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Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa

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Abstract

Process-based forestry models are seen by the South African forestry industry as potentially useful tools for improving predictions of growth and water use in forest plantations. The 3-PG process-based forest model was evaluated in South Africa using limited *Eucalyptus* and *Pinus* trial data, with encouraging results. Some uncertainty exists, however, over whether 3-PG will prove to be a practical forest management tool on forestry estates that typically comprise scores of compartments (planted even-aged stands) covering a wide range of site conditions, species/clone and tree age. Two important questions require answers: (i) is 3-PG capable of modelling growth over a wide range of site growth potential to useful accuracy and (ii) are there practical methods for estimating or measuring all of the required parameter values for the model?

To answer these questions, 12 stands of *Eucalyptus grandis* × *camaldulensis* hybrid clones, representing early, mid and late rotation age, and covering a wide range of site growth potential in the Zululand region (KwaZulu-Natal Province), were intensively studied over a period of 12 months. Measurements of initial and final biomass, leaf area index, biomass allometric ratios, litterfall, specific leaf area, sap-flow rates, pre-dawn xylem pressure potential and weather conditions were made throughout the year. Two influential site parameter values (maximum available soil-water capacity and a soil fertility rating) required indirect estimation, since relevant information was lacking and difficult to obtain from the field. A pragmatic approach to estimating these parameters is described. Annual tree growth predicted by the model, and daily ranges of sap flow, were compared to field measurements.

Predictions of annual growth increment (dry mass of stems and branches) were acceptable for 11 of the 12 stands ($Y = 0.85X + 1.7$, $r^2 = 0.84$). The twelfth stand, which had an extremely high annual growth increment, high leaf area and year-long access by the trees to shallow groundwater, was substantially underpredicted. This is attributed to likely physiological adaptions to the long-term absence of water stress at this site. We conclude that 3-PG can realistically simulate growth and water use over a wide range of rotation age and growth conditions. Preliminary sets of model parameter values for a range of diverse stands may be estimated over a relatively short period using simple field equipment and techniques. Further testing of these parameter values at physiologically significant times over the remainder of the rotation is recommended to test model output and permit fine-tuning of parameters.

Keywords: 3-PG; *Eucalyptus*; Growth; Process-based model; Water use

1. Introduction

Improving predictions of growth and water use in forest plantations is seen by the South African forestry

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industry as an important research goal. Forest growth and yield is widely predicted using empirical growth models, but these are insensitive to changes in weather conditions, especially rainfall, and management strategies, both of which are known to strongly influence growth rates. The hydrological impacts of forest plantations remain a controversial issue, and much clarification on the spatial and temporal patterns of tree water use, and how these vary with site conditions, is still required.

The 3-PG process-based forest model (Landsberg and Waring, 1997) allows prediction of both growth and water use in forest plantations, and experience in many countries has shown it to yield realistic predictions for a wide variety of forests (Landsberg et al., 2000, 2003; Waring, 2000; White et al., 2000; Tickle et al., 2001; Sands and Landsberg, 2002). Preliminary testing of the model against limited *Eucalyptus* and *Pinus* trial data in South Africa has been encouraging (Gush, 1999; Dye, 2001). Some reservations exist, however, over whether 3-PG will prove to be a practical forest management tool on estates that typically comprise scores of compartments covering a wide range of site conditions, species/clones and tree ages. Two questions in particular require answers: (i) is 3-PG capable of modelling growth over a wide range of site growth potential to useful accuracy, and (ii) are there practical methods for estimating or measuring all of the required parameter values for the model? This paper describes an investigation of 3-PG parameterisation and performance in a diverse selection of *Eucalyptus* stands in the Zululand region of South Africa.

2. Materials and methods

2.1. Study sites and experimental strategy

We selected 12 stands of *Eucalyptus grandis* × *camaldulensis* hybrid clones that represented a wide range of tree age, standing biomass, site quality and climatic conditions. Six of the stands were located in the drier Bushlands district (mean annual precipitation (MAP ~ 1100 mm)), while the remaining six stands were situated in the wetter kwaMbonambi district (MAP ~ 1390 mm). Details of the stands are summarised in Table 1; their location is shown in Fig. 1. Soils at all sites were Fernwood (MacVicar et al., 1977) medium-textured deep sands of marine origin.

We foresee that, given clear evidence of the potential value of 3-PG model predictions, plantation managers would request technical assistance in setting up 3-PG for entire plantations, or for areas that still comprise many different stands. We believe that a practical set-up strategy for the model would be to develop a preliminary set of parameter values on the basis of available site information and also measure some key structural and physiological features of the stands over a minimum period of a year. Model predictions would then need verification against subsequent growth and other appropriate data, possibly supplemented by strategically timed key physiological measurements, to permit further fine-tuning of parameter values. This study was therefore designed to evaluate the practicality of developing an initial parameter set on the basis of 1 year of field measurements in the stands, and evaluating the success of the model in matching observed annual growth increments and transpiration rates over all 12 stands.

2.2. The 3-PG model

The 3-PG forest growth model is based on absorbed photosynthetically active radiation (APAR, a measure of the amount of incident light intercepted by the canopy). It has a monthly time-step and predicts growth and water use on the basis of standard climate, stand and soil descriptors. The structure of the model is well described in the literature (Landsberg and Waring, 1997; Sands and Landsberg, 2002). We used an EXCEL-based version of the model (3-PGpjs; Sands, 2000) that has become the standard version for non-spatial simulations of forest stands. This version may be downloaded, together with a detailed manual, from the web site http://www.ffp.csiro.au/software.

2.3. Weather data

Weather data were recorded over a 12-month period from July/August 2000 to July/August 2001, to coincide with the programme of field measurements. 3-PG requires monthly rainfall (mm), monthly mean daily solar radiation (MJ m^{-2} per day), monthly mean daily temperature (°C), number of frost days per month, and

Table 1
Site details of the test sites located in the Bushlands and kwaMbonambi districts

	Bushlands						kwaMbonambi					
	Low site index			High site index			Low site index			High site index		
Stand age	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Compartment	A04c	B04	F05	A10b	A05a	A05c	NP23	RG20b	NH01	NA24b	NK25	NP20b
Area (ha)	6.4	12.4	7	9	14.7	20	4.9	4.1	4.2	4.7	4.7	5
Co-ordinates	28°07′S 32°17′E	28°06′S 32°17′E	28°04′S 32°19′E	28°07′S 32°17′E	28°07′S 32°17′E	28°07′S 32°16′E	28°54′S 31°57′E	28°35′S 32°03′E	28°42′S 32°00′E	28°41′S 32°01′E	28°41′S 32°03′E	28°44′S 31°57′E
Estate	Bushlands	Bushlands	Bushlands	Bushlands	Bushlands	Bushlands	Nseleni	Rattray	Nseleni	Nseleni	Nseleni	Nseleni
Planting date	May 1997	July 1995	May 1993	November 1998	April 1995	September 1994	April 1997	May 1994	April 1993	March 1997	September 1995	June 1993
Age at start (years)	3.08	4.92	7.08	1.58	5.17	5.75	3.17	6.08	7.14	3.25	4.75	7.00

