for construction timber or pulp production, which may lead to shorter rotation lengths or influence selection of tree species. In Malaysia, Yatim & Hoi (1987) demonstrated that rubberwood, acacia, eucalypt and pine could all generate charcoal of industrial-grade quality. However, differences in charcoal properties can be expected to occur between species or within a single species because of differences in age at harvesting, climate or site aspects (Mészáros et al., 2004).

Eucalypt is one of the main species planted in Brazil for industrial purposes. Eucalypt plantation for energy usually involves applying two coppices, with the first thinning at 7 years, the second at 14 years and the final harvesting at 21 years after planting. The cycle may be shortened (to 5- or 6-year intervals) depending on the region and soil type. Through economic studies

involving farmers with eucalypt plantations in southern Brazil, Rodigheri (1997) observed that firewood producers used a short rotation period of four to six years, depending on their need for wood.

A shortening of the rotation period for biofuel plantation forests may adversely impact soil structure and soil fertility.

Plantation forests are usually established on low fertility soils. Eucalypt is sensitive to low mineral nutrients availability and therefore, in order to achieve productive plantations it is highly recommended to regularly apply fertilizer to replenish the nutrients lost in each rotation (Barros et al., 1992; Gonçalves et al., 2000a).

In conjunction with soil nutrient replenishment, it is also necessary to monitor the nutrient distribution over the various components of the system.

Because most plantations are located in low productive areas, an impact on plantation productivity can be caused by nutrient losses occurring during exploitation and harvesting of the wood, or by erosion of deforested areas. This is particularly so when complete removal of biomass is practiced (Brown et al., 1997). Such losses can be minimised through simple procedures, such as the use of fertilisers, harvesting in strips (as opposed to clear cut), increasing rotation length and careful construction of roads (Van Hook et al., 1982; Nambiar, 1996)

It is also important to keep harvesting residues on-site (e.g. leaves, twigs and bark), seeking maximum conservation of the remaining stock of nutrients, mainly for phosphorous and potassium (Poggiani et al., 1983, Turner & Lambert, 1983; Bruijnzeel & Wiersum, 1985; Pande et al., 1987, Andrade et al., 2006).

After timber removal, the management of organic matter without burning, the use of forestry equipment which produces less soil compaction and the decrease of machinery movement on the ground can be beneficial (Bouillet et al., 2000, Gonçalves et al. 2000a; Laclau et al., 2000).

The change in rotation length warrants studies of the chemical, physical and biological site conditions of young and fast-growing plantation forests, because these factors can influence the productivity of the next rotation and therefore the sustainability of forestry operations. A comprehensive assessment of forest site condition may also identify required actions to preserve the productive potential of the soil in successive rotations (Gonçalves et al., 2000 b).

In view of the above the aim of this study is to evaluate a 3-year old plantation forest of *Eucalyptus urograndis*, with respect to soil physical and chemical conditions three years after site preparation and liming/fertilising. In addition we evaluate tree growth, biomass and wood properties, as well as nutrient stock of the harvestable wood, bark, canopy and litter. This should allow us to evaluate the impact of short-rotation forestry for bio-energy purposes. It also provides a baseline for future studies in this forest at the end of the first rotation and after harvesting.

### Material and methods

The coordinates of the study plot are 48°16'32" W and 23°21'21" S. The elevation is 696 m above sea level (a.s.l.).

The climate is Cwa, according to the Köppen classification, *i.e.* mesothermic with a dry winter, and an average annual rainfall between 1,300 and 1,400 mm. Monthly average temperatures range from 15-16 °C in July to 22-23 °C in January. The dry season is in winter, between April and September.

The soil is a well-drained Quartzipsamment (USDA classification system) or Arenosol (FAO classification system) or Neossolos Quartzarênicos (Brazilian classification system) on a consolidated sandstone formation with minimum depth of 2.5 m. The soil has a moderately developed A horizon and a clay fraction less than 6%. These soils occupy 15% of the *Cerrado* biome (Brazilian savannah ecosystem; Adámoli et al., 1986) and are used for intensive agriculture, cattle pasture and reforestation projects. They are typical for flat areas in the landscape, but because of their sandy texture they are also very susceptible to erosion as a consequence of poor land management. Quartzipsamments have a low natural fertility and a limited plant available water capacity, leading to frequent water stress in the dry season. Soil nutrients become exhausted within a few years after fast-growing plantation establishment, which requires a well-planned fertiliser management strategy (liming, fertilisation) to ensure continued productivity.

This study site was a pasture that was planted with *Eucalyptus urograndis*, a hybrid between *E. urophylla* and *E. grandis*, in 2005. Before tree planting at 3 x 2 m spacing (1670 trees ha<sup>-1</sup>), the soil was subsoiled, using one shank in row, and fertilised with 80 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub>, 150 kg ha<sup>-1</sup> of K<sub>2</sub>O; 150 kg ha<sup>-1</sup> of N; 5 kg

ha<sup>-1</sup> of B and limed by adding 1 Mg ha<sup>-1</sup> of dolomitic limestone. As such the study forest can be considered not to have experienced nutrient deficiencies and would exhibit optimal growth in the absence of water stress. The plantation was established to provide pulpwood at a relatively short 7-year rotation period. Consequently, thinning and pruning operations were not realised. A plot measuring 400 m<sup>2</sup> (20 m x 20 m) was randomly selected in the 3-year old plantation forest. The plot counted 63 trees and diameter at breast height (DBH) varied between 0.067 m and 0.173 m. Among these trees, 13 had a DBH below 0.118 m and 21 a DBH above 0.173 m.

### Soil sampling and analytical procedures

Soil samples were collected at random at three points in the plot with a soil auger, at four depths (0-5 cm, 5-10 cm, 10-20 cm and 20-30 cm). At one of these sample points, an extra sample at 60-80 cm depth was also collected. The samples were analyzed for pH, organic matter content, exchangeable P, K, Ca, Mg, Al amounts and particle size at the Laboratory of Soil and Plant Tissue Analysis of the Embrapa-Florestas, Curitiba, Brazil.

Available P and exchangeable K were extracted with 1N HCl, as described by Bloise et al. (1979). Other exchangeable ions, organic matter content and pH (H<sub>2</sub>O and CaCl<sub>2</sub>) were analysed according to the procedures of Embrapa (1997).

Soil core samples were collected in the plot for measurement of soil physical aspects and plant water availability. The 0-10 cm samples had four repetitions whereas those at greater depth had three repetitions. These samples were analysed using ceramic plates for macro- and micro-porosity, total porosity, aeration and bulk density following Embrapa (1997). The moisture retention curve was determined at tensions of -6, -10, -100 and -1500 kPa (Black, 1965).

