

Water use and yields of *Eucalyptus grandis* hybrids plantations in Brazil during a rotation for pulp production

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Abstract

The water balance and growth of *Eucalyptus grandis* hybrid plantations in Brazil are presented based on six years of intensive catchment hydrology, physiological and forest growth surveying, and modelling. The results show a balance between water supply by precipitation and output through evapotranspiration (considered as canopy interception, soil evaporation and trees transpiration) and runoff. The annual average evapotranspiration was 1092 mm and average precipitation was 1147 mm. The runoff is normally low, only 3% of the precipitation, because of high soil infiltration and the flat topography where the trees are planted. Evapotranspiration rates varied from 781 mm to 1334 mm during the years of the study and are strongly influenced by variations in annual precipitation and leaf area index. When the precipitation was close to the regional mean annual precipitation of 1350 mm there was enough water to supply the demands of the trees and produce some runoff. Biomass production was high and the peak annual growth rate was 95 m³ ha⁻¹ year⁻¹. The UAPE model (Soares & Almeida, 2001) was used to estimate the water balance and the widely used 3-PG

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model (Landsberg & Waring, 1997) was used to estimate forest growth and water-use efficiency.

Keywords: Eucalyptus plantations, water balance, water use modelling, water-use efficiency.

1. Introduction

Water use by eucalypt plantations has historically been a controversial matter in many parts of the world. Research has shown that it depends on the region, species, environmental conditions and land-use practices (Calder, 1998; Dye, 2000; O'Loughlin & Nambiar, 2001; Almeida & Soares, 2003). Local populations and some environmentally oriented Non Government Organisations (NGOs) claim that these plantations dry out the soil. Timber and pulp companies need to improve their understanding of water use by plantations in order to adjust their management practices to achieve long-term sustainability and to answer the questions of different stakeholders. Meeting the demands of markets needing more and more guarantees of environmentally sustainable practices also means that improved knowledge of the hydrology of fast-growing forests is essential.

The rotation length of eucalypt plantations grown for pulp in Brazil is around six to seven years. Growth rate and leaf area index vary during the cycle, as well as seasonally. This leads to the question of how water use varies with time, and how water use can be analysed at different scales from individual trees (Wullschleger *et al.*, 1998) to stands or landscapes (Hatton & H.Wu, 1995). Analysing the water use for as many years as possible over single or multiple growth cycles should help understand and answer some of the key hydrological questions about these fast-growing plantations. Variability in the meteorological factors affecting tree water use reinforces the need for multiple-year analysis in order to reach robust conclusions. Measurements of the components of the hydrological cycle allow the development and testing of models to quantify water use in different areas (Whitehead & Kelliher, 1991; Vertessy *et al.*, 1996; Xu, 1999) as well as identifying the effect of water deficits on forest growth (Battaglia & Sands, 1997).

Setting up an experimental catchment for long-term monitoring within its extensive eucalypt plantations was part of a programme carried out by Aracruz Celulose S.A. in Brazil to address their hydrological issues (Soares & Almeida, 2001; Almeida & Soares, 2003). We also used data from several intensive ecophysiological campaigns carried out under different conditions of water availability, starting in 1995 (Mielke *et al.*, 1999; Mielke *et al.*, 2000; Almeida, 2003). A complete network of hydrological, meteorological and forest growth measurements provided most of the data analysed in this work.

In this paper we present an analysis covering around six years (October 1998 to June 2004) of plantation growth over the age range two to seven years. This represents most of a single growing cycle as the trees in this region are clear-cut at seven-years old. We start the analysis at the beginning of the hydrological year, which is October 1st for the east Atlantic coast in Brazil. This paper addresses the following scientific questions:

- How much water do *E. grandis* hybrids plantations use during a rotation, and how much goes to the different components of the water balance?
- How does precipitation affect forest growth?
- How does soil moisture vary in the soil profile? How does it respond to root distribution?
- Are variations in water table levels consistent with the water balance during the rotation cycle?
- Is runoff consistent with the water balance? Does runoff vary with forest age and canopy cover or with rainfall intensity?
- Is forest growth correlated with water use?

We analysed data sets on hydrometeorology, soil moisture, water table level, runoff measurements, plant physiology and rainfall interception. The study was based on a water-use model named UAPE (Soares & Almeida, 2001) set up for eucalypt plantations and, for growth estimates, on a process-based model called 3-PG (Landsberg & Waring, 1997). The 3-PG model was previously calibrated and validated for the study area (Almeida, 2003; Almeida *et al.*, 2004a).

2. Materials and methods

2.1. Study area

The study area – the Aracruz experimental catchment, for which we will use the acronym MBE, for “Microbacia Experimental” – is a catchment of 286 ha with 190 ha of *Eucalyptus grandis* hybrid plantations and 86 ha of Atlantic rainforest. It is located at 19° 51' S, 40° 14' W on Brazil's Atlantic coast and is representative of 40,000 ha of plantation land for dominant soil type, soil texture, vegetation cover, drainage network, climate and topography (Soares & Almeida, 2001; Almeida & Soares, 2003; Almeida, 2003). The site was conveniently located, of adequate size and had a good road network (Mielke *et al.*, 2000).

2.2. Measurements to quantify forest growth and water use

We used data from intensive ecophysiology measurements that included maximum and hourly stomatal conductance and the effect of vapor pressure deficit (VPD) on stomatal conductance reported in Mielke *et al.* (1999), Mielke *et al.* (2000), Mielke (2001 – unpublished report) and (Almeida, 2003). Measurements of foliage, stem and root biomass, wood density and specific leaf area were made at annual intervals. Litterfall, rainfall interception and leaf area index (LAI), soil moisture, stand volume, diameter at breast height (DBH) – from which mean annual increments (MAI) were calculated – and basal area (BA), were measured monthly. Allometric equations between DBH and stem, foliage and root mass were previously established (Almeida, 2003).

2.3. Forest management

The eucalypt trees were planted at a density of 1111 trees per hectare (3 x 3 m). The rotation length is 6 - to - 7 years for pulp production and 14-to-17 years for solid wood products, which includes thinnings at 6 and 10 years, reducing the number of trees to 500 and 250 respectively. Before planting the soil was ripped to 60 cm depth and weeds were controlled. NPK fertiliser was applied when the seedlings were planted. Additional nutrients were applied during the first two years after planting.

FIG. 1. ABOUT HERE

2.4. Meteorological data

Meteorological data have been continuously recorded by three fully automatic weather stations located in the experimental catchment since 1995. We used the data from 1998 to 2004. These provided daily measurements of precipitation (mm), air temperature ($^{\circ}\text{C}$), air relative humidity (%), global solar radiation (W m^{-2} and $\text{MJ m}^{-2} \text{ day}^{-1}$), net radiation (W m^{-2}), photosynthetically active radiation (PAR) ($\mu\text{mol m}^{-2} \text{ s}^{-1}$), wind speed (m s^{-1}) and wind direction (degrees). The stations are installed on towers above the tree canopy. The instruments are scanned each minute and the data integrated to give ½-hour, hourly, daily and monthly means, and total monthly rainfall and radiation. The data are stored in data loggers, and relayed daily by radio and checked for consistency in the central office. Table 1 shows maximum, minimum and average values of monthly meteorological data from the catchment weather station from 1998 to 2004.

TABLE 1. ABOUT HERE

2.5. Biomass allocation

Three trees of each of the five genotypes studied were destructively sampled yearly in the experimental catchment. One tree was selected with stand average DBH; one was one standard deviation above and one, one standard deviation below the average. These samples provided values of DBH and tree height, stem, bark, branch, root and foliage biomass, and wood density. The data were used in the 3-PG model to predict forest growth, using the allometry between tree diameter and stem biomass (Almeida, 2003).

2.6. Leaf area index

The growth and water use rates of eucalypt plantations depend on the species, age and interactions with environmental factors. Variations in canopy biomass are important in explaining these interactions during a rotation. Leaf area index (LAI , $\text{m}^2 \text{ m}^{-2}$) was estimated monthly using the LAI-2000 plant canopy analyser (PAI). The LAI-2000 measurements were made using the two-sensor method (Li-Cor, 1992) with a reference sensor collecting data

above the canopy and the measuring sensor located below the canopy. LAI-2000 measurements were also made in permanent growth plots. Monthly LAI-2000 records were obtained from 25 readings randomly recorded in each area.

