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Testing the 3-PG process-based model to simulate *Eucalyptus* growth with an objective approach to the soil fertility rating parameter

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ABSTRACT

We evaluated the ability of the 3-PG process-based model to simulate *Eucalyptus* response to changes in fertility and climate by calibrating the model with two tropical *Eucalyptus* trials that had complete production data. Validation was performed using independent data from forty paired-plots (with and without fertilization) monitored for 2 years. The model captured the influence of water and nutrients on C gain and allocation pattern during calibration. The model also responded well to soil fertility and climate conditions during validation, and was particularly sensitive to LAI estimates. The fertility rating paramater needed by 3-PG model was established using an objective approach based on the fertilization response of the paired-plots. Actual wood production ranged from 2 to 51 Mg ha^{-1} yr^{-1}, compared with model estimates of 10 to 42 Mg ha^{-1} yr^{-1} ($r^2 = 0.78$). We concluded that process-based models can play an important role in improving the management of these almost-agricultural forests, mainly on regions with high rainfall variability.

INTRODUCTION

Eucalyptus is the dominant and most productive planted forest in Brazil (9 to 39 Mg ha^{-1} yr^{-1}, Stape 2002), with more than 3.5 million hectares intensively managed mainly for charcoal, pulpwood and sawtimber products (Simoes et al. 1981, FAO 1999, Neilson 2000). Growth and yield models based on stand attributes are the current tools for predicting wood increments and wood supplies (Campos et al. 1988, Scolforo and Machado 1990). Site index is still the central concept embodying the average environmental quality that sites may have on tree growth (Scolforo and Machado 1990, Burkhart 1997, Reed 1997). Classic growth and yield models limitations for forest production estimates include: (i) they cannot be used to estimate productivity on non-forested landscapes; (ii) in the short term, these models are insensitive to inter-annual climatic variations, which can dramatically affect final production of short-rotation forests due to 1 or more years of bad growing conditions, and (iii) changes in management practices between rotations can alter empirical relationships (Gonçalves et al. 2000, Eldridge et al. 1994, Seixas et al. 1995).

Empirical models do not allow the insertion of the forest production in a broader ecosystem framework regarding the associated use of natural resources (Running and Gower 1991, Landsberg and Gower 1997, Kimmins 1997) and the forest-soil feedback throughout the detritus C and nutrient cycling (Parton et al. 1994, Burger and Kelting 1998), which have increasing economical and social relevance (Brown et al. 1997).

Process-based models describe forest productivity based on plant physiological processes that control growth (i.e., photosynthesis, allocation, respiration, transpiration, nutrition and litterfall), and many have been developed (see summary in Landsberg and Gower 1997). Despite the appeal of mechanistic simulations of growth and resource use under different environmental conditions, process-based models are rarely used as management tools (Kimmins 1997, Landsberg and Waring 1997). The limited application of these models likely results from the greater complexity of process-based models, the large number of required parameters (and the difficulties of obtaining estimates), the need of extensive input from environmental files, and models' incomplete documentation. However, recent reviews of process-based models suggest that simple models based on absorbed photosyntheically active radiation (PAR) (Battaglia and Sands 1998, Makela et al. 2000) may overcome these difficulties. APAR models calculate photosynthesis by first estimating the amount of PAR absorbed by the canopy and its ability to fix C. The ability of radiation to produce photosynthesis is modulated with a light-use-efficiency parameter (Monteith 1977), which changes with environmental factors that affect stomatal conductance or the activity of the photosynthesis pathway (Jarvis and Leverenz 1983, Sands 1996, Goetz 1997). This "top-down" approach to the physiology of forest growth reduces the number of required parameters and eliminates many of the non-linearities of these processes at finer scales (Medlyn 1998). Furthermore, water and C sub-models can be coupled throughout canopy processes (McMurtrie et al. 1990, Landsberg and Gower 1997), and the high complexity of nutrient soil dynamics can be lumped into fertility-rating scaling factors (Landsberg and Waring 1997, Battaglia and Sands 1997).

The incorporation of process-based models as a management tool by the large and expanding forest sector in the tropics may allow: (i) assessments of the risks of climatic variation on forest productivity and profitability, (ii) estimations of potential productivity for regional forestation planning, (iii) identification of environmental factors limiting growth and estimated resource uses, (iv) a framework for management and breeding programs, and (v) evaluation of the long-term forest productivity when coupled with soil-models. As a step in this direction, we evaluated the 3-PG model (Landsberg and Waring 1997) for *Eucalyptus* plantations in Brazil. The model was selected due to its concise structure, dynamic carbon allocation regulation, sensitivity to environmental factors and site management practices, successful parameterisation and validation for other forest systems (Law et al. 1999, Coops et al. 1998, Landsberg et al. 2000), and adequate documentation (Sands and Landsberg 2002).

Our test of the utility of the 3-PG model had 3 components. First, we calibrated the model with data from one fertilization trial with *E. saligna* in Hawaii. Next, the model was re-calibrated for an irrigation and fertilization trial with *E. grandis* x *urophylla* in Brazil. Third, we evaluated the model's performance against independent growth data from forty pairs of control and fertilized inventory plots monitored for two years in northeastern Brazil, with a further comparison with the predictions of an empirical model. Additionally, we investigated the fertilization response as an index to scale the fertility-rating parameter needed to run the 3-PG model.

MATERIALS AND METHODS

Overview of the calibration and validation steps

Calibration and validation of the 3-PG model involved three steps: (i) calibration for 6-years of production of an *E. saligna* fertilization trial in Hawaii; (ii) re-calibration for 2-years of production of an *E. grandis x urophylla* irrigation trial in Brazil; and (iii) validation against independent production data of forty paired control-fertilized *E. grandis x urophylla* inventory plots in Brazil, monitored during two distinct climatic (rainfall) years, with a further comparison with a null-empirical yield model fitted for the control plots and used to estimate the 2 years growth. During calibration (steps i and ii), the model was tuned for the treatments with no water or nutrient limitations and verified for the treatments with limited nutrient (Hawaii) or water (Brazil) supplies. Validation of the 3-PG model (step iii) initially utilized the fertilized inventory plots, because a site-specific fertility rating parameter was required (ranging from zero to 1, and set as 1 in these plots). Based on the validation results for wood increment and LAI outputs, a new parameterisation and second run for 3-PG were undertaken. Finally, 3-PG was run for the control plots, scaling a fertility-rating factor for each site based on the fertilization response of the stands.

3-PG Model

The 3-PG is a monthly-step process-based forest model (Landsberg and Waring 1997, Sands and Landsberg 2002) of the APAR family (after Monteith 1977), for which weather, site and species-specific parameter requirements are supposed to be relatively easy to obtain. 3-PG has a biophysical submodel which estimates monthly evaporation and canopy transpiration using the Penman-Monteith model. Canopy conductance in the Penman-Monteith model is controlled by the most restrictive factor controlling stomatal aperture: vapor pressure deficit (VPD) or soil water limitation. The vapor pressure deficit modifier (f_D) is negatively and exponentially related to average monthly VPD through the coefficient of stomatal response to VPD (k_g). Soil water balance is the difference between precipitation and evapotranspiration. Water is drained if water holding capacity in the rooting zone is exceeded. The soil water modifier (f_θ) is inversely related with soil moisture and depends on soil texture.

The forest production submodel estimates gross primary production (GPP) based on the monthly intercepted PAR times a theoretical maximum canopy quantum efficiency (α^*) reduced by physiological (age, VPD or soil water) or environmental modifiers (temperature, soil fertility and frost). Soil fertility is expressed as a simple rating factor, with a subjective approach. Intercepted PAR is calculated based on the Beer Lambert's law, and LAI is estimated from the foliage biomass and specific leaf area. Net primary production (NPP) is estimated as GPP times a NPP:GPP ratio (0.45 ± 0.05) to account for respiration. NPP is primarily allocated to the root compartment, inversely proportional to the harshness of the environment (defined as the minimum value between f_D and f_θ) and soil fertility, within maximum and minimum allocation limits defined for the species. The fraction of NPP allocated aboveground is partitioned between stem and foliage growth in a proportion that conserves the allometric relation of the trees, but varies with tree size. The establishment of this proportion can be based on species- and site-specific allometrics for foliage and stem biomass and is represented in 3-PG by two partitioning parameters. Litterfall rate increases with age up to a maximum defined value. For this study, we coded the 3-PG model in Visual-Basic (based on Landsberg and Waring 1997, and Sands and Landsberg 2002). No mortality rate was employed, and the age effect on photosynthesis was not implemented.