Air capacity (% by volume of air-filled voids at 10 kPa matric potentials), macroporosity (% by volume of pores at 6 kPa matric potentials) and total available water (% volume of water drained between 10 and 1500 kPa matric potentials) were measured by moisture release (Black, 1965; Oliveira, 1968). The soil physical properties were determined according to the methodology of Embrapa (1997).

Using a cone penetrometer (Soil Control 60, USA), the soil mechanical strength was measured in three replicates down to a depth of 60 cm on the planting row (PR) and in the inter-row space (IR) at distances of 0.5, 1.0 and 1.5 m from the planting row.

### Tree volume, biomass and nutrient content

All trees in the plot were measured for height and stem DBH using a clinometer and a flexible measuring tape, respectively. The trees were classified according to DBH into three diameter classes: 13 trees with DBH between 6.7 and 11.8 cm (lower class), 29 trees between 12.4 and 14.3 cm (middle class) and 21 trees between 14.6 and 17.3 cm DBH (upper class). Nine representative trees in the plot were harvested for biomass assessment, three from each of the three DBH classes.

The measurements made by the length and diameter of five segments of the stem (seg 1 to seg 5) and wood samples were taken at six points (disc 1 to disc 6): d1 = base (near soil surface), d2 at DBH measurement height, and d3, d4, d5 and d6, at 25, 50, 75 and 100% of the whole stem down to a minimum diameter of 5 cm, respectively.

The proportional distribution of the total volume of the tree for each segment was obtained through the calculations of volume per stem segment of the nine trees, based on the Equation of Smalian (Husch et al., 1993). The data indicated a distinct pattern for each DBH class (lower, middle and upper) allowing estimation of the volume segment of all trees in the plot from their DBH, their height measurement and form factor. These data were then used to estimate the biomass for each stem segment and nutrient content of the remaining trees in the plot.

One specimen of each DBH class (lower, middle and upper) had 4 cm wide discs cut in each of its reference points (d1-d6) for nutrient content analysis and for laboratory analysis of wood density by immersion in water (Vital, 1984). Measurements were also made of the biomass, separating leaves, twigs and the upper part of stem (the end of the stem after d6). For nutrient content analysis, each subsample was separately picked from branches and leaves, from three different trees in the plot. The canopy and the upper part of the stem of six additional trees were fresh-weighted with leaves and twigs attached, but no samples were taken.

The bark was removed from the stem disc samples for density evaluation and nutrient analysis by each stem compartment.

Samples of wood discs, leaves and stems were dried at 60 °C, weighed, and grinded to be chemically analyzed for N, P, K, Ca, Mg, Fe, Mn, Zn, Cu and total Carbon. Nitroperchloric digestion was used in order to

determine the levels of P, K, Ca and Mg. Phosphorous was determined by using ammonium molybdate absorption, potassium by flame photometry and Ca and Mg by atomic absorption, according to the methodology of Embrapa (1997). For nitrogen analysis, sulfuric digestion was performed followed by the Micro Kjeldahl method. These procedures are in accordance with the methodology proposed by Sarruge and Haag (1974).

The estimation of the sapwood and bark biomass was made based on the discs of the sampled trees. The determination of basic density was performed with the separation of bark and sapwood for the six discs of wood (d1 to d6). The mean density of discs at the trunk section extremities was used to calculate the density of each segment we used.

The estimated biomass of bark and wood of the six non-sampled trees was calculated based on the volume of each of its segments and the basic density values found in the segments (seg) of the sampled trees, according to each DBH class (lower, middle and upper).

The estimated biomass of bark and wood of six non-sampled trees, was calculated based on the volume and the basic density of the segments, according to each class (lower, middle and upper).

The nutrient analysis data of three standard tree samples were applied to each DBH class. The nutrient values for the trunk were calculated similar to the density determination for each segment.

For each of three standard trees sampled, we calculated the percentage of leaves and branches to total canopy biomass. These values were subsequently used to estimate leaf and branch biomass of other six sample trees in the plot. For the remaining trees, the canopy biomass was estimated by a linear equation relating basal area to biomass. The procedures described above were applied per DBH class, in order to calculate separately leaf and branch biomass for each tree in the plot.

The concentrations of macronutrients and micronutrients in leaves and branches, multiplied by the corresponding dry weight, were used to calculate the nutrient content in biomass of the trees crown for each of three DBH classes. For the other six trees, the leaf and branch biomass and the nutrient concentrations of the trees sampled were estimated for each DBH class. The nutrients of three sub-standard trees were also used to calculate the canopy nutrients content for the remaining trees in the plot.

### Litter standing crop

For the sampling of litter standing crop, a sampler plate of 0.5 m x 0.5 m was used. It was randomly placed on the litter layer, with three replicates between the lines and another three in the planting row. The moist litter below the plate was cut, weighed and sampled. The sample was dried at 60 °C and weighed for moisture content analysis. Nutrient concentrations were measured using the methods described above. The total biomass and nutrient content of the litter layer were reported for the plot and extrapolated to a hectare.

### Data Analysis

Descriptive and graphical analysis of data collected in the study were performed in order to check for heterogeneity, means and standard errors. The variables were also analyzed using linear models and variance analysis (Faraway, 2005). The models were built according to the design used and the factors of interest for each variable (age and diameter classes within age). The adjustment of the model to the data was determined by the use of probability plots with simulated envelopes of the normal distribution. Differences between treatments were observed by orthogonal contrasts (Mason et al., 2003).

## Results

### Soils

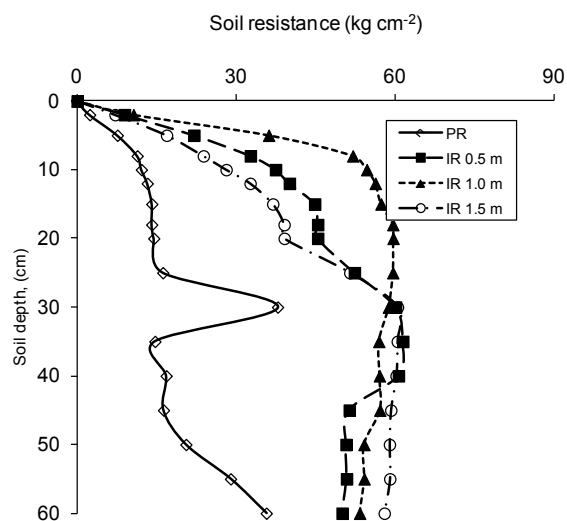
The key soil characteristics of the plot is shown in Table 1. Generally, the nutrient stock was highest in the first layer (0-5 cm). For P, the highest levels were observed in topsoil, down to 20 cm depth. Calcium and magnesium, however, exhibited higher stocks at a depth of 60 and 80 cm. Texture analysis showed that between 64% and 69% of particle size fraction was coarse sand, whereas 2-6% was clay and silt in the top soil (2%). The remaining size fraction was of fine sand.