Values of *LAI* obtained with the LAI-2000 were compared with those determined from biomass sampling and destructive leaf area determination in 38 trees of different genotypes and age from six stands. The result of the comparison is consistent with other studies, which showed the LAI-2000 underestimates *LAI* (Battaglia *et al.*, 1998; Cutini *et al.*, 1998; Hingston *et al.*, 1998). The correction equation, presented in Almeida (2003), is:

$$LAI = 1.317 PAI - 0.380 \quad r^2 = 0.814 \quad n = 38 \quad SE = 0.376 \quad (1)$$

2.7. Soil moisture

Nine access tubes for neutron probes were installed to measure soil moisture in the first 2.8 m in each plot for each genotype. Three tubes were also installed to take measurements to 5.8 m. Measurements were taken at vertical intervals of 20 cm. The measurements started in 1995 at a weekly frequency, but the interval was sometimes extended to a fortnight during dry periods. The neutron probe was calibrated for every tube monthly during one year, against the moisture content of field soil samples collected at different depths and measured gravimetrically.

2.8. Water table level

A network of five piezometers was installed in the catchment based on a previous hydrogeological study (Albuquerque *et al.*, 1997; Blanco *et al.*, 1997). These provided measurements of water table level at three-hourly intervals that were integrated to give weekly average values of the water table level during the study period. Variations in this level, and its relationship with the growth phase of the plantation were analysed.

2.9. Runoff

Runoff was measured automatically from 1996 in a weir located at the end of the catchment drainage system (see Fig 1) using a shaft encoder designed for water level measurements, and a data logger. A calibration curve was developed to convert the water level readings into volumes of water, allowing quantification of the water yield during the whole measurement

period. The measurements were taken every five minutes and converted to daily water production. The inter-annual variability in water yield was quantified and compared to the rainfall variation.

2.10. *Precipitation interception*

A precipitation interception experiment was conducted in the catchment in 1995 and 1996. Throughfall was measured by two automatic rain gauges plus 25 conventional rain gauges installed in one of the permanent growth plots. Interception and stemflow were measured after rainfall events. The volume of water reaching the soil by stemflow was insignificant over a two-year period. After this period rainfall was collected above and below the canopy by three automatic rain gauges (CS-700, Hydrological Service). The results of the precipitation interception study were reported in Soares and Almeida (2001). They found interception values of 11% of total precipitation, which is consistent with the values found by Prebble and Stirk (1980) for *Eucalyptus melanophloia*.

2.11. *Stomatal conductance and leaf water potential*

We used stomatal conductance (g_s) measured hourly at two levels in the canopy on 13 days over a period of about two months in 1999 for modelling purposes. Results from a previous similar campaign in the same area were reported by Mielke *et al.* (1999) and Mielke *et al.* (2000). These campaigns provided data that made it possible to identify significant differences between genotypes in terms of stomatal conductance and the effect of VPD on canopy conductance (g_c) reported in Almeida (2003).

2.12. *Growth and yield*

Twelve circular permanent growth plots of 825 m² each were established in the catchment. Monthly measurements of tree height, DBH and stem numbers in each plot were used to estimate MAI, basal area and stand volume.

2.13. *Water-use efficiency*

The water-use efficiency (WUE), defined as the amount of dry matter produced by the plant per unit of water transpired (Landsberg, 1999a), was calculated using the corresponding annual volume increments measured in the permanent sample plots (m³ ha⁻¹, not including

branches and foliage) and the estimates of annual evapotranspiration made by the UAPE model. WUE from the 3-PG model was obtained as the annual wood volume increment divided by evapotranspiration, both predicted by the model. WUE values were also converted to a mass basis obtaining the annual estimations of WUE with UAPE and 3-PG model

3. Models

3.1. Water balance model

The model UAPE (acronym for “Uso de Água em Plantações de Eucalipto”) calculates the daily water balance in the rooting zone. The stored available water at the end of a given day (i) is obtained as the storage available the previous day (i-1), plus the net income (rainfall – interception, $P - I_{cp}$) (mm day⁻¹), minus the output (transpiration + soil surface evaporation + runoff, $E_t + E_s + Q_{liq}$) (mm day⁻¹). Mathematically:

$$\Delta\theta = \theta_{solo}(i) - \theta_{solo}(i-1) = (P - I_{cp}) - (E_t + E_s + Q_{liq}) \quad (2)$$

Where $\theta_{solo} = \sum \theta_v \Delta Z$ integrates soil moisture in mm for the various soil layers in the root zone. Q_{liq} is the net vertical water flux (upward – downward) at the boundary between the root zone and its neighbouring deeper layer.

We used the classic Penman-Monteith parameterization to estimate daily transpiration (E_t , mm.day⁻¹) as in Running & Coughlan (1988), Waring & Running (1998), Landsberg (1999b), and Soares & Almeida.

$$E_t = \frac{1}{L} \left[\frac{\Delta R_n + \rho_a c_p g_a D}{(\Delta + \gamma)(1 + g_a / g_c)} \right] t \quad (3)$$

Here Δ is the slope of the saturation vapor pressure curve (mbar °C⁻¹), at temperature T, R_n is average daylight canopy net radiation (W m⁻²), ρ_a is air density (kg m⁻³), γ is the psychometric constant (mbar °C⁻¹), c_p is the specific heat of the air (J kg⁻¹ °C⁻¹) and D is vapor pressure deficit of the air (mbar). In the denominator g_a is canopy aerodynamic conductance (m s⁻¹), g_c is canopy conductance to water vapor (m s⁻¹), L is the latent heat of vaporization of water (J Kg⁻¹), and t is the daylight length (s day⁻¹). Canopy conductance, g_c is given by $g_c = g_s \text{ LAI}$, where g_s is the average stomatal conductance (converted into m s⁻¹ units).

From the ecophysiology campaigns (Mielke *et al.*, 1999), we developed three equations:

- relating predawn leaf water potential, Ψ_l , to relative available soil moisture (equation 4);
- correcting g_s for the effect of Ψ_l (equation 5);
- correcting g_s for the effect of water vapor deficit, D (equation 6).

$$\Psi_l = 0.33 \left(\frac{\theta}{\theta_{\max}} \right)^{-0.57} \quad (4)$$

In equation (4) θ is the current water content in the soil rooting zone (mm) and θ_{\max} is the matching water holding capacity (mm).

$$g_s = g_{s\max} - m_w(\Psi_l - \Psi_{l\min}) \quad (5)$$

In equation (5) $g_{s\max}$ is the maximum conductance, without moisture deficit in the soil when the radiation threshold is reached in the morning. $\Psi_{l\min}$ is the water potential at stomatal closure (around -2.0 MPa), and m_w is the slope of the relationship for eucalypt ($-0.7 \text{ cm s}^{-1} \text{ MPa}^{-1}$).

$$g_{sD} = g_s + S_D D \quad (6)$$

In equation (6) S_D is the slope (negative) of the linear decrease of g_s with water vapor deficit ($\text{cm s}^{-1} \text{ kPa}^{-1}$). Then, g_{sD} is the average daily conductance corrected for both soil moisture availability and vapor pressure deficit.

Soil evaporation, E_s , was estimated from the Penman-Monteith equation with soil conductance falling rapidly as soil moisture drops, as in Choudhury & Monteith (1988) and Soares & Almeida (2001).

A water flow sub-model was developed and coupled to the water balance. In this the soil was divided into several layers. Movement of water between the layers was calculated using Darcy's law. It was assumed that hydraulic conductivity remained constant for the time step (one day), which is a fair assumption, as soil moisture content in a layer does not change

significantly in one day. Hydraulic conductivity was estimated from soil texture following Campbell (1974) and Clapp & Horneberger (1978). During long periods of drought, water withdrawal from the rooting zones may lead to inversion in water potential gradients, leading to upward fluxes from deeper layers. A detailed description of the UAPE model can be found in Soares & Almeida (2001).