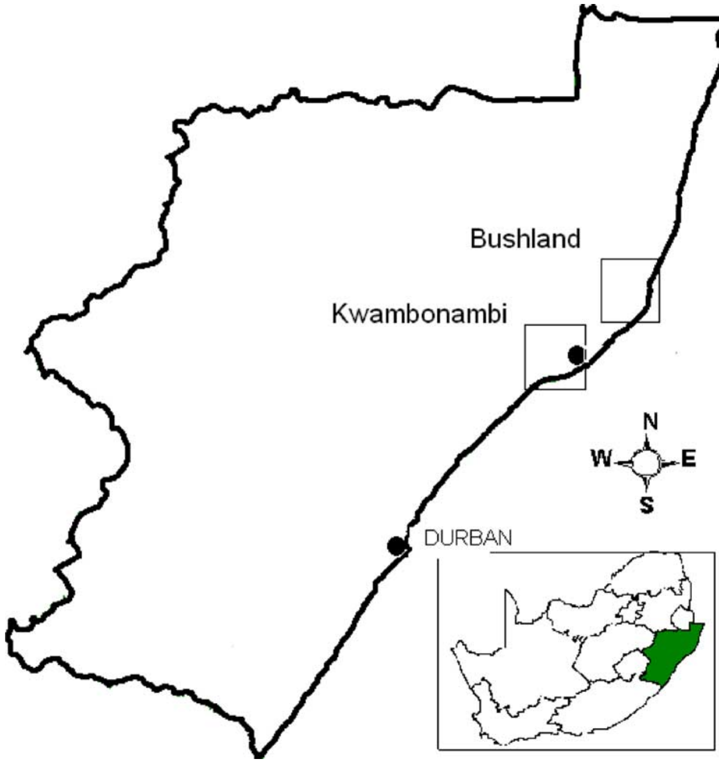


Fig. 1. The location of the Bushlands and kwaMbonambi districts in which the test sites were located.

monthly mean daylight vapour pressure deficit (mbar). Months were defined as starting on the 15th and ending on the 14th, to coincide with the timing of field visits to the sites. A tipping bucket rain-gauge recorded rainfall at an automatic weather station (AWS) situated close to the Bushlands sites (28°8.232′S, 32°16.331′E). A gap in the data record occurred from 11 October 2000 to 27 November 2000 due to a faulty data logger. This gap was patched using daily rainfall data recorded at a gauge situated at Bonamanzi (28°4.042′S, 32°18.198′E), a distance of 8 km from the Bushlands AWS. The kwaMbonambi sites were more dispersed than the Bushlands sites, and two gauges were used. Rainfall recorded at the kwaMbonambi Fire Protection Service gauge (28°35′45″S, 32°05′23″E) was applied to RG20b, NK25, NA24b and NH01, while rainfall recorded in a monthly gauge designated Hugo's house (28°43′40″S, 31°56′55″E) was applied to NP20b and NP23 (see Table 1). This gauge consisted of a standard 8 in. (203.2 mm) rim fitted to a large plastic container. The monthly catch was measured in millilitres and converted to an equivalent depth of water.

A Hobo temperature and humidity sensor (Onset Computer Corporation, P.O. Box 3450, Pocasset, MA, USA) was attached to a tree stem in compartments A04c (Bushlands) and NP23 (kwaMbonambi). These sensors were protected from rain by a plastic shelter that allowed free movement of air around the sensor, and programmed to provide hourly mean temperature and relative humidity. Hourly temperature values were averaged from 0100 to 2400 h and daily means averaged over each month. Hourly temperature and relative humidity data were used to calculate vapour pressure deficits (D). Vapour pressure deficit was averaged over each day (D_{day}) from 0600 to 1800 h, and used in the calculation of monthly means. The absence of frost at the sites was confirmed from inspection of daily minimum temperatures.

Hourly solar radiation (R_s) data were available from LI-COR pyradiometers (LI-COR, Inc., P.O. Box 4425, Lincoln, NE, USA) recorded at the AWSs at Bushlands and Heatonville (31°45′40″S, 28°45′30″E). Mean hourly R_s in units of W m^{-2} were converted to MJ m^{-2} per day, and then used to calculate mean daily R_s from 0600 to 1800 h. Mean daily R_s was averaged over each month. A comparison of mean monthly R_s recorded at the two stations showed only minor differences. Consequently, Heatonville data were used to patch the missing data in the Bushlands AWS data record.

2.4. Stand data

The following stand descriptors are required by 3-PG, and were recorded in each of the 12 test sites.

2.4.1. Allometric relationship between tree diameter and stem mass

This relationship is required by the model to ensure that allocation of new growth to foliage and stem proceeds in a balanced fashion as the trees grow. Biomass data were recorded to derive the necessary coefficients of the equation describing the relationship of tree diameter at breast height (B) to dry mass of stems and branches per tree (w_S). In each compartment, three sample trees (representing small, medium and large size classes of tree) were destructively sampled. Total fresh mass of stem, branches and leaves were recorded in the field. Sub-samples were returned to the laboratory where fresh and oven-dried mass was recorded. These ratios were used to estimate total dry mass of stem, branches and leaves.

2.4.2. Tree density, annual increment of stem and branch mass

Measurements of diameter at breast height, tree height and tree density were made from 5 July until 19 September 2000 in sample plots at each of the 12 test sites. The number of sample trees per plot varied from 58 to 80, depending on initial planting espacements, plot size and tree mortality. Tree diameters were measured with callipers, while the heights of approximately 20 trees were measured using a Suunto clinometer (Suunto Oy, Valimotie 7, Vantaa, Finland). The heights of the remaining trees in the sample plots were estimated from their diameter using a regression equation based on the 20 measured trees. Plot means of diameter at breast height and height were calculated. A second survey of trees within the same sample plots took place at the end of the 12-month measurement period. This time, all tree heights were measured with a Vertex 3 hypsometer (Haglöf Sweden AB, Box 28, Klockargatan 8, Langsele, Sweden).

Stem volumes for every measured tree were calculated using the Schumacher and Hall (1933) individual tree-volume equation:

$$\ln(V) = a_0 + a_1 \ln(B + f) + a_2 \ln(H) \quad (1)$$

where V is utilisable volume (m^3), B the diameter at breast height (1.3 m) (cm over bark), H the tree height (m) and f the correction factor. Coefficients (a_0, a_1, a_2) used for this equation for *E. grandis* × *camuldulensis* were those obtained by Du Plessis (1996) and published in the South African Forestry Handbook (Bredenkamp, 2000). The volume of each measured tree was calculated, and then summed with others over each sample plot. Allowance was made for the loss of three trees destructively sampled for biomass measurements (described above). The calculated volume per hectare was thus based on the total standing volume in each plot of known area.

Problems were experienced in measuring stand volumes in compartment A04c at the end of the 12-month monitoring period. The tops of eight trees snapped off because of strong winds. Final tree heights were estimated from B using a B to H relationship determined from the undamaged trees.

The dry mass of stems was calculated by assuming a mean wood density of 500 kg m^{-3} volume of wood (Malan et al., 1994). The biomass data were used to estimate the additional mass of branches required to calculate above-ground woody mass (W_S, t DM ha^{-1}) as sum of stem and branch mass.

2.4.3. Leaf area index and specific leaf area

The leaf area index (L) of stands at the start of the measurement period was estimated through destructive sampling of trees. Leaves on all sample trees were stripped off and their fresh mass recorded in the field. Dry mass was calculated on the basis of sub-sample ratios of fresh to oven-dry mass recorded in the laboratory. Total sub-sample leaf area of the fresh leaves was measured with a LI-COR LI-3100 area meter, and used to calculate specific leaf area (σ, area of leaves per unit of dry mass; m^2 kg^{-1}). Total leaf area of each sample tree was then used to estimate the stand L by assuming that each tree represents a mean of all the trees of that size class in the plot.