Hawaii and Brazil trials

The Hawaii fertilization trial and Brazil irrigation and fertilization trial were used for 3-PG calibration due to the fact that they: (i) represented typical high-productive tropical *Eucalyptus* plantations, *(*ii) had complete C budgets with above- and belowground C allocation estimates during 6 years (Hawaii) or 2 years (Brazil), (iii) had high water and nutrient regime treatments used for calibration, and (iv) presented a control treatment with low fertility (Hawaii) or low water supply (Brazil) for a preliminary test of the model. Although process models should ideally be calibrated for both C and water balances (Waring and McDowell 2002), only the C budget was evaluated in this study because the 3-PG biophysical water submodel had already been shown to adequately estimate the water balance of a clonal *Eucalyptus* trial in Brazil (Stape 2002).

The Hawaii fertilization experiment was an *E. saligna* (originated from seeds) plantation located 13 km NNE of Hilo (19° 50' N, 155° 07' W) and planted in April 1994. Annual precipitation averages more than 4000 mm/yr, mean annual temperature averages 21.0°C, and the soil is a well-drained, deep (>2 m) Typic Hydrandept. The experimental design consisted of a factorial with two spacings and three fertilization regimes in 3 completely randomized blocks. For this modeling study, just the 3 x 3 m spacing with control and high fertilization regimes were used (control and fertilized treatments). A weather station provided daily averages for photosynthetically active radiation (PAR), air temperature, relative humidity and daily total precipitation, summarized on monthly files. Detailed information regarding the experiment is found elsewhere (Binkley and Resh 1999, Barnard 2000 and Giardina and Ryan 2002).

The Brazil irrigation and fertilization trial (details on Chapter II) was located on the northeastern coast of Brazil, about 20 km SW of Entre-Rios (11° 58' S, 38° 07' W) with a mean annual temperature of 25.5°C and an average rainfall of 1040 mm/yr. The slopes were gentle (< 3%), with deep (> 3 m), excessively drained sandy isohyperthermic Typic Haplustox soil. The plantation was established in June 1996 with an *E. grandis* x *urophylla* clone at 3.0 m x 3.0 m spacing, and treatments were installed when the plantation was 3 years-old. A 2 x 2 factorial with 4 replicates, was used with two-levels of nutrient and water regimes. High fertilization and irrigation regimes (> 2100 mm/yr) were designed to eliminate any nutrient or water limitation on eucalyptus growth. No fertilization effect was observed in the experiment, so we analyzed results as averages across irrigation regimes (rainfed and irrigated treatments), and fertility rating was considered to be 1 (not limiting). A monthly meteorological file with maximum and minimum temperatures, vapor pressure deficit (VPD) and photosynthetically active radiation was derived based on weather data from 2 close meteorological stations (Stape 2002).

Aboveground woody biomass (AWB) and leaf area index (LAI) were estimated every 3 months (in Hawaii) or 6 months (in Brazil), along with yearly estimates of aboveground net primary production (ANPP), total belowground carbon allocation (TBCA) and gross primary production (GPP) for each plot and year. TBCA was determined by the mass-balance technique

(Giardina and Ryan 2002) and represents all C allocated to the roots, while GPP was obtained as the sum of ANPP, TBCA and aboveground autotrophic respiration (Ryan 1991). The Hawaii experiment was used for calibration due to its larger data set. The re-calibration for Brazil conditions allowed the evaluation of the species-specific parameters in the model.

Calibration procedures

The number of parameters to be tuned was minimized by keeping constant all possible site- or species-specific parameters that were locally determined or derived from literature data (Table 1). The chosen outputs to evaluate the model during the calibration phase were the yearly estimates of GPP, ANPP, TBCA, average LAI and the AWB at the end of each year. These variables capture three crucial processes: (i) the total amount of C fixed (GPP), (ii) the C allocation pattern (TBCA and ANPP), and (iii) the aboveground partitioning between wood and foliage (AWB and LAI). We estimated TBCA from the model as 2 times the belowground NPP, assuming that respiration equals production (Binkley and Ryan 1998, Law et al. 1999). The tuning process was conducted to simultaneously match predicted and observed values of GPP, ANPP, AWB and LAI (TBCA was not incorporated because it was a linear combination of GPP and ANPP), using a weighted sum of squares (Young et al. 1979), which is a way of normalizing the sum of squares of each variable to its absolute magnitude:

$$WSS = \sum_{i=1}^{v} \frac{n_i \sum_{j=1}^{ni} (P_j - O_j)^2}{(\sum_{j=1}^{ni} O_j)^2}$$

where WSS is the weighted sum of squares, v is the number of variables ($v = 4$), n_i is the number of predicted-observed pairs for the variable i ($n = 6$ and 2 for Hawaii and Brazil), and P_j and O_j are the predicted and observed values. The tuning process used an automated optimization procedure in Visual Basic to minimize WSS with constraints to limit the search within feasible values of the tunable parameters. The optimization routine was initialized several times with different combinations of initial values for the parameters, and the final parameterisation was based on the visual inspection of plotted observed and simulated outputs. As criteria for the goodness of fit of the model, we expected the simulated line to pass within 1 or 2 standard deviations about the observed data points.

Hawaii calibration

The parameters tuned for Hawaii were: fertility rating, coefficient of stomatal response to VPD, and foliage-stem partitioning parameters (Table 1). Two tunings were implemented. First, the fertilized treatment data were used, and the fertility-rating parameter was fixed as 1.0. After this calibration, a new tuning was done for the control treatment only for the fertility-rating parameter. The model was initialized using the average 7 month-old biomass (January 1995) and run for 6 years with the same meteorological file for the control and fertilized treatments.

Brazil calibration

The species-specific parameters from the Hawaii *E. saligna* were evaluated for simulating the *E. grandis* x *urophylla* clone production for the irrigated treatment. Next, local SLA, litterfall and allometrics for the clone (Stape 2002) were applied, and tuning was carried out for maximum canopy quantum efficiency and the stomatal response to VPD. With no further tuning, the weather file was changed (without irrigation supply) and the model run to simulate the rainfed treatment. In all cases, the model was initialized at 3.5 years of age and run for 2 years.

Validation: site descriptions and measurements

The 3-PG performance was evaluated by its ability to predict two years of independent aboveground woody biomass increment measured in forty inventory plots located in five areas of commercial plantations (Table 2) in northeastern Brazil (within a 60-km radius of Entre-Rios, 11°58'S, 38°07'W) selected in July of 1999. The final parameterisation obtained for the Brazil experiment was used. Concomitantly, a traditional empirical yield model, based on age, site index and basal area was developed and used as a null-model to estimate the 2 years production of the control plots. This tropical area has a uniform mean annual temperature of 25.5°C and a pronounced inter-annual variability in rainfall (Stape 2002).

