PREDICTING *EUCALYPTUS* PRODUCTION IN SOUTHERN CHINA USING THE 3-PG MODEL

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HUA, L. Z., MORRIS, J., HE, X. B. & JIANG, X. D. 2007. Predicting *Eucalyptus* production in southern China using the 3-PG model. The 3-PG model was applied to predict plantation growth and yield in reference to climate, soil conditions, management and species. Tree growth in three *Eucalyptus* genotypes, *E. urophylla*, *E. urophylla* Clone U6 and *Eucalyptus* ABL12 (*E. tereticornis*) Clone W5, was monitored between 1999 and 2002 at Jijia on the Leizhou Peninsula, Guangdong. Parameter values for 3-PG were determined by calibration on the basis of monitoring data. The model was tested using additional growth data of the three genotypes from two sites on the Leizhou Peninsula. The calibration results for various stand variables were satisfactory (overall mean $r^2 > 0.93$ and mean accuracy > 88% for stand growth, accuracy > 82% for stand biomass and leaf area index). Root biomass was less accurately predicted because root systems actually extended to greater depth than we were able to assess. Independent testing of the calibrated model showed simulation accuracy for most variables was > 91%. Stand volume (SV) responded positively to fertility but negatively to salinity for each species. SV was not closely correlated with rainfall, but under dry condition, it significantly declined with rainfall decrease. It implied that soil water was not a main limiting factor on stand growth in the rainy area.

Keywords: *Eucalyptus* plantations, growth prediction, southern China, calibration, plantation growth

HUA, L. Z., MORRIS, J., HE, X. B. & JIANG, X. D. 2007. Meramal penghasilan *Eucalyptus* di selatan China dengan menggunakan model 3-PG model. Model 3-PG digunakan untuk meramal pertumbuhan serta hasil ladang berdasarkan iklim, keadaan tanih, pengurusan dan spesies. Pertumbuhan tiga genotip *Eucalyptus* iaitu *E. urophylla*, *E. urophylla* Klon U6 and *Eucalyptus* ABL12 (*E. tereticornis*) Klon W5 dipantau dari tahun 1999 hingga tahun 2002 di Jijia yang terletak di Semenanjung Leizhou, Guangdong. Nilai parameter untuk 3-PG ditentukan melalui penentukuran berdasarkan pemantauan data. Model tersebut diuji menggunakan data pertumbuhan tambahan bagi tiga genotip tersebut dari dua tapak di Semenanjung Leizhou. Keputusan penentukuran bagi pelbagai pemboleh ubah dirian adalah memuaskan (min keseluruhan $r^2 > 0.93$ dan min kejituan > 88% bagi pertumbuhan dirian, kejituan > 82% bagi biojisim dirian dan indeks luas daun). Ramalan biojisim akar adalah kurang jitu kerana sistem akar menjalar melebihi daripada kedalamanan yang dapat kami nilai. Ujian tak bersandar bagi model yang ditentukur menunjukkan kejituan simulasi bagi kebanyakan pemboleh ubah adalah > 91%. Isi padu dirian (SV) bertindak balas dengan positif terhadap kesuburan tetapi sebaliknya terhadap kemasinan setiap spesies. SV tiada kaitan rapat dengan hujan. Namun, dalam keadaan kering, nilainya menurun dengan signifikan apabila hujan berkurangan. Ini menunjukkan bahawa air tanih bukan merupakan faktor pengehad terhadap pertumbuhan dirian di kawasan yang mengalami hujan.

INTRODUCTION

Eucalypts were introduced into Guangdong province, China in the late nineteenth century. Today, due to their fast growth, high production and good wood properties, *Eucalyptus* plantations have become dominant in southern China, with an area of approximately 1.54 million ha managed mainly for pulpwood (Qi 2002). As well as their key role in the production of timber and fibre, *Eucalyptus* plantations in China have an important ecological role in the restoration of degraded lands (Zhou *et al.* 2002).

With good seedling material and intensive management adopted in southern China the rotation ages of *Eucalyptus* plantations are as short as four or five years. This is too short to leave enough time for reversal or correction

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of suboptimal establishment or management decisions. In this situation, a well-validated model such as the Landsberg and Waring (1997) 3-PG model (the acronym stands for Physiological Principles for Predicting Growth) may be particularly valuable as a predictor of the implications of planting season, spacing, species choice or appropriate management practices for growth on a given site (Morris & Baker 2003).

The 3-PG model is a monthly time-step forest growth model. It is based on a number of well-established principles and some recently confirmed constants that greatly simplify calculations. The model aims to bridge the gap between conventional empirical, mensuration-based growth and yield models and process-based carbon balance models (Landsberg & Waring 1997). Its structure is not site- or species-specific, however, it needs to be parameterized for individual species. It is remarkably different from empirical forest growth models that are insensitive to changes in weather conditions, especially rainfall and management strategies, both of which are known to strongly influence growth rates (Dye *et al.* 2004).