A LI-COR LAI-2000 plant canopy analyser was used to record monthly L at all sites. The purpose was to provide an independent check on the estimates based on destructive sampling, and to look for possible seasonal trends in L. Readings were timed, as far as possible, for early morning and late afternoon to reduce the likelihood of light reflection through the canopy. A 90° mask was fitted over the sensor to exclude the shadow of the instrument operator. At each compartment, the first above-canopy reading was taken in the nearest open space. Eight below-canopy readings were taken as quickly as possible at random positions in the stand. As stems and branches also intercept sunlight, a correction applicable to *Eucalyptus* trees was used to estimate the true L of the canopy alone. The correction (Battaglia et al., 1998) takes the following form:

$$L\,(\text{true}) = 1.54 \times \text{PAI}\,(\text{canopy analyser}) - 0.11, \quad r^2 = 0.997 \tag{2}$$

where PAI represents the entire plant area index sensed by the instrument. Limited data from South Africa supports the use of this correction factor in *E. grandis* stands (Dye, 1998).

2.4.4. Litterfall

Five litter traps were installed at each of the test sites and catches were recorded at monthly intervals. Each trap consisted of a wire frame suspending a catch bag made of shade cloth that collected over an area of 0.332 m^2. The catch bags were emptied at each monthly visit. Leaves were separated from twigs, and then oven-dried before weighing. The mean leaf mass from catch bags was multiplied by 30120.5 to scale up to a hectare. A significant number of litter traps were stolen, causing gaps in the data record.

2.4.5. Sap flow

Monthly periods of sap-flow data were recorded at selected sites to evaluate the realism of rates of transpiration predicted by the model. In any particular month, hourly sap-flow data were recorded in a single sample tree from one of the kwaMbonambi sites with higher growth potential and one of the Bushlands sites with lower growth potential. Data from early, mid and late rotation stands were sampled sequentially throughout the year.

Three vertically aligned holes were drilled radially into the sapwood at four positions around the trunk. A line heater was inserted into the central hole, while temperature-sensing thermistor probes were implanted 10 mm above and 5 mm below the heater. Each sensor-probe pair thus gave a point estimate of sapwood temperature. Thermistors were implanted to depths of 4, 9, 16 and 24 mm beneath the cambium. This sampling arrangement has been shown to result in good estimates of sap flow in *E. grandis* (Olbrich, 1991). Heat-pulse velocity readings were taken at hourly intervals during daylight hours. Details of the theory, instrumentation and data analysis relating to sap flow are provided by Olbrich (1991) and Dye (1996).

2.4.6. Pre-dawn xylem pressure potential

Pre-dawn xylem pressure potential (ψ_{pd}) readings were made during the 2000 and 2001 dry winter seasons. A maximum of five leaf samples per site were obtained by shooting stones into the canopy with a catapult. Detached and undamaged leaves were swiftly inserted into a Scholander pressure chamber (PMS Instrument Co., 2750 N.W. Royal Oaks Drive, Corvallis, OR, USA) and a minimum counter pressure applied to the chamber to bring the sap to the exposed cross-sectional surface of the petiole.

2.4.7. Fertility rating

3-PG requires a fertility rating, FR (0-1) describing the soil fertility in the rooting zone. This is extremely difficult to estimate for trees with well-developed roots that explore deep soil profiles, as is the case in the Zululand sites. The fertility of the upper 1 m of soil is often very low, and may bear little relation to site productivity. As deep soil excavation is problematic in loose sands, we assumed that FR is correlated to the growth potential of the site (Landsberg, 2000). One measure of this is the site index. This was calculated for each stand using a modified Clutter and Jones difference form equation (Clutter and Jones, 1980):

$$\text{SI} = \exp\left\{\left[\left(\ln(H_\text{d}) - \frac{b_2}{\text{AGE}} - b_3\right)\left(\exp\left(b_1\left(\frac{1}{\text{AGE}_\text{SI}} - \frac{1}{\text{AGE}}\right)\right)\right)\right] + \frac{b_2}{\text{AGE}_\text{SI}} - b_3\right\} \tag{3}$$

where SI is the site index (m), H_d the dominant height at current age (m), AGE_{SI} the site index base age (taken to be 5 years) and AGE is current stand age. Coefficients for this equation were obtained from Mondi Ltd. for their *E. grandis* × *camuldulensis* plantations in coastal Zululand.

3. Results

3.1. Weather data

Appendix A summarises the monthly weather data used in the simulations of the Bushlands and kwaMbonambi sites.

3.2. Stand data

3.2.1. Allometric relationship between tree diameter

Fig. 2 illustrates the relationship between B and w_S for the combined kwaMbonambi and Bushlands sites. We assume from this figure that the fitted curve adequately describes the trends displayed by both sets of data.

3.2.2. Branch fraction and calculation of stem and branch biomass

Appendices B and C summarise the calculations leading to the estimation of tree (w_S) and stand (W_S) stem and branch biomass at the start and end, respectively, of the sample period in each stand, and the annual growth increment. Mean diameter at breast height and height of sampled trees were used to calculate stem volume using Eq. (1). This stem volume was converted to stem mass, assuming a basic wood density of 500 kg m^{-3}. The additional woody biomass contributed by the branches and bark was estimated from tree age using the relationship in Fig. 3 derived from biomass measurements recorded from destructively sampled trees. The site index and annual increment of W_S were calculated for each site (Appendix C).

3.2.3. Leaf area index

Appendix D shows the calculations that lead to L. It is assumed that the mean foliage mass of the three sample trees adequately represented the stand. The values of W_F (foliage dry mass, t ha^{-1}) defined the

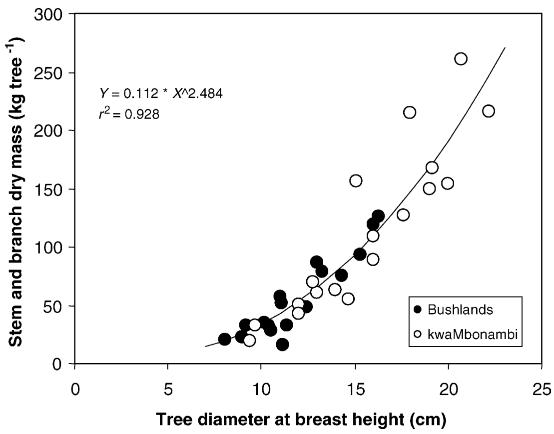


Fig. 2. The relationship between tree diameter at breast height (B) and w_S for destructively sampled trees from the Bushlands and kwaMbonambi sites. The trend is defined by a non-linear regression fitted to the data.

starting W_F in the simulations, as well as the end of year W_F used to gauge the accuracy of W_F simulated by the model.

At Bushlands, most estimates of L were between 2 and 3.5, but with a declining trend over the 12-month period. At kwaMbonambi, there was greater variation, which is largely due to the consistently higher L at NP20b. Excluding this stand, L was mostly between 2 and 3.5. Appendix D also illustrates the specific leaf area (σ) measured in foliage sub-samples. A mean of

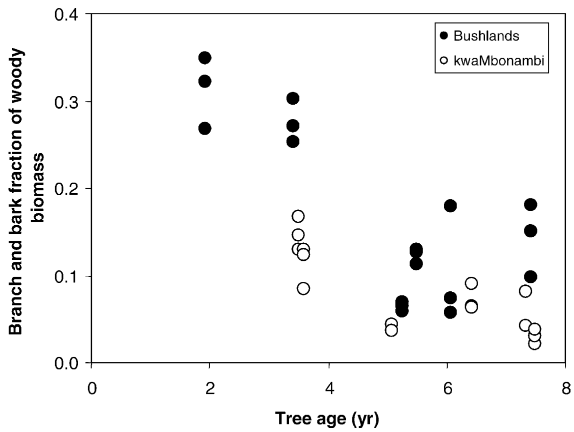


Fig. 3. The relationship between tree age and the fraction of woody biomass (w_S) consisting of branches and bark, as recorded in three sample trees in each of the Bushlands and kwaMbonambi sites.