The 6 year-old, first-rotation stands were chosen to capture regional differences in soil and productivity (mean annual increment at age 6 ranged from 7 to 20 Mg ha^{-1} yr^{-1}). All sites were located in flat or modest slopes (< 3%) and site preparation included slash-and-burning of the initial vegetation (pasture, secondary forest or savanna), disking and harrowing. Forests were planted in July of 1993 at 3.5 m x 2.6 m or 3.0 m x 3.0 m spacings and fertilized with 22 kg N ha^{-1}, 36 kg P ha^{-1} and 19 kg K ha^{-1}. The 4 month-old clonal cuttings were produced in a shade-house and selected for uniform size (25 to 35 cm in height) (Stape et al. 2001). Chemicals were applied yearly to control leaf-cutting ants (sulfluramid) and during the first 2 years to control weeds (glyphosate). All stands consisted of monoclonal *E. grandis* x *urophylla* plantations (Clones COP-0204, 0321, 0477, 0670, 1341 or 2361). In each stand, a circular inventory plot of 471 m^2 had been measured yearly since 2 years of age. The diameters at breast height (DBH, at 1.30 m) were measured for all trees, as well as the first 20 heights and the heights of the 4 dominant trees. A high fertilization regime was designed to eliminate any nutrient deficiency and evaluate the fertilization effect on growth. A paired-plot was installed in July of 1999 in each of the stands within 30 meters of the original inventory plot (control plots), with the same form and dimension to be fertilized (fertilized, or “twin” plots). Fertilizers were applied at high rates of: 600 kg Ca ha^{-1} and 300 kg Mg ha^{-1} (as lime); 4 kg B ha^{-1}, 2 kg Cu ha^{-1} and 2 kg Zn ha^{-1} (as FTE micronutrient fertilizer) in September of 1999, followed by quarterly fertilizations with 126 kg N ha^{-1} (as ammonium sulphate), 21 kg P ha^{-1} (as superphosphate) and 79 kg K ha^{-1} (as KCl). All fertilizers were broadcast, applied during 2 years. Trenches (0.25 m wide and 0.80 m deep) between plots minimized any fertilizer effect on the control plots. From July 1999 to August 2001, all paired-plots were measured every 6 months and aboveground woody biomass (stem plus bark and branches) was estimated between 2 and 4 years-old using a general allometric equation and for measurement at 5 years-old or older local equations were used. The annual aboveground woody biomass productions represent the summed growth of individual trees between July 1999 and June 2000, and between July 2000 and June 2001. The site index, defined as the average height of the largest 100 trees per hectare at 5 years-old, was directly determined by the average of the 4 biggest trees in each plot at 5 years-old. Leaf area index was estimated for each plot on July of 1999 and June of 2000 with the regional allometrics and considering an average SLA of 8.5 m^2 kg^{-1}. On March of 2001 LAI was estimated using optical procedures with a Ceptometer-AccuPAR Model 80 (Decagon Devices, Pullman, USA), and the same LAI value was used for June 2001. LAI was interpolated monthly between estimates. For each site, an interpolated meteorological file with monthly PAR, VPD, rainfall and temperatures was created based on daily weather data from local meteorological stations (Stape 2002). A light-use-efficiency was estimated for each year and plot as the ratio between wood increment and APAR. Water holding capacity for each site (a 2 m profile was considered for water budget) was estimated by a general equation developed for the region based on soil texture (Stape 2002).

Validation: first and second 3-PG model runs

The 3-PG model was validated by estimating two growing periods (1999/2000 and 2000/2001) for the fertilized plots (fertility ratings set as 1). The periods presented very distinct rainfall totals (wet year with 1845 mm/yr, and normal year with 1287 mm/yr, Table 3). The model was provided with the initial stand and soil conditions at 6 years-old, together with the respective monthly meteorological files for the two growing years. The monthly growth estimates were summed to obtain the year estimates.

Based on the validation results of wood increments, LAI, and water balance for the first 3-PG run, a slight re-parameterisation was implemented by manually changing the SLA parameter (Table 1). A second 3-PG run was executed; statistics calculated, and results compared with the first run.

3-PG model run for control plots

Site-specific fertility-rating factors were needed to obtain 3-PG simulated values for the control plots using the second parameterisation. For that purpose, we investigated the use of the fertilization responses as an objective index for the fertility rating parameter. Fertilization response (FER, in Mg ha^{-1} yr^{-1}) was defined as:

$$\ln(AWB_2) = \alpha_0 + \alpha_1 S + \alpha_2 / A_2 + \alpha_3 \ln(BA_1) A_1 / A_2 + \alpha_4 (1 - A_1 / A_2) + \alpha_5 S (1 - A_1 / A_2)$$

where WNPP is the wood increment, IWB is the initial wood biomass (at age 6), and the subscripts C and F are for control and fertilized plots. Indeed, this adjusted fertilization response did not differ from the non-adjusted due to the paired-plot design. Fertilization responses were evaluated just for the wet year (rainfall > 1500 mm, Table 3), because the differences in growth due to fertilization among sites are clearest when water is not a limiting factor. Fertilization response did not relate with initial biomass (data not shown), and no covariate adjustment was needed.

To test if the fertility-rating parameter representation in 3-PG was in line with fertilization responses, we selected the 3 sites with the highest fertilization responses (29.0, 22.9 and 19.0 Mg ha^{-1} yr^{-1}) and 3 sites with no responses (-3.3, -2.3 and -0.8 Mg ha^{-1} yr^{-1}). For each one, the fertility-rating parameter was tuned to match the wood increment during the wet year. For the high fertilization response sites, the tuned fertility-rating parameters were 0.61, 0.72 and 0.78, while for the non-responsive sites, the fertility-rating parameters were 0.88, 1.01 and 1.10. Due to the coherent directional trend of the fertility-rating values, we estimated all the fertility-rating factors (FR) by scaling between 0.6 (maximum fertilization response, arbitrarily chosen based on highest responsive plot) and 1.0 (no fertilization response), during the wet year (FR = 0.4 (29 – FER)/29 + 0.6), where 29 Mg ha^{-1} yr^{-1} was the highest observed fertilization response. With the site-specific fertility-ratings, 3-PG was run for control plots and compared with the SC model estimates.

Empirical yield-model

The Sullivan and Clutter model (from now on called SC model, Clutter et al. 1983) has been successfully and routinely applied in Brazil for *Eucalyptus* (Scolforo and Machado 1990, Campos et al. 1988). This model is derived from two production equations, one for basal area and one for aboveground woody biomass based on age and site index, which are mathematically manipulated to obtain the biomass yield equation:

$$FER = \left(\frac{WNPP_F}{IWB_F} - \frac{WNPP_C}{IWB_C}\right).\left(\frac{IWB_F + IWB_C}{2}\right)$$

where BA is basal area (m² ha^{-1}), S is the site index (m), A is the stand age (months), AWB is aboveground woody biomass (Mg ha^{-1}), and α_i are coefficients to be estimated, and the subscripts 1 and 2 on AWB and BA stand for their values at ages A_1 and A_2. The available data from 2 to 6 years-old for the 40 control inventory plots were used to estimate the SC model coefficients using ordinary least square procedures in SAS (Table 4). After estimating SC model parameters, basal area at age 6 and site index of the control plots were provided to estimate wood biomass at ages 7 and 8.

Fertilization response and soil fertility and canopy indices

A complete soil and stand characterization were prepared for each site, and a total of 38 soil, 8 bioassay and 16 stand indices (Table 5) were obtained for the control plots. The sampling and laboratory procedures for soil, bioassay and canopy indices are fully described in Stape (2002).

Statistical analysis

For each set of simulated and observed aboveground woody biomass production, the following statistics were obtained to help evaluate model performances: model efficiency (EF), root mean square error (RMSE), the *a* and *b* coefficients of the linear relation between predicted (P_i) and observed (O_i) data, and the coefficient of determination (r^2) (Loague and Green 1991):

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

$$RMSE = \sqrt{\sum_{i=1}^{n}(Pi - Oi)^2 / n}$$

The best model should have EF and r^2 close to the unity, RMSE close to zero, and *a* and *b* not significantly different from zero and 1, respectively. As we were interested in yearly production estimates, all analyses were done considering a total of 80 observed-simulated pairs (n= 2 years times 40 plots).

Analyses of variances were performed considering fertilization and site (block) as the main effects, with year as a repeated measurement factor for variables estimated for both the wet and normal years: wood increment, LAI, canopy N, canopy P, APAR and LUE. The initial wood biomass of the stands and its interaction with fertilization were tested as potential covariates for the wood increment analysis, but both were shown to be non significant (*P* = 0.51 and *P* = 0.33, respectively) due to the blocking. For variables evaluated just once, or analyzed independently at the beginning or end of the study period, an ANOVA having fertilization and block as the mains effects were used: total soil C, total soil N, and biometric stand attributes. Year and block were the main effects for meteorological data analysis.

To investigate the relation between fertilization response and soil or stand –canopy indices, multiple regressions with a stepwise procedure in SAS were used, with fertilization response as the dependent variable and the indices as independent variables. The minimal inclusion significance of a variable was set at $p = 0.10$. Due to the large number of soil independent variables we utilized the following steps to avoid over parameterisation: (i) independent variables were classified into soil-physical, soil-lab incubations, soil-fertility and soil-bioassay groups (Table 5); (ii) fertilization responses were regressed against the independent variables of each group, separately; and (iii) groups were aggregated by taking, at most, the best 3 variables of each group during the isolated analysis. Residual analysis checked for normality and homocedasticity. For the stand indices no grouping was necessary.