The total porosity, aeration porosity and macro porosity were similar for all analysed depths. In the soil

surface layer (0 to 5 cm) the available water was 1.7 to 2.3 times higher than in the subsoil.

Tables 2 and 3 show statistical analysis of soil penetrometer resistance measurements in the experimental plot, collected at different depths in the planting row (PR) and at increasing distances of 0.5, 1.0 and 1.5 m from the row. The changes in resistances with depth are shown in Figure 1.

In the planting rows, the average resistance at all depths was significantly lower than that measured at other points between the planting rows ( $p < 0.001$ ). The resistance at a distance of 1 meter from the planting row was also significantly higher ( $p < 0.001$ ) than that at 0.5 and 1.5 m for the 0-10 cm and 10-20 cm depths (Table 3 and Figure 1). The soil resistance difference was not significant between 0.5 and 1.5 m from the row planting. The highest values of resistance, between 50 and 60 kg cm<sup>-2</sup>, were observed below 30 cm depth without deep tillage (0.5, 1.0 and 1.5 meters, Figure 1).



**Figure 1.** Soil penetrometer resistances depth profiles in the planting row (PR) and at inter-row distances (IR) of 0.5 to 1.5 m from planting rows in a 3-year old *E. urograndis* plot.

**Table 1.** Chemical and physical properties of soil in a plot of 3-year old *E. urograndis*.

| Variable   | Soil depth (cm) |                |                 |                 |       |
|--|-----------------|----------------|-----------------|-----------------|-------|
|  | 0-5             | 5-10           | 10-20           | 20-30           | 60-80 |
| pH (CaCl <sub>2</sub> )                                  | 4.14 ± 0.06     | 3.92 ± 0.04    | 3.91 ± 0.02     | 4.00 ± 0.06     | 4.36  |
| OC (Mg ha <sup>-1</sup> )                                | 4.014 ± 2.672   | 3.346 ± 1.981  | 8.242 ± 4.551   | 6.838 ± 6.451   | 14.0  |
| P available (kg ha <sup>-1</sup> )                       | 2.276 ± 0.783   | 2.464 ± 0.895  | 5.299 ± 2.658   | 2.818 ± 1.695   | 0.4   |
| K (kg ha <sup>-1</sup> )                                 | 11.651 ± 0.885  | 8.774 ± 0.416  | 9.897 ± 0.437   | 8.996 ± 1.901   | 10.9  |
| Ca (kg ha <sup>-1</sup> )                                | 169.97 ± 3.064  | 110.16 ± 8.594 | 226.47 ± 74.794 | 239.77 ± 37.674 | 683   |
| Mg (kg ha <sup>-1</sup> )                                | 118.11 ± 5.291  | 46.66 ± 1.671  | 100.92 ± 24.889 | 100.58 ± 21.06  | 408   |
| Al (cmol kg <sup>-1</sup> )                              | 0.400 ± 0.046   | 0.677 ± 0.030  | 0.653 ± 0.047   | 0.580 ± 0.093   | 0.30  |
| Coarse sand (%) 2 – 0.2 mm                               | 67.50 ± 2.50    | 64.67 ± 1.33   | 66.00 ± 1.73    | 66.00 ± 2.00    | 69.0  |
| Fine sand (%) 0.2 – 0.05 mm                              | 25.50 ± 1.50    | 29.00 ± 1.00   | 28.33 ± 0.67    | 28.67 ± 0.67    | 29.0  |
| Clay (%)   | 6.00 ± 2.00     | 6.00 ± 1.15    | 5.67 ± 1.86     | 5.33 ± 1.76     | 2.00  |
| Silt (%)   | 2.00            | 0.33           | -               | -               | -     |
| Bulk density   | 1.377 ± 0.004   | 1.407 ± 0.032  | 1.434 ± 0.077   | 1.373 ± 0.037   |       |
| Total Porosity (cm <sup>3</sup> cm <sup>-3</sup> )       | 0.467 ± 0.008   | 0.469 ± 0.015  | 0.449 ± 0.011   | 0.436 ± 0.017   |       |
| Aeration Porosity (cm <sup>3</sup> cm <sup>-3</sup> )    | 0.282 ± 0.009   | 0.305 ± 0.034  | 0.284 ± 0.020   | 0.310 ± 0.009   | -     |
| Macropores (cm <sup>3</sup> cm <sup>-3</sup> ) > 0.05 mm | 0.257 ± 0.015   | 0.296 ± 0.034  | 0.269 ± 0.023   | 0.292 ± 0.010   | -     |
| Available water (cm <sup>3</sup> cm <sup>-3</sup> )      | 0.077 ± 0.027   | 0.034 ± 0.011  | 0.038 ± 0.008   | 0.046 ± 0.018   | -     |

Standard errors of the mean (SEM) are indicated by plus-minus signs.

**Table 2.** Averages and standard errors of soil penetrometer resistances in kg cm<sup>-2</sup>, down to 60 cm of soil depth as obtained at different points in the 3-year-old *E. urograndis* plot.

| Points <sup>1</sup> | Soil depth (cm) |            |            |            |
|---------------------|-----------------|------------|------------|------------|
|                     | 0-10            | 10-20      | 20-40      | 40-60      |
| PR                  | 8.3 ± 2.1       | 14.0 ± 1.1 | 21.4 ± 5.7 | 25.4 ± 3.8 |
| IR 0.5m             | 25.3 ± 4.1      | 43.9 ± 2.8 | 58.6 ± 2.8 | 50.8 ± 2.6 |
| IR L 1.0m           | 38.4 ± 5.5      | 58.2 ± 0.8 | 58.1 ± 1.0 | 54.7 ± 1.8 |
| IR L 1.5m           | 19.0 ± 2.9      | 36.9 ± 3.5 | 58.1 ± 1.8 | 58.8 ± 0.8 |

<sup>1</sup> PR = planting row; IR = inter-rows; IR 0.5m, IR 1.0m, IR 1.5m from distance of PR; Standard error of the mean (SEM) are indicated by plus-minus signs.