Since the initial publication of 3-PG (Landsberg & Waring 1997), the model has been widely applied to various species in Australia (Sands & Landsberg 2002), UK (Landsberg *et al.* 2001, Waring 2000), Brazil (Almeida *et al.* 2003, 2004a, b) and South Africa (Dye 2001, Dye *et al.* 2004, Esprey *et al.* 2004, Campion *et al.* 2005). The experience in these countries has shown it to yield realistic predictions for a wide variety of forests. The model was modified into a spatial version which allowed remotely sensed observations to be utilized as inputs for predicting forest productivity across landscapes (Coops *et al.* 1998a, b, Coops & Waring 2000, 2001). Taking account of new factors and processes, an extended version of the model, allowing for the prediction of water use and growth in areas with saline soil conditions or saline irrigation, was developed by Morris and Collopy (2001). The modifications in the extended model, with Microsoft Visual Basic-user interface, include: (1) new mortality function including early mortality before the self-thinning rule takes effect; (2) dynamic diameter distribution prediction; (3) early growth adjustments for photosynthetically active radiation (PAR) before canopy closure; (4) soil water availability subject to root system development; (5) addition of a root zone salinity modifier and a simple salt-balance model; (6) inclusion of shallow groundwater as a source of plantation water uptake; and (7) canopy conductance modified by mean daytime temperature, mean daytime vapour pressure deficit (VPD), soil moisture, stand age and root zone salinity. The work described in the present paper applied the extended 3-PG model to simulate plantation growth of three *Eucalyptus* clones, in order to provide a tool for decision making to optimize the sustainable productivity of *Eucalyptus* plantations for forest managers and planners in China. The model was parameterized and tested against three years of observation data collected between September 1999 and September 2002 at Jijia and Hetou forest farms on the Leizhou Peninsula, Guangdong, China. In addition, it also evaluates the growth potential of three *Eucalyptus* genotypes under given conditions of rainfall and soil changes.

MATERIALS AND METHODS

The 3-PG model

Structure

The model (see Table 1 for summary of abbreviations and symbols) simulates dynamic monthly changes of forest properties and environment by a series of functions that model the carbon balance, water balance, salt balance and solar radiation changes. It predicts the total carbon fixed (gross primary production: P_G) from monthly solar radiation absorbed by a forest canopy (φ_{pa}) and the forest canopy quantum efficiency (radiation utilization efficiency), modified by climate, soil and management

Table 1 Abbreviations and symbols used in the text and in equations

Definition	Name
Monthly photosynthetically active radiation (PAR)	φ_p
Monthly solar radiation absorbed by a forest canopy	φ_{pa}
Gross primary production (g C m^{-2})	P_G
Net primary production (g C m^{-2})	P_N
Leaf area index	LAI
Vapour pressure deficit (kPa)	VPD
Dimensionless modifier of monthly frost days	f_{frost}
Dimensionless modifier of stand age	f_{age}
Dimensionless modifier of species minimum, maximum and optimum temperature for growth	f_{emp}
Dimensionless modifier of root zone salinity tolerance	f_{salt}
Dimensionless modifier of soil moisture ratio	f_θ
Dimensionless modifier of monthly vapour pressure deficit	f_D

factors. Net primary production (P_N) is a constant fraction c_{pp} of P_G (Waring *et al.* 1998). P_N can be expressed as

$$P_N = \varphi_{pa}(1-e^{(-k.LAI)}) \cdot f_{frost} \cdot f_{age} \cdot f_{temp} \cdot f_{salt} \cdot \min(f_D, f_\theta)(\alpha_c + \beta \cdot f_{nut}) \cdot c_{pp} \quad (1)$$

where

φ_p = monthly photosynthetically active radiation (PAR)
k = canopy extinction coefficient
LAI = leaf area index which is a function of foliage mass and specific leaf area
c_{pp} = the ratio P_N/P_G
f_{frost} = a function of monthly frost days
f_{age} = a function of stand age
f_{temp} = a function of species minimum, maximum and optimum temperature for growth
f_{salt} = a function of species root zone salinity tolerance
f_θ is a function of soil moisture availability
f_D = a function of species stomatal response to VPD
α_c = canopy quantum efficiency coefficient
β = a modifier for which takes into account fertility ranking (FR) response
f_{nut} = a function of site fertility index and fertility decline.

In the model, f_{frost}, f_{age}, f_{temp}, f_θ, f_D and f_{salt} took values between 0 (system 'shutdown') and 1 (no constraint). Except for soil moisture and VPD, the effects of the modifiers on growth were applied multiplicatively. Only the more limiting of soil moisture and VPD factors were used, i.e. if soil moisture was more limiting than VPD, tree growth was assumed to be constrained by soil moisture during that period.

The carbon fixed by forest canopy was partitioned into foliage, stems and roots using allometric relations of foliage and stem biomass with tree diameter. Stem volume production was obtained from wood biomass with an allowance for branches and bark.

A submodel in the 3-PG model predicts forest canopy transpiration using well-established and widely-used Penman-Monteith equation. Estimates of forest canopy conductance (g_c) account for the effects of soil moisture, stand age, root zone salinity and temperature. The function adopted for g_c which differs from the original 3-PG version (Landberg and Waring 1997) is shown in Equation (2).

$$g_c = g_{cm} \cdot f_{soil} \cdot f_{age} \cdot f_{temp} \cdot f_{salt} \cdot f_D \cdot LAI/3 \quad (2)$$

where

g_{cm} = maximum forest canopy conductance
f_{soil}, f_{age}, f_{temp}, f_{salt} and f_D = available soil moisture, stand age, mean daytime temperature, root zone salinity and VPD modifiers respectively.

Input data for modelling

The 3-PG model requires the following four categories of information to predict stand growth:

(1) climate: monthly radiation, rainfall, maximum and minimum temperature, daytime VPD, wind speed and frost days. The model can be run for any number of years, using either long-term averages or actual time sequence from any number of years.
(2) site factors: latitude, site fertility rating (FR), fertility decline, soil salinity, maximum available soil water, maximum rooting depth, water table depth and a general descriptor of soil texture.
(3) management factors: initial stem biomass (foliage, stems and roots), initial stem numbers (stocking density), volume and salinity of irrigation water, irrigation frequency, planting month and rotation age.
(4) physiological parameters: canopy quantum efficiency coefficient, canopy extinction coefficient, specific leaf area, maximum litterfall ratio, root allocation and turnover, stem allocation, branch fraction, basic wood density, mortality and the modifiers for limitations due to age, VPD, temperature, salinity and nutrition.