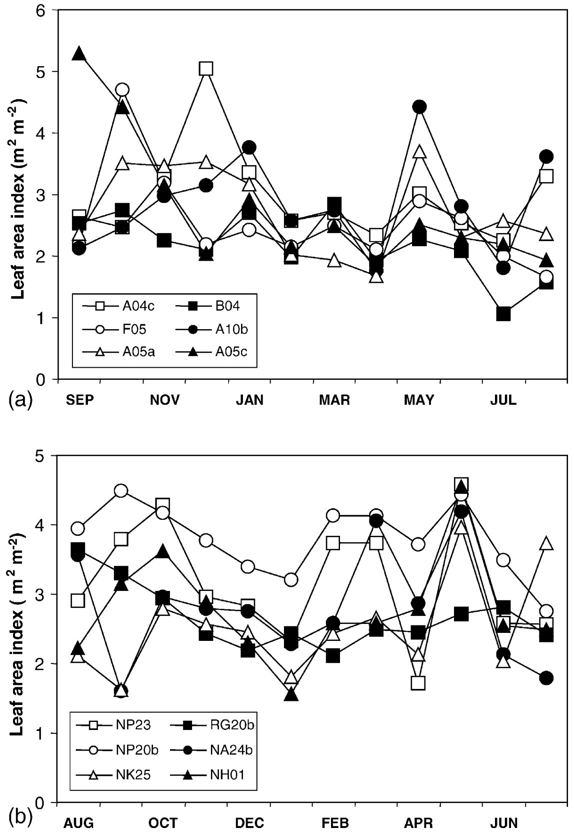


Fig. 4. Monthly leaf area index (L) estimated with a LI-COR canopy analyser at (a) the Bushland and (b) the kwaMbonambi sites. The figures were corrected using Eq. (2).

all sub-samples was used in the model simulations (Fig. 4).

3.2.4. Sap flow

Fig. 5 illustrates the range of daily sap flow (l per day) recorded in single sample trees at different times of the year. Box and whisker plots illustrate the median and 25 and 75% percentiles, non-outlier maximum and minimum values, and outliers. Despite each box and whisker reflecting daily sap flows in only one sample tree, the diagrams reveal a clear difference between the two groups of sites. Median daily flows range from approximately 30–64 l per day for the more productive sites at kwaMbonambi (NP20b, NP23, NK25), and from approximately 15–34 l per day for the less productive sites at Bushlands (B04, F05, A04c). Seasonal differences are not clearly expressed, owing to the loss of some data sets due to equipment problems, and probable physiological variation among successive sample trees in a plot. These results nevertheless provide a useful guide to the range of sap-flow rate that 3-PG should predict.

3.2.5. Litterfall

Storms had a marked effect in increasing the litter catch in traps, and the effects of a severe January storm are apparent in the recording for both districts (Fig. 6). Seasonal variation in litterfall was especially evident at the kwaMbonambi sites: lowest rates occurred during the summer months, but these gradually increased during the dry winter (Fig. 6b). A similar dry season increase was evident at the Bushlands sites. 3-PG does not make provision for month-by-month variation in litterfall rate, but rather assumes a constant rate throughout the year. A mean W_F of 2.94 t ha^{-1} for the Bushlands sites was estimated (Appendix D). A mean annual litterfall rate of approximately 2.4 t ha^{-1} is equivalent to an annual leaf turnover rate of 0.82, and a monthly rate of 0.068. Mean W_F for the kwaMbonambi sites was 3.55 t ha^{-1}. A mean annual litterfall rate of approximately 3 t ha^{-1} is equivalent to an annual turnover rate of 0.85, and a monthly rate of 0.071.

3.2.6. Pre-dawn xylem pressure potential

A comparison of ψ_{pd} between the Bushlands and kwaMbonambi sites is difficult because of the limited sampling that took place at kwaMbonambi. Nevertheless, the expected higher level of water stress at the drier Bushlands sites is apparent (Appendix E). Severe water stress was experienced by trees at the Bushlands sites B04, F05, A10b and A05c, while indications of stress were also evident at the kwaMbonambi sites RG20b and NA24b.

3.3. Parameter estimation strategy and model performance

3-PG requires two sets of input parameters: a set of species parameters defines the structural and physiological characteristics of the species being simulated, while a set of site and initialisation parameters describes the principal soil and climate conditions, and starting biomass pertaining at each site.

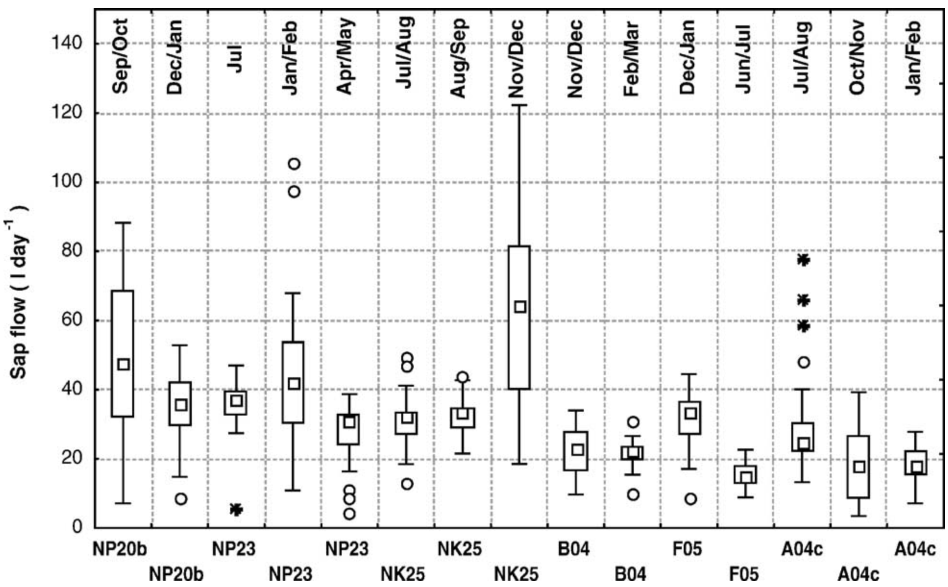


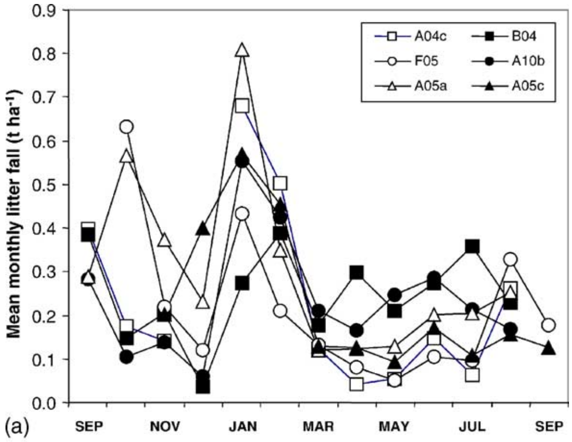
Fig. 5. Variation in daily sap flow recorded at three kwaMbonambi sites (NP20b, NP23, NK25) and three Bushlands sites (B04, F05, A04c) at different times of the year.

