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3-PG model enhancement by modifying soil water availability in a tropical *Eucalyptus urophylla* plantation

Aprimoramento do modelo 3-PG pela modificação da disponibilidade de água no solo em *Eucalyptus urophylla*

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Abstract

3-PG is a widely process-based model used to estimate forest growth. After 20 years of use, along with progress in scientific knowledge, some model processes can be improved, such as soil water balance. The objective of this study was to assess the enhancements in the 3-PG model for *Eucalyptus urophylla* by changing the soil water availability, which considers the depth of the root system in the soil profile as stand ages. To set up the model and assess the improvement, a site in Sao Paulo state, Brazil, was used. From this trial two treatments were selected: 1) control (operational fertilization, without irrigation) and 2) fertilized and irrigated. The model enhancement for rooting depth and the maximum amount of water available was based on a measured relationship between the above-ground height and below-ground root depth, by replacing the constant value of the available soil water in the original 3-PG with a dynamic amount that increases as the root system grows. This modification increased the model efficiency to estimate the stem biomass and the leaf area index. This work can be used by researchers and forest managers using the 3PG model, as there was a significant improvement in stem biomass estimates, where the root mean square error (RMSE) decreased from 18.22 (original) to 12.16 (increased) Mg ha^{-1} yr^{-1} for non-irrigated treatment, increasing the model accuracy in forest biomass estimates

Keywords: Eco-physiological modeling; Process-based modelling; Forest modelling; Forest growth.

Resumo

O 3-PG é um modelo baseado em processos amplamente difundido, usado para estimar o crescimento florestal. Após 20 anos de uso, juntamente com o avanço do conhecimento científico, alguns processos dentro do modelo podem ser aprimorados, como o balanço hídrico do solo. O objetivo deste estudo foi avaliar uma potencial melhoria no modelo 3-PG em termos de disponibilidade de água no solo considerando a profundidade de raiz que varia com a idade do povoamento. Para configurar o modelo e avaliar a melhoria, foi utilizado um sítio no Estado de São Paulo, Brasil. Deste ensaio foram selecionados dois tratamentos: 1) testemunha (adubação operacional, sem irrigação) e 2) adubado e irrigado. O aprimoramento do modelo para a profundidade de enraizamento e a quantidade máxima de água

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disponível foi baseado em uma relação medida entre a altura acima do solo e a profundidade da raiz abaixo do solo, substituindo o valor constante da água disponível no solo no 3-PG original por uma quantidade dinâmica que aumenta a medida que o sistema radicular cresce. Essa modificação aumentou a eficiência do modelo para estimar a biomassa do caule e o índice de área foliar. O aprimoramento do modelo pode ser incorporador por pesquisadores e gestores que utilizam o modelo 3PG devido à melhora significativa nas estimativas de biomassa do caule, onde o erro quadrático médio (RMSE) diminuiu de 18,22 (original) para 12,16 (aumentado) Mg ha^{-1} ano^{-1}.

Palavras-chave: Modelagem ecofisiológica; Modelagem baseada em processos; Modelagem florestal; Crescimento florestal.

1. INTRODUCTION

Physiological Principles Predicting Growth (3-PG) has a high acceptance in the forestry sector due to its relatively easy data processing and it has served as a tool to aid strategic decision making and silvicultural management (Landsberg, 2003; Almeida et al., 2004b). It was developed by Landsberg & Waring (1997), and modified by Sands & Landsberg (2002), Sands (2001), Landsberg & Sands (2011). The 3-PG model has already been calibrated for: *E. globulus* (Sands & Landsberg, 2002), *E. urophylla x grandis* (Stape, 2002; Stape et al., 2004b; Borges, 2009; Almeida et al., 2010; Alvares, 2011), *Pinus taeda* (Landsberg et al., 2001; Subedi et al., 2015; Subedi & Fox, 2016; Gonzalez-Benecke et al., 2016), *Picea glauca* (Amichev et al., 2016), *Tectona grandis* (Behling, 2009) and for mixed species (Forrester & Tang, 2016). In the specific case of the genus *Eucalyptus*, the model has been used in: Brazil (Almeida et al., 2004a; Stape et al., 2004b; Silva, 2006; Almeida et al., 2007; Almeida et al., 2010; Alvares, 2011), Australia (Sands & Landsberg, 2002), South Africa (Dye, 2001; Esprey et al., 2004; Campion et al., 2005) and Portugal (Fontes et al., 2006).

The soil water balance of the 3-PG model is represented by a single layer with a monthly period, where the maximum available soil water (ASW_{Max}), the difference between the maximum and minimum soil water retention, is specified by the user as an input. The water input in the forest system is composed by precipitation (PPT), and irrigation (IRR), the processes of interception of water give the output of water by the canopy (INT), evapotranspiration (EPT), surface runoff and percolation. The available soil water (ASW) was derived as (Equation 1):

$$ASW = PPT + IRR - (EPT + INT) \quad (1)$$

If the available soil water (ASW) > ASW_{Max}, the model considers that the excess water left the system. This water availability limits forest growth, as a modulator (fθ), influencing the canopy quantum efficiency. This modulator is calculated using two empirical parameters that describe the relationship between the relative transpiration rate and the volume of water contained in the soil.