3-PG outputs

Outputs from 3-PG can be either monthly or annual values. They include stem, root and foliage biomass (t ha^{-1}), available soil water (mm), stand transpiration (mm), canopy leaf area index, stand volume (SV) (m^3 ha^{-1}), diameter at breast height (dbh) (cm), mean dominant height (H) (m), stocking (stems ha^{-1}), canopy conductance (m s^{-1}), gross photosynthesis (g C m^{-2}), net photosynthesis (g C m^{-2}), water use efficiency (m^3 Ml^{-1}), basal area (m^2 ha^{-1}), sapwood area (m^2 ha^{-1}), and sap flux density (l m^{-2} day^{-1}).

Study sites

The two study sites are located within Jijia (20° 54' N, 109° 52' E) and Hetou (21° 05' N, 109° 55' E) forest farms in the Nandu River catchment of central Leizhou Peninsula of Guangdong Province, China (Figure 1). The climate is tropical, with long-term monthly mean temperatures of around 16 °C in January and 28 °C in July. Annual rainfall ranges from 1300 mm in the south to 1800 mm in the north of the peninsula with large variation from year to year and over 80% of the rainfall occurring between April and September. Typhoons that can bring high intensity rainfall and strong storms occur two or three times every year during this season. The site has an altitude of 70 m and the topography is flat to undulating. The two sites are approximately 40 km apart.

Meteorological data

Two automatic weather stations with a 0.1 mm tipping bucket rain gauge and meteorological sensors (SC1 pyranometer, PTAT temperature sensor, Vaisala humidity sensor and cup anemometer from Tain Instruments, Box Hill, Australia) were installed on a mast at 7.5 m above ground level in an open area. These are situated close to the monitoring plots within the plantations at Jijia and Hetou and recorded between September 1999 and December 2002.

Half-hourly observations of solar radiation, rainfall, air temperature, relative humidity and wind speed were recorded using a Micropower data logger also from Tain instruments. Daily weather data were estimated by integration of or averaging the half-hourly values and monthly values are readily calculated from these data. Mean vapour pressure deficit (VPD) during daylight hours was estimated from maximum and minimum temperature data (Dye 2001). Monthly mean wind speed was used to estimate aerodynamic conductance in the calculation of transpiration using the Penman-Monteith equation.

Forty months of climate data for modelling the growth of *Eucalyptus* plantations were available from the meteorological stations at Jijia and Hetou. In addition, a relationship between observed solar radiation and daily sunshine duration at a meteorological station at Zhanjiang (approximately 100 km to the north of Jijia) was derived by regression analysis, and used to estimate monthly solar radiation over the four years from 1996 to 1999 and in 2003. In a similar fashion, data sets for temperature, rainfall, wind speed and VPD were similarly extended by regressions on the corresponding Zhanjiang data.

According to observed climate data in the same period, daily total solar radiation at Hetou was slightly less, averaging 94% of the Jijia daily values ($y = 0.94x$, $r^2 = 0.86$). However, VPD at Hetou was higher than at Jijia, by 17% on average ($y = 1.17x$, $r^2 = 0.83$), due to differences in temperature and relative humidity. Monthly means of daily maximum temperature were 1 to 2 °C higher at Hetou throughout the year. Table 2 shows the differences between climate variables for Hetou and Jijia.

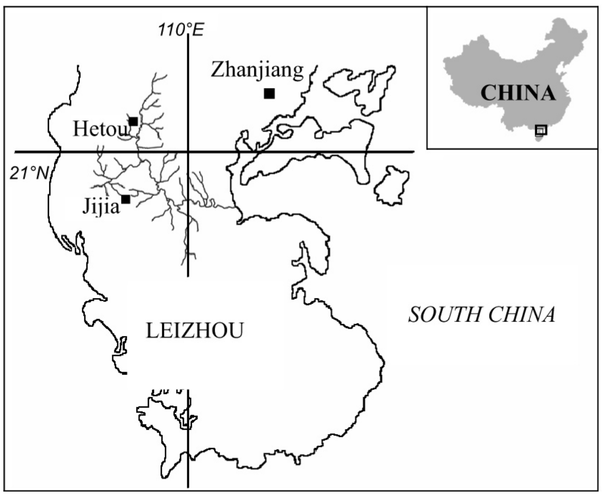

Figure 1 Leizhou Peninsula and Zhanjiang, Guangdong Province, showing the Nandu River catchment and locations of the monitored plantations at Jijia and Hetou (Morris *et al.* 2004)

Soil data

A detailed soil survey of the two plantation sites was carried out (Lane *et al.* 2004, Morris *et*

Table 2 Average values of daily or monthly meteorological data and their standard errors (n = 365 except for rainfall data (n = 12)) between September 1999 and August 2000 at Jijia and Hetou

Climate variable	Jijia	Hetou
Solar radiation (MJ m^{-2} day^{-1})	11.0 ± 0.3	10.4 ± 0.2
Daytime VPD (kPa)	0.52 ± 0.02	0.61 ± 0.02
Rainfall (mm)	128.3 ± 46.0	124.7 ± 47.5
Maximum temperature (°C)	27.2 ± 0.3	28.7 ± 0.4
Minimum temperature (°C)	17.9 ± 0.3	18.3 ± 0.3

al. 2004). Moisture release characteristics and particle size distribution of the soil were assessed at four locations using soil samples taken at every 0.3 m to a depth of 4 m at four locations. Bulk density was determined at 0.2 m intervals to 0.8 m as the mean of three samples collected using 200 cm^3 fixed volume sampling cylinders. Soil moisture content at half-hourly intervals at depths of 0.5, 1.5, 2.5 and 3.5 m in the soil profile was monitored using buried soil moisture sensors (MP-406 from Agri-Tech Instruments, Beijing). The Jijia site has a basalt-derived and highly-weathered red soil with high clay content of up to 63%, whereas the Hetou site has a sandy soil formed from quaternary sediments with high sand content of up to 74%. Mean bulk densities range from 1.2 to 1.0 g cm^{-3} at Jijia and from 1.7 to 1.5 g cm^{-3} at Hetou. Available soil water was determined as the difference between field moisture content and moisture content at wilting point (estimated as -1500 kPa).