All analyses were performed on SAS 8.1 (SAS Institute Inc., Carry, NC, USA 2001) with multiple comparisons with a significant level of 0.05 to protect against type I error.

RESULTS

Calibration

For the Hawaii trial, a maximum canopy quantum efficiency of 0.060 mol C mol^{-1} APAR was considered because values as high as 0.053 were locally estimated (Giardina et al. 2002). Tuning the coefficient of stomatal response to VPD (k_g, which affects canopy quantum efficiency and allocation to roots) and to the foliage-stem partitioning parameters (which influence wood biomass and LAI estimates) resulted in an adequate time series simulation of the C budget fluxes (GPP, ANPP and TBCA) and the wood biomass and LAI state variables (Table 1, Figure 1). The model performance for the control treatment was also satisfactorily achieved by decreasing the fertility rating (FR) to 0.85 (Figure 2), which reduced canopy quantum efficiency and increased allocation to roots.

Applying the Hawaii calibration of the model to the irrigated clonal *E. grandis* x *urophylla* treatment in Brazil trial led to directionally wrong trends for the C fluxes and LAI, increasing from the first to the second year, instead of decreasing (data not shown). The magnitude and trend of the LAI values were readily adjusted by replacing the foliage-stem partitioning parameters from Hawaii with ones derived from 24 sampled trees in the Brazil trial (Stape 2002, Table 3). After this modification, GPP remained low, so a tuning process was carried out for k_g (VPD response) and maximum canopy quantum efficiency, after altering the species-specific parameters based on local data (Table 1). The search for quantum efficiency was limited between 0.060 (Stape 2002) and 0.080 mol C mol^{-1} APAR, and after tuning, the highest value was kept (Table 1). Model performance was then considered sufficient, despite the somewhat underestimation of the LAI (Figure 3.a).

Applying this set of parameters to run 3-PG for the rainfed treatment provided a good simulation of the C fluxes and state variables, except for a slight LAI underestimation (Figure 3.b). Overall, we considered the calibration for Brazil species and conditions to be satisfactory to begin the validation phase.

Validation

Wood biomass of the 40 stands varied by 3-fold at 6 years of age (42 to 118 Mg ha^{-1}), due to different locations (climate), soil groups and probably clonal genotypes (Tables 2 and 3). The two production years had distinct rainfall regimes (1845 *versus* 1287 mm, for the wet and normal years, Figure 4.a), leading also to higher transpiration rates and available soil water in the root zones for the wet year (Table 3). The paired control and fertilized plots did not differ initially for any soil or biometric attributes (Figure 4.b and Table 5). Wood increments were affected by both fertilization and year, and presented a fertilization-year interaction (Figure 5). Increments for both control and fertilized plots were higher for the wet year (29.3 and 37.9 Mg ha^{-1} yr^{-1}, respectively) than for the normal year (15.1 and 17.3 Mg ha^{-1} yr^{-1}) (Figures 4.b and 5). Fertilization response was also higher for the wet year (8.6 *versus* 2.2 Mg ha^{-1} yr^{-1}) (Table 6), and did not correlate with initial biomass (r^2=0.01).

For the fertilized plots, the 3-PG first run presented a strong correlation between observed and simulated values (r^2 =0.81, Figure 6.a), although the slope of the linear regression line (0.48) differed significantly from 1, mainly due to an overestimation of the wood production for the normal year (25.2 versus 17.3 Mg ha^{-1} yr^{-1}). The wet year had satisfactory estimates (36.2 versus 37.9 Mg ha^{-1} yr^{-1}, Figure 6.a).

A re-parameterisation of 3-PG was implemented because the overestimated wood production during the normal year was also associated with both a very low simulated LAI compared with observed values (1.7 *versus* 2.5 m^2 m^{-2}, Figure 9.a) and with no soil water deficit (data not shown), despite the low soil available water (Table 3). Among the tunable parameters that could affect LAI, model sensitivity was high for the specific leaf area (SLA), which was changed from 8.5 to 11.5 m^2 kg^{-1}, within the range observed for the species (Stape 2002), resulting in a better simulation (r^2 = 0.83, higher slope, Table 7, Figure 6.b). This second 3-PG run for the fertilized plots adequately predicted wood increments (≅ 36 Mg ha^{-1} yr^{-1}) and LAI (3.3 m^2 m^{-2}) for the wet year, and improved estimates for the normal year, increasing LAI (from 1.7 to 2.3 m^2 m^{-2}) and soil water deficits (data not shown), and decreasing production (from 25.2 to 21.0 Mg ha^{-1} yr^{-1}).

This final parameterisation of the model was used to simulate control plot production after scaling a fertility-rating factor for each site (Figure 7). The observed and simulated results were strongly correlated (r^2 = 0.71), with a high slope coefficient (0.63) and small RMSE (Table 7). Across the 40 sites, the observed and simulated wood increments and LAI for wet year were equivalent (29.3 *versus* 30.3 Mg ha^{-1} yr^{-1}, 3.1 *versus* 3.1 m^2 m^{-2}), but small differences persisted for the normal year (15.1 *versus* 18.3 Mg ha^{-1} yr^{-1}, 2.8 *versus* 2.0 m^2 m^{-2}) (Figure 9.b).

The SC model effectively described the growth trend of the stands between 2 and 6 years old (r^2=0.94, Figure 4.b and Table 4), but it was unable to correctly predict the wood production for either wet or normal years (Figure 8), underestimating the wood production for the wet year by almost one third (20.2 *versus* 29.3 Mg ha^{-1} yr^{-1}) and overestimating it for the normal year by two thirds (25.0 *versus* 15.1 Mg ha^{-1} yr^{-1}).

The superior predictive ability of the 3-PG model for the yearly productions of the control plot relative to the SC model was clear (Table 7, Figures 7, 8 and 9.b).

Fertility indices

Very few of the fertility indices (Table 5) correlated with the fertilization response in the wet year (data not shown). No physical or bioassay indices presented a correlation with fertilization response, while 8 fertility indices showed a negative correlation (mineral N extracted with boiling salt solution, extractable P, extractable K, extractable Mg and cation exchange capacity, from 0 to 15 or 0 to 30 cm depth). Interestingly, the majority of the fertility indices correlated negatively (although not all were significant) with the fertilization response (data not shown), indicating stronger responses on less fertile soils. Using the stepwise procedure, extractable potassium at 0-0.15 m, phosphorus at 0-0.30 m and cation exchange capacity at 0-0.15 m explained 56% of the variation of the fertilization response. We developed a soil fertilization response index (SFRI) with the linear combination of these soil attributes (Figure 10.a). Among the stand properties, only canopy N and canopy P (Table 5) presented a slight negative correlation with fertilization response (Figure 10.b). Fertilization response tended to decrease as the content of N in the canopy increased, which we termed canopy fertilization response index (CFRI, Figure 10.b).

DISCUSSION

From the 38 parameters needed to run 3-PG, we tuned a maximum of 3 for each calibration step. The majority of the parameters were locally assessed or obtained from other studies. Maximum canopy quantum efficiency, foliage-stem partitioning parameters and stomatal response to VPD (or the maximum stomatal conductance) were the key parameters tuned in this study, and are recognized as the most influential ones through sensitivity analyzes performed in other studies (Landsberg and Waring 1997, Law et al. 1999, Waring and McDowell 2002, Landsberg et al. 2000).

The complete C budgets from the fertilization and irrigation experiments were critical for the calibration of the 3-PG model and the partial evaluation of its descriptive structure of C fixation, and above- and belowground C allocation. For both the Hawaii and Brazil trials, the calibration using the treatments with the highest supplies of nutrients and water set the fertility and soil moisture modifiers fixed as 1, and let the vapor pressure deficit be the primary modifier control on both C fixation (by affecting canopy quantum efficiency) and allocation (by affecting root partitioning). Under these circumstances, model calibration was achieved satisfactorily. Averaged across years 2 to 6, 3-PG simulated an average GPP of 4.6 kg C m^{-2} yr^{-1} with 36% allocated belowground for *E. saligna* in Hawaii, which is practically identical to the observed GPP of 4.4 kg C m^{-2} yr^{-1} with 34% allocated belowground (Figure 1). For Brazil, simulated GPP was 6.3 kg C m^{-2} yr^{-1} (28% allocated belowground), well within the 95% confidence interval for estimated GPP of 6.7 kg C m^{-2} yr^{-1} (and 28% allocated belowground) (Figure 3.a).

