Water budget model of Eucalyptus Forest using a canopy characterization by Remote Sensing techniques and a soil water flux parameterization

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ABSTRACT

This paper deals with the development of a water budget model for Eucalyptus forest, using a conceptually simple one-dimensional mass balance approach within the root zone of the forest. The model uses Leaf Area Index to quantify the forest structure important for mass and energy exchange, and this represents a key simplification for regional scale applications. Remote Sensing vegetation indexes and mixture modeling techniques were used to estimate LAI. A five-layered water balance model, with water movement between layers along hydraulic gradients, was developed and parameterized for a eucalypt plantation (*Eucalyptus grandis* Hill ex.Maiden hybrids) in Brazil. Available soil water controls stomatal conductance and hence transpiration, which is calculated by the Penman-Monteith equation. The remote sensing derived LAI was used to compute the canopy conductance that drives the Penman-Monteith formulation. The model accounts for changes in the depths of the water table. The test period was from October 1995 to September 1996 in a nine-year-old plantation in an experimental catchment in eastern Brazil. Total transpiration for the year was 1116 mm, with 119 mm intercepted and re-evaporated and another 79 mm soil surface evaporation, giving evapotranspiration of 1314 mm compared to rainfall of 1396 mm. The water balance was closed by net flow below the root zone of about 53 mm and an increase in water storage (in the first layer) of 29 mm. The model also estimated a water deficit of 135 mm (difference between the potential and current transpiration) for the period. Upward flux from the water table was around 81 mm and piezometric measurements showed 1.5 m recession for the same period. The upward flux into the root zone was about 1 mm day^{-1} at the end of a long dry season; that kept the water storage in that zone to about 15% of capacity and helped prevent complete stomatal closure.

Comparison between estimated water storage and measurements confirmed that this model is a very promising tool for calculating water use by plantations. It can also provide water balance information and information about stomatal conductance for growth prediction models.

Keywords: water budget, remote sensing, soil water flux, eucalypt

1. INTRODUCTION

Leaf Area Index (LAI) is considered to be the most important single descriptor of the vegetation structure at regional scale, as it defines the exchanges of heat and mass at the interface with the atmosphere [9,10]. Consequently, it is a key parameter to models used in calculations of Net Primary Production and evapotranspiration processes [10]. Remotely sensed derived data associated with the canopy reflectance and structure, that can be obtained in a suitable timing and with good accuracy, have been used as inputs (state variables) into vegetation-soil-atmosphere models developed to work at regional scales [10,11]. There have been considerable efforts on estimating biophysical properties from vegetation indexes, such as the Normalized Difference Vegetation Index [11], NDVI and the Soil Adjusted Vegetation Index [4], SAVI. More recently, there have been attempts to use variables derived from spectral mixture analysis ("endmembers") known as fraction of vegetation, F_{GV}, fraction of shadow, F_{SH}, and fraction of soil, F_S [12,13].

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The first goal of this study was to verify the suitability of the vegetation indexes and the mixture models "endmembers" to estimate LAI of Eucalypt (hybrids of E. *grandis*).

The second goal is to compute the water balance for the Eucalypt plantation using the Penman-Monteith formulation to estimate transpiration, which is the main output of water from the system, using a closed catchment basin of 287 ha, instrumented with the best hydrological measurements system available, inside the regional farm. A soil water flux sub model was implemented to account for water movement within the aeration zone, which is important to explain why the soil layer beneath the root zone contribute moisture to the transpiration process. The model uses LAI to compute the canopy conductance, a critical variable in the estimation of transpiration.

2. THEORETICAL FUNDAMENTS

2.1. Vegetation index

The Normalized Difference Vegetation Index, NDVI, is given by:

$$\mathrm{NDVI} = \frac{(\rho_4 - \rho_3)}{(\rho_4 + \rho_3)} \qquad (1)$$

where ρ4 is the reflectance in the near-infrared band (TM4) and ρ3 is the reflectance in the visible red band (TM3). Under conditions of variation in reflectance due to soil surface humidity, soil organic matter, and shadows, the Vegetation Index can be affected [4,5,8]. The Soil Adjusted Vegetation Index[4], SAVI, takes into consideration the soil influence as shown in equation [3]

$$\mathrm{SAVI} = \left[\frac{(\rho_{I4} - \rho_3)}{(\rho_4 + \rho_3 + L)}\right] \cdot (1 + L) \qquad (2)$$

where L is a correction factor for the soil effect, varying from 0.25 to 0.75.