**Table 3.** Descriptive level of probability (p-value) of test F for soil resistances at different inter-row distances and soil depths in the 3-year old *E. urograndis* plot.

| Contrasts between points <sup>1</sup> on the plot by soil depth (cm) | F-value for soil penetrometer resistance |
|--|--|
| PR vs IR 0.5, 1.0 e 1.5m; soil depth 0-10 cm                         | <0.001                                   |
| IR 1.0 vs IR 0.5 e 1.5m; soil depth 0-10 cm                          | <0.001                                   |
| IR 0.5 vs IR 1.5m; soil depth 0-10 cm                                | 0.1511                                   |
| PR vs IR 0.5, 1.0 e 1.5m; soil depth 10-20 cm                        | <0.001                                   |
| IR 1.0 vs IR 0.5 e 1.5 m; soil depth 10-20 cm                        | <0.001                                   |
| IR 0.5 vs IR 1.5m; soil depth 10-20 cm                               | 0.1104                                   |
| PR vs IR 0.5, 1.0 e 1.5m; soil depth 20-40 cm                        | <0.001                                   |
| IR 1.0 vs IR 0.5 e 1.5 m; soil depth 20-40 cm                        | 0.9363                                   |
| IR 0.5 vs IR 1.5m; soil depth 20-40 cm                               | 0.9087                                   |
| PR vs IR 0.5, 1.0 e 1.5m; soil depth 40-60 cm                        | <0.001                                   |
| IR 1.0 vs IR 0.5 e 1.5 m; soil depth 40-60 cm                        | 0.9845                                   |
| IR 0.5 vs IR 1.5m; soil depth 40-60 cm                               | 0.0671                                   |

<sup>1</sup> PR = planting row; IR = inter-rows; IR 0.5m, IR 1.0m, e IR 1.5m from distance of PR.

### Stand characteristics

The average stand characteristics and total volume of the trees in the plot are presented in Table 4.

**Table 4.** Average characteristics of growth tree and total volume of wood, converted to hectare, to *E. urograndis* in 3-years-old plantation.

| Tree                      | Height (m) | dbh (cm) | Form factor | Volume of wood (m <sup>3</sup> ha <sup>-1</sup> ) |              |
|---------------------------|------------|----------|-------------|---|--------------|
|                           |            |          |             | with bark   | without bark |
| Commercial <sup>1</sup>   | 14.5       | 13.4     | 0.59        | 209.0   | 190.7        |
| <b>Total</b> <sup>2</sup> | 18.5±1.7   | 13.4±2.2 | 0.47        | 212.7   | 193.9        |

<sup>1</sup> Commercial = trunk, from base (soil surface) until the diameter of 5.0 cm; <sup>2</sup> Total = base until the top; Standard error of the mean (SEM) are shown in plus-minus sign; Bark represented 8.8% of the trunk volume of *E. urograndis* in the 3-year old plot. The trunk section with a diameter less than 5.0 cm, i.e. the difference between the total and commercial volume of wood, represented 1.7% of total volume of wood. Annual average increments in total volume with and without bark were observed of 70.9 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> and 64.6 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup>, respectively.

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### Canopy biomass

For the lowest tree class (DBH range 6.7-11.8 cm), the canopy biomass composed of leaves, branches and the uppermost section of the trunk (diameter less than 5 cm) was 4.77 ± 0.98 kg tree<sup>-1</sup>, whereas those for the middle (DBH 12.4-14.3 cm) and upper tree classes (DBH 14.6-17.3 cm) were 8.41 ± 0.28 kg tree<sup>-1</sup> and 11.80 ± 0.56 kg tree<sup>-1</sup>, respectively. Statistical analyses for the canopy biomass of these three classes are presented in Table 5.

**Table 5.** P-values for the F-statistic for orthogonal contrasts between DBH classes to canopy biomass of a 3-year old *E. urograndis* plantation.

| Contrasts            | Canopy <sup>1</sup> |
|----------------------|---------------------|
| classes l versus m,u | <0.001              |
| classes m versus u   | 0.012               |

l = lower; m = middle; u = upper DBH class. <sup>1</sup> leaves, branches and last stem.

The canopy biomass of three year old trees in the lower class (l) significantly differed (p < 0.001) from those of the middle and upper classes and that of the middle class also differed (p < 0.01) from that of the upper class.

Using the basal area of trees, we obtained a linear equation in order to estimate the biomass of leaves and branches for all trees in the plot:  $y = -6.41 + 990.83x$  (R<sup>2</sup> adjusted = 93 %), where  $x$  is the basal area of tree (m<sup>2</sup>) and  $y$  is the dry weight of leaves plus branches (kg). The canopy biomass calculated by this equation was about 9% higher than the value based only on canopy biomass of medium trees in the plot.

### Biomass and nutrient concentrations in canopy leaves and branches and in litter standing crop

Data of dry biomass and concentrations of carbon and nutrients in leaves and branches and in the litter layer are shown in Table 6.

**Table 6.** Biomass and concentrations of carbon and nutrients in leaves, branches and litter standing crop of a 3-year-old *E. urograndis* plantation forest.

| Variable                         | leaves       | branches      | Litter        |
|----------------------------------|--------------|---------------|---------------|
| Biomass (kg tree <sup>-1</sup> ) | 3.63         | 3.72          | 9.0 ± 1.02    |
| Carbon (g kg <sup>-1</sup> )     | 511 ± 1.58   | 505 ± 2.02    | 456 ± 6.63    |
| N (g kg <sup>-1</sup> )          | 18.62 ± 2.35 | 3.80 ± 0.13   | 9.04 ± 1.04   |
| P (g kg <sup>-1</sup> )          | 1.29 ± 0.05  | 0.556 ± 0.027 | 0.538 ± 0.024 |
| K (g kg <sup>-1</sup> )          | 9.46 ± 0.49  | 4.74 ± 0.05   | 1.61 ± 0.12   |
| Ca (g kg <sup>-1</sup> )         | 10.19 ± 0.52 | 5.34 ± 0.17   | 20.48 ± 0.83  |
| Mg (g kg <sup>-1</sup> )         | 3.40 ± 0.64  | 1.61 ± 0.07   | 3.84 ± 0.34   |
| Fe (mg kg <sup>-1</sup> )        | 108 ± 1.53   | 16.40 ± 0.89  | 658 ± 105.3   |
| Mn (mg kg <sup>-1</sup> )        | 244 ± 37.73  | 44.89 ± 1.76  | 467 ± 15.17   |
| Zn (mg kg <sup>-1</sup> )        | 14.27 ± 1.10 | 2.36 ± 0.93   | 6.80 ± 0.64   |
| Cu (mg kg <sup>-1</sup> )        | 6.80 ± 0.86  | 4.26 ± 0.25   | 10.73 ± 0.73  |

Standard error of the mean (SEM) are shown after the plus-minus sign.

The canopy biomass amounted to 7.35 kg tree<sup>-1</sup>, or 13.4 Mg ha<sup>-1</sup>, and was 18% lower than the mass of the litter standing crop (15.9 Mg ha<sup>-1</sup>). The biomass of the canopy was evenly distributed over branches (51%) and leaves (49%) was observed in Table 6.

Except for carbon, the nutrient concentrations in leaves were significantly higher than those in branches. The litter standing crop showed high levels of Ca, Fe and Mn in comparison to those values in fresh leaves and branches, whereas K showed depletion.

