Acta Scientiarum
http://www.uem.br/acta
ISSN printed: 1679-9275
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v35i4.16955

Water balance model and eucalyptus growth simulation in the rio doce basin, Brazil

Welliam Chaves Monteiro da Silva[1], Aristides Ribeiro[1*], Júlio César Lima Neves[2], Nairam Félix de Barros[2] and Fernando Palha Leite[3]

*[1]Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Av. P. H. Rolfs, s/n, 36570-000, Campus Universitário, Viçosa, Minas Gerais, Brazil. [2]Departamento de Solos, Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil. [3]Celulose Nipo Brasileira S.A., Ipatinga, Minas Gerais, Brazil. *Author for correspondence. E-mail: ribeiro@ufv.br*

ABSTRACT. Although the 3-PG model is widely used for forest productivity calculations, there are processes that do not present appropriate physical treatment. The aim of this study was to generate a tool to improve the water balance calculation in the model to enhance the energy balance and transpiration process. The calculation of transpiration was modified to account for variations in solar radiation with the inclination and azimuth of the terrain; the vapor pressure deficit was changed based on the relative humidity and air temperature; and the stomatal conductance varied according to solar radiation, vapor pressure deficit and air temperature. The water storage in the soil varied with the depth of the root system and the total water availability (TWA) in the soil. The assessment was also changed from a monthly to an hourly basis. The study was conducted in areas surrounding Cenibra, and the data were collected from the Rio Doce river basin, in the Brazilian state of Minas Gerais. Taken together, these modifications improved growth - modeling processes and enhanced the capacity of this analytical tool to differentiate intra - region productivity.

Keywords: tilt surface, solar radiation, stomatal resistance, ecophysiological model.

Modelo de balanço de água e simulação do crescimento do eucalipto na bacia do rio doce, Brasil

RESUMO. Apesar do modelo 3-PG ser um dos mais utilizados para cálculos de produtividade florestal, existem nele processos que não apresentam tratamento físico adequado. O objetivo deste estudo foi gerar uma ferramenta para aperfeiçoar o cômputo do balanço hídrico no modelo, visando uma melhora no balanço de energia e no processo de transpiração. Foram feitas modificações no cálculo da transpiração, de maneira que a radiação solar variou de acordo com a inclinação e azimute do terreno, o déficit de pressão de vapor foi alterado com a umidade relativa e temperatura do ar, e a condutância estomática foi modificada com a radiação solar, o déficit de pressão de vapor e a temperatura do ar. Outra modificação importante foi no armazenamento de água no solo que variou com a profundidade do sistema radicular e disponibilidade total de água no solo. Também foi feita a mudança de base mensal para horária. O estudo foi realizado em áreas da empresa Cenibra, com dados de regiões da bacia do rio Doce, Estado de Minas Gerais. As modificações apresentaram resultados que permitiram observar uma melhora nos processos do modelo de crescimento, de forma que a ferramenta de simulação foi capaz de diferenciar a produtividade intra - regiões.

Palavras-chave: superfície de inclinação, radiação solar, resistência estomática, modelo ecofisiológico.

Introduction

Modeling has become a highly important tool for the design and prediction of the performance of plants under different conditions to improve the understanding of the ecophysiology of this organism.

Plant growth modeling is also an organized and structured method to examine the procedures and interactions that determine crop yields.

One of the advantages of using models is the ability to estimate the values of the systems they represent. However, because of the complexity of plant growth and development, models cannot address all of the processes and variables involved in crop growth. Thus, in spite of the excellent results obtained, models are only a simplification of reality.

Process - based models predict forest productivity based on the physiological processes that control plant growth (photosynthesis, biomass allocation, respiration, transpiration, nutrition and leaf and twig drop). Landsberg and Waring (1997) developed a forest growth model called "Physiological Principles in Predicting Growth" (3-

PG), which considers constant and variable physiological relationships.

The forest growth 3-PG model uses physiological principles to estimate forest productivity in even - aged and monospecific plantations. Forest growth can be realistically estimated and easily standardized for a particular forest type with only a few adjustments (LANDSBERG; WARING, 1997; PÉREZ-CRUZADO et al., 2011); therefore, 3-PG has become an appropriate and widely used model for the prediction of forest development.

One advantage of the 3-PG model is that it incorporates the following submodels:

a) carbohydrate assimilation (biomass production); b) biomass distribution among leaves, stem (wood) and roots; c) soil water balance; d) biomass allocation to variables of interest for forest growth; and e) dendrometric characteristics.

These submodels and their interactions largely represent procedures that influence plant development (DYE et al., 2004; ESPREY et al., 2004; NIGHTINGALE et al., 2008a).

The 3-PG model estimates the amount of radiant energy absorption in the canopy and the carbohydrate conversion and allocation to different tree parts (leaves, bark, wood and roots). It also describes plant growth, based on energy, temperature and nutrition level (soil fertility). The model incorporates empirical relationships derived from the experimental measurements and physiological processes used in models of carbon balance, thereby facilitating the calculation of complex physiological processes and reducing the amount of data.

The 3-PG model primarily requires the following input data in simulations. 1 - Climate variables: Monthly average of the maximum and minimum air temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), rainfall (mm), vapor pressure deficit (mbar) and number of frost days per month. 2 - Soil variables: Fertility, soil texture and water availability. 3 - Plant variables: Initial leaf, wood and root biomass, tree populations and allometric relationships.