2.2. Spectral mixture fractions

The radiance from every single pixel can be assumed to come from its different elements, as a linear combination of these components. Typically, the pure components (named "endmember") in a forested area are green vegetation, shadow and soil[12]. One can use the following model to account for the reflectance from a pixel in a particular spectral band:

$$r_i = \sum_{j=1}^{n} (a_{ij} . x_j) + e_i , \qquad (3)$$

where
ri = reflectance of a "pixel", in the ith spectral band;
aij = reflectance of the jth endmember of a pixel, in the ith spectral band;
xj = fraction of the jth endmember of a pixel,
ei = residual in the ith spectral band

One can estimate the fractions of each endmember in a pixel by many methods ,the most popular being the least squares estimation, constrained and unconstrained solutions[13].

The vegetation indexes were correlated with light attenuation based measurements (LAI 2000), carried out over stands of ages ranging from 12 months to 84 months old. The use of these techniques for estimating Eucalypt LAI have been demonstrated by [6].

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2.3. Water balance in the root zone

Soil water content in the tree root zone on day i is the water content of the previous day (θi-1), plus net input (precipitation, P – interception, I) minus outgoing water (transpiration, Et, + soil evaporation, Es, + net runoff, Q_{net}). For a given period of time, net runoff is the difference between deep drainage below the root layer and upward flux into the same layer:

$$\Delta\theta = \theta_i - \theta_{i-1} = (P - I) - (E_t + E_s + Q_{net}) \qquad (4)$$

Where E_s is soil evaporation and Q_{net} is net runoff. The water content of any given layer (θ, mm) is given by the volumetric water content (θ_v, cm^3/cm^3) x thickness of the layer, *Z* (in mm):

$$\theta = \theta_v \times Z \qquad (5)$$

Soil evaporation, E_s, is estimated using the Penman-Monteith approach with the soil resistance increasing rapidly as water availability drops from its maximum value, following [2,15]. The attenuation of radiation by the canopy, given by the Beer-Lambert law, is used to estimate the available radiation at the soil level. Since little radiation reaches the soil when LAI is greater than 2.5, estimated soil evaporation is frequently less than 10% of transpiration. Estimation errors on Es are not a problem. The model was implemented with the following equation for estimating the soil conductance, g_s (m s-1):

$$g_s = 0.0025.\frac{\theta}{\theta_{max}} \qquad (6)$$

Daily transpiration is estimated using the Penman-Monteith formulation [9,10], as follows:

$$E_t = \frac{1}{L}\cdot\left[\frac{\Delta R_n + \rho_a c_p g_a D}{(\Delta+\gamma)(1+g_a/g_c)}\right]\cdot t \qquad (7)$$

Where E_t is canopy transpiration (mm day^{-1}), 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}), *D* is vapor pressure deficit from canopy to air (mbar), g_a is canopy aerodynamic conductance (ms^{-1}), considered to be constant at 0.08 ms^{-1} (no need for wind speed), g_c is canopy conductance to water vapor (ms^{-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 $g_c = g_s \cdot LAI$, where g_s is the stomata conductance (converted into ms^{-1} units) and *LAI* is Leaf Area Index (m^2m^{-2}). The canopy conductance is a critical variable in the computation of E_t, and it depends on LAI, which can be depicted by remote sensing techniques.

With field experimental data, we have developed functional relationships between pre-dawn leaf water potential, Ψ_l, and soil water availability (equation 8). Then, another relationship between maximum canopy conductance and Ψ_l was implemented (equation 9), along with a linear correction for g_c as a function of water vapor deficit (equation 10).

$$\Psi_l = 0.33\cdot\left(\frac{\theta}{\theta_{max}}\right)^{-0.57} \qquad (8)$$

$$g_s = g_{s\,max} - m_w(\Psi_l - \Psi_{l\,min}) \qquad (9)$$

with Ψ_{lmin} being the leaf water potential inducing stomata closure (around –2.0 MPa), and m_w the slope.