### Density and concentration of carbon and nutrients in wood and bark

Data of bark and sapwood density, as well as their carbon and nutrient concentrations and significance levels for differences between sapwood and bark are summarised in Table 7, whereas a statistical analysis

for DBH classes is presented in Table 8. All values are based on the average of six discs sampled (the base of the trunk to 5.0 cm in diameter). There were no statistical differences between DBH classes, neither for sapwood nor for bark density. The sapwood density was about 45% higher than that of bark. Significant differences were observed for carbon and nutrient concentrations of the sapwood data and also for the bark.

Nutrients concentration in wood showed significant differences between classes of DBH for Ca and Mn.

Trees in the middle DBH class had higher contents of Ca and Mn when compared to those in the upper class ( $p < 0.01$  and  $p < 0.05$ , respectively). In contrast, trees in the lower class had a higher Mn concentration than those in the other classes ( $p < 0.01$ ). In bark, it was observed significant differences for carbon, N, K, Zn and Cu concentrations ( $p < 0.01$ ), with trees in the lower DBH class presenting higher concentrations of K, Zn and Cu than those in the middle and upper classes ( $p < 0.01$ ).

**Table 7.** Means, standard errors and significance levels of differences of wood density and carbon and nutrient concentrations between three DBH classes evaluated for each wood component, sapwood and bark, of 3-year-old *E. urograndis*.

| DBH classes <sup>1</sup> for sapwood             |           |           | DBH classes <sup>1</sup> for bark                |              |             |
|--|-----------|-----------|--|--------------|-------------|
| l  | m         | u         | l  | m            | u           |
| <b>density (g cm<sup>-3</sup>) ns</b>            |           |           | <b>density (g cm<sup>-3</sup>) ns</b>            |              |             |
| 0.36±0.01  | 0.37±0.01 | 0.38±0.01 | 0.25±0.01  | 0.26±0.01    | 0.26±0.01   |
| <b>C<sub>total</sub> (kg kg<sup>-1</sup>) ns</b> |           |           | <b>C<sub>total</sub> (kg kg<sup>-1</sup>) **</b> |              |             |
| 0.53±0.92  | 0.53±2.54 | 0.53±1.28 | 0.51±3.24  | 0.52±0.92    | 0.51±1.83   |
| <b>N (g kg<sup>-1</sup>) ns</b>                  |           |           | <b>N (g kg<sup>-1</sup>) **</b>                  |              |             |
| 2.11±0.23  | 2.22±0.06 | 1.88±0.13 | 3.30±0.11  | 4.36±0.174.3 | 3.41±0.16   |
| <b>P (g kg<sup>-1</sup>) ns</b>                  |           |           | <b>P (g kg<sup>-1</sup>)</b>                     |              |             |
| 0.12±0.01  | 0.12±0.02 | 0.11±0.01 | 0.55±0.07  | 0.53±0.08    | 0.53±0.14   |
| <b>K (g kg<sup>-1</sup>) ns</b>                  |           |           | <b>K (g kg<sup>-1</sup>) **</b>                  |              |             |
| 2.19±0.11  | 1.92±0.18 | 2.03±0.19 | 6.75±0.20  | 5.86±0.42    | 5.36±0.09   |
| <b>Ca (g kg<sup>-1</sup>) **</b>                 |           |           | <b>Ca (g kg<sup>-1</sup>) ns</b>                 |              |             |
| 0.39±0.05  | 0.58±0.10 | 0.29±0.02 | 9.46±1.82  | 13.46±2.601  | 11.44±2.04  |
| <b>Mg (g kg<sup>-1</sup>) ns</b>                 |           |           | <b>Mg (g kg<sup>-1</sup>) ns</b>                 |              |             |
| 0.23±0.05  | 0.19±0.04 | 0.20±0.05 | 2.53±0.33  | 3.11±0.36    | 2.79±0.38   |
| <b>Fe (mg kg<sup>-1</sup>) ns</b>                |           |           | <b>Fe (mg kg<sup>-1</sup>) ns</b>                |              |             |
| 19.9±2.61  | 17.6±3.41 | 15.6±2.41 | 89.6±18.0  | 66.33±7.83   | 64.77±19.49 |
| <b>Mn (mg kg<sup>-1</sup>) **</b>                |           |           | <b>Mn (mg kg<sup>-1</sup>) ns</b>                |              |             |
| 11.0±0.71  | 8.60±1.03 | 6.65±0.94 | 108.8±5.9  | 115.3±9.511  | 119.7±26.71 |
| <b>Zn (mg kg<sup>-1</sup>) ns</b>                |           |           | <b>Zn (mg kg<sup>-1</sup>) **</b>                |              |             |
| 3.46±0.17  | 3.57±0.52 | 3.86±0.96 | 9.21±0.68  | 2.62±0.642.6 | 4.66±1.19   |
| <b>Cu (mg kg<sup>-1</sup>) ns</b>                |           |           | <b>Cu (mg kg<sup>-1</sup>) **</b>                |              |             |
| 1.42±0.16  | 1.31±0.23 | 1.86±0.27 | 3.50±0.25  | 2.04±0.26    | 1.98±0.40   |

<sup>1</sup> l = lower; m = middle; u = upper DBH. ns: not significant ( $p > 0.05$ ); \* $p < 0.05$ ; \*\*  $p < 0.01$ .

**Table 8.** P-values for the F-statistic for orthogonal contrasts between DBH classes concentrations of carbon and nutrients for sapwood and bark wood of 3-year-old *E. urograndis* (F-test).

| Class          | component | Total C | N      | K     | Ca    | Mn    | Zn     | Cu    |
|----------------|-----------|---------|--------|-------|-------|-------|--------|-------|
| class l vs m,u | wood      | -       | -      | -     | 0.570 | 0.008 | -      | -     |
| class m vs u   | wood      | -       | -      | -     | 0.007 | 0.151 | -      | -     |
| class l vs m,u | bark      | 0.0017  | 0.006  | 0.004 | -     | -     | <0.001 | 0.001 |
| class m vs u   | bark      | 0.5459  | <0.001 | 0.219 | -     | -     | 0.119  | 0.887 |

l = lower; m = middle; u = upper dbh class.



### Biomass, carbon and nutrient contents in above-ground tree components and in litter standing crop

Estimates of the biomass, carbon and nutrient contents in the aboveground tree components and in litter standing crop are given in Table 9.

The biomass and nutrient content of the roots was not studied because these remain in situ after harvesting and nutrients stored in roots would therefore be available for the next rotation.

Aboveground tree biomass had 52% of the carbon content and the litter layer biomass had 46% of the carbon content.

Harvesting of trees with removal of stem wood only, i.e. leaving the bark, canopy and litter layer on-site

ensures that between 68% and 95% of N, P, Ca, Mg, Fe and Cu would remain available for the next rotation. This percentage is slightly lower for K and Zn, of which 54% of the total would remain on site. The removal of bark in the field after harvesting ensures that on average 10% more nutrients remain available for the next rotation. This holds in particular for the macronutrients P, K, Ca and Mg, for which gains are between 12% and to 21%. Ca and Mg had the highest proportions in the bark considering to the total stored in the trunk (67% and 56%, respectively).