The ASW and ASWmax depend on soil the profile and the root systems depth; the last one is dynamic and has a strong relationship with tree´s dimensions; however, this is not modeled by the original 3-PG. That is why the knowledge of the trees' root system is fundamental to explain the basic eco-physiological processes, especially those related to mineral nutrition and water balance of a forest stand (Mello et al., 1998). However, the knowledge of the relationship between the above- and below-ground growths are still very incipient, mainly due to the difficulty of measuring the root system. Christina et al. (2011) analyzed the relationship between the vertical growth above ground (tree height) and below ground (root system depth) of *Eucalyptus grandis*. They observed a growth of 85% in depth of the root system in relation to the average height of the trees, in stands with height up to 20 meters and in deep soils (more than 15 meters) without physical constraints. Other studies (Laclau et al., 2001; Bouillet et al., 2002) provided relevant information about the root system dynamics, like the root system's vertical and horizontal distribution and how it changes with age, which is useful to improve the eco-physiological models that need this type of information.

Other studies proposed modifications in process-based models related with the dynamic of soil water. Recently, a new water balance sub-model was introduced into 3-PG, to model the root dynamics and in consequence the ASW. Almeida & Sands (2016) proposed this enhancement which: i) divided the soil profile into root and root-free zones, ii) modeled separately canopy transpiration and soil evaporation, and iii) used two different time resolution approaches. Estimations were improved under this enhancement; however, more detailed data is required, and for cases where soil or climatic information is limited or inadequate there is no advantage of using the new water balance sub-model they proposed. Marsden et al. (2013) also incorporated an increasing ASW, as the root system grows, into the G´Day model. This model requires daily data and soil water retention by layer. APSIM is another effort, recently developed, which consider daily information, and requires data of soil water holding capacity by soil layer (APSIM Initiative, 2019).

For those cases where there is no soil and climatic information available or it is not as detailed as required by these models, we propose an empirical approach based on the relationship found by Christina et al. (2011). This relationship was introduced to consider root dynamics and its effects on water stress. The objective of this study was to assess the enhancements in the 3-PG model for *Eucalyptus urophylla* by changing the soil water availability, which considers the depth of the root system in the soil profile as stand ages. We hypothesized that this change is going to be reflected in a better estimation of wood growth by 3PG model.

2. MATERIAL AND METHODS

2.1. Site description

The study was carried out in Mogi-Guaçu (22º18'S and 47º05'W, altitude 312 m), São Paulo state, Brazil. This trial was planted in October 2000 and ended in October 2007 and is part of the Brazil Eucalyptus Potential Productivity project, which had the objective to investigate the main factors that affect tree growth in *Eucalyptus* plantation in Brazil (Stape et al., 2010). The soil corresponds, on the Brazilian soil classification system, to a dark red eutrophic Oxisol (Santos et al., 2018), with more than 5 m depth. Average clay, sand and silt content are 43, 40, and 17% respectively, with an increase up to 49% in clay content at one-meter depth. According to analysis done at 0-20 layer, pH ($CaCl_2$) is around 5.6 and organic matter content was 23 mg dm^{-3}. Soil water content was 1.5 mm cm^{-1}. This soil does not have any physical restriction for root growth.

This area was previously cultivated with *Citrus*. The climate is subtropical with the coldest month above 0 °C, at least one month´s average temperature above 22 °C, and at least four months averaging over 10 °C. 70% or more of the annual precipitation occurs during the warmest six months. According to Köeppen´s classification, the climate corresponds to the monsoon climate (Cwa). The average annual rainfall is 1,278 mm and the average annual temperature of 21.4º C.

2.2. Experimental Design

The experiment was a factorial with two factors: water and nutritional regime and four replications. The nutritional regime factor was composed of two levels: operational fertilization (T) and the operational + extra fertilization (F). The water regime factor had two levels: irrigated (I) and non-irrigated (N). The extra fertilization and irrigated levels were selected to avoid any nutrient or water deficiency. The experimental plots were formed by 12 x 12 plants, the plantation spacing was 3 m x 2.75 m, with an approximate area of 1,188 m^2/plot. The irrigation applied averaged 6 mm day^{-1} on dry days to avoid water deficit. Irrigation were tailored to exceed potential evapotranspiration estimated by Thornthwaite & Mather (1951) each week. Irrigation started in

January 2001, at 3 months of age and finished in October 2006 at 6 years of age (Figure 1). Two border lines and trenches up to a depth of 1 meter were excavated to install a plastic film to avoid water movement between plots, and then the trenches were backfilled.

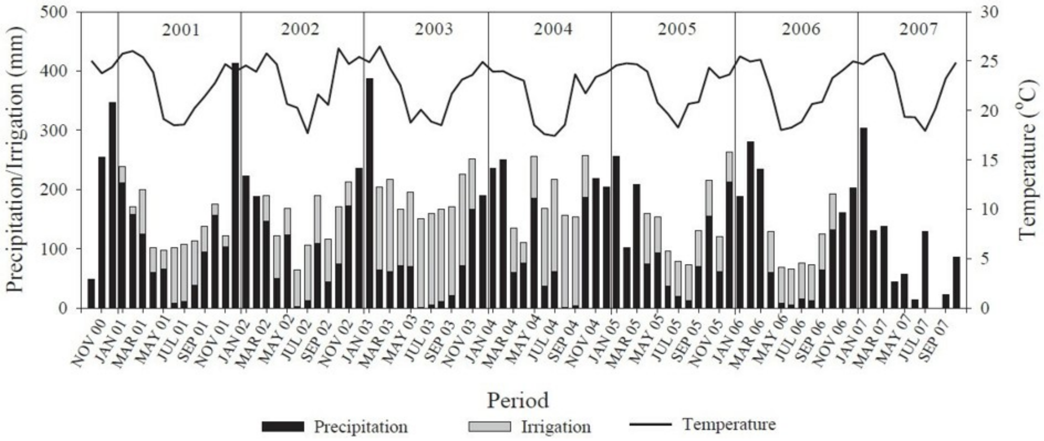

Figure 1. Monthly rainfall, irrigation, and average temperature during the trial assessment from October 2000 to October 2007.