After these calibrations, 3-PG runs for the control treatments in each trial were a test for the way the model described effects of nutrition (Hawaii) or soil water (Brazil) on C fixation and belowground allocation. Across all years, decreasing fertility rating from1.0 (fertilized) to 0.85 (control), 3-PG estimated a GPP of 3.7 kg C m^{-2} yr^{-1} with 40% being allocated belowground, almost identical to the observed average GPP value of 3.7 kg C m^{-2} yr^{-1} and 43% allocated belowground (Figure 2). The Brazil simulation of the rainfed treatment estimated average GPP as 4.4 kg C m^{-2} yr^{-1} (31% allocated belowground), well within the 95% confidence interval for estimated GPP of 4.8 kg C m^{-2} yr^{-1} (32% allocated belowground) (Figure 3.b). These results seem to support the model's description of both water and nutrient effects on C gain and allocation.

The production ecology of *E. saligna* in Hawaii clearly differed from that of *E. grandis* x *urophylla* in Brazil, so it is not surprising that the Hawaii calibration was not sufficient for Brazil. *E. saligna* in Hawaii allocated more C to foliage NPP than the Brazilian *E. grandis x urophylla* clone (9 and 4% of GPP, respectively, Giardina et al. 2002 and Stape 2002) and the allometrics (tuned for Hawaii and established for Brazil) efficiently captured these trends. Local climate also influences LAI (Hatton et al. 1998), and the wetter Hawaiian site supported more LAI. The two genotypes also presented distinct parameter values for stomatal response to VPD, canopy quantum efficiency, and litterfall rates, with the Brazil clone being less sensitive to VPD, having higher canopy quantum efficiency and lower litterfall rates. Although the tuned parameters have an unknown degree of uncertainty, they evidence the potential use of process-based models as a framework for breeding programs by identifying the important parameters that control production, and assessing their natural variability among the population (Blake and Suiter 1988, Jarvis et al. 1989).

The empirical structure of the SC model makes it naturally insensitive to inter-annual climatic variations (Clutter et al. 1983, Kimmins 1997). Nevertheless, this adequately fitted SC model was useful to highlight the under- and over-estimation errors associated with the use of empirical model estimates as a surrogate for a specific year production in areas with high climatic variations (Figures 4, 5 and 7). In contrast, the behavior of 3-PG even for the first run (Figure 6.a) showed its generality and flexibility to accommodate distinct sites and weather conditions. The diversity of clones (Table 2) among the sites probably contributed to reduce the performance of the model. The inadequacy of the simulated LAI in the first 3-PG run can be credited to an inadequate calibration phase that had already shown an underestimation of the LAI (Figure 3.a). LAI is the most important state variable in APAR-like models because it integrates C and water fluxes (Law et al. 1999). In our study, the second 3-PG run with an increased SLA resulted in larger simulated LAI and lower wood production (Figure 9.a), because higher transpiration rates induced water deficits that counteracted the potential increase in C fixation with the larger LAI. SLA was the only parameter manually changed for the second 3-PG run; other parameters that directly affect LAI (litterfall, foliage:stem partitioning parameters) or water balance (rainfall interception, available soil water) should be better investigated in a second calibration with the irrigation trial. Moreover, shedding of leaves by *Eucalyptus* in response to drought is common in the region (Stape 2002) and should be added explicitly to the model given the relevance of LAI (Landsberg and Waring 1997, Sands and Landsberg 2002).

The description of root C allocation in 3-PG as a function of both soil fertility and environmental harshness (water deficit) predicts higher fertility influences for wetter conditions (Stape et al. 1997, Fisher and Binkley 2001). Indeed, 3-PG simulated fertilization responses of 5.1 and 2.7 Mg ha^{-1} yr^{-1} for the wet and normal year, respectively, in line with the observed values of 8.6 and 2.2 Mg ha^{-1} yr^{-1}. Furthermore, the model correctly estimated a higher light-use-efficiency for the fertilized plots during the wet year, but not during the normal year (Table 6). These results show that an adequate description of the C allocation process is crucial for the correct yearly estimates of wood production for *Eucalyptus* in areas with large interannual climatic variability and intense silvicultural practices.

Predictions of wood increment and LAI were reasonable for control plots with the 3-PG model (Figure 9.b), indicating that the fertility-rating scheme (based on fertilization responses) was adequate. The absence of correlation between fertilization responses and mean annual increment or site index ($r^2 < 0.04$) made clear that soil fertility needs to be considered as an independent concept in forest modeling. In this region, MAI and site index correlate well with water supply (Stape 2002), and the adequate evaluation of soil fertility restrictions among stands depends on the occurrence of years with regional large rainfall rates or the use of the fertilized paired-plot design (Hart and Binkley 1985). Fertilization responses as a function of soil properties are species-, region- and management-specific (Hart et al. 1986, Gale et al. 1991), and in particular for our study (same basic genotype, management and geology) a soil fertilization response index could be derived (Figure 10.a) to predict the fertility-rating parameter. The use of fertilized paired-plots associated with the plantation inventory network over a regional area can be proposed to be used as a process-based modeling tool to estimate the fertility rating factor. Alternativelly, N in the canopy showed up as a more general index, which is in line with the observed increase in LAI (Figures 9.a and 9.b) and leaf nutrient content (Table 6) on fertilized plots.

In Brazil, LAI is not assessed during inventory surveys on a regular basis (Campos et al. 1988), but this could be implemented easily using light meters (Cuttini et al. 1998), and would provide essential information for process-based APAR model evaluations for tropical plantations.

CONCLUSIONS

The empirical yield model was adequate to describe growth for average environmental conditions, but inadequate for a climate that varied between years. Moreover, the empirical model was not sensitive to management factors that would drive production beyond or below historic average situations.

The adaptation of the 3-PG process-based model for tropical *Eucalyptus* plantations was relatively easily achieved through model calibration and testing using complete C budget data from trials with water and nutrient manipulations. For these trials, after 3-PG calibration for the treatments with no-limiting resources, the model representation of the effects of soil water deficit and soil fertility over C gain and allocation was supported by the experimental results of the control treatments.

The use of the paired control-fertilized inventory plots design allowed both the 3-PG validation for the fertilized condition and the identification of a protocol to scale fertility index among sites based on the fertilization responses. Although soil attributes were identified as adequate predictors of these fertilization responses (K, P and CEC), quantifying nitrogen in the canopy sounded like a more generalist approach.

The simulated growth values between 10 and 42 Mg ha^{-1} yr^{-1} (average of 26 Mg ha^{-1} yr^{-1}) for all plots and years was highly correlated (r^{-2} = 0.78, n = 160, $P < 0.0001$) with the observed values between 2 and 51 Mg ha^{-1} yr^{-1} (average of 25 Mg ha^{-1} yr^{-1}). These results indicate that species- and site-specific parameters that affect LAI are particularly important to be adequately estimated or tuned, and for our study further tuning would likely improve the model's case-specific usefulness.

Overall, the APAR model approach required a reasonable level of localized tuning, and was able to predict yearly growth better than the SC empirical approach. The superiority of the APAR model was especially evident in capturing the effects of interannual variations in precipitation and fertilization effects in northeastern Brazil. We concluded that the 3-PG model presented high suitability to be incorporated as a management tool for *Eucalyptus* plantations, which will require LAI assessment by inventory surveys.