The nutrients stored in the litter layer amounted, on average, to 45% of those in the aboveground forest ecosystem (aboveground tree + litter layer) (Table 9).

**Table 9.** Biomass, carbon and nutrient content in tree components of a 3-year old *E. urograndis* plantation forest.

| Variable               | Canopy | Upper stem portion | Trunk | Wood  | Bark | Tree         | Litter | Total        | Stock <sup>1</sup> |
|------------------------|--------|--------------------|-------|-------|------|--------------|--------|--------------|--------------------|
| Biomass                |        |                    |       |       |      |              |        |              |                    |
| Mg ha <sup>-1</sup>    | 13.4   | 1.4                | 75.6  | 70.9  | 4.7  | <b>90.4</b>  | 15.9   | <b>106.3</b> | 35.4 (33)          |
| Carbon                 |        |                    |       |       |      |              |        |              |                    |
| Mg ha <sup>-1</sup>    | 6.8    | 0.7                | 39.6  | 37.2  | 2.4  | <b>47.1</b>  | 7.4    | <b>54.5</b>  | 17.3 (32)          |
| N kg ha <sup>-1</sup>  | 161.4  | 3.2                | 159.8 | 141.6 | 18.3 | <b>324.4</b> | 140.6  | <b>465.0</b> | 323.5 (70)         |
| P kg ha <sup>-1</sup>  | 12.4   | 0.3                | 9.7   | 7.1   | 2.6  | <b>22.4</b>  | 8.2    | <b>30.6</b>  | 23.4 (77)          |
| K kg ha <sup>-1</sup>  | 95.5   | 4.2                | 155.8 | 129.2 | 26.6 | <b>255.5</b> | 25.4   | <b>280.9</b> | 151.7 (54)         |
| Ca kg ha <sup>-1</sup> | 107.3  | 1.0                | 90.3  | 29.5  | 60.8 | <b>198.5</b> | 331.9  | <b>530.4</b> | 501.0 (94)         |
| Mg kg ha <sup>-1</sup> | 34.3   | 0.8                | 25.7  | 11.3  | 14.4 | <b>60.8</b>  | 67.0   | <b>127.8</b> | 116.5 (91)         |
| Fe kg ha <sup>-1</sup> | 0.8    | 0.03               | 1.4   | 1.1   | 0.4  | <b>2.3</b>   | 8.9    | <b>11.2</b>  | 10.1 (90)          |
| Mn kg ha <sup>-1</sup> | 2.0    | 0.03               | 1.1   | 0.5   | 0.6  | <b>3.2</b>   | 7.7    | <b>10.9</b>  | 10.3 (95)          |
| Zn g ha <sup>-1</sup>  | 110.4  | 4.8                | 277.5 | 259.1 | 18.4 | <b>392.8</b> | 175.5  | <b>568.3</b> | 309.1 (54)         |
| Cu g ha <sup>-1</sup>  | 76.6   | 3.5                | 108.7 | 98.7  | 10.0 | <b>188.8</b> | 118.6  | <b>307.4</b> | 208.8 (68)         |

<sup>1</sup> (values in parenthesis are the stock percentage for each variable after wood harvest without bark).

## Discussion

### Soils

With exception of phosphorus, the nutrient stocks observed in the soil of the 3-year old *E. urograndis* plantation are typical for Quartzipsament soils. Sandy soils have a greater capacity for nutrient desorption, which leads to an overestimation in terms of P availability. Elevated stocks of Ca and Mg down to soil depths between 60 and 80 cm suggest that after limestone had been applied during planting leaching occurred from the surface to deeper layers in the soil profile. However, research into application of lime and leaching of Ca and Mg has shown that leaching from the addition of lime is slow

and not always results in significant increases in levels of these nutrients deeper in the profile (Quaggio et al., 1982; Pavan et al., 1984; Raij, 1989; De Maria et al., 1993).

Due to the high sand fraction, these soils are characterised by low levels of exchangeable cations and a low activity of the exchange complex. Therefore, such soils would be exhausted within a few rotations, and there is a need for proper management practices to guarantee favourable production conditions, with emphasis to development of management strategies to improve soil's water retention. In general, adding Ca through liming, in combination with adequate fertilization (N, P, K) is necessary when such soils are used for establishment

of fast-growing, short rotation plantation forests. The topsoil layer contains most of nutrients, so care should be taken to ensure that this layer remains as undisturbed as possible during forestry activities (Mello et al., 2007). When plantations are established on sloping terrain with this soil type, the susceptibility to erosion can further affect the sustainability of the plantation forest. Bruijnzeel & Wiersum (1985) showed nutrient losses associated with surface erosion during the first three years after establishment of *Agathis* plantations in Java to represent a major portion of overall nutrient losses over a 40-year rotation period.

Due to the low cation exchange capacity of soil, leaching of nutrients from the decomposing slash after harvesting may also occur with percolation to groundwater. As greater rainfall occurs during the time of year when temperatures are also greater, conditions are more favourable for plant growth, and the roots of newly planted eucalypts, as well as developing undergrowth vegetation, may efficiently absorb nutrients from the soil solution. Thus, the most critical period for nutrient loss occurs between harvest and the establishment of new ground cover, when consumption of water and recovery rates for nutrients are much lower than in the period before harvesting (Waterloo, 1994; Bruijnzeel, 1998).

The low soil water retention capacity of these sandy soils may also affect the forest productivity. In our study, the available water in topsoil was higher than in subsoil. Furthermore, a high density of fine roots in the superficial soil layer was observed in eucalypt stands (Coelho et al., 2007; Mello et al., 2007). Jetten (1996) showed improved soil water retention on Quartzipsamments in Guyana after mechanized harvesting.

According to Voorhees et al. (1989), the soil resistance to penetration is an indicator of fracture planes or soil weakness, whereas the bulk density is more related to the pore volume. Commonly, sandy soils have a relatively high macroporosity, so compaction has to be extremely high to cause a drastic reduction in porosity (Dedecek & Gava, 2005). The Least limiting water range (LLWR) is a soil quality assessment parameter that incorporates penetrometer resistance, soil moisture retention characteristics and bulk density (Leão & Silva, 2004).

Zou et al. (2000) observed that in coarse sandy soil, an initial low compaction increased the LLWR, but further moderate to high compaction decreased LLWR. LLWR is therefore sensitive to variations in forest management

practices, including mechanized harvesting practices, and is a potential indicator of soil physical condition for sustainable forest management (Zou et al. 2000; Leão & Silva, 2004).