Although in recent years 3-PG has become one of the most widely used models to calculate forest productivity (ALMEIDA et al., 2004; RODRÍGUEZ-SUÁREZ et al., 2010; STAPE et al., 2004; NIGHTINGALE et al., 2008a and b), the physical treatment of some procedures, such as the water balance calculation, are not adequately represented in the model.

The standardization of various forest growth models to region - specific conditions, such as soil - climate, must also be improved to make this method even more useful for understanding forest growth. Thus, improved estimates of these processes might result in significant gains in the simulation of forest plantation growth.

The aim of this study was to generate a new tool to compute water balance using the 3-PG model to improve the transpiration process with respect to stomatal control, which is regulated through variations in air temperature, vapor pressure deficit and energy balance, and to enhance the treatment of energy balance with respect to variations in solar energy according to the face of exposure and slope of the terrain. The time scale for the water balance calculation was changed from a monthly to an hourly basis.

Material and methods

The 3-PG model was originally designed on a monthly basis. In our study, the time scale for the water balance calculation was converted to an hourly basis. Simulations were performed using the 3-PG model in its "original" format with modifications developed in this study.

The radiation and water balance calculations were modified to simulate the growth of eucalyptus plantations based on the concepts of 3-PG (radiation use efficiency, carbon partitioning and allometric equations).

Changes with regard to radiation balance were based on the variation of solar energy in relation to the exposed surface and land slope (IQBAL, 1983; KAMALI et al., 2006; MEFTI et al., 2003). For the water balance calculation, the treatment of transpiration was modified with regard to the stomatal control through variations in air temperature, vapor pressure deficit (VPD) and global solar radiation. The water storage capacity (WSC), which varies with the depth of the root system, and the total soil water availability (TWA) were also modified.

The variables in the original model were utilized on a monthly scale. In this study, the variables involved in the water and energy balance calculations were used on an hourly scale and later converted to a monthly scale to apply the simulations for 3-PG eucalyptus growth models.

Estimation of Transpiration

For the estimation of transpiration (Eq. 1), the Penman - Monteith equation (ALLEN et al., 1998) was used on an hourly basis, which includes aerodynamic components and energy balance. The solar radiation was corrected, i.e., the radiation was adjusted, according to the inclination and azimuth angle of the areas.

The treatment of surface stomatal conductance was corrected according to the vapor pressure deficit and variations in solar radiation and air temperature, based on equation (4) (CARNEIRO et al., 2008), which was developed for the same study region.

In the original 3-PG model, the VPD is treated as dependent on air temperature only; therefore, Allen et al. (1998) proposed the treatment of the VPD with relation to the relative humidity and air temperature.

The reflection coefficient (α) was also included in this simulation of transpiration and corrected according to the zenith angle, based on equation (27).

$$T = \frac{\Delta(R_n - G) + M' \rho_a C_p (e_s - e_a)/r_a}{[\Delta + \gamma(1 + r_d/r_a)]\lambda} \tag{1}$$

where:

T = canopy transpiration (mm h^{-1});

λ = latent evaporation heat flux (MJ m^{-2} s^{-1});

Δ = curve declivity of vapor saturation pressure (kPa $^{o}C^{-1}$);

Rn = net radiation (MJ m^{-2} s^{-1});

G = soil heat flux (MJ m^{-2} s^{-1});

M' = time conversion factor = 3600;

ρ_a = absolute air density (kg m^{-3});

γ = psychrometric coefficient (kPa °C^{-1});

C_P = specific heat at constant pressure, 1013 (10^{-3}) MJ Kg^{-1} °C^{-1};

(e_s - e_a) = vapor pressure deficit (kPa);

r_a = aerodynamic resistance (s m^{-1});

r_d = surface resistance (s m^{-1}).

In this model, stomatal conductance was used to determine the plant resistance against water loss through transpiration.

The canopy resistance was calculated according to the equation below.

$$r_d = \frac{r_e^*}{LAI} \tag{2}$$

r_d = surface resistance (s m^{-1}).

r_e^* = stomatal resistance, as determined through limits in soil water availability(s m^{-2}); and

LAI = leaf area index (m^2 m^{-2}).

$$r_e^* = \frac{r_e}{K_S} \tag{3}$$

Stomatal resistance (r_e) was calculated using the equation of Carneiro et al. (2008):

$$r_e = 1694.6 \left(\frac{(VPD\, T)}{Rgi\ 277.78} \right)^{1.0568} \tag{4}$$

$$Ks = \frac{\log(WS_i + 1.0)}{\log(CAD + 1.0)} \tag{5}$$

Ks = coefficient of soil moisture (adimensional);

WS_i = water storage on day in mm (equation 35);

WSC = water storage capacity in mm (equation 36);

Ln = Neperian logarithm;

Rgi = correction of the global incident solar radiation (diffuse and direct) in MJ m^{-2} h^{-1} (equation 23).