Comparisons between water input through precipitation and output by evapotranspiration in the catchment were made at annual intervals, taking evapotranspiration to be the sum of transpiration by the trees, soil evaporation and intercepted rain

3.2. *The 3-PG model*

The 3-PG model, developed by Landsberg and Waring, (1997) and modified by Sands and Landsberg (2002) is a simple process-based forest growth model. It has been described in a number of publications and is being used in several parts of the world for different tree species (Landsberg *et al.*, 2000; Sands & Landsberg, 2002; Landsberg *et al.*, 2003; Almeida, 2003). The time step is monthly and the state of the stand is updated each month. The model requires climatic data inputs, a basic knowledge about the local soil water holding capacity, an indication of soil fertility and initial tree numbers per hectare. It also requires initial values for stem (including bark and branches), foliage and root mass per hectare to initialise the model at a selected age. The climate input data needed are monthly total short wave incoming radiation, monthly mean temperature and vapor pressure deficit, and total monthly rainfall.

The model incorporates simplifications of some well-known relations, with the aim of describing complex physiological processes so that they can be applied to plantations or even-aged, relatively homogeneous forests. These simplifications were described by Waring and McDowell (2002). 3-PG is driven by radiation; the efficiency with which radiation is converted to biomass is constrained by environmental modifiers, namely; temperature, VPD, frost, available soil water (SW), stand age and site nutritional status. Nutritional status is described by an index called the fertility rating (FR) that ranges from one for a site where nutrients are not limiting to growth down to zero for the poorest sites. All modifiers vary from zero (representing total limitation), to one (no limitation). Biomass partitioning is affected by growing conditions and tree size. The model has sub-models for stem mortality and soil water balance. The stand properties are determined by the biomass pools, specific leaf area and

branch and bark fractions. 3-PG needs to be parameterised for individual species or different genotypes within a species. The calibration and validation of the 3-PG model for the study area is presented in Almeida (2003) and in Almeida *et al.* (2004a). We used 3-PG to estimate the water use, water-use efficiency and forest growth at a monthly time step by comparing water use and biomass production over a period of six years.

4. Results

The results presented are based on observed data and/or predictions using the UAPE and 3-PG models.

4.1. Leaf area index

Peak LAI occurred closed to the third year of the rotation and coincided with the end of the wet season: there was a strong effect of tree age that reduced the LAI (Fig 2). Based on observed data we established an equation that represents LAI according to stand age for this site:

$$LAI = -0.016A^4 + 0.200A^3 + 0.532A^2 + 0.925A - 0.302 \quad (7)$$

$$R^2 = 0.794$$

where A is the stand age in years after planting. The 3-PG model adequately predicted the observed changes in LAI during the rotation (Fig. 2)

Fig. 2 ABOUT HERE

4.2. Soil moisture profile

Root system depth, established by excavation, varied from 0.80 m at age two to 1.6 m at age seven years. These data was no clear and direct relationship between the soil moisture extraction patterns and the root systems of the trees, Drought moisture was extracted mainly from the first metre of the soil (Fig. 3). An exception was the measurement made in 2001, which shows a more uniform soil moisture profile down to 1.6 m.

Fig. 3 ABOUT HERE

4.3. *Water balance*

Rapid water consumption was observed throughout the rotation, with higher soil depletion associated with higher evapotranspiration caused by the higher vapor pressure deficits and radiation during the summer (Fig. 4a). The UAPE model was able to reproduce the main soil water trends.

Estimations of soil moisture by 3-PG model indicates that monthly time step are sometimes too long to detect variations in soil moisture that occurred during the month (Almeida *et al.*, 2004a) (Fig 4b).

Fig. 4a and 4b ABOUT HERE

A comparison between observed and predicted available soil water showed that the highest biases are associated with the low values, which can be directly correlated with the depth of measurements (Fig. 5).

Fig. 5 ABOUT HERE

Water use estimated by the UAPE model varied from 635 to 1092 mm with an average of 953 mm (Table 3). Transpiration by the trees was the highest component, representing 81% of total evapotranspiration. Evapotranspiration changed significantly between years, and were associated with changing LAI. The regression model of evapotranspiration (ETP) as a function of annual precipitation (P) and LAI for the period October 1998 to June 2004 had the following form:

$$\text{ETP} = 266.92 + 91.041 \text{ LAI} + 0.536 \text{ P} \quad r^2 = 0.957 \quad p < 0.0427 \quad (8)$$

TABLE 2 ABOUT HERE

Fig. 6 shows periods of water deficit (above the unity line) and periods when the trees used less water than the precipitation (below the unity line). The rainfall average for this region is 1350 mm. The year 2002/2003 was very atypical with only 634 mm rain, which was clearly insufficient to supply the requirements of the trees.

Fig. 6 ABOUT HERE

4.4. *Runoff*

The average observed runoff was only 3.13% of the precipitation (Fig. 7), indicating that most of the precipitation remained in the soil and was used by the trees or evaporated. Most of runoff comes from intensive rains when the soil is saturated. The highest precipitation event of 281 mm in three hours produced 36 mm of runoff. No significative increase in runoff was observed after harvesting in the previous eucalypt plantation in 1996.

Fig. 7 ABOUT HERE

4.5. *Water table level*

There was some small variation between estimation and observed annual upward flux (Table 2) due the lag between the soil water flux and the direct response of the water table; however analysis of the entire rotation indicates very good agreement between the variation of the water table level and the estimates of upward flux. Observed and predicted annual runoff were compared and showed an average difference of 27 mm across the 6 years of the study.

TABLE 3 ABOUT HERE

There were marked variations in the water table level that were clearly associated with the stage of tree growth and the position of the piezometers in the catchment (see Fig.1). After harvest in 1996 the water table level in piezometer *a* was 24 m above sea level – equivalent to 26 m below the soil surface. During the growth cycle of the trees, the water table level first increased by about 10 m then declined from 0.1 m yr⁻¹ to 1.29 m yr⁻¹ in the subsequent years (from 1998 to 2004).

Thinning appeared to lower or at least reduce the variation of the water table level. In 2004 the whole catchment was harvested. Obviously all the area with native forest remained intact. After harvest in 2004 (except for the block with piezometers *a* (thinned) and *c*) the water table level remained more stable. Piezometers *b* and *d* showed lowering of the water table from 4.13 m and 2.44 m from October 1999 to October 2004. Piezometer *a*, indicated that, despite

the reduction in water table level during the rotation, the final level in 2004 was 7.05 m higher than the level at the end of the previous rotation (Fig 8 and Table 4).

Fig. 8 ABOUT HERE

Table 4 ABOUT HERE

4.6. *Forest growth and water use efficiency*

Despite the increase in precipitation in 2002, CAI remained the same as in the previous year, but was directly affected by the dry year in 2003 (Fig. 9). There was a good agreement between observed CAI and that predicted by the 3-PG model.

The values obtained of WUE are consistent with other studies (Pereira *et al.*, 1986; Landsberg, 1999a). The normalised WUE for the annual effects of VPD, explains part of the variation in WUE for the first three years but not for the last two years of the study.

There was a significant reduction of WUE when the trees become older (Fig. 9a and Table 5). The most significant example was associated with the high precipitation that occurred in the year 2002, when growth was relatively low. Tree growth was strongly affected by the drought that occurred in 2003. A comparison between WUE calculated using the UAPE model and the 3-PG model, including VPD effects (Landsberg, 1999a), indicates that the 3-PG estimations are consistently higher than UAPE, particularly during the last two years when the growth reduction occurred (Table 5). Fig. 9b indicates that the LAI (represented as average annual) has a direct influence in WUE.

Fig. 9 ABOUT HERE

TABLE 5 ABOUT HERE

Analysis of monthly forest growth data demonstrated that there was good agreement between monthly stem volume estimated by 3-PG and the data from permanent sample plots obtained during the rotation, except during the last year (Fig. 10).

Fig. 10 ABOUT HERE

Discussion

The reduction in LAI with age in fast growing eucalypt plantations was observed in most of the planted area of the MBE and in other regions and had been reported in other studies (Watson *et al.*, 1999; Xavier *et al.*, 2002). This decline of LAI explains, in part, the reduced water use by the trees (Watson *et al.*, 1999) at the end of the rotation compared with that of 3-4-year-old trees. Knowledge of LAI values helps to set realistic limits on the hydrological fluxes (Waring & Running, 1998) that can be simulated by models such as UAPE or 3-PG. The 3-PG model reproduced very well the variation of LAI during the rotation, including effects of seasonality, except for the last year when LAI was underestimated. In view of the importance of LAI in the process of growth and water use, the causes of its decline require further study (Ryan *et al.*, 2004).