Soil conditions must be favourable to a rapid expansion of roots to ensure a good initial development of tree. According to our penetrometer measurements, the lowest values, 8-25 kg cm<sup>-2</sup>, occur in the planting row soil profiles. This suggests that deep tillage on line just before planting was effective in reducing the soil resistance. In this type of soil, the highest resistances in the topsoil were recorded at a distance of 1 m from the planting row, in particular at depths between 10 cm (38 kg cm<sup>-2</sup>) and 30 cm (58 kg cm<sup>-2</sup>, Figure 1). This suggests that machines used for site preparation before planting did compress the soil to some extent as their tires pass more frequently at this distance from planting row. At distances of 0.5 m and 1.5 m of planting row, the maximum resistance occurred at depths between 30 cm and 40 cm.

Dedecek & Gava (2005), evaluating soil compaction after harvesting of *Eucalyptus* coppice on sandy soil, observed a maximum resistance layer (60 kg cm<sup>-2</sup>) at 20 to 30 cm depth, which coincides with our results observed for tyre tracks.

Sands et al. (1979), assessed the compaction of sandy soils in radiata pine forests and observed that root penetration was severely restricted above a critical penetration resistance of about 30 kg cm<sup>-2</sup>. These authors discussed the importance of organic matter on the maintenance of a favourable structure in sandy soils, as well as to the site sustainability.

### Growth and volume of tree

With an average commercial stem height of 14.5 meters and a DBH of 13.4 cm, the observed forest growth is higher than those observed elsewhere in São Paulo State for *E. urograndis* by Brigatti et al. (1980; height of 13.5 m and DBH of 10.3 cm) and Braga (2008; height 11.9 m and DBH of 12.0 cm).

We observed a total aboveground tree biomass of 90.4 Mg ha<sup>-1</sup> and an annual average increment, in total volume with and without bark of 70.9 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> and 64.6 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup>, respectively. Recently, forestry companies have succeeded in increasing plantation forest productivity values through investments in research and development for breeding techniques, such as cloning, biotechnology, and hybridization (BSS, 2008). This caused the average yield (according to the planted area)

of *Eucalyptus* plantations in Brazil to increase from 36.7 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> in 2005 to 40.5 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> in 2007, which represents a gain of 10.4%. Based on the annual growth rate observed at this site it should be considered as highly productive. This suggests that the observed soil, water and nutrient conditions did not pose constraints to tree growth at this forest age.

### Canopy biomass

The statistical differences observed in the canopy biomass of the 3-year old *E. urograndis* stand (Table 5) and the linear relation observed between the basal area of the trees and the combined biomass of leaves and branches, demonstrated the importance of stratified sampling based on DBH classes. Therefore it is necessary to measure the DBH frequency distribution in order to determine the appropriate class boundaries to better estimate the canopy biomass, as well as the nutrient content accumulated in the trees.

The canopy biomass amounted to 13.4 Mg ha<sup>-1</sup>, or 15% of the tree biomass, which is in the range observed by Spangenberg et al. (1996), who published biomass values for leaves and branches from 7.5-21.2 Mg ha<sup>-1</sup> for plots of *E. urograndis* in 4.5-year old plantations at different sites in the eastern Amazon, Brazil.

### Biomass, concentrations of carbon and nutrients in above-ground tree components and litter standing crop

The observed biomass of litter layer of *E. urograndis* (Table 6) had accumulated over three years and amounted to 9.0 kg per tree (1.5 kg m<sup>-2</sup>). The litter standing crop was 2.8 times higher than that of a 9-year-old *E. grandis* plantation forest in Rio Grande do Sul State in south Brazil (0.54 kg m<sup>-2</sup>; Freitas et al., 2004).

Our canopy biomass (13.4 Mg ha<sup>-1</sup>, Table 10) amounted to 53% and 78% of those found in 8-year old Australian *Eucalyptus globulus* plantation forests on grey sands and red soils, respectively (Mendham et al., 2003).

The higher concentrations of Ca, Fe and Mn in litter layer, comparing to those in fresh leaves and branches, suggest that these nutrients are immobilised in structural tissue and accumulate on soil surface. Ca was the nutrient with the highest concentration in the litter layer, which was also observed by Freitas et al. (2004) for 9-year-old *E. grandis* forests in south Brazil.

### Density, concentrations of carbon and nutrients in wood and bark

The densities of sapwood and bark were not related to the DBH of the tree trunk. The sapwood basic density at 0.37 g cm<sup>-3</sup> was on an average of 45% higher than that of bark. Gatto et al. (2003), analysing the wood of *Eucalyptus* plantations and of native forests, found that the wood basic density ranged near 0.44 g cm<sup>-3</sup> for *Eucalyptus* and 0.46 g cm<sup>-3</sup> for native trees, and considered as slightly dense woods.

For the production of firewood and high-quality charcoal, one of the most important considerations is that wood density should be high. In the case of an earlier harvest for energy use, the wood basic density observed for the 3-years old *E. urograndis* (0.37 g cm<sup>-3</sup>) was well below of the required density for charcoal, which therefore limits its use for biofuel.

Sturion et al. (1988) studied the wood quality of *Eucalyptus viminalis* plantations for energy purposes in relation to different cutting ages and found that the wood density increased on average by 8% between age four (0.49 g cm<sup>-3</sup>) and age seven (0.53 g cm<sup>-3</sup>). Rodigheri (1997) interviewed farmer owners of *Eucalyptus* plantations in south Brazil and observed that some of them, when requiring firewood, harvested trees at four, five or six years of age. However, most of the interviewed farmers extracted the wood at age seven, applying two coppices for the plantation.

According to Simon (2005), harvests of trees occur at 3.5 years old in *Acacia mearnsii* plantations in south of Brazil for financial reasons of the producers, due to a large demand for wood and bark. This practice brings, as a consequence, lower forest productivity, low wood density and lower tannin concentration in the bark.

Although there were some significant effects of tree DBH on the concentration of carbon as well as of nutrients in tree components (Table 8), the results have shown that these occurred regardless of tree size.

### Biomass, carbon and nutrient content in aboveground tree components and litter standing crop

Naturally, higher nutrient exports and environmental damage during harvesting and subsequent site preparation for planting leads to a greater potential of compromising the sustainability of plantation forest, particularly in soils with low nutrient status and low water availability (Jorgensen et al., 1975; Bruijnzeel, 1998; Gonçalves et al., 2000b).

To maintain high growth rates in short-rotation plantations, nutrients inputs through fertilising, especially of N, P and base cations, will often be required, as its natural sources from the atmosphere (precipitation and dust) and rock weathering (soil formation) are insufficient to replace the nutrients losses from the site during and after harvesting (Bruijnzeel & Wiersum, 1985; Waterloo, 1994; Bruijnzeel, 1991, 1998).