Stand observations

Plantations at both Jijia and Hetou forest farms are typically established using machine soil cultivation, with manual weed control and fertilizer application. Twelve growth monitoring plots were established in stands of three most widely planted genotypes. *Eucalyptus urophylla* (Eu) was planted in June 1996, *E. urophylla* Clone U6 (U6) in December 1997, and *E. tereticornis* Clone W5 (W5) in December 1997 at Jijia and Eu, in June 1996, at Hetou. The plot at Hetou is 0.16 ha in area and all plots at Jijia ranged from 0.022 to 0.025 ha. Stand density in the Hetou growth plot is 1350 stems ha^{-1} and in the Jijia growth plots, the values vary from 1735 to 2882 stems ha^{-1}. In each plot, diameters over bark at dbh were measured on all trees at approximately six-monthly intervals between September 1999 and March 2003 at Jijia and between September 1999 and August 2000 at Hetou. The total number of trees for dbh measurements were 988, 1097, 1957 for Eu, U6 and W5 respectively at Jijia over 3.5 years and 638 for Eu at Hetou over 1 year. In each plot, heights of a subset of 5–10 largest trees at Jijia and 32 largest trees at Hetou were measured using a Vertex hypsometer (Forestor Instruments, Sweden) at the corresponding period. Table 3 shows the time courses of measured stocking and standard errors of H and dbh for each species. Individual tree measurements were used to calculate stand dbh and H. Stand volumes were determined from plot measurements of dbh and H as (Liang *et al.* 2002)

$$V = {}^{1}/_{3} \times dbh^2 \times H \times P \qquad (3)$$

where P is stand stocking density.

The aboveground biomass of three genotypes at Jijia was measured by harvesting six trees per genotype in 2000 and 2001. The sample trees represented the diameter frequency distribution of each genotype. The oven-dry (80 °C) mass of each of the aboveground biomass components (leaves, live and dead branches, stem bark and stem wood) were estimated by sampling procedure. A sample of 100 leaves per tree was used to measure specific leaf area by scanning and image analysis, and used to calculate total tree leaf area. A single allometric relationship between stem mass and diameter fitting the observations from all 11 stands is shown in Figure 2. By contrast, the variation in specific leaf area and branch fraction with increasing tree diameter in Eu and W5 is shown in Figure 3, displaying a clear difference between the species. Quantifying these relations from biomass measurements ensures that the model parameters derived from

Table 3 Summary of half-yearly measured stocking (N) and standard errors (SE) of mean dominant height (H) and mean diameter at breast height (dbh) for three *Eucalyptus* genotypes: *Eucalyptus urophylla* (Eu), *E. urophylla* Clone U6 (U6) and *Eucalyptus* ABL12 Clone W5 (W5) at Jijia

Eu					U6					W5				
Age (months)	H		dbh		Age (months)	H		dbh		Age (months)	H		dbh	
	N	SE(m)	N	SE(cm)		N	SE(m)	N	SE(cm)		N	SE(m)	N	SE(cm)
39	15	0.5	153	0.3	21	21	0.1	160	0.1	21	10	0.8	286	0.1
45	37	0.5	151	0.3	27	41	0.4	160	0.2	27	55	0.4	286	0.1
57	15	0.4	151	0.3	39	15	0.2	160	0.2	32	26	0.7	286	0.1
63	15	0.5	140	0.3	45	21	0.3	156	0.2	45	25	0.2	279	0.1
71	16	0.7	133	0.4	53	21	0.3	154	0.2	53	32	0.4	274	0.1
75	15	0.5	130	0.4	57	15	0.3	155	0.3	57	26	0.2	274	0.1

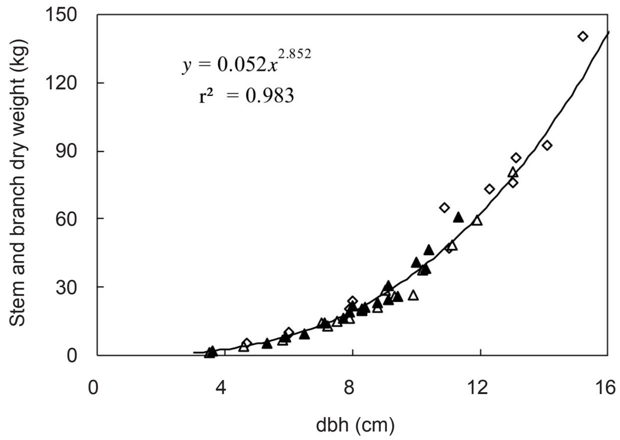

Figure 2 The allometric power curve relationships of stem and branch biomass with dbh in 11 stands of Eu (open diamonds), U6 (open triangles) and W5 (filled triangles) aged 15 to 71 months at Jijia. The trend is defined by a non-linear regression fitted to data.

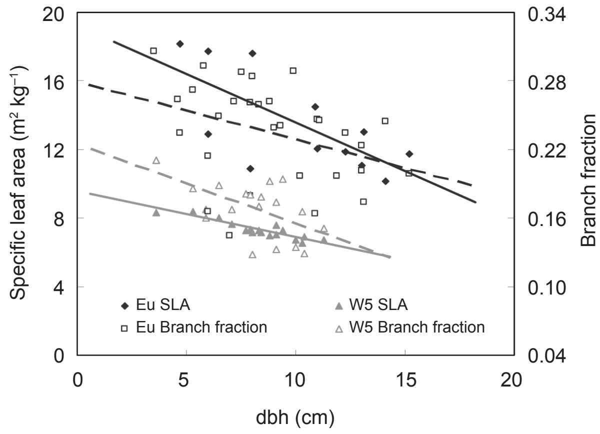

Figure 3 Variation in specific leaf area and branch fraction with increasing stem dbh in the Jijia plantations

them are well founded in actual growth data. Of the three genotypes, root biomass was measured only in Eu and W5, in May 2002. In both Eu and W5 plots, six sample trees per genotype which spanned the range of diameters were excavated to measure the biomass of their coarse roots and some cores to 0.6 m were taken to estimate the biomass of fine roots. Daily water use of Eu plantations at Hetou was measured by Morris *et al.* 2004 between October 1999 and September 2000 using the heat pulse method as described by Edwards and Warwick (1984) and modified by Olbrich (1991).