Subsoiling up to the depth of 60 cm were performed, as well as leaf-cutting ant control done seven days prior to the clear cutting and every year afterward with 0.3% sulfluramide. Weeds were prevented with Glyphosate at 2.88 kg of active ingredient ha^{-1}, so, the site was kept without any competing vegetation. The amount of nutrients applied in the treatment with operational fertilization was 33 kg N ha^{-1}, 44 kg P ha^{-1}, 27 kg K ha^{-1}, 2 kg B ha^{-1}, without the application of Ca and Mg in the soil. For the treatment with potential fertilization, 640 kg N ha^{-1}, 238 kg P ha^{-1}, 498 kg K ha^{-1}, 996 kg Ca ha^{-1}, 180 kg Mg ha^{-1}, 5 kg B ha^{-1} were applied. The operational fertilization was applied until the second year when the canopy closed. The potential fertilization occurred from the establishment until the end of the experiment every three months. Potential fertilization is considered the application of a dosage of fertilizer higher than the operational dose used so that there would be enough nutrients available in the soil to avoid any deficiency [For more details of fertilization see Lemos (2011)]. For the calibration of the 3-PG model, the two most differing treatments were used: operational fertilization without irrigation (TN) and potential fertilization and irrigation (FI).

2.3 Dendrometric data, and leaf area index.

The stem growth and leaf area index (LAI) were measured from the installation of the experiment to the rotation age at 7 years. These data were used to calibrate the 3-PG model. The LAI was collected monthly by the indirect method of determination using a ceptometer AccuPAR Model LP-80 Decagon Devices, Pullman, USA, in the period between 12 and 77 months of age. The measurements of the incident PAR (Photosynthetically Active Radiation) were performed following the methodology used by Bréda (2003), at the time of the highest solar incidence. Measurements of the PAR transmitted were taken underneath the canopy immediately after the incident PAR. Twelve systematized points per plot were collected, distributed equally on the row and between plantation rows, making up the two diagonals of the plot. At each sampling point, measurements were taken at the four cardinal points. With the measurements of incident PAR (Io), PAR transmitted (I) and considering the light extinction factor (k)= 0.5 (Stape et al., 2010), we estimated the LAI by the Beer-Lambert equation (Equation 2).

$$LAI = -\left(\frac{1}{k}\right) ln\left(\frac{I}{I_o}\right) \quad (2)$$

Dendrometric measurements of total height and diameter at breast height (DBH) were collected in the plots quarterly, between 5 and 78 months of planting age. The volume was calculated with an equation developed for the clone used in the experiment (Equation 3).

$$V = exp(-10.049541 + 1.863489. ln(DBH) + 1.043579. ln(Ht)) \quad (3)$$

where V is the stem volume in m^3 $tree^{-1}$, DBH is the diameter at breast height in cm and Ht is the total height in meters.

Destructive samples in plots installed in the experiment to determine tree biomass were carried out at 12, 30 and 84 months of stand. These measurements were used to determine stem biomass based on DBH and height (Stape et al., 2010; Equation 3) and allometric equations between leaf biomass, stem and DBH (Sands, 2001; Equation 4) necessary for the parameterization of the 3-PG model.

$$Ws = 0.0050. DBH^{1.751}. Ht^{1.542} \quad n = (169) \quad (4)$$

where Ws is stem biomass in kg, DBH is the diameter at breast height in cm and Ht is the total height of the tree in meters (Equation 5).

$$p_{FS} = a. DBH^{n_P} \quad (5)$$

where pFS refers to the relation between the partitioned biomass for foliage and stem, DBH is the stem diameter at breast height in cm, a and np are the model coefficients (Figure 2).

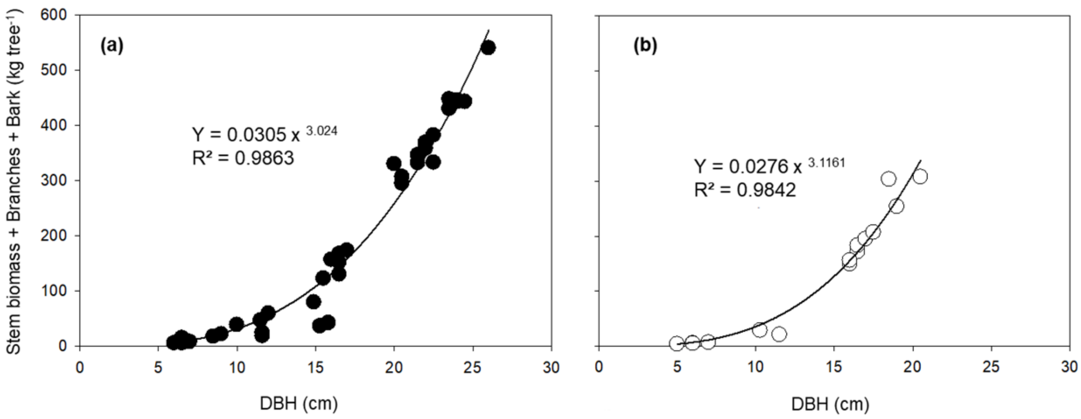

Figure 2. The allometric equation, stem, branches, and bark biomass (kg $tree^{-1}$) as a function of DBH (cm) for fertilized and irrigated treatment-FI (a), and operational and non-irrigated treatment-TN (b).

The bark and branch fraction (ρBB) were determined by age, in order to estimate only stem biomass by the model. At 12 months, the proportion of the bark and branches fraction (ρBB0) was 31.5% for the FI treatment and 31.9% for the TN treatment. At the age of 84 months, this fraction (ρBB1) became 9.5% and 9.3%, respectively. The mean age in bark and branch fraction (tbb) was 4 years. To compare biomass among treatments we applied an ANOVA test for each age.