Incident solar radiation at the Top of the Atmosphere (R_0) in MJ m^{-2} h^{-1}:

$$\begin{aligned} R_0 = \frac{12(60)}{\pi} G_{SC} d_r [(\omega_2 - \omega_1) sen\phi\ sen\delta + \\ + \cos\phi \cos\delta (sen\omega_2 - sen\omega_1)] \end{aligned} \tag{6}$$

G_{SC} = solar constant = 0.0820 MJ m^{-2} min^{-1};

δ = solar declination (rad), equation 26; and

ϕ = latitude (rad).

$$dr = 1 + 0.033 \cos\left(\frac{2\pi}{365} J \right) \tag{7}$$

dr = relative earth - sun distance (rad); and

J = number of day of the year.

$$\omega_1 = \omega - \frac{\pi\, t_1}{24} \tag{8}$$

$$\omega_2 = \omega + \frac{\pi\, t_1}{24} \tag{9}$$

t_1 = duration of calculation period (hour), i.e., 1 for a one - hour period or 0.5 for half - an - hour period;

ω_1 = solar time angle at the beginning of the period (rad); and

ω_2 = solar time angle at the end of the period (rad);

The time angle (ω) is the angle between the position of the sun and the local meridian. Due to 24 - hour Earth rotation, this angle varies 15° every 60 minutes and is negative in the morning, positive in the afternoon and numerically equal to zero at noon.

$$\omega = \frac{\pi}{12} [(T_1 + 0.06667(L_Z - L_m) + S_C) - 12] \tag{10}$$

T_1 = (hour + 0.5)

T_1 = standard clock time at the midpoint of the period [hour]. For example, for a period between 14 and 15 h, t = 14.5;

ω = solar time angle at the midpoint of one - hour or shorter period (rad); and

L_Z = longitude of the center of the local time zone (degrees west of Greenwich).

$$Lz = -\left(\frac{L_m}{15.0}\right)15 \tag{11}$$

L_m = longitude of the measurement site (degrees west of Greenwich);

$$S_C = 0.1645\sin(2b) - 0.1255\cos(b) - 0.025\sin(b) \tag{12}$$

Sc = seasonal correction for solar time (hour).

$$b = \frac{2\pi(J-81)}{364} \tag{13}$$

where:

J = number of day of the year; and

b = fit equation.

The correction for the variation in solar radiation during the day with regard to terrain inclination and exposed surface areas was based on the vertical angle of incidence of direct sun rays (θ) (IQBAL, 1983), where:

$$\cos\theta = A\cos\omega_1 + B\sin\omega_1 + C \tag{14}$$

$$A = \cos i\cos\phi\cos\delta + \sin i\cos A_Z\ \sin\phi\cos\delta \tag{15}$$

$$B = \sin i\cos\delta\sin A_Z \tag{16}$$

$$C = \cos i\sin\delta\sin\phi - \sin i\cos A_Z\ \sin\delta\cos\phi \tag{17}$$

where:

δ = solar declination (equation 26);

ϕ = latitude in radians;

θ = incidence angle of direct sun rays (degrees);

ω_1 = time angle (degrees);

A, B and C = parameters of simplification of the equation;

A_z = azimuth angle or surface orientation (rad); and

i = surface inclination angle (degrees).

$$A_z = A_{zd}\left(\frac{PI}{180}\right) \tag{18}$$

A_{zd} = azimuth angle or surface orientation (degrees).

The hourly diffuse solar radiation was estimated using a previously described mathematical model (FACCO et al., 2009). This model utilizes a combination of linear and nonlinear cubic equations, in which different intervals between global and atmospheric radiation are considered (R_o) (FACCO et al., 2009).

The direct and diffuse solar radiance was determined using the following equation:

$$I_d = M\ R_g, M_T = \frac{R_g}{R_0} \tag{19}$$

$M = 1 - 0.221M_T$, for $M_T \leq 0.20$ (20)

$M = (0.798 + 2.442M_T - 9.634{M_T}^2 + 6.9381{M_T}^3)$, (21)
for $0.20 > M_T \leq 0.80$

$M = 0.135$, para $M_T > 0.80$ (22)

where:

I_d = diffuse solar radiation on a plain surface (MJ $m^{-2} h^{-1}$);

M = ratio between i_d and R_g (adimensional);

M_T = ratio between R_g and R_0 (adimensional); and

R_g = global solar radiation (MJ $m^{-2} h^{-1}$).

$$\begin{aligned} Rgi = &\left(Dn\,Cos\theta\right) + (I_d\ Cos\left(\frac{i}{2}\right)Cos\left(\frac{i}{2}\right)) + \\ &+\ ((DnCosZ + I_d)\ \alpha\sin\left(\frac{i}{2}\right)\sin\left(\frac{i}{2}\right)) \end{aligned} \tag{23}$$

where:

Rgi = corrected incident global solar radiation (diffuse and direct) in MJ $m^{-2} h^{-1}$;

i = surface inclination angle;

θ = angle of incidence of the direct sun rays (degrees); and

α = coefficient of reflection (albedo), equation 27.

$$Dn = \frac{I_d}{Cos(Z)} \tag{24}$$

where:

Dn = normal direct solar radiation on the surface (corrected direct); and

Z = zenith angle.

$$Cos(Z) = Sin\phi\ Sin\delta + Cos\phi\ Cos\delta\ Cos\omega_1 \tag{25}$$

where:

ϕ = latitude (rad);

δ = solar declination (rad);

ϕ = (ϕ pi)/180 (conversion of the latitude to radians); and

ω_1 = solar time angle at the beginning of the period (rad).

The solar declination, for a particular day of the year, was calculated using the equation:

$$\delta = (23.45\sin(\frac{360}{365}(284 + J)))\frac{PI}{180} \quad (26)$$

J = number of day of the year;

$$\alpha = (0.1715\ \exp(0.0056 Cos(Z)\frac{180}{PI})) \quad (27)$$

$$RS_W = 0.0036 Rgi \quad (28)$$

RS_W = incident global solar radiation (W m^{-2}).

$$Rns = (1.0 - \alpha)Rgi \quad (29)$$

Rns = short - wave net radiation (MJ m^{-2} h^{-1}).