Statistical analyses

For each set of simulated and observed values of stand variables, the following statistics were obtained to help evaluate model performance: the coefficient of determination of linear regression and accuracy or mean accuracy. The r^2 values give the proportion of the variance in the observed values explained by the simulated values. Accuracy is expressed as: $(1 - |\text{observed} - \text{predicted}| / \text{observed}) \times 100\%$ and the mean accuracy is the average value of several accuracies.

Calibration procedures of the model

The majority of parameters were assigned values on the basis of direct measurements such as branch fraction and wood density or from sources outside the study, although it was sometimes essential to infer soil characteristics of the root zone including water holding capacity and rooting depth. The parameters difficult to measure were estimated by systematically and objectively changing them based on background information of the physiology and structure of the modelled species using a calibration procedure. In all cases, the model was initialized for all stands at planting stage with 0.04 kg seedling and initial fractions of biomass between foliage, root and stem were 0.5, 0.4 and 0.1 respectively. All runs began with the planting stage. Detail model calibration procedures can be referred to Landsberg *et al.* (2003).

A set of default parameter values for *Eucalyptus globules*, extensively planted in Australia, were obtained from Morris (1999) and applied to the three genotypes studied here as a useful starting point. The default parameters for which we had field data were modified accordingly. The calibration procedure was by hand, aided by a scenario generator linked to the model that allowed many combinations of possible parameter values to be efficiently explored. Major calibrated physiological parameters, site factors and derived from this study are presented in Table 4. This table indicates whether the value given was obtained directly from observed data, was estimated by fitting output from the model to observed data, or was some generic default.

The extinction coefficient was measured with some difficulty from biomass studies in

Table 4 Meaning and major calibration parameter values for three *Eucalyptus* genotypes and key site factors in southern China

Definition	Name	U6	Eu	W5	Value source*	Parameter class
Extinction coefficient	k	0.55	0.55	0.55	DO	Canopy structure and process
Constant in modifier for VPD (kPa^{-1})	k_g	0.5	0.5	0.5	D	
Canopy quantum efficiency coefficient (g C MJ^{-1})	α_c	2.4	2.4	2.4	DO	
Modifier of α_c for fertility response (g C MJ^{-1})	β	1.4	1.4	1.4	DO	
Conversion of dry biomass to carbon	ω	2.2	2.2	2.2	D	
The ratio of P_N/P_G	c_{pp}	0.47	0.47	0.47	D	
Maximum canopy conductance (m s^{-1})	g_{cx}	0.012	0.012	0.012	DO	
Fraction of intercepted rainfall evaporated from canopy	–	0.15	0.15	0.15	D	
Constant for parabolic law mortality	P_{af}	-0.45	-0.85	-0.45	F	Stem mortality
Constant for -3/2 law mortality	P_c	505	405	482	F	
Power for -3/2 law mortality	n_N	1.5	1.5	1.5	D	
Maximum stand age as used in age modifier (years)	M_a	80	80	80	D	Age modifier
Power for age effect in f_{age}	n_{age}	5	5	5	DO	
Average root turnover rate (per month)	γ_r	0.025	0.025	0.025	DO	Root turnover
Parameter for root allocation	R_1	0.5	0.6	0.5	DO	Root allocation
Parameter for root allocation	R_2	2.8	2	2.8	DO	
Maximum litterfall rate (per month)	γ_{fx}	0.08	0.1	0.08	O	Litterfall
Constant in litterfall function	c_γ	15	15	15	DO	
Constant in litterfall function	k_γ	4	4	4	DO	
Constant in foliage allocation	a_{fc}	0.1	0.1	0.1	DO	Foliage allocation
Constant in foliage allocation	n_{fb}	1.8	1.8	1.7	DO	
Constant in foliage allocation	a_{ff}	0.8	1.5	1.2	DO	
Coefficient in stem allocation	a_s	0.052	0.052	0.052	O	Stem allocation
Coefficient in stem allocation	n_s	2.85	2.85	2.85	O	
Maximum temperature for growth (°C)	T_{max}	32	32	32	DO	Temperature modifier
Minimum temperature for growth (°C)	T_{min}	10	10	10	DO	
Optimum temperature for growth (°C)	T_{opt}	27	27	27	DO	
Branch and bark fraction at age 0	P_{B0}	0.6	0.6	0.6	O	Branch allocation
Branch and bark fraction for mature stands	P_{B1}	0.15	0.25	0.15	O	
Decline factor for branch and bark	p_{Bd}	-0.4	-0.4	-0.4	DO	
Salinity in soil water for zero growth (dS m^{-1})	M_s	20	20	20	D	Salinity modifier
Specific leaf area at age 0 (m^2 kg^{-1})	σ_0	16	16	16	O	Specific leaf area
Specific leaf area for mature leaves (m^2 kg^{-1})	σ_1	11	11	7	O	
Specific leaf area decline factor	σ_d	-0.8	-0.8	-0.8	DO	
Soil water constant in f_θ	c_θ	0.5	0.5	0.5	DO	Soil modifier
Soil water power in f_θ	n_θ	6	6	6	DO	
Fertility rating	FR	0.9	0.9	0.9	F	Fertility effects
Fertility decline	Fd	0.1	0.1	0.1	D	
Mean wood density (kg m^{-3})	ρ	475	475	475	O	Basic density