The estimates of water use made by UAPE and 3-PG models were slightly different. One of the reasons is that 3-PG runs with a monthly time interval and UAPE with a daily interval. The differences is accentuates when rainfall was irregular, or concentrated over short periods, or when there was rapid reduction of soil moisture, as happened during the summer months when temperatures and vapor pressure deficits were high, and there were several weeks without rainfall (Almeida *et al.*, 2004a). The UAPE model explained 82% of water use by the trees and reproduced very well the reduction of soil moisture that occurred from the wet to the dry season. The poorer prediction of water use by 3-PG (Fig. 4b) was mainly at the end of the rotation when the LAI is low: The rates of water use calculated by the model were lower than those estimated by UAPE and 3-PG therefore tended to underestimate water use in part because 3-PG also underestimated LAI during this period.

The study region is subject to high rainfall variation compared with average historical precipitation. In the six years studied, four had rainfall below and two above the annual average. Evapotranspiration was higher than precipitation in three years but average evapotranspiration over the full rotation was 95% of the water input to the catchment. This indicates a balance between input and output but also suggests that a catchment covered with trees of the some age is likely to be more susceptible to variations in precipitation since tree

water –use varies with stand age. The average transpiration estimated by the UAPE model was 953 mm which is comparable with *Eucalyptus grandis* references (Dye, 1987; Whitehead & Beadle, 2004). Annual average evapotranspiration was 1092 mm and average precipitation was 1147 mm. Annual evapotranspiration varied from 781 mm to 1334 mm during the study and was strongly influenced by variations in annual precipitation and leaf area index.

Measurements and modelling of runoff show that the study area is very conservative in terms of water in the catchment, with very low runoff during the rotation. This is attributable to the local characteristics of soil and topography: as much as 98.9% of the rainfall infiltrated the soil. The low runoff is advantageous from the point of view of soil conservation and water distribution because catchments retain most of the precipitation: soil degradation by erosion should also be low (Martins, 2005).

Between June 1999 and April 2004 an average reduction in water table depth of up to 3.2 m was observed. A maximum reduction of 6.4 m occurred in piezometer *c*, which can be equated to 192 mm of water in the soil profile (Soares & Almeida, 2001). A comparison between the height of the water table when the trees were planted and at the end of rotation (line *a* in Fig. 8) indicated that there was an increase of 7.0 m in the depth of the water table during the full rotation. Analysing the data from individual piezometers in relation to silvicultural management suggests that the block thinned to about 500 trees ha⁻¹ had less effect on the water table level than the unthinned blocks. The block with piezometer *c* was maintained without harvest but became stable after the clear cutting from the other blocks after April 2004. This is a good indication of a possible useful forest management practice on a catchment scale: one can speculate that the maintenance of trees of at least two different ages distributed in the catchment will result in reduced variation in water table levels.

Several studies have demonstrated that growth of *Eucalyptus grandis* plantations in Brazil (Stape *et al.*, 2004; Almeida *et al.*, 2004b), and in other places such as South Africa (Dye, 1996) is strongly affected by climate. Rainfall distribution affects the availability of soil water and vapor pressure deficit may restrict growth through its effects on stomata. These effects can be identified by analysing plantation growth in terms of CAI and MAI for different years and regions using 3-PG (Almeida & Landsberg, 2003; Almeida, 2003). The WUE varied drastically during the rotation going from maximum of 4.2 gDM kg⁻¹ to a minimum of 0.8

gDM kg⁻¹ estimated by UAPE and 4.2 gDM kg⁻¹ to 1.9 gDM kg⁻¹ estimated by 3-PG to suggest that stands receiving water close to historical average rainfall, and with LAI around 3.0 – 3.5, convert water to biomass more efficiently.

The results obtained from six years of study and modelling allow us to answer important questions regarding fast growing eucalypt plantations in Brazil and establish further research requirements. The questions posed at the beginning of this paper were:

- How much water do *E. grandis* hybrids use during the rotation cycle?

Transpiration by the trees was the main component of water use. The maximum annual transpiration ($> 1000 \text{ mm yr}^{-1}$) was observed when the plantations were 33- to 44-months old (year 1999 – 2000) and 57- to 68-months (year 2001 – 2002) when the rainfall was 1272 and 1507 mm respectively. The historical average annual rainfall based on 37 years of daily data is 1350 mm, which appears to be sufficient to meet the plantation demand for water in this environment. Inter-annual variations in precipitation and LAI were the main determinants of water use. It has been shown previously in this plantations that the trees exert strong stomatal control (Mielke *et al.*, 1999) and are very dependent on distribution of precipitation for high growth rates. During the dry season an upward flux of water in the soil was observed, which provided enough water for the trees to avoid total stomatal closure and maintain transpiration at lower rates (Soares & Almeida, 2001).

The reduction in LAI towards the end of the rotation tends to affect water use (Soares & Almeida, 2001). This is most clearly illustrated by comparing evapotranspiration in the years 1999/2000 and 2003/2004 (see Table 2), when it was 1247 mm and 1119 mm, respectively, despite the fact that there was 13% more precipitation in the 2003/2004 season than in 1999/2000. Soil evaporation and rainfall interception also depend on LAI and rainfall intensity and duration. Our measurements show maximum interception of 168 mm per year when the LAI was between 3.5 and 4.0 m² m⁻², which coincides with lower soil evaporation. Plantations older than five years tend to reduce their water use mainly as result of the reduction of leaf area.

- How does the precipitation affect forest growth?

Several studies (Myers *et al.*, 1996; Calder, 1998; Landsberg, 1999a; Dye, 2000; Almeida & Landsberg, 2003; Almeida, 2003) demonstrate that total precipitation and its distribution during the year have a strong influence on forest growth. In this study, growth was positively influenced by the high precipitation in 2000 and strongly negatively affected by the low precipitation in 2003. However, high precipitation during 2002 did not lead to increased growth rates. Thus something other than water availability affected tree growth in the later stages of the rotation. The strongest overall relationship was clearly between CAI and LAI (Fig. 10a and Fig. 10b), but more detailed investigation is required to determine whether this is a direct causal relationship. Interpretation appears to be straightforward because lower LAI later in the rotation results in less radiation interception and less dry matter production, but the question is ‘what causes the reduction in LAI when growth conditions appear to be good?’ Ryan *et al.* (2004) have identified this late rotation decline in growth rate as an important problem. Other studies show that in some cases vapor pressure deficit can exert stronger effects on forest growth than precipitation, but VPD is normally less variable than precipitation between years in this environment (Almeida, 2003).

- How does soil moisture vary in the soil profile? How does it respond to root distribution?

Trees used water preferentially from the top metre of soil. This is attributable to fine roots being concentrated mainly in the first 60 cm of soil. The development of larger roots in deeper layers has more influence from 6 years of age (Almeida, 2003). More detailed study of fine root length and water use is required to obtain more definitive answers to this question, but the soil moisture profiles presented here indicate that much of the variation in soil moisture under this short rotation forest is related to seasonal variation in water availability rather than to stand age.

- Are variations in water table levels consistent with the water balance during the rotation cycle?

The estimations of water table variation produced by UAPE model are consistent with the observed data (see Table 2). The results show a strong influence of the forest management stand age and rainfall distribution on water table level.

- Is the runoff consistent with the water balance? Does the runoff vary in the forest age and canopy cover?

A direct comparison between observed runoff measured in the weir and the runoff estimated by UAPE was not possible since the model treats deep drainage as runoff. This means that the runoff estimated by the model tends to be higher than observed; however the analysis presented in Table 5 indicates that the average runoff and upward flux are very similar. Logically runoff would be expected to be a function of rainfall intensity (see Fig. 7), however plantation age did have clear effects as well.

Is forest growth correlated with the water use?

Eucalypt plantations in Brazil have the highest growth rates recorded for woody vegetation (Whitehead & Beadle, 2004). The growth observed in this experimental catchment was affected by stand age, which affected LAI, and available water.