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$$g_{cD} = g_c + \left[\frac{f_{gc} \cdot g_c - g_c}{3}\right] \cdot D \quad (10)$$

with f_{gc} equals the fraction of g_s for D=3 *KPa*. The term within square brackets gives the slope of g_c vs. D. Then, g_{cD} is the daily average conductance, corrected for both soil water storage and vapor pressure deficit, to be used in equation (7).

The aeration zone of the soil is divided into 5 layers: 1) the root zone, 2) a layer having the same thickness and functioning as a secondary storage to the roots, 3) a layer that goes down to where the texture changes from clayey to sandy, 4) first in the sandy textural class and, 5) finishing at the water table. The net runoff in equation 5, takes the water flow between layers 1 and 2 into consideration. The water flux between a pair of layers is estimated using Darcy's law:

$$F = -K_S(\Psi)\frac{\Delta\Psi}{\Delta Z} \quad (11)$$

Where F is the volume flux of water through a unit cross-sectional area per unit time in the direction of the lower potential, and Z is the distance. The hydraulic pressure potential ($\Delta\Psi/\Delta Z$) is the difference between the gravitational potential, Ψg (+0.01 MPa m-1), and the matric potential, Ψm. As long as Ψg is greater than Ψm water will flow downward through the soil. When the gravitational potential is exactly balanced by the soil matric potential, water flow equals zero. Finally, under conditions of Ψm gradient (opposite direction) greater than Ψg, the water flow direction will be upward.

The non-saturated hydraulic conductivity is estimated following [1,3]. The average matric potential of each individual layer was estimated daily using soil water characteristic curves obtained from deformed soil samples representing the textural classes found in the experimental basin. When Ψm is expressed in cm of water and θ_v is cm3cm-3, the two characteristic curves representing the two textural classes found in the study site are (EMBRAPA, 1995).

$$\Psi_m = 8 \cdot 10^{27} \times \theta_v^{-16.8} \quad (12)$$

Representing the three layers in the sandy clay loam textural class (surface to 10 m deep).

$$\Psi_m = 9 \cdot 10^{20} \times \theta_v^{-14.7} \quad (13)$$

Representing the two layers in the sandy loam, from 10 m down to the water table.

Then, each of the five layers in the soil aeration zone can be represented by a pair of Ψ, $K_S(\Psi)$, obtained from [1,3], such that the fluxes between all of them can be computed at the daily time step (the same used to compute the water balance in the root zone).

3. FIELD MEASUREMENTS

A total of 130 stands were sampled for biophysical descriptors. For each stand, 25 measurements of LAI at different positioning were taken, using a pair of LAI-2000 (inside/outside the canopy) under conditions of diffuse light. The field sampling was done daily during 3 months. The stands selected for sampling were minimum size of 9 hectares, corresponding to a minimum one hundred 30 x 30 m pixels for each individual stand, for statistical robustness. A LANDSAT TM image over the sampled Eucalyptus forest was acquired during the "in situ" experiment. A more detailed description of this field campaign, can be found in [16,18].

The testing of the model was done using the hydrological year from October/1995 through Semptember/1996, the last year before the felling of the eucalypt plantation (9 years old) at the catchment. The hydrometeorological equipment and measurements at the catchment included:

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⊟Sixteen access tubes for neutron probes designed to measure soil moisture in the first 2,8 m of the soil, at vertical intervals of 20 cm. The measurements started in 1995 at a weekly frequency (sometimes every other week or once every 15 days depending on the weather).

⊟One piezometer measuring the water table since 1994. Four new tubes were installed at the beginning of 1999. The piezometers reach a depth of 55 m; soil samples were taken for texture characterization that the time of installation.

Three fully automatic weather stations, measuring precipitation (mm) above and below the canopy, air temperature (°C), relative humidity (%), global solar radiation (Wm^{-2}), net radiation (Wm^{-2}), PAR ($\mu mol\ m^{-2}\ s^{-1}$), wind speed (ms^{-1}) and wind direction.

⊟Two precipitation interception experiments for Eucalyptus and natural forest, established in 1994.

⊟A V-notch weir measuring water discharge out of the basin, built in 1996.