Our strategy was to develop a single set of species parameter values that applies to all sites, assuming that variation in growth and evapotranspiration (E_T) among the sites is largely accounted for by differences in site conditions and starting biomass. This was to minimise the amount of arbitrary changes to those species parameters for which field evidence is very difficult to obtain.

A set of default species parameter values applicable to *Eucalyptus globulus* provided a useful starting point. Those parameters for which we had field data were modified accordingly. With this preliminary parameter set, we determined whether 3-PG could duplicate the highest observed growth increments. Starting biomass of stems and branches (W_S) and foliage (W_F) were based on the results of the first biomass survey at each site. Starting root biomass (W_R) was estimated as being approximately 25% of total tree biomass (Shepherd, 1985). A complete list of species parameters used in simulations for each site is shown in Appendix F.

There were strong indications that the two stands showing the highest annual growth increment (NP20b and NP23) had continuous access to the water table. NP20b in particular was situated close to a lake, and measurements of ψ_{pd} indicated little water stress during the dry seasons (Appendix E). The parameter describing maximum available soil water (θ_{max}) was therefore increased until a point (1500 mm) where the soil-water modifier remained close to one (no water stress) in every month of the year. It was found that 3-PG could still not simulate the high growth increments in these two stands, despite FR being set close to maximum. Modelled foliage mass (W_F) declined over most sites in response to the high rate of litterfall based on field measurements. Changes were made to two species parameters to increase above-ground growth, stabilise W_F and L at realistic levels, and match the higher growth increments. Canopy quantum efficiency was raised from 0.055 to 0.07 mol mol^{-1}, which is in line with recent estimates of this parameter for *Eucalyptus* trees (Landsberg et al., 2003), while the minimum fraction of net primary production (P_N) allocated to roots was reduced from 0.25 to 0.2. The species parameter set was kept unchanged for all subsequent simulations.

We then evaluated which 3-PG site parameter values were required to match the lowest recorded growth increments. Particular attention was again given to θ_{max} and the fertility rating (FR), which have a large influence on simulated growth and E_T. Both parameters are recognised amongst 3-PG modellers as



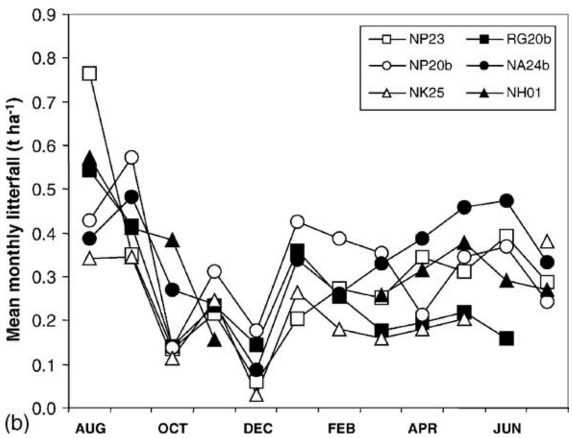


Fig. 6. Monthly litterfall estimated from litter traps at (a) the Bushlands and (b) the kwaMbonambi sites.

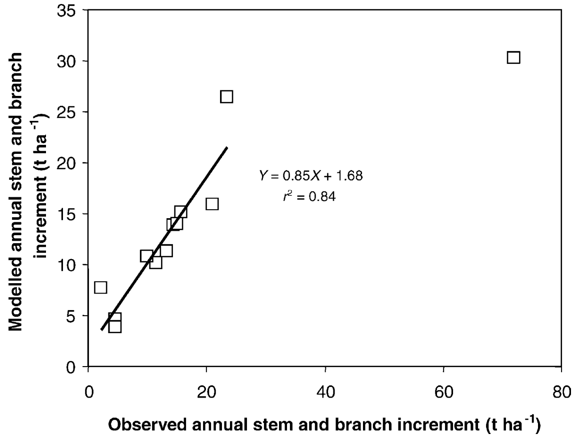


Fig. 7. Comparison of simulated and observed annual (W_S) growth increment for 12 study sites. The outlier data point was excluded from the regression analysis.

being difficult to quantify. θ_{max} may be very hard to estimate where tree roots extend deep into subsoils in which variable proportions of rocks complicate the estimation of water-holding capacity. Deep soil/subsoil profiles may also be difficult to excavate, as in the loose, deep, sandy soils of coastal Zululand. No satisfactory index relating FR to foliar or soil nutrient status has yet been developed (Landsberg, 2000). The problem is magnified in sandy Zululand soils, where a very wide range of soil fertility may be encountered (Noble et al., 1991), and where nutrients are easily leached and may not necessarily be concentrated in the surface horizons of the deep, coarse-textured and well-drained soils.

Both θ_{max} and FR were reduced for the sites showing lowest annual growth (A05c, A04c, F05) until a reasonable match with observed data was obtained. Having defined the range of θ and FR required to simulate the maximum and minimum growth increments, the final parameter fitting step was to estimate θ_{max} and FR for the remaining intermediate sites. We took care to avoid assigning parameter values in a manner that merely produces the best-fit to observed growth data. Values of both parameters were varied experimentally, but constrained by having to increase consistently with observed increases in the increment of W_S at each site. In the sequence of sites from NP20b to A05c, FR declines consistently from 1.0 to 0.2, while θ_{max} declines from 1500 to 150 mm (Appendix G). Eleven of the sites describe a well-defined trend between simulated and observed growth increment ($r^2 = 0.84$) with a slope of 0.85 (Fig. 7). The twelfth site (NP20b) had an extremely high annual growth increment ($W_S > 72$ t ha^{-1}) and both diameter (1.9 cm) and height (3.7 m) increments were large in comparison to those expected from 7-year-old *E. grandis* managed for pulpwood on a high quality site (Kassier and Kotze, 2000). Unusually high heat-pulse velocities were measured on clear days (Fig. 5), suggesting that xylem vessels may have been of larger diameter than usual. If true, then the greater efficiency of water transport to the leaves is likely to cause enhanced stomatal conductance, carbon assimilation and growth rate. A subsequent comparison of mean vessel diameter in samples of recent sapwood showed a significant ($t = 8.29$, $P < 0.001$) difference between NP20b (127.3 μm) and F05 (87.8 μm), supporting the hypothesis that continuous access to groundwater in NP20b had promoted changes in xylem structure leading to faster sap flow and growth. Considering that the trees are believed to have easy access to shallow groundwater, that they would have experienced little water stress and that they displayed the highest site index, this appears to be a plausible hypothesis. In a study of transpiration patterns of *Eucalyptus* species along a steep rainfall gradient in a north Australian savanna, Eamus et al. (2000) reported evidence that the intensity of dry season water deficits exerts control on tree water use during the wet season, possibly through an effect on xylem structure. There is a clear need for more physiological information from forest stands to bring greater certainty to some of the "hard to measure" physiological parameters. The move towards clonal eucalypts in South Africa has revealed a high degree of physiological variation amongst even the most productive clones (Dye et al., 1997), suggesting that a single set of species parameter values may be inadequate when applied to such genotypes.