Conclusions

The results obtained in this study show that *Eucalyptus grandis* hybrids in Brazil are on average, using water according to its availability. Modelled estimates give good agreement with observed data for all components of the hydrological cycle. Total evapotranspiration over the six years of the study was lower than the rainfall, with a ratio of 0.95. Overall effects on water table depth do not appear to be serious. Forest growth is affected by water availability, particularly by drought, but climatic effects on growth are confounded with the decline in LAI and growth in the later stages of the rotation, characteristic of these plantations. Long-term ecophysiological and hydrological studies at catchment scales appear to be the best way to continuously improve forest management techniques and optimise the use of water and to increase forest productivity.

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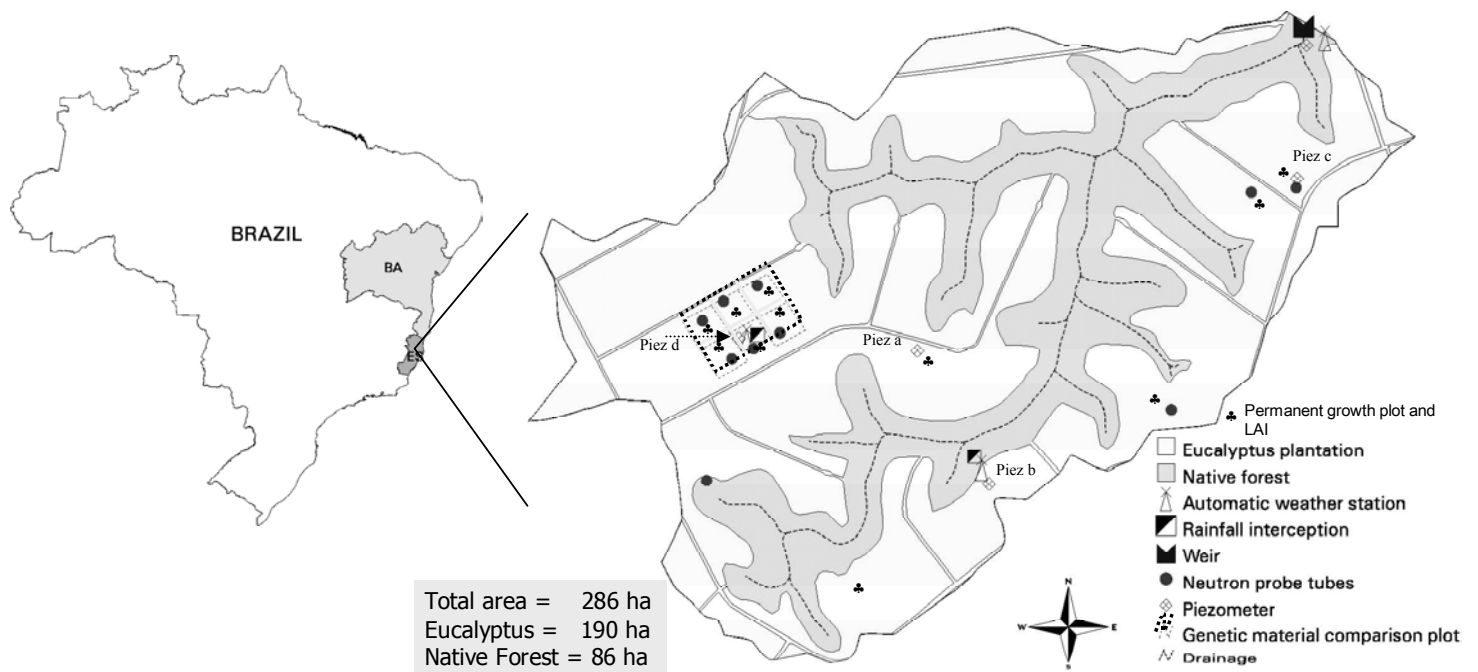


Fig. 1.