The data collected during intensive ecophysiology campaigns included LAI (both destructive and using a LICOR 2000 instruments), pre-dawn leaf water potential (Ψ_l), stomatal conductance, g_s, and root depth and distribution. There were intensive field measurements done on 13 sampling days[6] between November/1995 and August/1996 at the experimental catchment, including pre-dawn leaf water potential, Ψ_l, and stomata conductance, g_s.

4. RESULTS AND DISCUSSION

4.1. LAI from Remote Sensing Techniques

Among all vegetation indexes investigated to estimate regional LAI (derived for optical remote sensing), the best two were Fraction of Green Vegetation, F_{GV}, and the Soil Adjusted Vegetation Index, *SAVI*, with R^2 around 0.7, figure 1. Because SAVI is straightforward to obtain, we used it on a subset of the TM image to invert and obtain an "LAI image", shown on Figure 2. The stands show up rather clearly with well-defined boundaries, indicating homogeneity for LAI.

4.2. Water balance in the root zone

The components of the water balance of the 9 year-old Eucalyptus are shown in Table 1. Interception (re-evaporation) was 9% of precipitation, this value is in concordance with direct measurements during the study period, and soil surface evaporation was 7% of transpiration. Total evapotranspiration, was 1314 mm and the ratio evapotranspiration/precipitation was 0.94. The water balance was closed by a net flow below the root zone of about 53 mm and an increase in water storage (in the first soil layer) of 29 mm. The net flow has two components: runoff (deep drainage) of 152 mm and upward flux from layer 2 into layer 1 of 99 mm.

The model also provided an estimate of a soil water deficit (difference between potential and actual transpiration) of 135 mm for the period. This deficit was concentrated on dry months and reflects stomatal control of transpiration, induced by soil water availability. The estimated upward flux from the water table into the root zone was around 81 mm while piezometric measurements showed a 1.5 m recession for the period. A simple calculation indicates that 1 m variation of water table level represents about 55 mm loss (or gain) of water. Whether this is and accurate estimate may not be known until considerably more data are available, preferably from a whole growing cycle.

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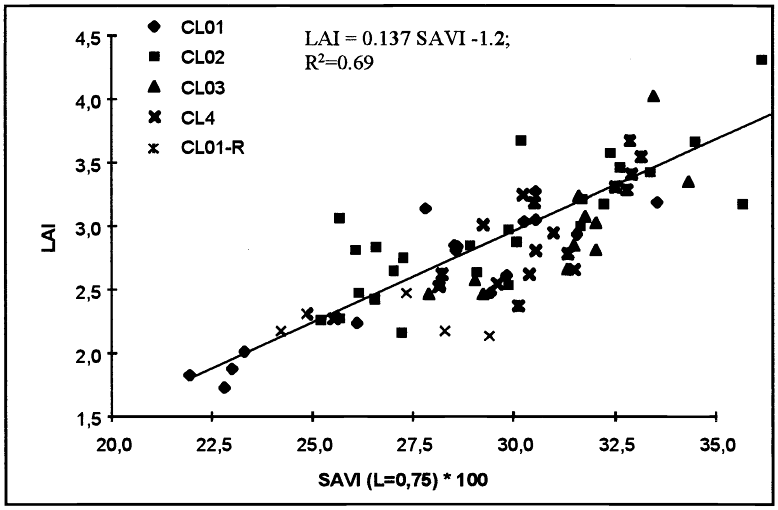

Figure 1 – Regression curve of LAI versus SAVI (L=0,75), using data from various clones (CL01, CL02, CL03, CL04 and CL01-R), altogether.