The long - wave net radiation was estimated using a regression equation, derived from the incident global solar radiation of the study region:

$$Rnl_W = -0.00002 RS_W{}^2 - 0.0272 RS_W - 1.3458 \quad (30)$$

Rnl_W = correction of the long - wave net radiation (W m^{-2})

$$Rnl = Rnl_W\ 0.0036 \quad (31)$$

Rnl = long - wave net radiation (MJ m^{-2} h^{-1})

$$Rn = Rns + Rnl \quad (32)$$

Rn = net radiation (MJ m^{-2} h^{-1})

If hours < 5 or hours >= 18, then

$$G = 0.1Rn \quad (33)$$

Or

$$G = (0.1131 RS_W + 2.3949)\,0.0036 \text{ (MJ m}^{-2}\text{ h}^{-1}) \quad (34)$$

G = soil heat flux (MJ m^{-2} h^{-1})

Experimental area

This study was conducted in the state of Minas Gerais in areas near Celulose Nipo - Brasileira SA (CENIBRA). Meteorological data from four regions of the Rio Doce basin in the state of Minas Gerais were used (Figure 1). The basin has a rather hilly relief, with altitudes ranging from 240 to 1273 m, which is representative of essential soil and climate differences at study sites (SOUZA et al., 2006) in the counties Belo Oriente (Rio Doce), Santa Barbara (Santa Barbara), Peçanha (Virginópolis) and Antonio Dias (Cocais) (Figure 1).

The region of Rio Doce belongs to the county of Belo Oriente, where the relief is plain and rather hilly, with a deep clayey soil medium of limited fertility. Annual average values of 1160 mm rainfall, 25.1°C air temperature and 66% relative humidity are observed. The meteorological station is located at a height of 240 m asl, and a annual water deficit of 402 mm is observed, using a climatic water balance (SOUZA et al., 2006).

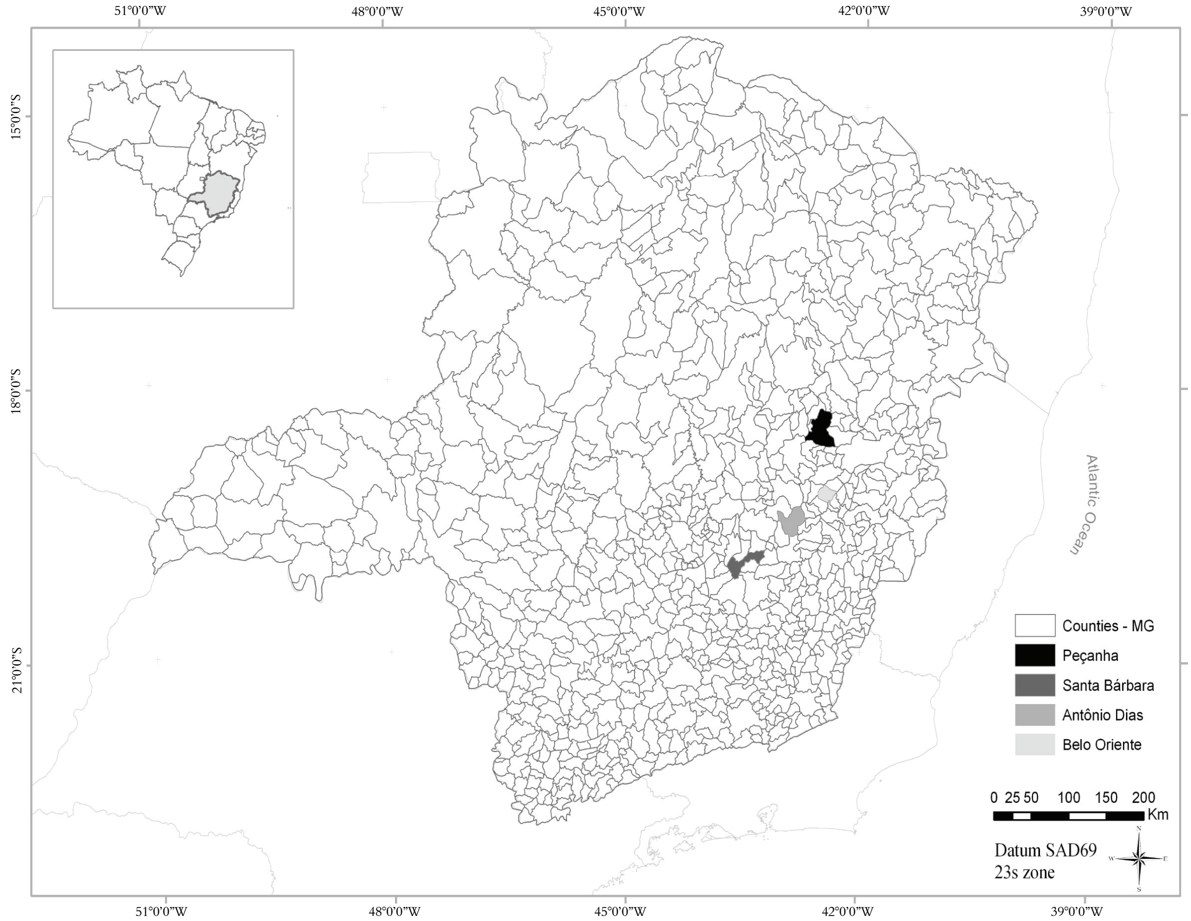
The region of Santa Barbara, county of Santa Barbara, is a soft, wavy and mountainous relief, with a shallow to deep sandy - clayey soil medium of limited fertility. Annual average values of 1424 mm rainfall, 22.7°C air temperature and 59% relative humidity are observed. According to the climatic water balance, an annual water deficit of 119 mm was determined (SOUZA et al., 2006). The meteorological station is located at an altitude of 847 m asl.