2.4. Parameterization and calibration of the original model

The parameterization and calibration of the 3-PG model were done using data obtained experimentally in the literature or adjusted (Table 1). The adjusted parameters, through the calibration process of the model, were those related to the Net Primary Productivity (NPP) partitioning: i) minimum fraction of NPP allocated to the root system and; ii) foliage/stem partitioning DBH = 20 cm.

Table 1. Parameters used for 3-PG calibration for treatments irrigated and fertilized (FI) and operational and non-irrigated treatment (TN)

Parameters	Units	Treatments		Source
		TN	FI	
Biomass Partition and Renewal				
Allometric relationships and partition				
Partition foliage / stem dbh=2	-	0.7	0.7	Almeida et al. (2004a)
Partition foliage / stem dbh=20	-	0.11	0.14	Tunning
Constant Coef. for eq. stem biomass / dbh	-	0.0276	0.0305	Adjusted
Power Coef. to eq. stem biomass / dbh	-	3.1161	3.024	Adjusted
Maximum fraction of PPL for root	-	0.6	0.6	Almeida et al. (2004a)
Minimum fraction of PPL for root	-	0.15	0.15	Tunning
Leaf Fall & Root Renewal				
Maximum litterfall rate	kg month^{-1}	0.10	0.13	Adjusted
Leaf rate t=0	1 month^{-1}	0.001	0.001	Sands & Landsberg (2002)
Age at which litterfall acquires average value	month	16	16	Adjusted
Monthly average root renewal rate	1 month^{-1}	0.015	0.015	Sands & Landsberg (2002)
PPL & conductance modifiers				
Temperature modifier (ft)				
Minimum temperature for growth	ºC	8	8	Stape (2002)
Optimum temperature for growth	ºC	21	21	Local average
Maximum temperature for growth	ºC	40	40	Stape (2002)
Frost modifier (fFrost)				
Lost productive days per day of frost	days	0	0	Adjusted
Groundwater modifier (fθ)				
Texture Coef. of soil water modifier	-	0.4	0.4	Landsberg & Waring (1997)
Power Coef. of soil water modifier	-	3	3	Landsberg & Waring (1997)
Structure of the canopy and processes				
Specific leaf area				
Specific leaf area for age 0	m2 kg-1	9	9	Adjusted
Specific leaf area for mature leaves	m2 kg-1	8.5	8.5	Adjusted
Specific leaf area for mature leaves	years	2	2	Adjusted
Interception of light				
Coefficient of light extinction absorbed canopy	-	0.5	0.5	Almeida et al. (2004a)
Age of canopy closure	years	1.5	1.5	Stape (2002)
Maximum ratio of rain evaporated at canopy	-	0.15	0.15	Lima (1993)
LAI for maximum rainfall interception	-	3.33	3.33	
Production and respiration				
Quantum canopy efficiency	molC molPAR-1	0.08	0.08	Almeida et al. (2004b)
PPL / PPB ratio	-	0.47	0.47	Landsberg et al. (2001)
Conductance				
Maximum canopy conductance	m s-1	0.021	0.021	Mielke et al. (1999)
LAI for maximum canopy conductance	-	3.33	3.33	
Stomatal Coefficient in response to VPD	1 mBar-1	0.047	0.047	Almeida et al. (2004a)
Conductance in the boundary layer of the canopy	m s-1	0.2	0.2	Landsberg & Waring (1997)
Properties of the stand and stem				
Maximum stem biomass at 1.000 trees / ha	kg tree-1	300	300	Stape et al. (2004b)
Fraction branch and bark (fracBB)				
Branch and foliage fraction for mature stand	-	0.319	0.315	Adjusted
Fraction branch and foliage at age 1	-	0.093	0.095	Adjusted
Intermediate age between the branch and foliage fraction	years	4	4	Adjusted
Basic Density				
Minimum basic density - for mature trees	t m-3	0.45	0.45	Adjusted
Maximum basic density - for old trees	t m-3	0.55	0.55	Adjusted
Intermediate age between basic density	years	4	4	Adjusted
Stem height				
Constant Coef. in the stem height ratio	-	0.9051	1.2366	Adjusted
Power Coef. of DBH x stem height	-	1.194	1.0668	Adjusted
Power Coef.of N. of trees x stem height	-	0	0	Adjusted
Soil class	-	Site specific	Site specific	Adjusted

Calibration was done first in the FI treatment plots, without limitation in the availability of nutritional and water resources. Once calibrated, the parameters determined were used in the calibration of the TN treatment plots. For the studied soil the available water capacity for the plant (AWC) was 1.5 mm cm^{-1} of soil. In the calibration, we considered 3 meters as effective depth; a value usually adopted for *Eucalyptus* plantations (Ferreira, 2007; Stape et al., 2004b). The AWC used in the parameterization was 300 mm. Stem growth and leaf area index (LAI) were analyzed as response variables. The climatic data used was obtained from a station located in the region of Mogi-Guaçu (temperature, precipitation) and Piracicaba (monthly global radiation). The use of the monthly global radiation of another meteorological station was possible, because it is located 95 km away, at the same altitude and latitude and has a similar average maximum temperature. The initial age for the beginning of stand growth estimation was 1 year because the 3-PG does not estimate seedlings and initial stand conditions well (Sands & Landsberg, 2002). The version of the 3-PG model used was 2.7., which is open for download from the 3-PG official website (Sands, 2010).