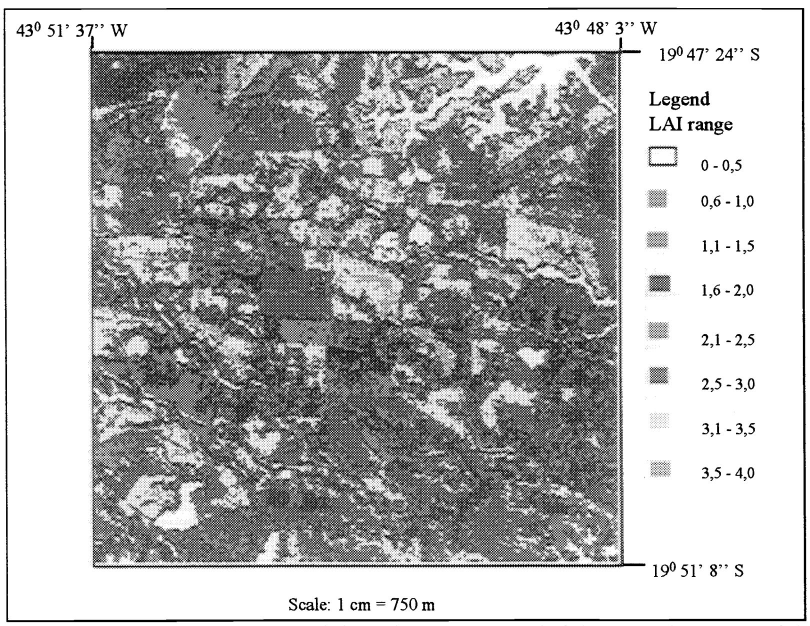

Figure 2. LAI obtained from the inversion of the relationship with SAVI on the LANDSAT TM image.

Table 1. Water balance of 9-years old eucalyptus plantation – from October 1995 to September 1996.

	Component of hidrological cycle	Value (mm)
Input	Precipitation	1396
Output	Intercepted evaporation	119
	Soil evaporation	79
	Runoff	53
	Transpiration	1116
Storage change		29

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The main test of the water balance model is the comparison between measured and modeled root zone soil moisture (Figure 3). The overall agreement (soil moisture measured weekly or every other week by neutron probes) was very good. Nearly identical rates of measured and estimated soil moisture loss during January 1996 (a dry month commencing with soil water at maximum capacity, as a result of 770 mm of rainfall during the 3 previous months) indicate that the estimation of transpiration is accurate. From April through mid September (dry fall/winter season), modeled and measured soil moisture contents match well; during the month of August the match was perfect, indicating that the soil water flux parameterization and calculations were able to account for the upward moisture flux that balances transpiration, maintaining about 30 mm of minimum available water (13% of capacity). This assessment is also supported by the fact that corresponding measured Ψl (-1.3 MPa) did not induce stomata closure [7]; and conductance remained at about 35-38 % of maximum. This corresponds to an average transpiration deficit of 2.5-3.0 (3.5-4.0 mm being the potential transpiration), a 70-75 % reduction.

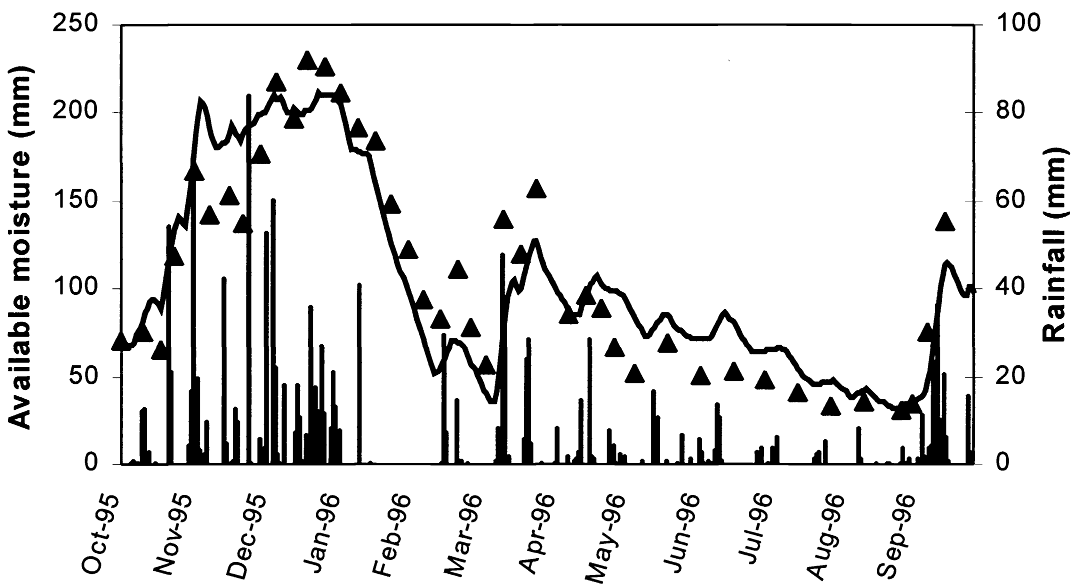

Figure 3. Estimated water storage (line) vs. measured water storage in the root zone (2.5 m) (triangles), along with precipitation (bars) for the hydrologic year October/95-September/96.