The region of Virginópolis, county of Peçanha, is a soft and hilly relief, with deep, clayey soil medium of limited fertility and average annual values of 1,137 mm rainfall, 22.1°C of air temperature and 60% relative humidity. The annual water deficit, according to the climatic water balance, is 162 mm (SOUZA et al., 2006), and the meteorological station is located at an altitude of 1,015 m asl.

The relief in the region of Cocais, county Antonio Dias, is rather mountainous, with deep, sandy - clayey soil of limited fertility. Average annual values of 1258 mm rainfall, 21.2°C air temperature and 66% of air relative humidity are observed. An annual water deficit of 148 mm was determined using the climatic water balance (SOUZA et al., 2006). The altitude of the meteorological station is 1273 m.

The following meteorological data were used: mean temperature (°C), relative humidity (%), wind speed (m s^{-1}), solar radiation (MJ m^{-2}) and rainfall (mm). The meteorological data were collected on an hourly basis, using automatic weather stations, from April 2000 to April 2006.

The database of the forest inventory contained information on the month and year of planting, the trunk diameter at breast height (cm) and the total tree height (m).



Region	County	Latitude	Longitude	Altitude (m)*	Mean temp. (°C)	Rainfall (mm)	Water stress (mm)**
Virginópolis	Peçanha	18°42'24"S	42°29'25"O	1015 m	22.1	1137	203
Cocais	Antônio Dias	19°29'19"S	42°51'54"O	1273 m	21.2	1258	148
Santa Bárbara	Santa Bárbara	19°59'00"S	43°18'19"O	847 m	22.7	1424	195
Rio Doce	Belo Oriente	19°18'50"S	42°23'38"O	240 m	25.1	1160	429

*Values correspond to the location of the meteorological stations. **Thornthwaite and Matter 1948.

Figure 1. Location of the studied counties and meteorological stations in the State of Minas Gerais.

Based on biometric models, which were calibrated for the reality of the stand areas and with input variables such as the trunk diameter at breast height (DBH) and tree height, the mean annual increment (MAI) was estimated in 2004 and 2005 for each plot.

Simulations

In this study, simulations were performed for three exposed terrain surfaces (azimuth): north (N), south (S) and plain (East - West). We considered two inclination classes of the field (0-15 and > 15°). Significant differences in the radiation incidence were observed in studies conducted in the same region (FACCO et al., 2009), with slopes between 0 and 15 and above 15°.

In this study, the simulations were performed using the original 3-PG (LANDSBERG; WARING, 1997) and the parametric model, which incorporated the water balance, coefficient of soil moisture, solar radiation and transpiration.

The proposed growth model was initially parameterized, according to the region - specific ecophysiological characteristics for the development of plantations. The parameterization of the original and proposed models was similar to the previously described values (GUIMARÃES et al., 2007), except for the transpiration value, which represents the relationship between the net (NPP) and gross (GPP) primary production and was obtained in a sensitivity analysis based on values of Landsberg and Waring (1997).

Water balance

A submodel of water balance (described below) was coupled with the 3-PG model to simulate the growth of eucalyptus plantations.

The water balance was calculated for the soil layer, which contains roots and varies depending on the plant growth stage. Once the depth of the root system is determined, the control volume and maximum quantity of plant - available water can be inferred. In this control volume, the water entry and exit is calculated to determine the variation in the water amount stored in the soil using the following formula:

$$WS_i = WS_{i-1} + PTH - IPC - PERC - ET \tag{35}$$

where:

WS_i = water storage on day i (mm);

WS_{i-1} = water storage on the day before (mm);

PTH = total rainfall on day i (mm);

IPC = total intercepted rainwater by the canopy and by the litter on day i (mm);

PERC= percolation into the useful soil layer where roots were found on day i (mm);

ET = canopy transpiration on day i (mm).

The calculation of the water balance began in the month when the accumulated rainfall was sufficient to reach the maximal capacity of available water in the soil.

The model was fed with hourly data of an automatic meteorological station.

The total water storage capacity of the soil must be calculated to the soil depth that corresponds to the real depth of the root system of the crop as follows:

$$WSC = TWA\ EDRS \tag{36}$$

where:

WSC = available water capacity in soil in mm m^{-1};

TWA = total water available, in mm m^{-1} of soil depth; and

EDRS = effective depth of the root system, in cm.

$$TWA = \left(\frac{CCamp - PmPer}{10} da \right) \tag{37}$$

where:

CCamp = field capacity, % in weight;

PmPer = wilting point, % in weight; and

da = apparent soil density, g cm^{-3}.

The field capacity values, wilting point and soil density were determined in the soil samples collected from the study areas.

For the effective depth of the root system (EDRS), a soil section containing at least 80% of the root system of the crop must be considered. This depth depends on the crop and the soil depth of the area. The effective depth of the root system was estimated using a previously proposed equation (FACCO et al., 2009):

$$EDRS = 287.31(1.0 - \exp(-0.19483\ age)^{1.0219} \tag{38}$$

Using the interception of precipitation, Moura et al. (2009) showed that the forest cover causes a reduction in the total rainwater that reaches the ground, which consequently influences the dynamics of the surface runoff that reaches the hydrologic network and the process of infiltration that feeds subsurface water.