2.5. Enhancement of the 3-PG model for maximum water retention

To calculate the maximum amount of water in the soil available for plants (ASWmax, in mm) as a function of root exploration of the soil, the relationship between height and root depth described by Christina et al. (2011) was used, which is defined as Equation 6:

$$ASW\,max_i = Ht_{i-1}\ .\ 0{,}8513\ .\ W_{cont}\ .\ 100 \quad (6)$$

Ht $_{i-1}$ is the tree height in the previous month (m), Wcont is the maximum soil water retention in mm cm^{-1} of soil, and i is the period. The user provides the initial model height. The parameters maximum and minimum capacity of water retention in the soil and the amount of initially available water were removed from the original 3PG model. The parameters introduced were: initial mean height of the stand in meters, maximum water retention in the soil (Wcont, mm cm^{-1} of soil) and maximum soil depth (profmax, m). Then, for the enhanced 3-PG model, the ASWmax varies with the depth of the root system (eq. VI). However, it is limited by maximum soil depth. In this study, the ASWmax limit adopted was the presumed effective depth of the root system, in this case, 5 meters, because 95% of fine roots mass is found up to this depth (Christina et al., 2011).

The performance of the 3-PG model in estimating stem biomass before and after the enhancement was evaluated by: a) efficiency of the model (EF, equation VII) and b) the root mean square error (RMSE, equation VIII). The best model should have EF and R^2 close to the unit, and RMSE close to zero (Mayer & Butler, 1993; Faraway, 2005) (Equations 7-8).

$$EF = \frac{\sum_{i=1}^{n}(O_i-\bar{O})^2 - \sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (7)$$

$$RMSE = \frac{100}{\bar{O}} * \sqrt{\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}} \quad (8)$$

where O represents the observed value, P is the estimated value, i period of observation $\bar{O}$ is the mean value and n refers to the number of observations.

3. RESULTS

3.1. Characterization of forest growth and yield.

The stem biomass growth in the FI treatment compared to the TN treatment presented an average gain of 21.9% (Figure 3). The mean estimated yield at 77 months of age (6.5 years) was 213.0 Mg ha^{-1} (mean annual increment of 32.8 Mg ha^{-1} $year^{-1}$, about 65 m^3 ha^{-1} $year^{-1}$) for the FI treatment and 166.3 Mg ha^{-1} (MAI of 25.3 Mg ha^{-1} $year^{-1}$, equivalent to 51 m^3 $ha^{-1}year^{-1}$) for the TN treatment.

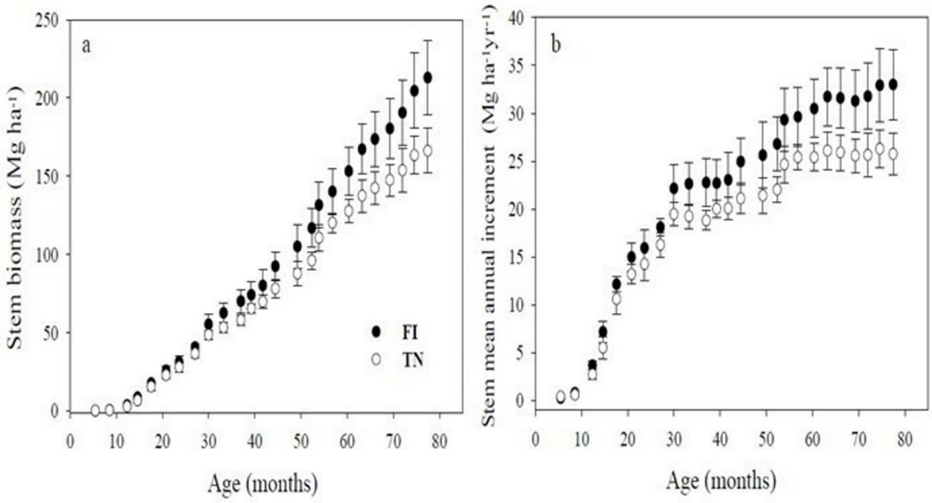

Figure 3. Stem biomass growth (Mg ha^{-1}) and Mean Annual Increment ((Mg ha^{-1} year^{-1}) at different ages, under the fertilized and irrigated treatment (FI) and no fertilized treatment (TN). A vertical line represents the standard error. From 60 months on treatments were different according to ANOVA test ($p<0.05\%$).

The difference between both treatments occurs after month 60; before that moment statistical differences were not found, and the difference between both treatments increased until the last assessment moment (month 80). At this age, stem mean annual increment for TN is at its maximum and has remained constant during the previous 20 months. On the other hand, the FI continued increasing at decreasing rates.

3.2. Improvement of the 3-PG model for maximum soil water retention

The improvement in soil water availability in the 3-PG model consisted of changes in the maximum amount of available water in the soil (ASWmax), which is a constant value in the original model, and it is variable in the enhanced model because it increases with the root system growth in depth as the stand ages, up to the depth of 6.3 m (Figure 4). This enhancement made it possible to improve the growth estimate in stem biomass and leaf area index in TN and FI treatments (Figures 5 and 6, respectively).