The simulated monthly rate of transpiration was checked against observed sap-flow data. The highest simulated monthly sap-flow (expressed as a mean daily rate over the month) corresponds very well to the measured median daily sap-flows (Appendix H). However, the simulated minimum monthly sap-flow rates are nearly all lower than the observed lowest daily sap-flow rates. We believe this discrepancy is due to the simple manner in which 3-PG calculates the availability of soil water to tree roots. Roots are considered able to completely exhaust available soil water in soil with a fixed water-storage capacity. In reality, the availability of soil water is likely to be less clear cut, with the deepest (sinker) roots penetrating below the major soil-water storage zone to tap deeper subsoil water reserves. Such dimorphic root systems (Jacobs, 1955; Kimber, 1974) have been described for several *Eucalyptus* species (Knight, 1999). Although root densities may be low in the deeper strata, slow rates of uptake are sufficient to keep the tree alive until the higher soil strata are again recharged by rainfall. 3-PG requires improvement in this area. An additional means by which trees are able to access soil water from below the rooting zone during dry periods has recently been described by Soares and Almeida (2001). They describe an upward flux of water from a deep water table towards a 2.5 m deep rooting zone in an *E. grandis* plantation. This flux was close to 1 mm per day, and prevented the stomata from closing down completely.

The upper range of total yearly sap flow simulated for the six sites accords with results obtained in a previous study, where continuous sap-flow measurements in three clones indicated annual sap flows varying from 900 to 1400 mm (Dye et al., 1997). The lower range of simulated annual sap-flow at the Bushlands sites is believed to be unrealistically low, as a result of the likely access to deep soil-water reserves during dry periods.

The fertility ratio (FR) was empirically determined to range from 0.2 to 1.0. While we have no direct means of verifying that this range is realistic, we note that in a study of 19 Tasmanian *Eucalyptus* plots covering a wide range of site indices, Landsberg (2000) found that the best model predictions were obtained when FR was allowed to vary from 0.1 to 0.9.

4. Discussion and conclusions

The primary objective of this study was to determine whether 3-PG could be practically parameterised to simulate annual growth increments in a collection of *Eucalyptus* stands showing wide variation in tree age, site quality and growth rate. Successful application of the 3-PG model to such multi-stand situations that characterise forestry estates in South Africa depends largely on the choice of appropriate values for the species- and site-specific parameters, many of which are difficult to measure in the field. Several recent studies have demonstrated that 3-PG can be parameterised to simulate tree growth over a wide range of site conditions with useful accuracy (Sands and Landsberg, 2002; Stape, 2002; Landsberg et al., 2003), but this success is to some extent a reflection of the availability of background information on the physiology and structure of the species being modelled. South African forest plantations consist of a relatively large number of species and clones growing over a very wide range of site conditions, and there is a scarcity of required species and site information for 3-PG modelling. This study was a test of whether, in the absence of adequate background knowledge, realistic simulations are possible using a parameter set that is (i) based on a limited amount of field data; (ii) relies heavily on default *Eucalyptus* values for most of the species parameters, and (iii) resorts to a fitting procedure to estimate the important site characteristics of θ_{max} and FR. The results showed that such an approach can give rise to a useful preliminary set of parameter values, and that these can be estimated over a period as short as 1 year. A subsequent period of model testing and tuning is recommended to test model predictions. Such a two-phase parameterisation process is believed to be a feasible procedure for model implementation in forest plantations where month-by-month growth predictions are required to continually update yield forecasts.

This study revealed some useful insights into the availability of data in forestry areas, the similarity between *E. grandis* × *camaldulensis* attributes and other plantation *Eucalyptus* species, and the practicality of various field methodologies. Suitable climate data are often unavailable for specific forest sites. Weather stations are especially scarce in South African forestry areas, many of which are situated in rugged topography where spatial extrapolation of weather station data is complex. We recommend that forest managers wishing to apply 3-PG on a continuing basis should purchase one or more automatic weather stations to provide the necessary input weather data. Of the five input variables required by 3-PG, rainfall was found to show the greatest spatial variability, and consequently needs to be measured as close as possible to the simulation sites.

Growth increments were readily calculated from ''before and after'' measurements of diameter at breast height and height in a sample of trees, and by making use of volume equations supplied by the forest owner. A far greater effort was required to obtain the allometric ratio of diameter at breast height to the dry mass of stem and branches. Much allometric data exist in the literature, but where relevant information is unavailable for a particular species, destructive harvesting of a sample of trees is necessary. Sampling in three or four age classes of tree to cover a range of tree size may be sufficient to describe a species or clone in a particular area, especially where tree heights, taper and wood density are not influenced by significant gradients in altitude and temperature. Branch dry mass as a fraction of total woody biomass is another required model parameter that may be obtained from biomass measurements.

Stand leaf area index (L) is an important determinant of stand growth and water use, and simulated L needs to be verified against field measurements. Instruments such as the LI-COR canopy analyser are generally convenient to use across multiple stands, although some difficulty was experienced at sites where no suitable nearby clearing existed in which to measure ''above-canopy'' light. The specific leaf area (σ) of trees varies greatly according to species, leaf age, position in the canopy, and nutrition (Lambers and Poorter, 1992; Reich et al., 1995), and is believed to be an important parameter accounting for differences in the growth rate of tree species (Landsberg et al., 2003). In eucalypts, σ can vary from 20 (Cromer et al., 1993) to 3.5 (Landsberg et al., 2003), with leaf age accounting for much of this variation. The mean value of 7.6 recorded in this study for non-juvenile trees is reasonably close to the value of 10.0 recorded for *Eucalyptus saligna* in Hawaii, and a range from 8.5 to 11.0 recorded for *E. grandis* × *urophylla* in Brazil (Stape, 2002). Leaf samples representing all parts of the canopy of a small number of sample trees are likely to adequately represent a particular species or clone, but care should be exercised in extrapolating results to stands experiencing very different growing conditions.

Accurate rates of litterfall are essential to simulate correct foliage biomass through the rotation. Information on both leaf areas and litterfall rates are very useful in fixing the amount of P_N allocated to foliage which, given similar information on stem and branch mass, casts light on the amount of P_N allocated to roots. The monthly litterfall rate (expressed as a fraction of foliage biomass) estimated in this study (0.07) is substantially higher than the rate (0.027) recommended for *E. globulus* (Sands and Landsberg, 2002), but is similar to a rate of 0.07 recorded for *E. grandis* × *urophylla* in Brazil, and a rate of 0.11

recorded for *E. saligna* in Hawaii (Giardina and Ryan, 2002).

Water is considered to be the main factor limiting growth of plantation trees in southern Africa (Schönau and Grey, 1987; Grey et al., 1993), and the capacity of the soil to store water is known to be strongly correlated to site productivity (Louw, 1999).

Soil profile descriptions for forest plantations are widely available, but mostly restricted to a depth of approximately 1 m. It is widely reported that tree roots (especially *Eucalyptus*) extend deeper into the subsoil (Knight, 1999) where water supply to roots is likely to be more reliable than in upper horizons. This study has demonstrated consistent underestimation of water use by trees during periods of low soil-water availability, pointing to probable subsoil water utilisation. It is in most instances impractical to adequately measure the extent of subsoil water storage. The fitting process adopted in this study provided a first estimate of θ_{max} at each site. Estimates obtained in this way can be checked for realism by monitoring drought stress during dry periods. Assuming accurate simulation of water movement into and out of the soil, the onset of drought stress can provide a useful indication of whether the soil/subsoil storage capacity is markedly over- or underestimated. Measurements of pre-dawn xylem pressure potential performed with a Scholander pressure chamber are not suited to multi-stand studies, due to the difficulties of obtaining sample leaves in pre-dawn darkness from tall canopies. We believe that remote-sensing techniques offer better prospects for efficiently monitoring the spatial development of stress in forest plantations.