The interception of the plant cover was estimated according to Costa et al. (2006):

$$IPC = PTH\ 0.12 \tag{39}$$

The water percolation was estimated using the following equation:

$$PERC = WS_{i-1} - WSC \tag{40}$$

where:

IPC = total intercepted rainwater from the canopy and the litter on day i (mm);

PTH = total rainfall on day i (mm);

PERC = percolation into the useful soil layer where roots were found on day i (mm);

WS_{i-1} = the initial storage was equal to TWA, that is, WS_{i-1} = TWA.

Determination of the mean annual increment

For calibration of the modified model, a forestry inventory database was used, which contained information on the month and year of planting, the trunk diameter at chest height (cm) and the total height of the trees (m). Based on biometric models, which were calibrated to the planted area, trunk diameter at breast height (DBH) and total height of the trees, the mean annual increment (MAI) was estimated for each plot. Thus, 28 trees were randomly selected, and the DBH and total height were measured. The total height and DBH of the other trees were estimated using adjusted biometric models.

To estimate the height of the trees, the following model was used:

$$LnHT = b_0 + \frac{b_1}{DBH} + b_2 * LnHd + \xi \qquad (41)$$

where,

HT = height of the tree which was not measured (m);

$b_0, b_1, b_2 =$ coefficients determined using regression analysis and the variables for DBH, Hd and observed height;

DBH = Diameter at Breast Height (cm);

Hd = mean height of the dominant trees of the plot; and

ξ = random error.

To estimate the mean annual increment (MAI), the following biometric model was used:

$$LnVarv = \beta_0 + \beta_1 LnDBH + \beta_2 * LnHT + \xi \qquad (42)$$

where:

$Varv$ = tree volume (m^3);

$\beta_0, \beta_1, \beta_2$ = coefficients for each location studied, obtained from the local company (Table 1);

Table 1. Values of the coefficients β0, β1, β2 for each location studied.

Location	β_0	β_1	β_2
Cocais	-10.142538	1.836628	1.106458
Virginópolis	-10.373936	1.809317	1.199962
Rio Doce	-10.143457	1.856938	1.095924
Santa Bárbara	-10.156326	1.870474	1.079379

DBH = Diameter at Breast Height (cm);

HT = height of the tree (m) – estimated by the LnHT equation (Eq.41); and

ξ = random error.

The trunk volume per hectare was calculated using the following formula:

$$\frac{V}{ha} = \frac{\Sigma\, Varv \ * 10000}{Plot\_Area} \ (m^3) \qquad (43)$$

and the mean volume by:

$$IMA = \frac{\frac{V}{ha}}{Age\ (years)} \ m^3\ ha^{-1} year^{-1} \qquad (44)$$

Results and discussion

Figure 2 shows the correlations between the MAI modeled and observed data in all four regions studied: Cocais, Virginópolis, Rio Doce and Santa Barbara.

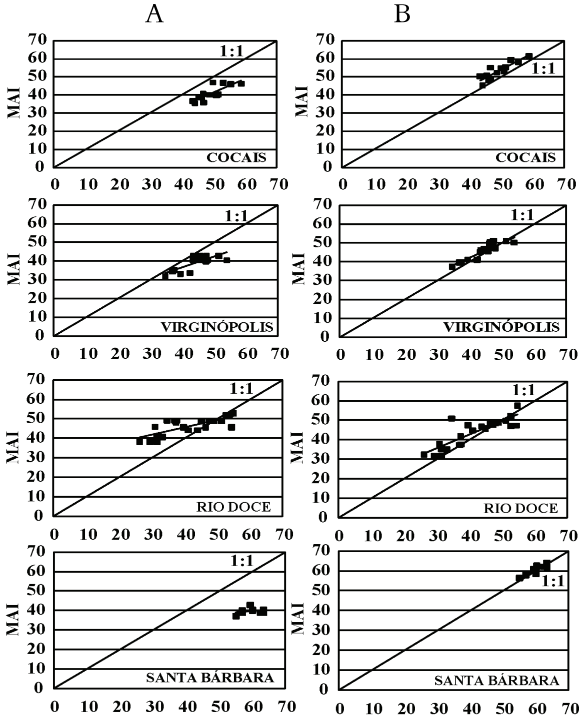


Figure 2. Correlation between the data from the mean annual increment (MAI – m^3 ha^{-1} yr^{-1}) observed (axis x) and simulated (axis y) using the original model (a) and between the observed (axis x) and simulated (axis y) MAI using the model proposed (b) for the regions of Cocais, Virginópolis, Rio Doce and Santa Bárbara.

These diagrams illustrate the correlations between the observed data using the original model (a) and the proposed model (b). The determination coefficients for the original model varied from 0.06 to 0.66, and the angular coefficient (Table 2) varied from 0.13 to 0.75.

Using the original model in simulations for the same study area, Guimarães et al. (2007) was able to differentiate the productivity between regions, based on variations in the soil - climatic characteristics of the Rio Doce basin.

Table 2. Statistical indices used in the performance analysis of the models: MBE (mean bias error), MAE (mean absolute error), RMSE (root mean square error), d (agreement index of Willmott), R^2 (coefficient of determination) and "b" (angular coefficient for linear fit through zero).