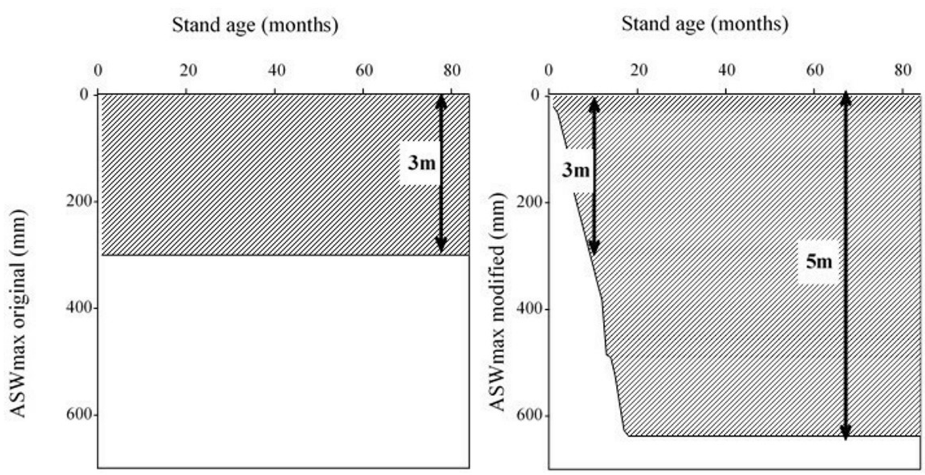

Figure 4. Maximum available soil water originally used by the 3-PG model (ASWmax original-left) and after enhancement (ASWmax modified-right) and a function of plantation age. The arrows represent root systems exploration depth.

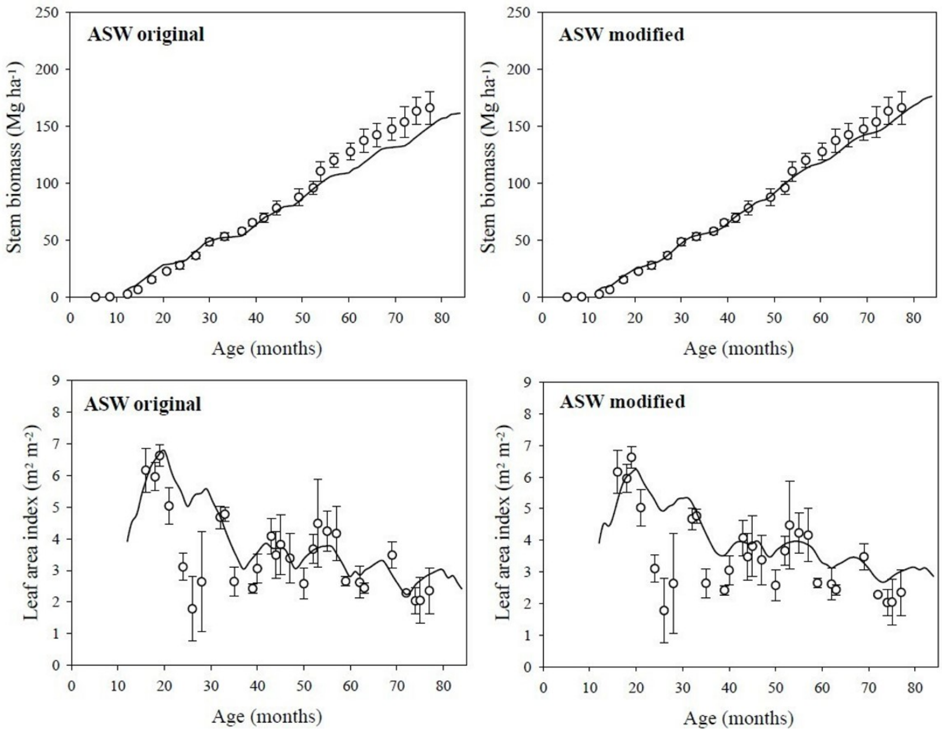

Figure 5. Stem biomass and leaf area index estimation for treatment TN using the original 3-PG and the enhanced 3-PG (ASW modified). The points represent field observations, and the continuous lines represent the 3-PG model estimation.

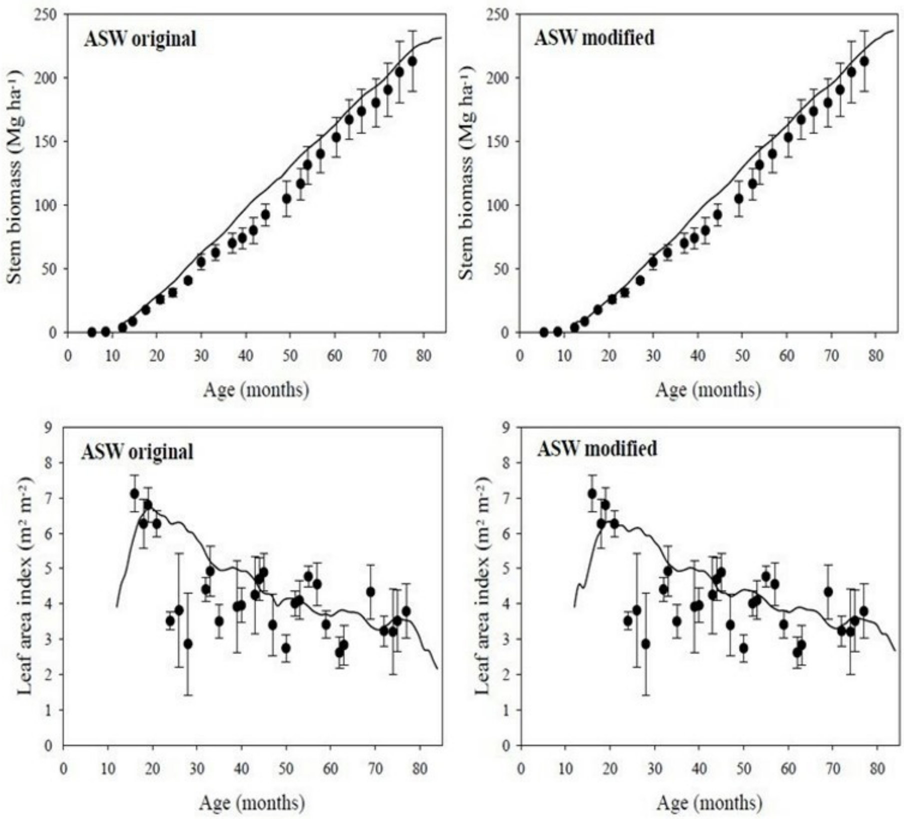

Figure 6. Stem biomass and leaf area index estimation for treatment FI using the original 3-PG and the enhanced 3-PG (ASW modified). The points represent field observations and the continuous lines represent the 3-PG model estimation

The enhancement introduced into the 3-PG model affected directly the physiological modifier (fphy), which is also affected by the vapor pressure deficit (fdpv) and the soil moisture modifiers (fθ). The vapor pressure deficit is not affected by the change introduced in the model; but the soil moisture is (Figure 7). The upper left panel shows the physiological modifier for both treatments using the original model; the top right panel shows the same information under the modified 3-PG.