The problem of estimating a soil fertility rating for stands is described by Landsberg et al. (2003). Ideally, it should be estimated by calibrating the model against data from a fertiliser trial (Stape, 2002). However, such information is often not available, and thus FR may need to be treated as a tunable parameter until a suitable single measure of soil fertility is developed.

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Appendix A

Monthly weather data including solar radiation (R_s) rainfall (P), vapour pressure deficit (D_{day}), applicable to the Bushlands and kwaMbonambi sites for the 12-month simulation period

	Month beginning												
	2000					2001							
	August	September	October	November	December	January	February	March	April	May	June	July	August
Bushlands sites													
R_s (MJ m^{-2} per day)	15.7	12.5	13.3	14.5	21.1	18.5	16.2	16.3	13.0	9.4	6.4	10.7	10.8
P (mm)	1.0	68.5	90.5	289.8	72.9	64.4	49.7	74.7	3.4	8.0	19.3	21.3	73.7
D_{day} (kPa)	1.40	1.06	1.21	0.88	1.23	1.48	1.14	0.80	0.98	0.98	0.93	1.08	1.14
Frost days	0	0	0	0	0	0	0	0	0	0	0	0	0
T (°C)	19.6	20.0	20.5	22.1	23.9	24.1	24.2	23.2	20.6	19.3	17.1	16.9	19.3
	July	August	September	October	November	December	January	February	March	April	May	June	July
kwaMbonambi sites													
R_s (MJ m^{-2} per day)	12.0	15.7	10.0	13.3	14.2	19.8	16.9	15.8	13.6	12.2	8.4	7.9	12.0
P (Hugo) (mm)	16.0	4.0	74.0	404.0	98.7	195.0	83.3	49.3	107.9	20.0	7.7	6.2	34.1
P (Kwambo FPS) (mm)	16.0	4.0	110.0	123.9	363.0	134.0	151.0	45.8	113.7	23.0	14.0	9.0	44.0
D (kPa)	0.84	1.22	0.99	1.05	1.27	1.34	1.13	1.14	0.80	0.98	0.84	0.85	1.06
Frost days	0	0	0	0	0	0	0	0	0	0	0	0	0
T (°C)	17.6	19.6	15.7	19.5	18.3	22.8	22.3	23.0	20.8	16.0	13.9	15.3	17.6

Appendix B

Stand volume and biomass at the start of the 12-month simulation period

	Bushlands						kwaMbonambi					
	Low site index			High site index			Low site index			High site index		
	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Compartment	A04c	B04	F05	A10b	A05a	A05c	NP23	RG20b	NH01	NA24b	NK25	NP20b
Date of survey at start	17 August	17 August	19 September	17 August	17 August	17 August	5 July	5 July	5 July	5 July	5 July	5 July
Stand density (ha^{-1})	1418	1143	1170	1330	1177	1220	1390	1098	1116	1316	1285	1211
Mortality (%)	0	0	1.25	6.25	2.5	5	0	2.5	3.75	1.25	7.5	14.3
No. of trees measured	80	80	79	75	78	76	80	78	77	79	74	58
Mean diameter at breast height (cm)	10.1	12.8	13.2	10	14.7	14.1	11.8	15.8	16.2	11.4	15.5	17.5
Mean height (m)	11.8	16.8	19.9	11.8	19	20.6	14	21.8	23.1	15.6	23.3	23.0
Mean stem volume (m^3 per tree)	0.0353	0.0837	0.1078	0.0347	0.1291	0.1277	0.0585	0.1698	0.2136	0.0624	0.1847	0.2209
Mean stem mass (kg per tree)	17.65	41.85	53.90	17.35	64.55	63.85	29.25	84.90	106.80	31.20	92.35	110.45
Stem and branch mass, w_S (kg per tree)	23.87	48.63	60.96	23.56	71.85	71.14	35.74	92.67	115.08	37.73	100.29	118.81
Stem and branch mass, W_S (t ha^{-1})	33.85	55.58	71.32	31.33	84.57	86.79	49.68	101.75	128.43	49.65	128.87	143.88

Appendix C

Stand volume and biomass at the end of the 12-month simulation period

	Bushlands						kwaMbonambi					
	Low site index			High site index			Low site index			High site index		
	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Compartment	A04c	B04	F05	A10b	A05a	A05c	NP23	RG20b	NH01	NA24b	NK25	NP20b
Date of survey at end	1 August	1 August	19 September	1 August	1 August	19 September	1 July	1 July	1 July	1 July	1 July	1 July
No. of trees measured	71	75	73	72	75	71	72	75	69	75	64	78
Mean diameter at breast height (cm)	11.1	13.3	13.8	11.7	15.1	14.4	13.3	16.7	16.2	12.3	16.3	19.4
Mean height (m)	11.8	19.5	19.9	13.7	21.0	20.5	16.9	24.0	23.5	16.7	23.5	26.7
Mean stem volume (m^3 per tree)	0.0416	0.1083	0.1155	0.0541	0.1543	0.1314	0.0915	0.2073	0.2309	0.0794	0.2085	0.3373
Mean stem mass (kg per tree)	20.80	54.15	57.75	27.05	77.15	65.70	45.75	103.65	115.45	39.7	104.25	168.65
Stem and branch mass, w_S (kg per tree)	27.09	61.21	64.89	33.49	84.74	73.03	52.62	111.85	123.93	46.43	112.47	178.36
Stem and branch mass, W_S (t ha^{-1})	38.41	69.96	75.92	44.54	99.74	89.10	73.09	122.81	138.31	61.10	144.52	215.99
Annual increment of W_S (t ha^{-1})	4.56	14.38	4.60	13.21	15.17	2.31	23.41	21.06	9.88	11.45	15.65	72.11
Site index at age 5 years (m)	14.58	19.61	17.48	21.12	22.01	19.71	19.85	22.85	25.09	19.94	25.45	27.01

Appendix D

Leaf area index (L) based on recorded leaf mass of trees sampled at the start and end of the 12-month simulation period. L modelled by 3-PG at the end of the simulation period is shown for comparison

	Bushlands						kwaMbonambi					
	Low site index			High site index			Low site index			High site index		
	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Compartment	A04c	B04	F05	A10b	A05a	A05c	NP23	RG20b	NH01	NA24b	NK25	NP20b
Start of period												
Mean leaf mass (kg)	2.26	2.43	1.41	2.49	2.53	1.73	2.67	2.76	2.93	2.04	1.72	4.02
Specific leaf area, σ ($m^2\ kg^{-1}$)	7.14						8.11					
Mean leaf area (m^2 per tree)	16.14	17.35	10.07	17.78	18.06	12.35	21.65	22.38	23.76	16.54	13.95	32.60
Stand density (ha^{-1})	1418	1143	1170	1330	1177	1220	1390	1098	1116	1316	1285	1211
Leaf area index, L ($m^2\ m^{-2}$)	2.29	1.98	1.18	2.36	2.13	1.51	3.01	2.46	2.65	2.18	1.79	3.95
Foliage biomass, W_F ($t\ ha^{-1}$)	3.20	2.78	1.65	3.31	2.98	2.11	3.71	3.03	3.27	2.68	2.21	4.87
End of period												
Mean leaf mass (kg)	2.49	2.19	2.68	2.38	3.79	2.03	3.02	3.56	3.78	1.94	2.42	4.99
Specific leaf area, σ ($m^2\ kg^{-1}$)	6.37						7.70					
Mean leaf area (m^2 per tree)	15.86	13.95	17.07	15.16	24.14	12.93	23.25	27.41	29.11	14.94	18.63	38.42
Leaf area index, L ($m^2\ m^{-2}$)	2.25	1.59	2.00	2.02	2.84	1.58	3.23	3.01	3.25	1.97	2.39	4.20
Foliage biomass, W_F ($t\ ha^{-1}$)	3.53	2.50	3.14	3.17	4.46	2.48	4.19	3.91	4.22	2.55	3.11	6.04
Modelled L	1.91	2.26	1.01	2.67	2.26	1.23	3.86	2.51	2.17	2.10	2.01	3.63