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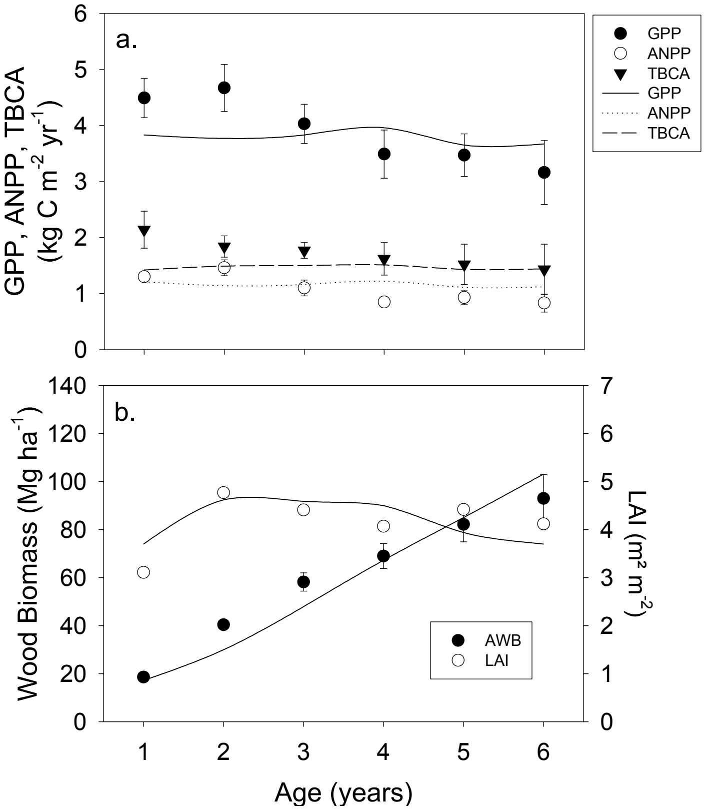
Figure 1. Observed (dots with standard deviation bars) and 3-PG simulated (lines) values of GPP, ANPP and TBCA (a), biomass accumulation and LAI (b) for *E. saligna* in Hawaii for the fertilized treatment (fertility rating equals 1.0) after calibration (tuning).



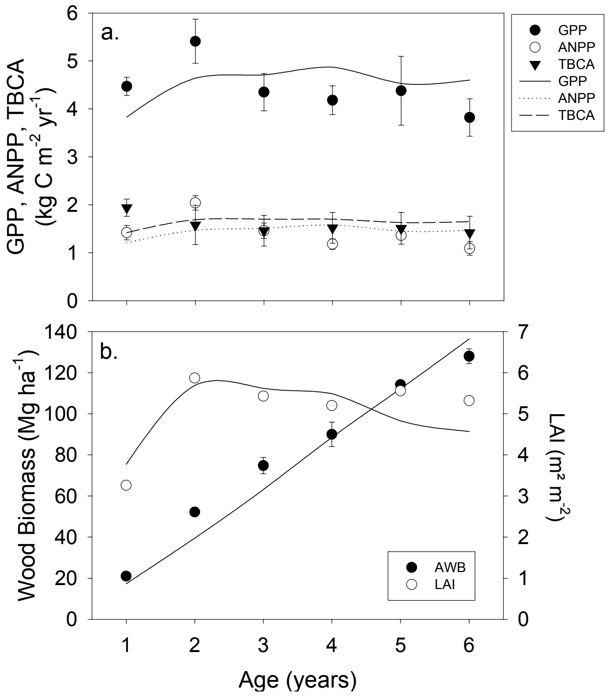
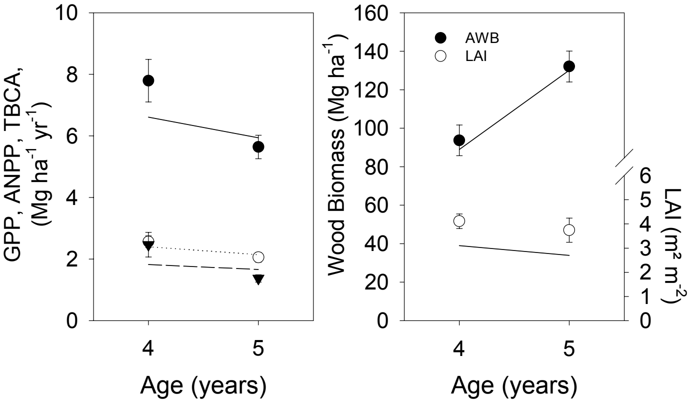


Figure 2. Observed (dots with standard deviation bars) and 3-PG simulated (lines) values of GPP, ANPP and TBCA (a), biomass accumulation and LAI (b) for *E. saligna* in Hawaii for the control treatment after calibration by tuning the fertility rating only (FR = 0.85).

a. Irrigated



b. Rainfed

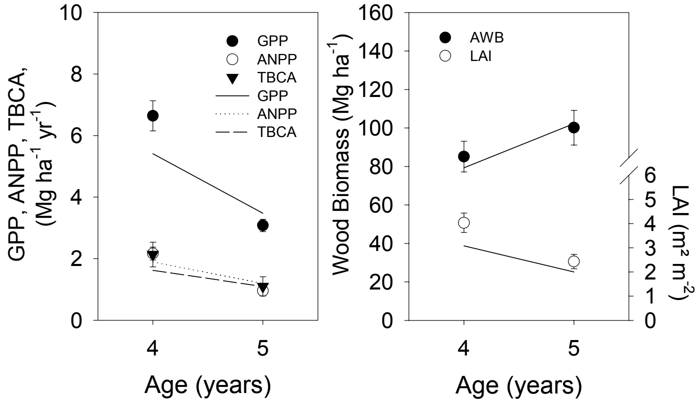


Figure 3. Observed (dots with standard deviation bars) and 3-PG simulated (lines) values of GPP, ANPP, TBCA, biomass accumulation and LAI for *E. grandis x urophylla* in Brazil for irrigated treatment (fertility rating equals 1) after calibration (tuning) (a). The same observed and simulated results for the rainfed treatment using the previous parameterisation (b).

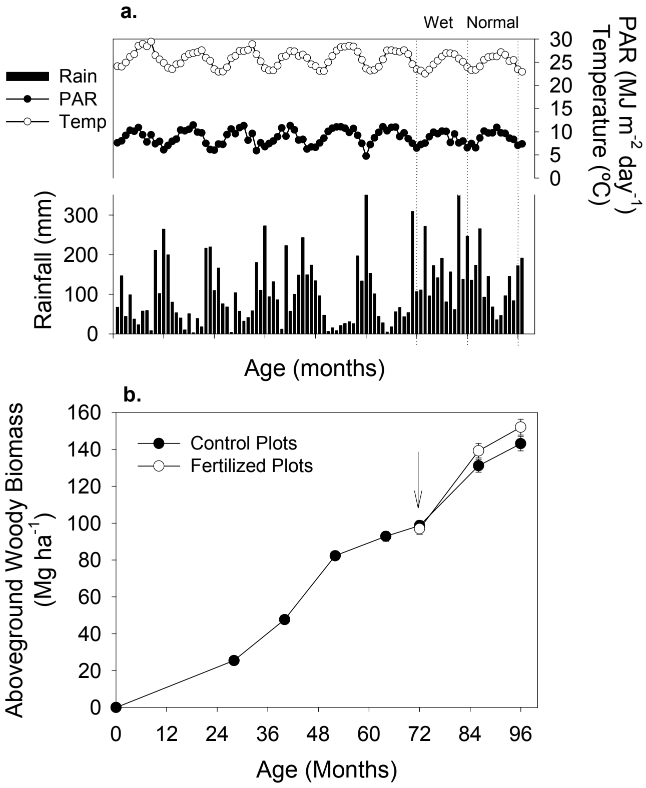


Figure 4. Average monthly meteorological variables (rainfall, PAR and temperature) for the complete rotation of the 40 studied sites indicating the last two wet and normal years (a). Average biomass accumulation (and standard error bars) for the control and fertilized plots (b). The arrow indicates the quarterly fertilization initialization.