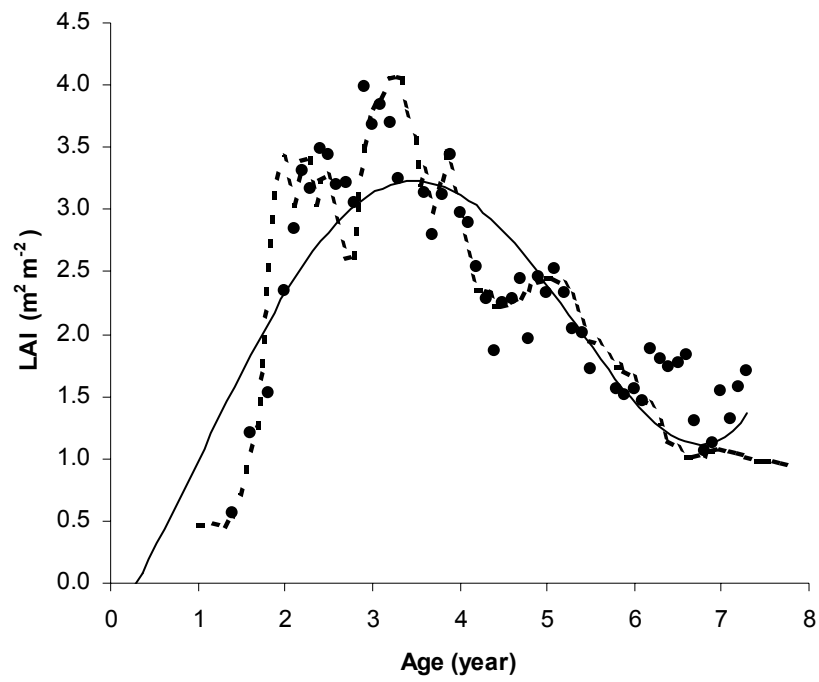


Fig. 2

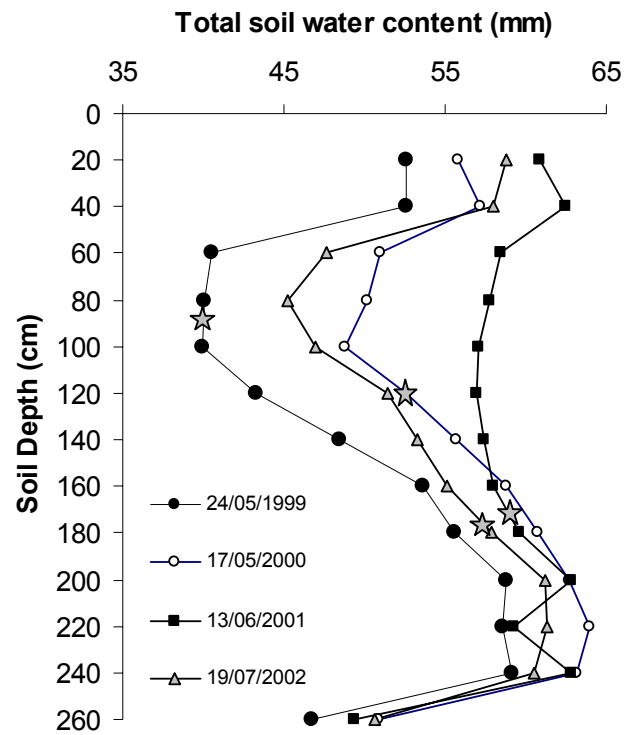


Fig 3

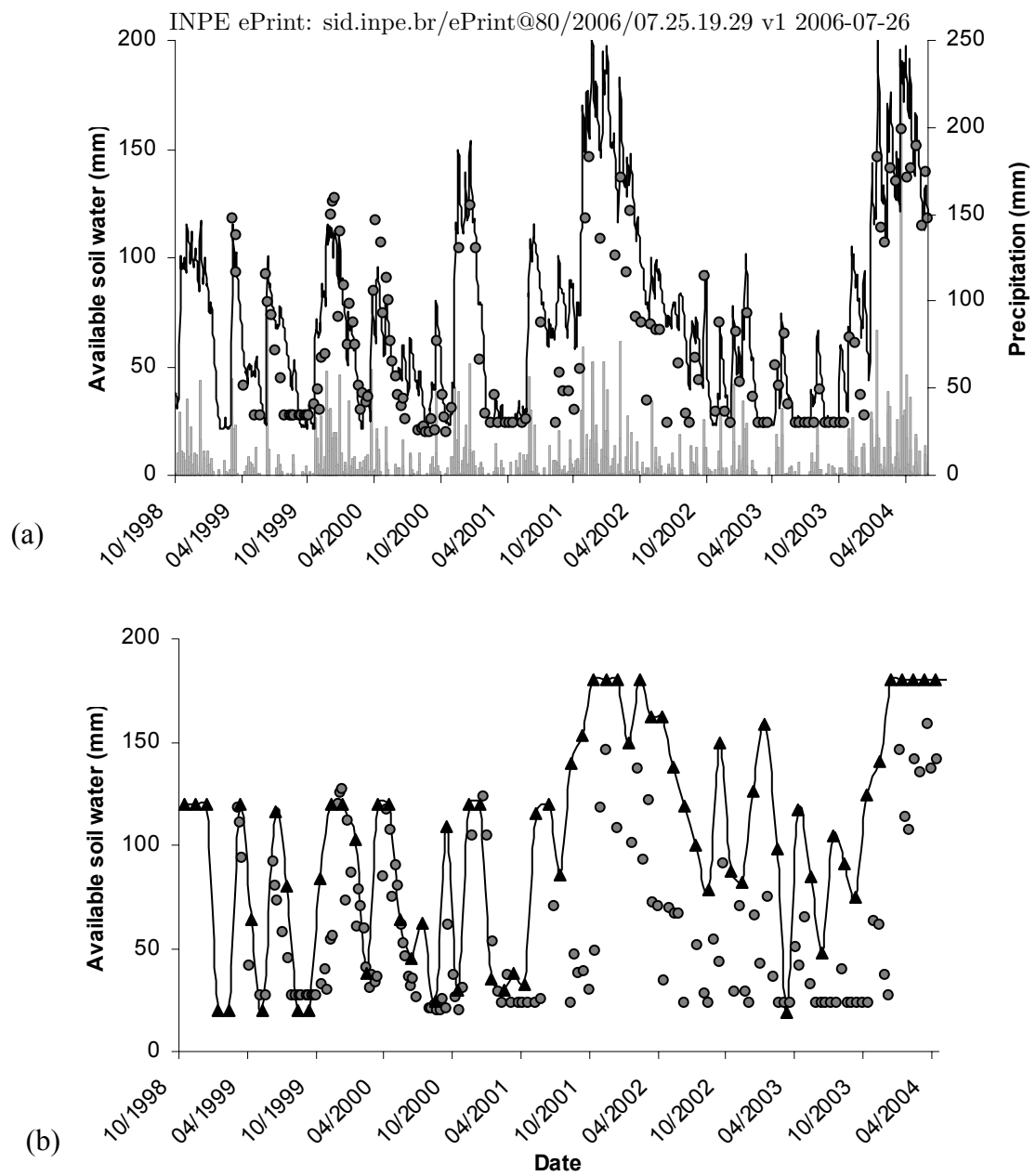


Fig. 4

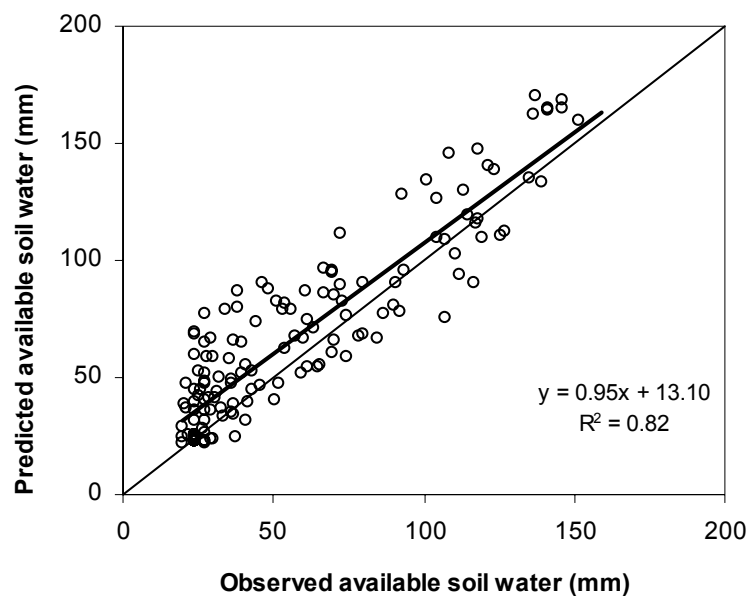


Fig. 5

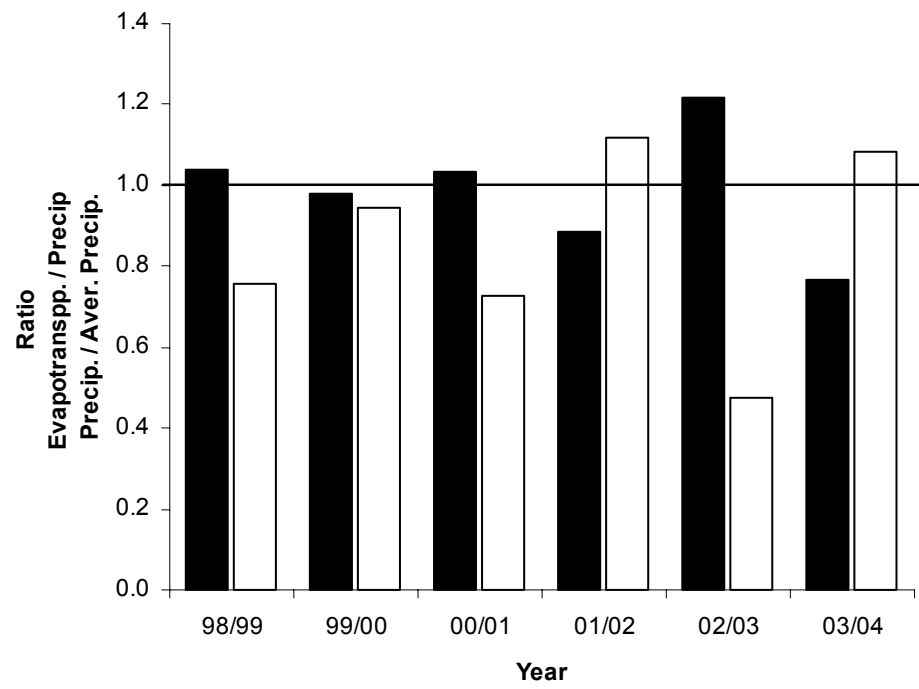