Management of such plantations should aim, for instance, to reduce nutrient losses by retaining bark and crown slash on site at the time of harvesting and distributing all organic material evenly over the site (Waterloo, 1994; Folster and Khanna, 1997) and by minimizing the area of bare soil (Cassells & Bruijnzeel, 2005).

Several studies suggest that in timber harvesting it is also important to manage the soil organic matter content without burning the waste and to use forestry equipment which produces lower compaction of soil as well as streamline the movement of machinery on the ground (Bouillet et al., 2000, Gonçalves et al. 2000a; Laclau et al., 2000; Cassells and Bruijnzeel, 2005).

It is also recommended to maintain the litter as a source of nutrients for the initial development of a new planting (Gonçalves et al. 2000a; Laclau et al., 2000, Sankaran et al. 2000; Bouillet et al., 2000; Andrade, 2002). On fertile soils in Australia, planted with *E. globulus* Labill, the removal of litter and all slash from the site, after harvesting did not affect tree growth at four years old in the second rotation. However, after several rotations, any management practice that affects the nutrients supply from the site may compromise the plantations productivity (O'Connell et al., 2000)

The bulk inputs of nutrients by rainwater in plantations of *E. grandis*, as measured at Itatinga, SP, Brazil (Andrade et al. 2003), at a distance of about 40 km from the study plot with an annual average rainfall in the region of 1.350 mm, amounted to 17.7 kg N, 2.0 kg P, 6.8 kg K, 24.0 kg Ca and 3.0 kg Mg. These values represent 12.5%, 28.5%, 5.3%, 81.5% and 26.9%, respectively for N, P, K, Ca and Mg, of the nutrients accumulated in the wood without bark in our plot of 3-year-old *E. urograndis*.

Considering the nutrient stock of biomass measured at the studied site, harvesting at this age would not result in a large nutrient export. As a consequence, the nutrients loss with the removal of wood would be compensated to a large extent by the annual input in precipitation.

Potassium would be the nutrient with lower replacement by rainwater, and it is leached from the soil profile more easily than other ions. Therefore, the trees harvesting at this age would require application of greater quantities of fertiliser than any other nutrients. Potassium also has a very important role in plant resistance to drought in sandy soils. Crops with K deficiency suffer earlier and more severely the drought effects (Informações Agronômicas, 2008).

In our study, the main problem of harvest after 3 years would be an increase in the intensity of intervention on the ground (e.g. added compaction), as well as more soil exposure. According to Bruijnzeel & Wiersum (1985), these conditions give less protection, promote soil erosion and are associated with nutrient loss which may also impair long-term sustainability.

Another important issue is the large amount of nutrients accumulated in the litter layer of the 3-year-old plantation. It must be considered that when the release of nutrients from organic matter increases, the chances of leaching losses increases as well, especially when there is still no new biomass of ground cover to use immediately the nutrients that are released by the decomposition of accumulated litter (Bruijnzeel, 1998).

The amount of nutrients removed can be high, even if only the stem is harvested, especially by repeated cutting of short-rotation crops. These losses are likely to be enhanced by faster organic matter decomposition at the exposed sites during the fallow period. Several factors including the amount of runoff, the size of the nutrients pool and the rate of organic matter mobilization affect the loss nature and extension (Gonçalves, et al., 2000a).

Addition of slash to the forest floor results in increased microbial mineralisation of organically bound nutrients, causing a sudden increasing in cation and anion concentrations in the soil solution. Depending on the soil environmental conditions (e.g. high rainfall in the early season after the dry season), some of these mineralised elements may be leached beyond the main rooting zone of the soil, especially when there is a reduction or even an absence of living roots (Folster & Khanna, 1997)

However within the system adopted in this study plot, as is a majority of *Eucalyptus* plantations in Brazil, there are one or two coppices. In this case, after the coppices, the trees roots are still absorbing nutrients from decaying slash and stumps, which reduces the critical period with a sudden drop of living biomass in the soil after

harvesting. When this reduction occurs in the biomass and the recovery of the ground cover is slow, the soils remain moist for longer periods of time as evaporation is decreased, which can contribute to increased surface runoff with associated nutrient and sediment losses, and higher leaching of nutrients to groundwater. This could therefore enhance nutrient outputs and soil loss from the system, potentially leading to a decline in site quality. In this sense, important factors that could influence this dynamic soil-plant-climate are: topography and soil type, conditions of the forest floor and soil after harvest, precipitation, incidence of solar radiation, temperature and water excess in this period of cutting followed by coppice of the stumps, as well as the recovery time of the biomass on the site.

These results, without considering the losses of soil nutrients by erosion, leaching and volatilization, especially in areas of flat relief, reinforce the claim of Evans (1999), that under certain conditions, the nutrients export on the forest plantation may threaten the sustainability of the site and that the most important care to maintain the site quality is usually related to the timber harvesting operations, to the conservation of organic matter and to management remnant vegetation.

### Conclusions

Elevated concentrations of Ca and Mg down to soil depths between 60 and 80 cm, suggest that limestone applied during planting had dissolved and the cations had percolated into the subsoil.

The values of soil resistance down to 60 cm depth in the planting row were lower than the values between planting rows, indicating that deep tillage in the planting row during preparation of the area for plantation was effective in reducing the soil resistance, which could enhance local root development and promote faster growth.

The values of soil resistance, down to 20 cm depth, in inter-row distance from 1.0 m of the planting row, were higher than those in the inter-row, which was attributed to the likely increase in soil compaction in that part of the area by vehicle tyre pressure on the soil during preparation for planting.

The average annual growth in total volume (including the bark) of  $70.9 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$  verified on this plot *E. urograndis* in 3-years-old represents a forest of high productivity.

The biomass of the canopy of *E. urograndis* in 3-years-old was different among the classes of DBH studied, which justified the sample using DBH class intervals, and showed the importance of making a analysis of trees distribution by class in the plot for the biomass and nutrients estimation accumulated in the canopy in the forest site.

The observed variation in DBH in 3-year-old stems did not relate to observed differences in wood density, suggesting that tree age is a more important factor for changes of this parameter than growth rate within an even-aged stand.

Concerning an early cut of *E. urograndis* forest plantations for traditional energy supply (firewood and charcoal), the wood density observed in this 3-year-old plantation was well below the values cited as adequate for this purpose.

Removal of trees bark and its disposal in the field after harvesting of the trees would be important to increase the nutrient availability at the forest site for a second rotation, as bark contained between 8% and 11% of the forest P, K, Ca and Mg contents.

The bark contained about 56% and 67% of the total Mg and Ca content of the stem, respectively.

The litter layer in the plot of *E. urograndis* contained on average of 45% of the accumulated nutrients in the biomass of the plot (above-ground tree biomass + litter).

A harvesting of trees in this 3-year-old plantation forest would not result in a large nutrient export if harvesting were limited to the bole, leaving bark and slash on-site. Such a forest management decision would contribute to forest sustainability at this site.

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