Appendix E

Mean pre-dawn xylem pressure potential readings, ψ_{pd} (MPa) recorded at the Bushlands and kwaMbonambi sites. Numbers in brackets indicate the number of leaf samples measured

	Bushlands						kwaMbonambi					
	Low site index			High site index			Low site index			High site index		
	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Compartment	A04c	B04	F05	A10b	A05a	A05c	NP23	RG20b	NH01	NA24b	NK25	NP20b
August 2000	−0.67 (6)			−0.64 (5)	−0.77 (3)							
September 2000	−0.65 (5)	−0.58 (3)	−1.00 (3)	−1.10 (3)	−0.92 (3)							
May 2001	−0.89 (5)	−1.59 (5)	−1.58 (4)	−1.06 (4)	−0.70 (5)	−0.99 (4)						
June 2001	−1.04 (5)	−2.03 (4)	−1.62 (5)	−1.60 (5)	−1.13 (3)	−1.57 (5)	−1.01 (5)					−0.95 (4)
July 2001	−1.40 (5)	−1.24 (5)	−1.38 (5)	−1.32 (5)	−0.84 (5)	−1.40 (5)	−0.92 (5)		−0.92 (5)	−1.84 (5)	−0.58 (5)	−0.78 (5)
August 2001								−1.67 (6)				

Appendix F

A summary of *Eucalyptus grandis* × *camaldulensis* species parameter values used in model simulations. A parallel set of parameter values for *E. grandis* can be found in Table 4 of Almeida et al. (2004)

Meaning/comments	Value
Foliage:stem partitioning ratio at $D_{bh} = 2$ cm (p_2)	1
Foliage:stem partitioning ratio at $D_{bh} = 20$ cm (p_{20})	0.15
Constant in the stem mass vs. diameter relationship (a_S)	0.112
Power in the stem mass vs. diameter relationship (n_S)	2.484
Maximum fraction of P_N to roots (η_{Rx})	0.8
Minimum fraction of P_N to roots (η_{Rn})	0.2
Minimum temperature for growth (T_{min})	5
Optimum temperature for growth (T_{opt})	24
Maximum temperature for growth (T_{max})	36
Days production lost per frost day (k_F)	1
Maximum litterfall rate (γ_{Fx})	0.07
Litterfall rate at $t = 0$ (γ_{F0})	0.001
Age at which litterfall rate has median value ($t_{\gamma F}$)	24
Average monthly root turnover rate (γ_R)	0.015
Maximum canopy conductance (g_{Cx})	0.03
Leaf area index for maximum canopy conductance (L_{Cx})	3.33
Defines stomatal response to vapour pressure deficit (k_g)	0.05
Canopy boundary layer conductance (g_B)	0.2
Value of m when FR = 0	0.5
Value of f_N when FR = 0	0.3
Moisture ratio deficit for $f_\theta = 0.5$ (c_θ)	0.7
Power of moisture ratio deficit (n_θ)	9
Maximum stem mass per tree at 1000 trees/ha	300
Maximum stand age used in age modifier	50
Power of relative age in function for f_{AGE} (n_{age})	4
Relative age to give $f_{AGE} = 0.5$ (r_{age})	0.95
Specific leaf area (σ_0) at age 0	7.6
Specific leaf area σ_1 for mature leaves	7.6
Age at which specific leaf area = $(\sigma_0 + \sigma_1)/2$	2.5
Extinction coefficient for absorption of PAR by canopy (k)	0.45
Age at canopy cover	0
Proportion of intercepted rainfall evaporated from canopy (I)	0.04
Canopy quantum efficiency (α_C)	0.07
Branch and bark fraction at age 0 (P_{BB0})	0.3
Branch and bark fraction for mature stands (P_{BB1})	0.1
Age at which $P_{BB} = (P_{BB0} + P_{BB1})/2$	3.5
Ratio net to gross primary production (Y)	0.47
Basic density (ρ, kg m^{-3})	0.5

Appendix G

A summary of 3-PG site and initialisation parameter values used in model simulations including those for fertility rating (FR), available soil water (θ) and biomass (W)

	Bushlands						kwaMbonambi					
	Low site index			High site index			Low site index			High site index		
	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
Compartment	A04c	B04	F05	A10b	A05a	A05c	NP23	RG20b	NH01	NA24b	NK25	NP20b
FR	0.2	0.9	0.2	0.8	0.9	0.2	0.9	0.9	0.7	0.7	0.9	1.0
Soil class	Sa	Sa	Sa	Sa	Sa	Sa	Sa	Sa	Sa	Sa	Sa	Sa
θ_{max} (mm)	150	300	150	300	300	150	1500	500	300	300	500	1500
θ_{min} (mm)	0	0	0	0	0	0	0	0	0	0	0	0
Initial θ	10	150	10	100	150	10	1500	250	60	60	250	1500
Initial age (years)	3	5	7	2	5	6	3	6	7	3	5	7
End age (years)	4	6	8	3	6	7	4	7	8	4	6	8
W_F (t ha^{-1})	3.20	2.78	1.65	3.31	2.98	2.11	3.71	3.03	3.27	2.68	2.21	4.24
W_R (t ha^{-1})	9.26	14.59	18.24	8.66	21.89	22.22	13.35	26.20	32.93	13.08	32.77	37.03
W_S (t ha^{-1})	33.85	55.58	71.32	31.33	84.57	86.79	49.68	101.75	128.43	49.65	128.87	143.88

Appendix H

Simulated mean daily sap flow in each month (l per day) and annual sap-flow (mm per year) for the six sites in which sap-flow measurements took place. The range of observed median daily sap-flow (Fig. 5) is also shown for comparison to model results

Month	Bushlands			kwaMbonambi		
	A04c	B04	F05	NP23	NP20b	NK25
July	2.7	24.2	1.5	18.1	25.4	13.0
August	15.9	25.9	14.4	29.0	37.8	20.5
September	19.6	25.5	5.8	27.6	35.1	20.2
October	1.9	3.9	2.3	32.1	40.8	24.4
November	1.4	2.5	4.0	35.7	45.5	27.7
December	2.9	3.3	6.3	32.7	41.6	24.6
January	5.7	5.3	9.2	37.2	47.4	9.6
February	0.7	1.3	7.8	34.6	44.0	5.9
March	11.2	6.7	12.1	19.6	25.0	1.9
April	15.5	20.9	11.9	18.5	23.6	7.8
May	16.5	23.5	9.3	27.0	34.3	17.8
June	12.3	18.9	11.9	26.8	34.1	18.7
Maximum	19.6	25.9	14.4	37.2	47.4	27.7
Minimum	0.7	1.3	2.3	18.1	23.6	1.9
Annual sap-flow (mm per years)	450	555	339	1412	601	740
Observed range of median daily sap-flow (Fig. 5)	14.7–33.4			30.9–64.3		

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