Fig. 6

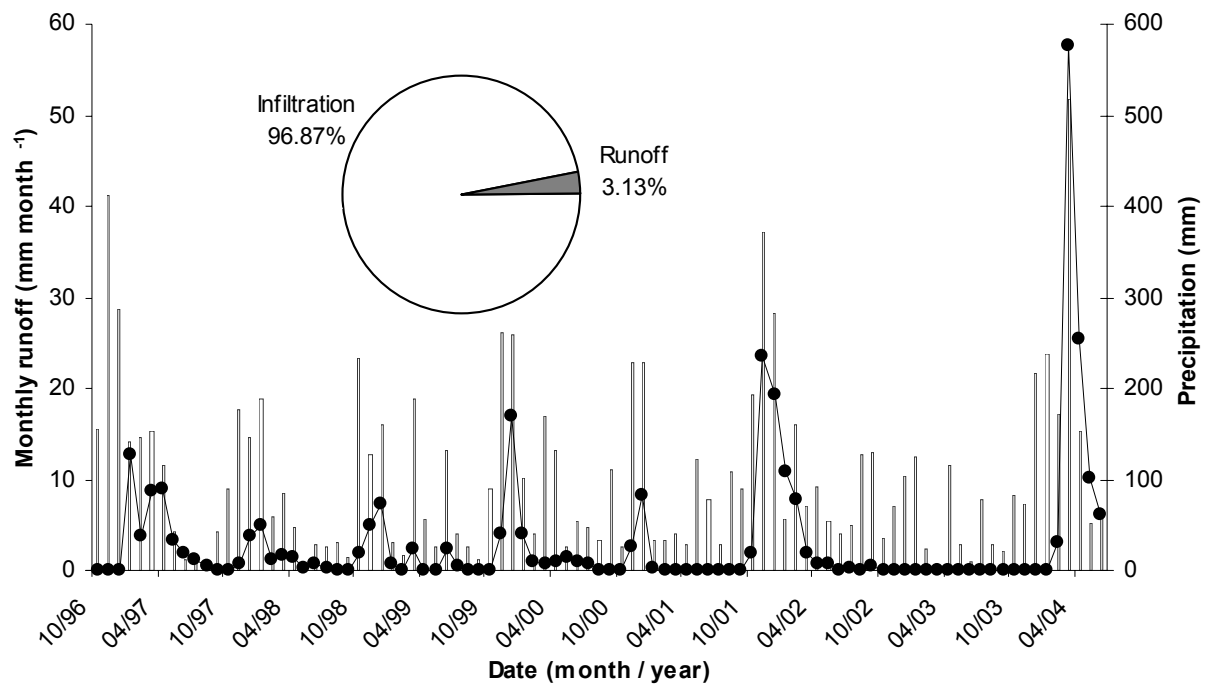


Fig. 7

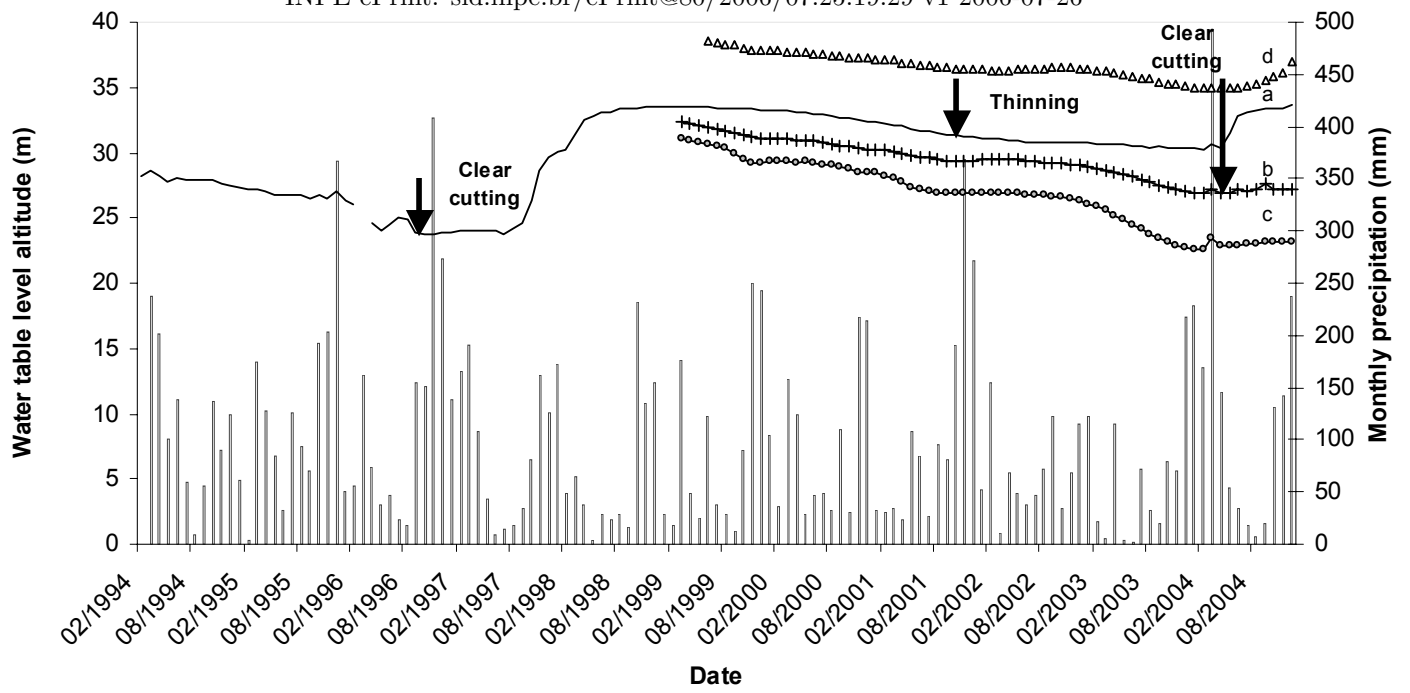


Fig. 8

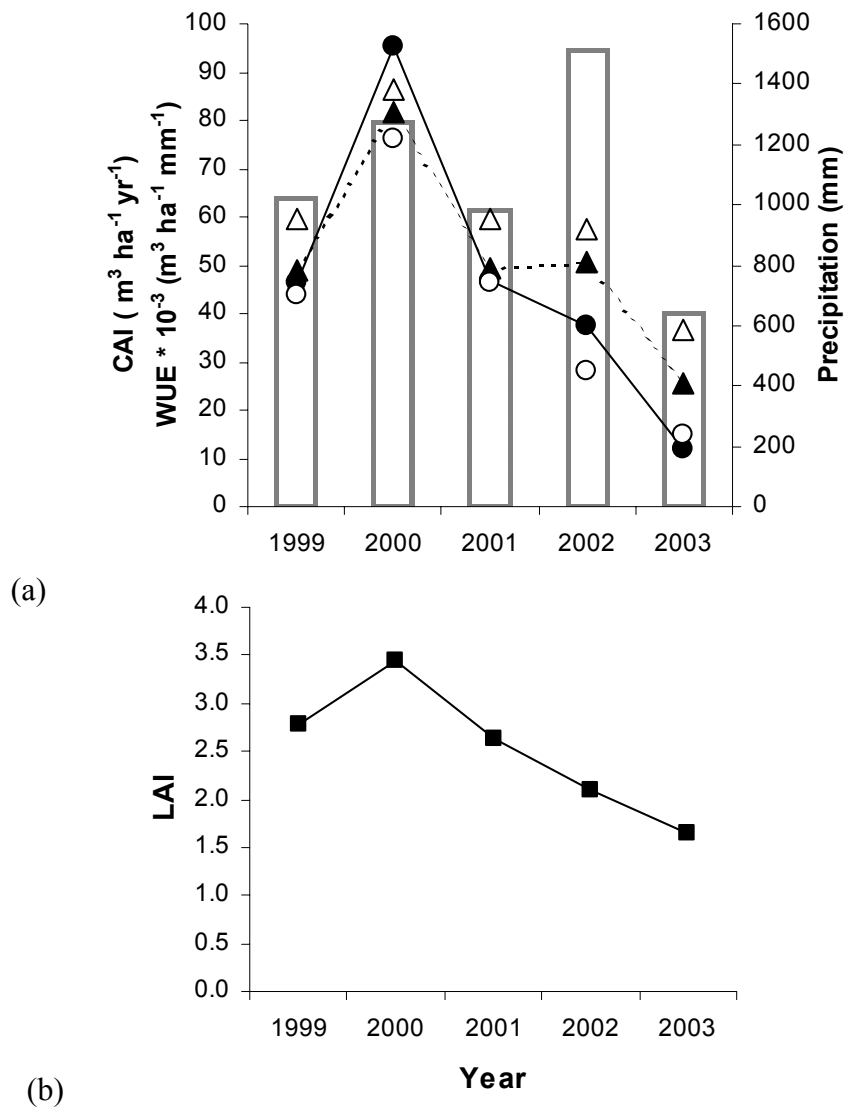


Fig. 9

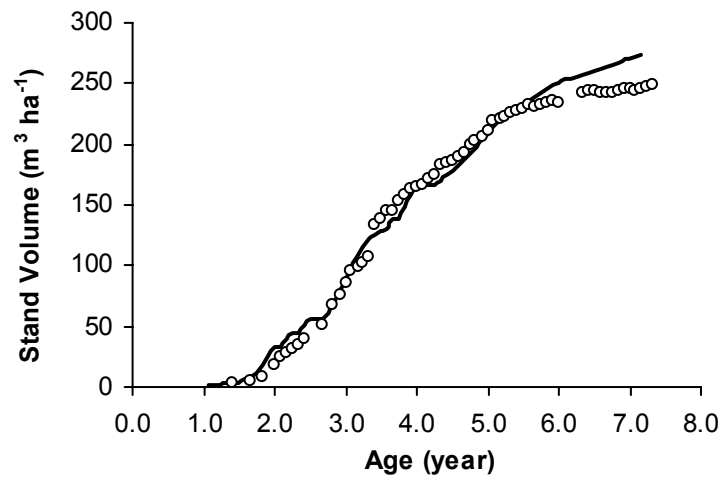


Fig. 10

Table 1.