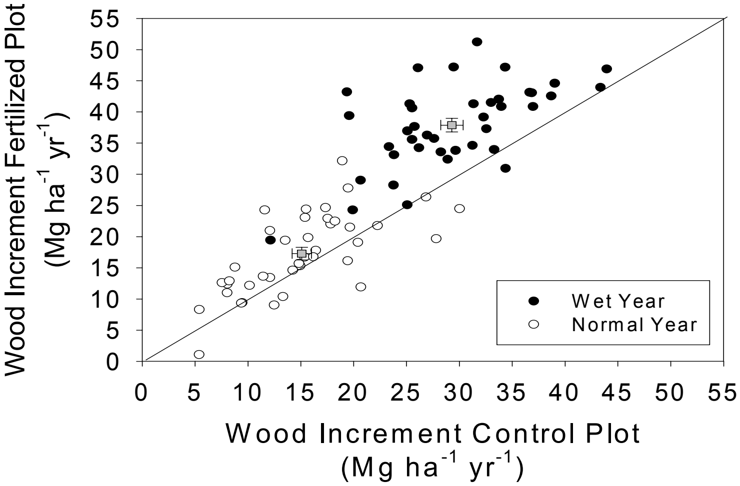
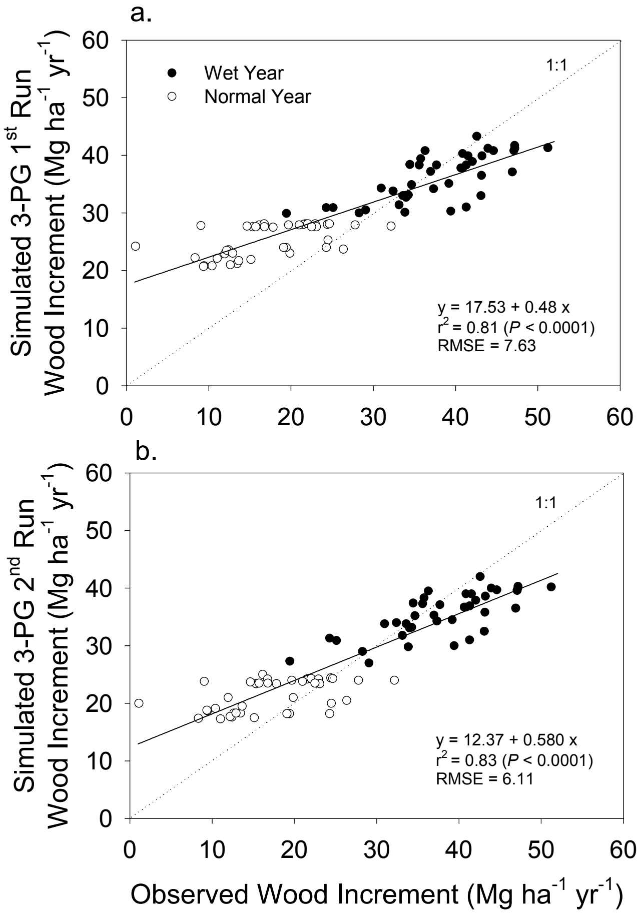


Figure 5. Wood increments during wet and normal years of the 40 paired-plots. Gray squares represent the average growth for the years with standard error bars.

Figure 6. Observed and simulated wood increments for the wet and normal years for 3-PG model on fertilized plots before (a) and after re-parameterisation (b).



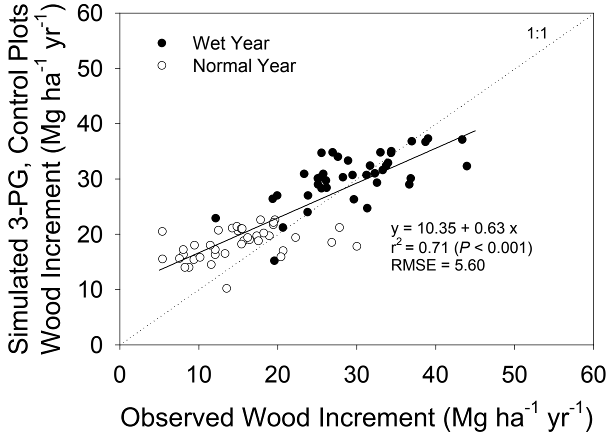


Figure 7. Observed and simulated wood increments for the wet and normal years for 3-PG model on control plots.

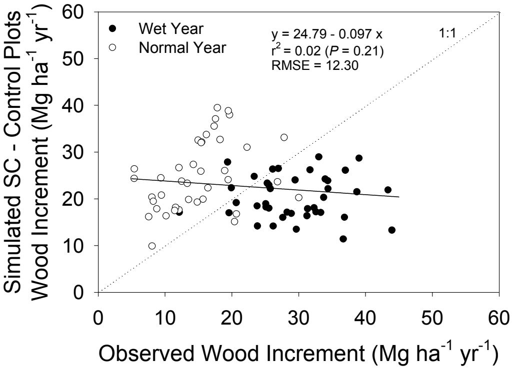
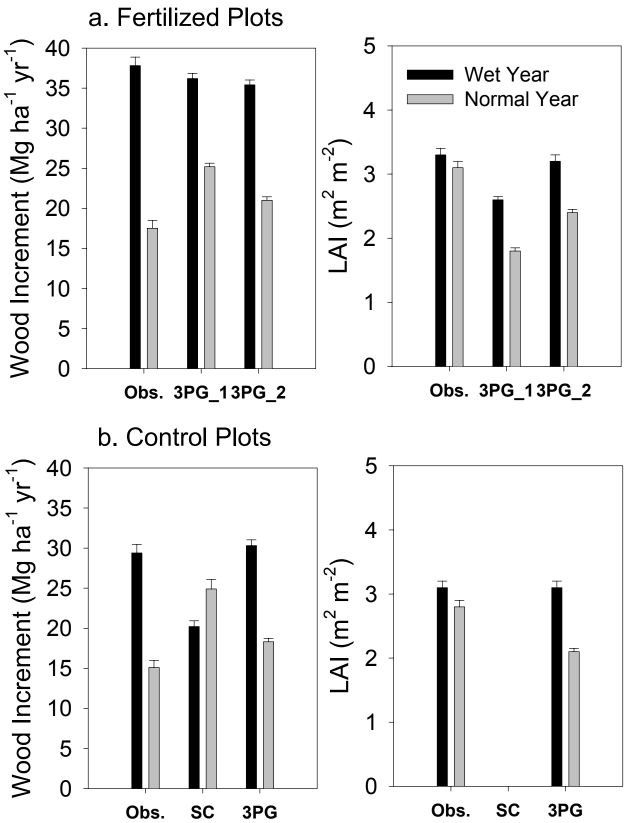


Figure 8. Observed and simulated wood increments for the wet and normal years for the SC empirical model on control plots

Figure 9. Average (with standard error bars) wood increment and LAI for the observed (Obs.) and 3-PG first (3PG_1) and second (3PG_2) runs of the 40 fertilized plots (a), and for the observed (Obs.), SC and 3-PG run of the 40 control plots (b) during wet and normal years.



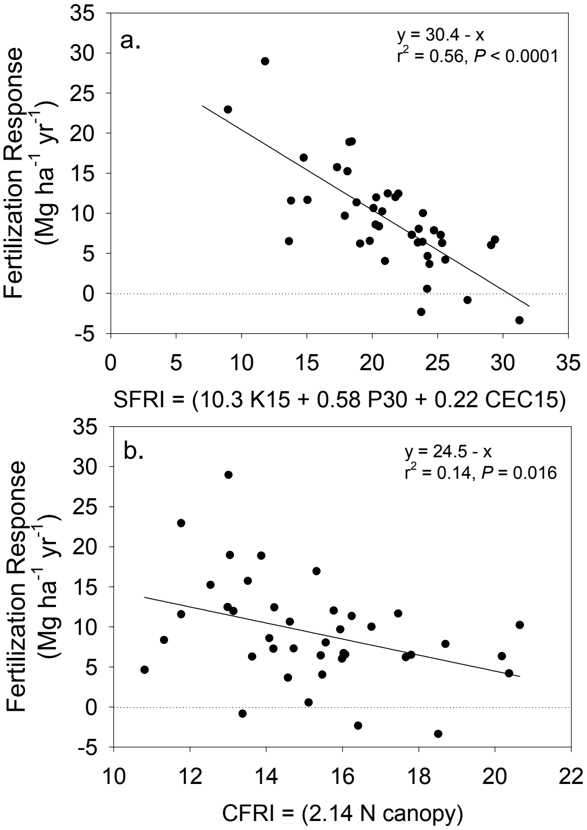


Figure 10. Relationship between fertilization response (FER) of the 40 stands during the wet year, and soil fertilization response index (SFRI) (a) and canopy fertilization response index (CFRI). K15 = K in mmol$_c$ kg^{-1} at 0-015 m, P30 = P in mg kg^{-1} at 0-0.30 m, CEC = CEC in mmol$_c$ kg^{-1} at 0-015 m, N canopy = N in the canopy in g m^{-2}. Fertility rating is estimated as FR = 0.4 (29-FER)/29+0.6).

Table 1. Main parameter values of 3-PG model after calibration for Hawaii (H) and Brazil (B) experimental trials.