	MBE	MAE	RMSE	d	R^2	b
Cocais Original	-8.49	8.49	8.87	0.73	0.66	0.75x
Cocais Proposed	3.82	3.82	4.37	0.93	0.78	0.91x
Virginópolis Original	-5.37	5.37	6.19	-0.34	0.59	0.58x
Virginópolis Proposed	0.86	1.69	2.06	0.84	0.84	0.79x
Rio Doce Original	4.49	5.78	7.52	0.29	0.56	0.38x
Rio Doce Proposed	1.94	3.19	4.86	0.71	0.73	0.70x
Santa Bárbara Original	-20.15	20.15	20.34	-14.10	0.06	0.13x
Santa Bárbara Proposed	0.45	1.31	1.44	0.78	0.74	0.71x

The coefficient of determination (Table 2) in the proposed model ranged from 0.74 to 0.84, respectively, for Santa Barbara and Virginópolis. The minor adjustment observed for Santa Barbara could reflect the smaller number of observational data available for analysis. A good fit was observed in Cocais and Rio Doce, with coefficients of determination of 0.78 and 0.73, respectively. The angular coefficient between the regions using the proposed model varied from 0.70 to 0.90.

Modifications to the transpiration calculations and improvements to the water balance, which, in contrast with the original model, considered variations in root growth with age, changes to the TWA in the soil and the "time step" permitted for obtaining better results. Thus, the proposed model obtained a significant gain in explanatory power, as demonstrated by the higher correlation coefficients and angular coefficients closer to 1. These improved results showed greater sensitivity to variations and the exponential gain of growth with age.

To improve the propose model, the transpiration calculation was adjusted, i.e., the methodology for calculating the stomatal resistance and vapor pressure deficit was modified. With these modifications, the model demonstrated that the total annual transpiration for Cocais ranged from 370 to 1,060 mm and that for Rio Doce ranged from 803 to 1,298 mm. In Santa Barbara, this value ranged from 451 to 1,478 mm, and in the region of Virginópolis, the total annual transpiration ranged from 707 to 1,024 mm. The original model showed annual transpiration totals ranging from 400 to 818 mm for Cocais, 465 to 683 mm for Santa Barbara, 559 to 802 mm for Rio Doce and 528 to 796 mm for Virginópolis.

The results obtained with the propose model are consistent with the values obtained in studies performed in the same region, and higher transpiration values than those obtained by the original model were observed (SOUZA et al., 2006). Because these regions are located in the tropics, i.e., regions with greater rain and atmospheric demands, high transpiration values and consequently productivity were expected.

With changes in transpiration, improvements in water balance with consideration for age - related root growth variations, and changes in the TWA of the soil and 'time step', a greater sensitivity to variations and an exponential gain in growth with age were observed.

Table 2 presents the statistical analyses (FEIKEMA et al., 2010; PEREIRA et al., 2009) of the original and proposed 3-PG models compared with the observed data at the four locations studied. The mean bias error (MBE) for the regions of Cocais, Virginópolis and Santa Barbara was underestimated with the original model, with values of -8.49, -5.37 and -20.15, respectively, and overestimated with the proposed model, with values of 3.82, 0.86 and 0.45, respectively. For the Rio Doce region, both models overestimated the values, with values of 4.49 and 1.94 for the original and proposed models, respectively.

For the mean absolute error (MAE), the values of the two models in the four regions ranged from 5.37 to 20.15 for the original model and from 1.31 to 3.82 for the proposed model. For the root mean square error (RMSE), however, the values ranged from 6.19 to 20.34 for the original and 1.44 to 4.86 for the proposed model.

The values of the Willmott index of agreement (D) for the original model varied from 14.10 to 0.73, indicating significant deviations in the regions of Rio Doce, Virginópolis and Santa Barbara. The results were significantly improved for the proposed model, with a level of agreement ranging from 0.71 to 0.93.

For the original model, the coefficient of determination (R^2) ranged from 0.06 to 0.66 and from 0.73 to 0.84 for the proposed model, indicating a generally good fit to the proposed model.

Although the fit of the proposed model to the line of equal values (1:1) was not perfect, the values of the evaluated indices were generally much better than those obtained using the original model.

Conclusion

Improving the calculation of environmental factors, such as vapor pressure deficit and solar irradiance, and modifying the water balance calculation to an hourly scale, which considers the TWA of the soil and the variation of root system depth with forest age, were useful in improving the estimation of the biomass gain in eucalyptus trees. These alterations had an important effect on wood volume gain.

Moreover, the changes to the 3-PG model improved the treatment of the procedures, and the computer simulation tool showed improvements in the differentiation of regional and intra - regional productivity. The proposed model is therefore no longer a tool for strategic planning only, but seems increasingly promising for use in forest management.

Acknowledgements

The authors would like to thank the Celulose Nipo - Brasileira (CENIBRA SA), the *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq – no.

481195/2004-1 and no. 311922/2006-6), the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the *Fundação de Amparo à Pesquisa do Estado de Minas Gerais* (CAG 61879/05) for support and financial assistance in developing and conducting this research.

References

ALLEN, R. G.; PEREIRA, L. S.; RAES, D.; SMITH, M. Crop evapotranspiration: Guidelines for computing crop water requirements. **Irrigation and Drainage**. Paper 56. Italy: UN-FAO, 1998.

ALMEIDA, A. C.; LANDSBERG, J. J.; SANDS, P. J. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. **Forest Ecology and Management**, v. 193, n. 1-2, p. 179-195, 2004.

CARNEIRO, R. L. C.; RIBEIRO, A.; HUAMAN, C. A. M. Y.; LEITE, F. P.; SEDIYAMA, G. C.; BARROS, N. F. Consumo de água em plantios de eucalipto - Parte 1: Determinação da condutância estomática em tratamentos irrigados e não irrigados. **Revista Árvore**, v. 32, n. 1, p. 1-10, 2008.