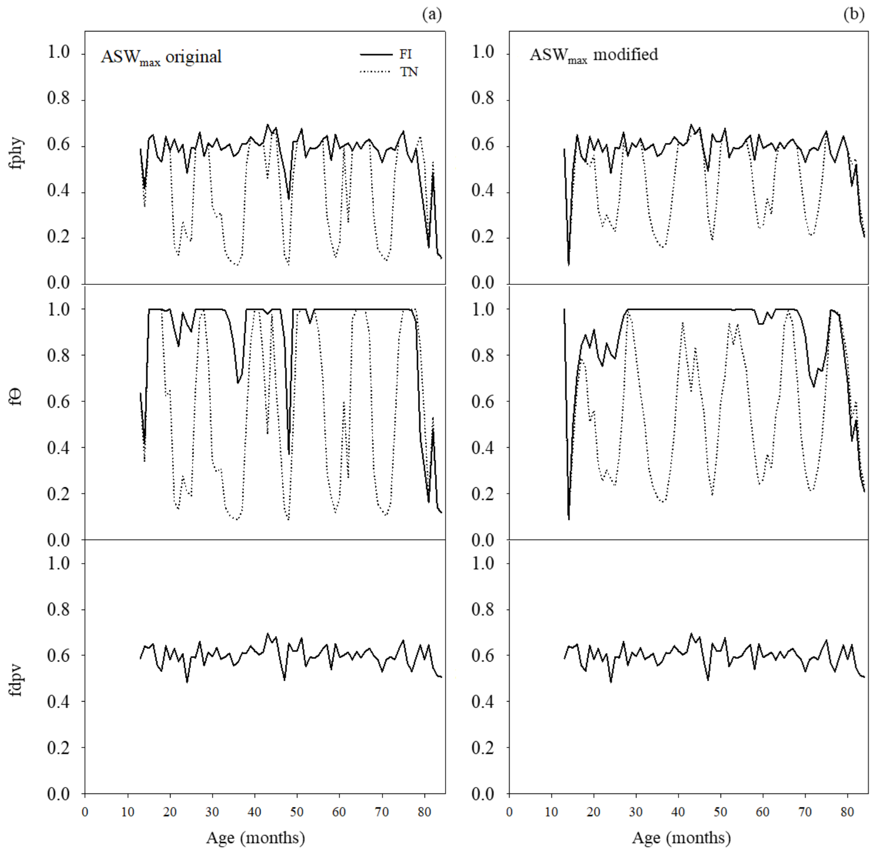

Figure 7. Physiological modifiers (fphy) comparison, soil moisture (fθ), and vapor pressure deficit (fdpv) estimated for treatments: (FI) e (TN) between original and enhanced 3-PG models

The efficiency of the model (EF) in estimating the stem biomass in TN treatment increased from 0.94 (original) to 0.98 (enhanced), and the square root of the mean error (RMSE) decreased from 18.22 (original) to 11.92 (enhanced). In the FI treatment, the efficiency of the model (EF) in estimating stem biomass had a slight increase from 0.93 to 0.95. However, the RMSE showed a small decrease from 18.72 to 17.85 for the original and enhanced, respectively. An improvement in biomass estimation is also attained if the maximum ASW were changed in the original model, by increasing the maximum root depth from 3 to 5 m. However, it does not reflect what happens in nature.

4. DISCUSSION

The original 3PG has a fixed soil depth, and once defined the soil texture and the water holding capacity, the soil water availability remains fixed. However, this is not what happens in nature, especially in cases when there is not a constraint for root growth. For this reason, the original 3-PG, in some cases, underestimates the stand growth because it does not consider that water availability is dynamic as roots grow.

More recently, Marsden et al. (2013), and Almeida & Sands (2016), incorporated into the G`Day and 3-PG models, respectively, a water balance sub-model, which considered different soil layers with different water holding capacities, and also a progressive root grow as the stand aged, simulating what occurs in reality. In both cases, there was an improvement in biomass estimation. However, it requires more data not always easily available. G´Day needs, aside from many other physiological parameters, daily meteorological data, and water retention for each soil layer. The 3-PG modification introduced by Almeida & Sands (2016), has also time steps lower than one month, which implies more data which not always is available, especially in undeveloped regions in the tropics. Both enhanced models are very useful for research and understanding of the physiological process associated with forest growth, but at the same time require more data, which constrains its operational use, its utilization in remote areas, or areas with no forest plantations.

In our case, the original 3-PG model underestimated the TN treatment after the 50th month, presenting a difference of 15 Mg ha^{-1} at 7 years, when compared with the observed value. This difference is mainly due to the water stress generated artificially by the model because the defined root system depth had already been reached at that moment. The 3-PG model parameterized and used for *Eucalyptus* in Brazil, was set up with an effective depth ranging from 2 to 2.5 meters (Stape, 2002; Almeida et al., 2004b; Stape et al., 2004a; Almeida et al., 2010), and probably for these sites 3-PG underestimates the forest productivity and yield at rotation age.