Parameter	Hawaii	Brazil	Unit	Source*
NPP/GPP ratio	0.50	0.50	-	Landsberg & Waring 1997
Canopy Quantum Efficiency	0.060	0.080	mol C/mol PAR	Specific (H). Tuning (B)
Specific Leaf Area	10.0	8.5 / 11.0	m^2/kg	Specific (H, B)
PAR Extinction Coefficient	0.5	0.4	-	Specific (H, B)
Age Canopy Cover	1.5	1.5	year	Specific (H, B)
Proportion of Intercepted Rainfall Evaporated	0.15	0.15	-	Lima (1996)
Canopy Albedo	0.2	0.2	-	Landsberg & Waring 1997
Maximum Stomatal Conductance	0.008	0.008	m/s	Mielke et al. 1999
Maximum Canopy Conductance	0.02	0.02	m/s	Landsberg & Waring 1997
Coefficient of Stomatal Response to VPD	0.468	0.324	1/kPa	Tuning (H, B)
Canopy Boundary Layer Conductance	0.2	0.2	m/s	Landsberg & Waring 1997
Maximum Litterfall Rate	0.110	0.070	1/month	Specific (H, B)
Age at which litterfall rate has median value	4	4	month	Specific (H, B)
Foliage/Stem Partitioning DAP=2	1.001	0.096	-	Tuning (H). Specific (B)
Foliage/Stem Partitioning DAP=20	0.212	0.034	-	Tuning (H). Specific (B)
Constant Coefficient at Stem Mass / DAP equation	0.066	0.065	-	Specific (H, B)
Power Coefficient at Stem Mass / DAP equation	2.50	2.68	-	Specific (H, B)
Maximum Fraction of NPP to Roots	0.8	0.8	-	Landsberg & Waring 1997
Minimum Fraction of NPP to Roots	0.25	0.20	-	Landsberg & Waring 1997
Fertility Parameter (FR)	1.00 / 0.85	1.00 - 0.60	-	Tuning (H, B)
Maximum Available Soil Water	300	80/160	mm	Specific (H, B)
Texture Coefficient for Soil Water Modifier	0.7	0.3/0.5	mm	Landsberg & Waring 1997
Power Coefficient for Soil Water Modifier	9	4/7	mm	Landsberg & Waring 1997
Maximum Growing Temperature	40	40	ºC	Sands & Landsberg 2002
Optimum Growing Temperature	22	25	ºC	Specific (H, B)
Minimum Growing Temperature	8	8	ºC	Sands & Landsberg 2002

* Study specific data for Hawaii from Giardina and Ryan (2002) and Giardina et al. (2002), study specific data for Brazil (Chapter II).

Table 2. Characterization of the genetics, location, soil taxonomy, soil clay content and total carbon (0 to 0.3 m) of the 40 studied stands of *E. grandis x urophylla*, grouped by area.

Area Nº	Plots (#)	Clones (#)*	Latitude (S)	Longitude (W)	Altitude (m)	Main Soil Order	Clay (%)	Carbon (kg m^{-2})
1	5	2	12º 02’	38º 28’	301	Quartzpsament	13 (7)	3.1 (0.7)
2	20	4	11º 47’	37º 55’	166	Ultisol	29 (10)	3.7 (0.8)
3	3	3	11º 50’	38º 28’	250	Oxisol	22 (3)	3.4 (0.3)
4	7	2	11º 53’	38º 30’	296	Oxisol	16 (3)	2.3 (0.4)
5	5	1	11º 55’	38º 31’	256	Quartzpsament	8 (3)	1.4 (0.3)

* COP-0204, 0321, 0477, 0670 and 1341.

Table 3. Rainfall, estimated transpiration and average soil available water (SAW, 0 to 2.0 m) during the two study periods for the 40 stands of *E. grandis* x *urophylla*, grouped by area. Values followed by different letters between years differ at $P = 0.05$.

Area	Rainfall	(mm)	Transp.*	(mm)	SAW*	(mm)
Nº	Wet Year	Normal	Wet Year	Normal	Wet Year	Normal
1	1691	1112	1211	886	65	49
2	2114	1518	1284	1091	116	76
3	1524	1028	1185	883	73	54
4	1520	1001	1180	833	70	52
5	1569	1051	1117	850	58	43
Mean	1845 a	1287 b	1230 a	971 b	92 a	64 b
(SD)	(274)	(234)	(60)	(122)	(25)	(13)

Average VPD wet year = 1.08 kPa, VPD normal year = 1.20 kPa

Rainfall, Transpiration: Area 2 > Area 1 > Areas (3, 4, 5) ($P < 0.001$)

SAW: Area 2 > Areas (1, 3, 4, 5) ($P < 0.001$)

* Transpiration and SAW based on measured and interpolated LAI

Table 4. Estimated coefficients of the Sullivan-Clutter model based on 40 stands measured yearly between 2 and 6 years-old (control plots). The empirical model predicts the wood biomass (AWB_2, Mg ha^{-1} yr^{-1}) at a future age (A_2, month) based on the initial basal area (BA_1, m^2 ha^{-1}), age (A_1, month) and site index (S, m).

$$\ln(AWB_2) = 2.319 + 0.015\,S - 44.508 / A_2 + 0.878 \ln(BA_1)A_1/A_2 - 0.220\,(1-A_1/A_2) + 0.175\,S\,(1-A_1/A_2)$$

$N = 200$

$P < 0.0001$

$R^2adj = 0.942$

Table 5. Variables used on stepwise regression procedures having fertilization response (FER) as the dependent variable and the independent variables organized by soil and stand-canopy categories.

Category	Variables
Soil-physical	Sand, silt, clay, bulk density
Soil-fertility	soil C, soil N, extractable nutrients (P, K, Ca, Mg), sum of bases, H+Al, CEC, pH
Soil-lab incubations	N resin bag, N boiling water, N anaerobic, N aerobic fresh soil, N aerobic dried soil
Soil-biosassay	Seedlings dry matter, and N, P, K, Ca and Mg contents
Stand-Canopy	Site index, LAI, leaf nutrient content (N, P, K, Ca and Mg), canopy nutrient content (N, P, K, Ca, Mg)

Table 6. Average canopy attributes, absorbed light, wood increment and light-use-efficiency by treatment (control and fertilized) and year (wet and normal), and the respective fertilization response. Values followed by different small letters (between treatments) or capital letters (between years) differ at P = 0.05. All significant fertilization responses are presented.

Variable	Year	Control	Fertilized	Response
LAI	Wet Year	3.2 A	3.3	-
($m^2\ m^{-2}$)	Normal Year	2.8 B b	3.2 a	0.4
N content	Wet Year	18.5 A b	20.0 B a	1.5
($g\ kg^{-1}$)	Normal Year	17.6 B b	23.0 A a	5.4
N canopy	Wet Year	7.1 A b	8.0 a	0.9
($g\ m^{-2}$)	Normal Year	5.2 B b	8.6 a	3.4
P content	Wet Year	1.12	1.17 B	-
($g\ kg^{-1}$)	Normal Year	1.10 b	1.72 A a	0.62
P canopy	Wet Year	0.43 A	0.48 B	-
($g\ m^{-2}$)	Normal Year	0.32 B b	0.62 A a	0.30
APAR	Wet Year	20.7 A	21.1	-
($TJ\ ha^{-1}\ yr^{-1}$)	Normal Year	19.7 B b	21.4 a	1.70
Wood	Wet Year	29.3 A b	37.9 A a	8.6
Increment ($Mg\ ha^{-1}\ yr^{-1}$)	Normal Year	15.1 B b	17.3 B a	2.2
LUE	Wet Year	1.41 A b	1.79 A a	0.38
($g\ MJ^{-1}$)	Normal Year	0.77 B	0.80 B	-

Table 7. Summary of the statistics between observed and simulated wood increment values for both years (N = 80).

Model Plots	SC Control	3PG 1st Run Fertilized	3PG 2nd Run Fertilized	3PG Control
Intercept *a*	24.79 (1.87)	17.53 (0.79)	12.37 (0.91)	10.35 (1.08)
Slope *b*	- 0.10 (0.08)	0.48 (0.03)	0.58 (0.03)	0.63 (0.04)
R^2	0.02	0.81**	0.83**	0.71**
RMSE	12.30	7.63	6.11	5.60
Model Efficiency	-0.68	0.61	0.75	0.65

** $P < 0.001$