COSTA, A. C. L.; BRAGA, A. P.; GONÇALVES, P. H. L.; COSTA, R. F.; SILVA JÚNIOR, J. A.; MALHI, Y. S.; ARAGÃO, L. E. O. E. C.; MEIR, P. Estudos hidrometeorológicos em uma Floresta Tropical chuvosa na Amazônia - projeto Esecaflor. **Revista Brasileira de Meteorologia**, v. 21, n. 3b, p. 283-290, 2006.

DYE, P. J.; JACOBS S.; DREW, D. Verification of 3-PG growth and water-use predictions in twelve Eucalyptus plantation stands in Zululand, South Africa. **Forest Ecology and Management**, v. 193, n. 1-2, p. 197-218, 2004.

ESPREY, L. J.; SANDS, P. J.; SMITH, C. W. Understanding 3-PG using a sensitivity analysis. **Forest Ecology and Management**, v. 193, n. 1-2, p. 235-250, 2004.

FEIKEMA, P. M.; MORRIS, J. D.; BEVERLY, C. R.; COLLOPY, J. J.; BAKER, T. G.; LANE, P. J. Validation of plantation transpiration in south-eastern Australia estimated using the 3PG+ forest growth model. **Forest Ecology and Management**, v. 260, n. 5, p 663-678, 2010.

FACCO, A. G.; RIBEIRO, A.; SEDIYAMA, G. C.; LEITE, F. P.; BARROS, N. F. Saldo de radiação em plantios de eucalipto em áreas de relevo ondulado. **Revista Árvore**, v. 33, n. 3, p. 471-480, 2009.

GUIMARÃES, D. P. G.; SILVA, G. G. C.; SANS, L. M. A.; LEITE, F. P. Uso do modelo de crescimento 3-PG para o zoneamento do potencial produtivo do eucalipto no estado de Minas Gerais. **Revista Brasileira de Agrometeorologia**, v. 15, n. 2, p. 192-197, 2007.

IQBAL, M. **An introduction to solar radiation**. Toronto: Academic Press, 1983.

KAMALI, G. H. A.; MORADI, I.; KHALILI, A. Estimating solar radiation on tilted surfaces with various orientations: a study case in Karaj (Iran). **Theoretical Applied Climatology**, v. 84, n. 4, p. 235-241, 2006.

LANDSBERG, J. J.; WARING, R. H. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. **Forest Ecology and Management**, v. 95, n. 3, p. 209-228, 1997.

MEFTI, A.; BOUROUBI, M. Y.; ADANE, A. Generation of hourly solar radiation for inclined surfaces using monthly mean sunshine duration in Algeria. **Energy conversion and Management**, v. 44, n. 19, p. 3125-3141, 2003.

MOURA, A. E. S. S.; CORREA, M. M.; SILVA, E. R.; FERREIRA, R. L. C.; FIGUEIREDO, A. C.; POSSAS, J. M. C. Interceptação das Chuvas em um Fragmento de Floresta da Mata Atlântica na Bacia do Prata, Recife, PE. **Revista Árvore**, v. 33, n. 3, p. 461-469, 2009.

NIGHTINGALE, J. M.; HILL, M. J.; PHINN, S. R.; DAVIES, I. D.; HELD, A. A.; ERSKINE, P. D. Use of 3-PG and 3-PGS to simulate forest growth dynamics of Australian tropical rainforests: I. Parameterisation and calibration for old-growth, regenerating and plantation forests. **Forest Ecology and Management**, v. 254, n. 2, p. 107-121, 2008a.

NIGHTINGALE, J. M.; HILL, M. J.; PHINN, S. R.; DAVIES, I. D.; HELD, A. A. Use of 3-PG and 3-PGS to simulate forest growth dynamics of Australian tropical rainforests: II. An integrated system for modelling forest growth and scenario assessment within the wet tropics bioregion. **Forest Ecology and Management**, v. 254, n. 2, p. 122-133, 2008b.

PEREIRA, D. R.; YANAGI, S. N. M.; MELLO, C. R.; SILVA, A. M.; SILVA, L. A. Desempenho de métodos de estimativa da evapotranspiração de referência para a região da Serra da Mantiqueira, MG. **Ciência Rural**, v. 39, n. 9, p. 2488-2493, 2009.

PÉREZ-CRUZADO, C.; MUÑOZ-SÁEZ, F.; BASURCO, F.; RIESCO, G.; RODRÍGUEZ-SOALLEIRO, R. Combining empirical models and the process-based model 3-PG to predict Eucalyptus nitens plantations growth in Spain. **Forest Ecology and Management**, v. 262, n. 6, p. 1067-1077, 2011.

RODRÍGUEZ-SUÁREZ, J. A.; SOTO, B.; IGLESIAS, M. L.; DIAZ-FIERROS, F. Application of the 3PG forest growth model to a Eucalyptus globulus plantation in Northwest Spain. **European Journal of Forest Research**, v. 129, n. 4, p. 573-583, 2010.

SOUZA, M. J. H.; RIBEIRO, A.; LEITE, H. G.; LEITE, F. P.; MINUZZI, R. B. Disponibilidade hídrica do solo e produtividade do eucalipto em três regiões da bacia do rio Doce. **Revista Árvore**, v. 30, n. 3, p. 399-410, 2006.

STAPE, J. L.; RYAN, M. G.; BINKLEY, D. Testing the utility of the 3-PG model for growth of *Eucalyptus grandis* X *urophylla* with natural and manipulated supplies of water and nutrients. **Forest Ecology and Management**, v. 193, n. 1-2, p. 219-234, 2004.

Received on April 26, 2012.
Accepted on June 28, 2012.