Values source — *O: observed, F: fitted, D: default, DO: derived from observed data

combination with above and below canopy radiation measurements. Specific leaf area and its variation with age were also determined from biomass studies. The site fertility parameters (fertility rating and fertility decline) were inferred from growth of vegetation on similar sites since there was no satisfactory means of estimating them from objective measurements of nutrient concentrations. The parameters for temperature response were estimated from monthly mean daytime temperatures within the natural or planted range of the species. Canopy quantum efficiency coefficient (α_c) was inferred from stand growth. The maximum canopy quantum efficiency (α_0) is 3.8 g C MJ^{-1} or 0.07 mol C (mol quanta)$^{-1}$ at FR = 1, consistent with the value estimated by Sands and Landsberg (2002). The allocations of photosynthate to tree variables were derived by allometric relations between leaf, root and stem (Figure 3) and dbh from biomass studies and regular litter fall monitoring.

RESULTS

Calibration results of the model

Calibration results for 3-PG, in the form of observed and predicted variable values after adjustment of parameters are shown in Figure 4 and Table 5.

Figure 4 provides a test of the performance of 3-PG against SV, dbh and H measurements for three genotypes in permanent plots at Jijia site. The lines on the figure are the 1:1 line, which provide a good visual impression

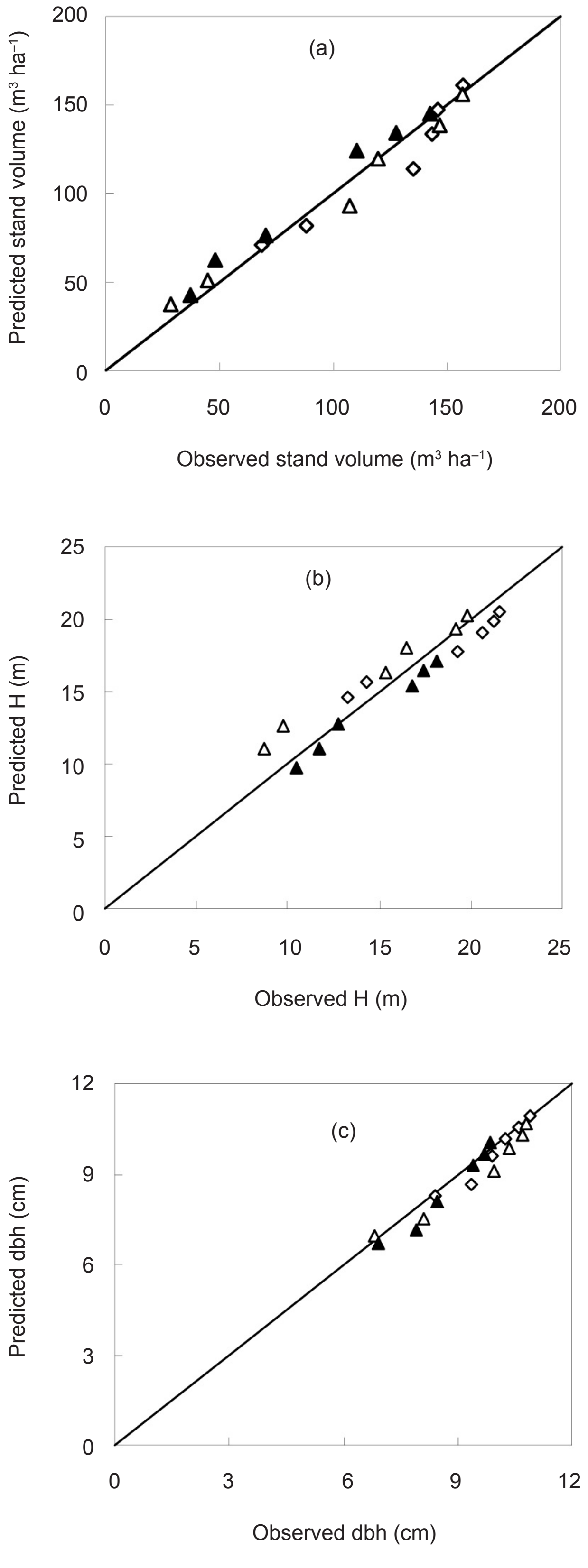

Figure 4 Comparison of predicted and observed time-series stand variables: (a) stand volume (SV), (b) mean dbh and (c) mean dominant height (H) in 11 stands of Eu (open diamonds), U6 (open triangles) and W5 (filled triangles) at Jijia in southern China. The statistic results are presented in Table 5.

of the correspondence between simulated and measured values. The statistics for the comparisons of Figure 4 are given in Table 5. These results show 3-PG simulations to SV, dbh and H for three genotypes planted in 11 plots. All r^2 values were larger than 0.93 (Table 5), i.e. 3-PG simulations account for more than 93% of the variation in SV, H and dbh for each species. More than 93% of the variation in SV for each species was predicted by the model, particularly in W5, where the value was 99%. More than 95 and 96% of the variation of H and dbh for each species was explained by the model, especially both U6 and W5, 99% of H. The mean accuracy for each species was high (all > 88%). For SV, the average prediction accuracy for the three *Eucalyptus* plantations was above 88% with the maximum being 93.9% for Eu. For dbh and H, mean accuracies were over 95%; the mean accuracy for H in both Eu and W5 was more than 92%, and for U6, 88.2%. Therefore, the quality of fit was very satisfactory for each genotype.

In some instances at a specific stand age, 3-PG over predicted stand volume, e.g. SV of W5 at 27 months (accuracy 70.4%) and H of U6 at 21 months (accuracy 69.1%). Table 6 shows good agreement between predicted and observed LAI, stem biomass and foliage biomass for Eu, U6 and W5 (all accuracy values exceeded 82%). Predicted values of root biomass were overestimated, with an accuracy of 59.4% in Eu and 73.3% in W5.