For *Eucalyptus*, deep roots are critical for water supply, especially in dry sites or sites with low water retention. According to Sana (1997), as cited in Laclau et al. (2001) and Bouillet et al. (2002), who worked with *Eucalyptus* planted in Congo, at 5,5 years of age most of the soil water absorbed by the plant during the dry season was below 5 meters in depth. This was also confirmed by Nambiar & Sands (1992) for *Pinus*, in which the deepest roots were essential for the plant water supply during the dry season, where there was a reduction in the moisture of the superficial layer of the soil. Even when the importance of the root system exploring the soil and water uptake is well known, this process is still poorly understood due to the difficulty of measurement underneath the surface (Gonçalves & Mello, 2000; Christina et al., 2011). Some studies show that the *Eucalyptus* root system is not limited to 2 meters, reaching up to 5 meters or more (Laclau et al., 2001; Bouillet et al., 2002; Christina et al., 2011), which could be the case in many plantations established on deep soils.

To simulate this root system dynamics and enhance 3-PG stem biomass estimates, Almeida & Sands (2016) proposed an improvement on the water balance sub-model, which is more similar to the real process. However, even when the ASW estimation was better for their study sites, their estimates of stem biomass and LAI for the Australian sites improved; but it was the opposite for the Brazilian site. The better estimation of ASW at early ages did not have any significant effect on stem or root mass estimation; maybe because at young ages, the tree's water demand is still low. But, for later ages, both water balance models tested had a significant difference in stem mass, root mass, and LAI estimation for the Brazilian site. In their model, they consider that root depth increased as root biomass increased using a factor to transform root biomass into volume explored by the root mass which is constant over time and climatic conditions. This shows the complexity of all the biological processes scientists are trying to model. In our case, the stem mass and LAI estimation improved with the new model, but it has been tested only on the same site where the root depth model was developed by Christina et al. (2011), and for a growth period when no drastic climatic event occurred, unlike the case of Almeida & Sands (2016). In their case study, a severe drought happened when the trees were 6 years old, which affected the way the whole system interacts and it is not represented by the model.

Despite the adoption of ASWmax as a variable with an effective depth greater than the usually utilized, it was verified that the model, with the enhancement we proposed, simulates adequately different water stress depending on the treatment applied. Water stress is represented in the model as the soil water modifier (fθ). The fθ together with the DPV modifier (fdpv) composes the physiological modifier (fphy), which limits the apparent quantum efficiency of the canopy and, consequently, the assimilation of carbon by the tree. As a consequence of the enhancement introduced, the soil water modifier (fθ), for both treatments was larger; which means the water stress was not as severe as in the original model. This issue could generate relevant differences in volume estimation in areas where there are deep soils with a high water holding capacity and the precipitation is not well distributed during the year, as is the case in many places in the tropics.

The enhancement introduced into the 3-PG model will permit us to compare the impact of a drought in stands with different ages. The effect could be stronger on younger stands (before canopy closure), because they have a shorter root system that constraints the soil volume explored by the root system (Christina et al., 2011; Lemos, 2011), but also because younger trees have a higher LAI and in consequence a higher transpiration surface (Lemos, 2011). A re-parameterization of the original model is possible, allowing a higher ASW only by changing the maximum root depth from 3 to 5 m, and it enhanced the biomass estimation but does not reflect what happens in reality. The ASW increases as the root system increases and using only a re-parameterization of the original model will overestimate the biomass in cases where a drought occurs or when the model is used in dryer areas. The water below the rooting zone is not available, and a simple re-parameterization will take it into account, impeding the simulation of early water stress (Marsden et al., 2013).

The possibility to model different climatic conditions using the enhanced model, could help to orientate where and when to apply silvicultural treatments to increase productivity. The evaluation of water supply is very important for selecting the best harvesting and silvicultural timing, especially for tropical conditions where rainfall and its distribution is the main limiting factor to reach higher productivities (Gonçalves et al., 2008).

For planning purposes, this enhancement on volume estimation will permit higher accuracy in assessing the impact of drought at the forest level and will allow an understanding the effect of volume variability on harvest planning (Scolforo et al., 2013) as well to forecast the effects of climate change in forest growth (Palma et al., 2021). The best example is the recent severe drought affecting drastically: Minas Gerais, Bahia, and Espirito Santo states in Brazil, which impacted timber supply significantly, generating losses and a supply deficit of raw material. In the future, drought scenarios analysis and stochastic programming should be used to minimize the effects of this kind of event, and the 3-PG will be used as a tool to assess the impact of drought in volume production, and by consequence in volume supply. This enhancement will bring new operational, practical questions that will be the starting point for further research.

5. CONCLUSION

Based on the analysis of a complete cycle of 7-years of clonal *Eucalyptus*, over a eutrophic soil, and with water supply levels (only rainfall and irrigation), it is concluded that the modification of ASW as a function of the root depth in the soil profile improved the growth estimates in stem biomass for *Eucalyptus* plantations. The enhancement introduced, follows the natural way of soil exploration by the roots of the trees, and the improvement in the estimates for the operational treatment, based on the square root of the mean error (RMSE), represented a decrease of 25%, which is a significant improvement in the model. This enhanced model allows a better estimation of stand biomass, without increasing too much the need for additional information. The model still has some issues that could be improved, because it still considers the soil as composed by as a single uniform layer, which introduces a bias, and its magnitude should be assessed. This enhanced model is useful for deep soils which are common on more developed soils on tropical regions where *Eucalyptus* is mostly planted. However, it is necessary for a better understanding of how the enhanced model performs under other soils, genetic material, and climatic conditions.

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