Figure 4 shows the time course of transpiration (mmday-1) for the hydrologic year October 1995 - September1996. The black line is a moving average using 7 days to filter out high frequency variation due to net radiation fluctuation. Transpiration (smoothed) ranged from 5.8 mm day-1during summer days with high soil moisture and radiant energy to 1.1 mm day-1 during winter days with low soil moisture and high VPD.

The high values for the period January through February 1996 (average 5.5 mm/day) corresponded to a drop in moisture availability of 160 mm for a 40 day period (both measured and estimated), with the gradient inversion supplying 50 mm of upward flux to the rooting zone. These results agree well with independent computation by [7], done for particular days of the intensive field measurements.

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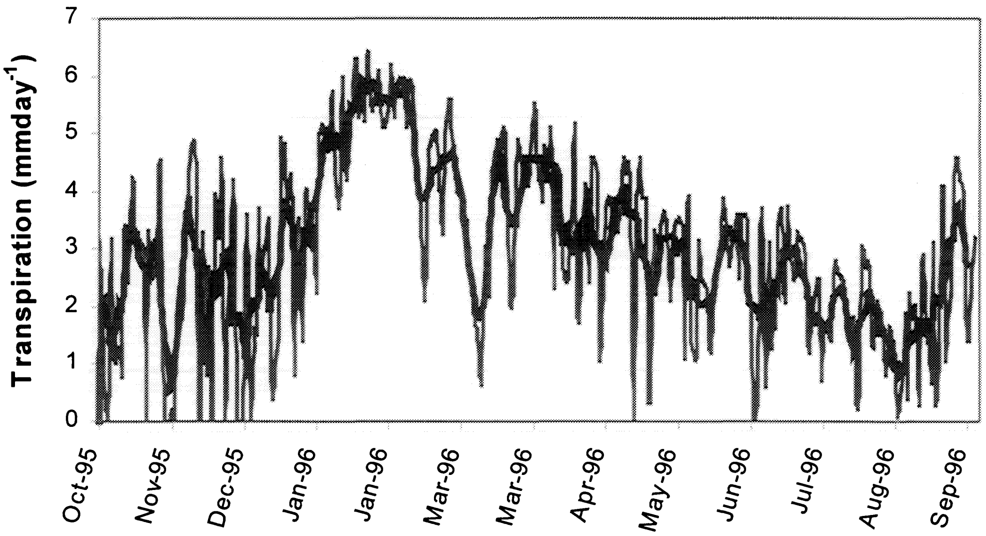

Figure 4. Transpiration ($mmday^{-1}$) (gray line) for the hydrologic year October/95-September/96. The black line is a 7-day moving average to filter out high frequency variations caused by fluctuations in net radiation.

5. CONCLUDING REMARKS

It was shown that optical remote sensing products can be used to estimate LAI of Eucalyptus forests with easy and adequate accuracy at regional scales. Among all products studied, the Soil Adjusted Vegetation Index, SAVI, and the Fraction of Green Vegetation, FGV, were the best estimators for LAI. With this, regional estimates of LAI can be used as inputs into hydrological (as in this study) and NPP models.

As for the water balance, the main conclusion from this work is that the model for estimating water use by plantations appears to have been successfully initialized and fitted to local Aracruz conditions. The agreement between modeled and independent measurements of water available in the rooting zone was excellent overall.

It became clear that the Eucalyptus plantations (E. *grandis* hybrids) are able to exert good stomatal control over water loss by transpiration. At the end of the dry season, transpiration was about 5 times lower than during moist, clear days conditions during the summer.

We have also demonstrated that the soil layer below the rooting zone functions as a secondary storage "reservoir" of water for the roots. An upward flux is established from that layer, driven by water depletion in the first layer causing a water potential gradient inversion.

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