Model test against independent data

To test whether 3-PG can predict stand growth and yield when it has not been fitted to the field data we used independent sets of measurements to test model performance. As climatic variation may produce large production fluctuation of the plantations (Almeida *et al.* 2004a), one test used the continuous data of the same stands from the same site at Jijia to see how SV responded to climate change. The other test used data from a different location at Hetou with similar plantation management.

Test on data from the same site

Three *Eucalyptus* genotypes at Jijia were measured in March 2003 and observed results including SV, dbh and H, were compared with model predictions. The comparisons of observed and

Table 5 Variance accounted for (r^2) by simulated values of stand volume (SV), mean dominant height (H), mean dbh for three commercial *Eucalyptus* genotypes: *Eucalyptus urophylla* (Eu), *E. urophylla* Clone U6 (U6) and *Eucalyptus* ABL12 Clone W5 (W5) respectively at Jijia

Species	SV (m^3 ha^{-1})		H (m)		dbh (cm)	
	r^2	Mean accuracy (%)	r^2	Mean accuracy (%)	r^2	Mean accuracy
Eu	0.93	93.9	0.96	92.1	0.95	97.8
U6	0.98	89.3	0.99	87.5	0.95	95.3
W5	0.99	88.0	0.99	94.5	0.97	96.6

Table 6 Summary of calibration results for stem biomass (WS), leaf biomass (WF), root biomass (WR) and leaf area index (LAI) and their standard errors for three *Eucalyptus* genotypes: *Eucalyptus urophylla* (Eu), *E. urophylla* Clone U6 (U6) and *Eucalyptus* ABL12 Clone W5 (W5) using the climate data from 1996–-2003, 1997–-2003 and 1997–-2003 respectively at Jijia

Species	Stand variables	Age (months)	Standard error (n = 6)	Observed	Predicted	A[a] (%)
Eu	LAI	57	0.35	3.20	3.05	95.3
	WF (t ha^{-1})	57	0.22	2.37	2.75	83.9
	WS (t ha^{-1})	57	4.66	79.56	89.90	87.0
	WR (t ha^{-1})	71	2.18	12.50	17.58	59.4
U6	LAI	39	0.07	3.64	2.99	82.1
	WF (t ha^{-1})	39	0.05	2.88	2.63	91.3
	WS (t ha^{-1})	39	0.77	62.93	57.80	91.6
W5	LAI	39	0.11	2.35	2.39	98.3
	WF (t ha^{-1})	39	0.16	3.47	3.22	92.8
	WS (t ha^{-1})	39	2.89	61.15	52.20	85.4
	WR (t ha^{-1})	53	1.33	11.74	14.88	73.3

[a] Accuracy = (1 – |observed – predicted|/observed) × 100%

Table 7 Summary of test results for stand volume (SV), mean dominant height (H), mean dbh and the standard errors (SE) of dbh and H for three *Eucalyptus* genotypes: *Eucalyptus urophylla* (Eu), *E. urophylla* Clone U6 (U6) and *Eucalyptus* ABL12 Clone W5 (W5) using the climate data from 1996–-2003, 1997–-2003 and 1997–-2003 respectively at Jijia

Species	Age (months)	SV			H					dbh				
		Observed (m^3 ha^{-1})	Predicted (m^3 ha^{-1})	A[a] %	N	SE (m)	Observed (m)	Predicted (m)	A[a] %	N	SE (cm)	Observed (cm)	Predicted (cm)	A[a] %
Eu	81	171.6	169.2	98.6	15	0.6	22.1	21.1	95.5	130	0.4	11.3	11.1	98.2
U6	63	158.1	167.0	94.4	17	0.2	19.5	20.1	96.9	152	0.3	10.9	10.9	100.0
W5	63	160.9	152.2	94.6	26	0.2	18.6	17.7	95.2	272	0.1	10.3	10.2	99.0

[a] Accuracy = (1 – |observed – predicted|/observed) × 100%

predicted values of stand variables and the statistics of the comparisons for three *Eucalyptus* genotypes are presented in Table 7. Table 7 shows that SV, dbh and H for three genotypes were accurately predicted by the model. The accuracies were very high (all > 92%). Predictive accuracies of the model for dbh (all > 99%) were very satisfactory.

Test on data from different sites

The mean annual increment (MAI) was estimated from SV. Monthly water use for Eu plantations was calculated from daily monitored data between October 1999 and September 2000 at Hetou. Using observed results of available soil water at 0-4 m depth (Morris *et al.* 2004) at Hetou, the maximum available soil water was set to 200 mm. Due to a higher sand content at Hetou than at Jijia, we assigned the two soil texture parameters c_θ and n_θ values of 0.5 and 5 at Hetou while they were 0.5 and 6 at Jijia. With these site parameters, climatic data (1996–2003) and the physiological parameters previously established by calibration, we predicted the growth and water use of Eu plantations at Hetou. Figure 5 shows the time course of predicted and observed MAI, dbh, H, water use (WU) and stand density (SD) for Eu, again demonstrating a satisfactory fit with field data. The statistics of the comparisons between