Variable	Unit		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (R)	mm	Max	229	170	495	144	108	122	97	95	153	232	408	274
		Min	28	18	5	23	3	8	15	18	12	31	68	112
		Average	104	78	151	83	42	49	43	39	63	113	202	206
		SD	71	66	146	42	29	36	27	26	54	69	121	61
Mean Temperature (T)	°C	Max	31.4	32.6	31.7	30.1	27.8	28.2	26.3	27.5	28.1	28.9	29.9	30.1
		Min	22.1	22.0	21.3	21.0	18.9	18.3	17.9	17.4	18.7	18.8	19.6	21.7
		Average	25.5	25.9	25.4	24.4	22.6	21.7	21.1	21.2	21.9	22.9	23.7	25.0
		SD	0.7	0.8	0.9	0.7	0.6	0.6	0.5	0.8	0.7	0.8	1.0	0.5
Global Radiat. (ϕ_s)	MJ m ⁻² day ⁻¹	Max	24.4	25.1	22.1	17.6	15.3	15.4	14.5	18.9	20.5	21.6	20.5	22.6
		Min	17.7	16.5	16.4	15.7	13.2	12.3	12.3	13.6	13.6	13.8	13.3	17.2
		Average	21.0	21.6	19.6	16.7	14.4	13.5	13.4	15.8	15.5	17.2	17.1	20.0
		SD	2.1	2.7	1.6	0.6	0.7	1.0	0.8	1.7	2.3	2.5	2.6	1.5
Daylight VPD	kPa	Max	1.00	1.25	1.38	1.03	0.97	1.15	0.91	0.97	1.18	1.14	1.13	1.09
		Min	0.48	0.53	0.48	0.46	0.52	0.41	0.40	0.39	0.34	0.36	0.34	0.41
		Average	0.73	0.88	0.79	0.73	0.74	0.67	0.63	0.75	0.70	0.77	0.67	0.73
		SD	0.18	0.27	0.27	0.18	0.16	0.24	0.18	0.18	0.24	0.26	0.34	0.25

Table 2.

Hydrological year balance factor	98/99	99/00	00/01	01/02	02/03	03/04	Average
Precipitation (mm)	1020	1272	979	1507	643	1461	1147
Runoff (mm)	30	62	17	128	0	155	65
Interception (mm)	117	168	134	135	77	97	121
Soil evaporation (mm)	89	70	71	107	69	106	85
Transpiration (mm)	851	1009	806	1092	635	916	885
Upward Flux (mm)	-50	-61	-101	-13	-114	121	-36
Stock variation (mm)	-22	18	42	52	-33	60	20
Evapotranspiration (mm)	1058	1247	1012	1334	781	1119	1092
Evapotransp./Precipitation rate (mm)	1.04	0.98	1.03	0.89	1.21	0.77	0.95

Table 3

	Hydrological year						Total	Average
	98/99	99/00	00/01	01/02	02/03	03/04		
Observed runoff (mm)	20	31	11	67	0	106	236	39
Predicted runoff (mm)	30	62	17	128	0	158	396	66
Runoff difference (mm)	-10	-32	-6	-61	0	-52	-161	-27
Observed upward flux (mm)	-48	-24	-57	-8	-104	0	-240	-40
Predicted upward flux (mm)	-50	-61	-101	-13	-114	60	-279	-46
Upward flux difference (mm)	2	38	44	4	10	-60	38	6

Table 4

Period	Piezometer identification			
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
	Water table level variation (m)			
10/97 - 10/98	7.10			
10/98 - 10/99	-0.10			
10/99 - 10/00	-0.73	-0.80	-0.78	-0.63
10/00 - 10/01	-1.29	-1.14	-1.90	-0.98
10/01 - 10/02	-0.50 ^T	-0.19	-0.27	0.15
10/02 - 10/03	-0.38	-1.83	-3.47	-1.19
10/03 - 10/04	2.96	-0.17 ^{CC}	0.00	0.21 ^{CC}
Total 10/99 - 10/04	0.05	-4.13	-6.42	-2.44
Total 10/97 - 10/04	7.05	-	-	-

Table 5

Year	Stem biomass production (kg ha⁻¹)	Water use efficiency UAPE (gDM kg⁻¹)	Water use efficiency 3-PG (gDM kg⁻¹)	VPD (kPa)	WUE (UAPE)*VPD (gDM kg⁻¹ kPa⁻¹)	WUE (3-PG)*VPD (gDM kg⁻¹ kPa⁻¹)
98/99	25,551	2.4	2.8	0.67	1.6	1.9
99/00	52,311	4.2	4.2	0.49	2.1	2.0
00/01	25,789	2.5	3.2	0.61	1.6	2.0
01/02	20,707	1.6	3.0	0.52	0.8	1.5
02/03	6,454	0.8	1.9	1.03	0.8	1.9

Fig. 1 Map showing location of the study area and detail of the experimental catchment.

Fig. 2 Observed leaf area index (filled circles) in the experimental catchment during the entire rotation and predicted leaf area index by 3-PG model (dashed line). The solid line is the representation of equation (7).

Fig. 3 Variation of soil moisture with soil depth on four representative days as measured using a neutron probe. The small grey stars in each line represent the root depth at respective dates.

Fig. 4 a-Variation in available soil water measured (dots) and predicted with the UAPE model during the stand rotation. Daily precipitation (bars) is shown in the right axis.
b- Variation in available soil water measured (dots) and predicted with the 3-PG model during the stand rotation (triangles).

Fig. 5 Comparison between available soil water observed and predicted by UAPE model.

Fig. 6 Ratio of annual evapotranspiration / precipitation (black bars) and annual precipitation /average annual precipitation (white bars). Bars below the unit line represent less water use than precipitation and the occurred annual precipitation was lower than annual average precipitation respectively.

Fig. 7 Monthly runoff and precipitation from 1996 to 2004

Fig. 8 Water table level variation from 1994 to 2004 in three piezometers located in the catchment. Piezometer *a* is located in a block harvested in 1996, planted in 1997 and thinned at end of 2001. Piezometer *b* and *d* are located in block planted in 1997 and harvested in 2004 and the area of piezometer *c* was planted in 1997 and was kept without harvested.

Fig 9 a- Current annual increment (CAI) ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$) observed during the hydrological year (October – September) (solid line and filled circles), CAI predicted by 3-PG model (dashed line and filled triangles), WUE calculated using observed growth data and evapotranspiration predicted by UAPE model (open circles) and WUE calculated by

3-PG model (open triangles). The right axes show respective annual (October - September) precipitation.

b- Annual average observed leaf area index

Fig 10 Stem volume predicted by 3-PG model and observed from permanent sample plots.

Table 1. Meteorological data from the Microbacia weather station during the period 1996 to 2004. Monthly average, maximum, minimum and standard deviation of precipitation (R) mean temperature (T), global radiation (ϕ_s), and daylight vapor pressure deficit (D).

Table 2. Results of water balance by hydrological year estimated by UAPE model.

Table 3 Annually water runoff and upward flux observed in the weir and in the piezometer respectively and estimated by UAPE model. The upward flux observed was calculated based on water table level variation. The year 03 / 04 refer to the period Oct 2003 to May 2004 since the plantation was harvested from June 2004.

Table 4 Annual water table level variations in four piezometers. The plantation stand in the block of piezometer a was thinned at the end of 2001 (T) and the blocks where piezometers b and d were harvested in the middle of 2004 (CC).

Table 5 Annual (from October to September) stem biomass increment, water use efficiency (WUE) calculated using stem growth from permanent sample plot and evapotranspiration estimated by UAPE model and WUE predicted by 3-PG model. WUE- UAPE and WUE- 3-PG normalised by average annual daylight VPD.

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