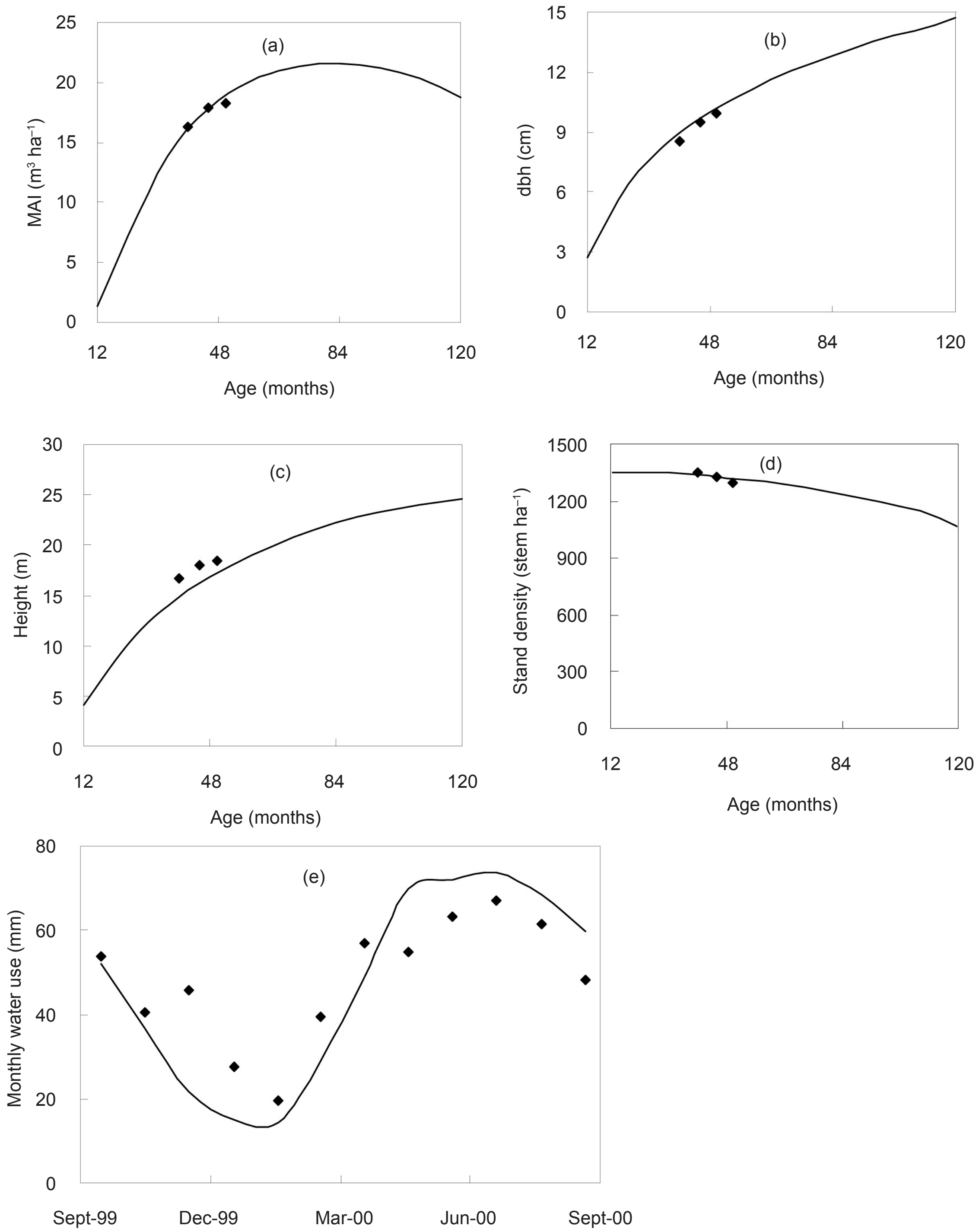

Figure 5 Test of 3-PG against data from *Eucalyptus urophylla* (Eu) at Hetou in southern China. Measured (filled diamonds) and predicted (solid line) time course of mean annual volume increment (MAI), mean dbh, dominant height and monthly water use

Table 8 Variance accounted for (r^2) by predicted values of mean annual increment (MAI), mean dbh, mean dominant height (H), monthly water use (WU) and stand density (SD) for *Eucalyptus urophylla* at Hetou

MAI (m^3 ha^{-1})		H (cm)		dbh (m)		WU		SD	
r^2	M[a] (%)	r^2	M[a] (%)	r^2	M[a] (%)	r^2	M[a] (%)	r^2	M[a] (%)
0.994	94.8	0.998	91.5	0.999	95.3	0.810	77.8	0.999	98.9

[a] Mean accuracy was the average value of accuracies and accuracy was calculated as: (1– | observed – predicted | / observed) × 100%

Table 9 Summary of test results for mean dominant height (H), mean dbh for *Eucalyptus urophylla* (Eu) and their standard errors (SE) at Hetou

Age (months)	dbh				H			
	N	SE (cm)	Observed (cm)	Predicted (cm)	N	SE (m)	Observed (m)	Predicted (m)
39	217	0.2	8.5	9.2	32	0.1	15.7	15.1
45	213	0.3	9.5	9.6	32	0.1	16.9	16.2
50	208	0.3	9.9	10.3	32	0.2	18.5	17.5

predicted and observed stand variables are given in Tables 8 and 9. The predicted MAI, dbh, H, and SD are satisfactory since r^2 was close to 1 and the mean accuracies were larger than 91%. The mean accuracy of the predicted WU was 83% except for December and February, illustrating that predicted values were acceptable. Predicted and observed annual water uses were very close, with 561.6 and 578.5 mm (1.58 mm day^{-1}, SE = 0.04 mm day^{-1}) respectively. The model underestimated water use in December and February by about 50%. Reasons for these could be established by detailed investigations of the data and model behaviour. Nonetheless, 3-PG was capable of predicting stand water use at annual and probably monthly scales with acceptable accuracy, as also noted by Morris and Collopy (2001).

Model evaluation

It is necessary that commercial forest companies or forest managers understand the probable productivity of new land in order to make decisions about purchase and development. The influence of climatic factors on potential productivity is illustrated by an analysis of the effects of rainfall variation on stand volume at age 10 years while other climatic variables were unchanged (Figure 6). Estimated SV achieved up to 223, 230 and 215 m^3 ha^{-1} for Eu, U6 and W5 respectively with averaged monthly weather data (AMWD) over 8 years from 1996 to 2003. We also noted that ~20% variation of rainfall has little influence on stand growth in this region, and even 40% decrease in rainfall only deduced SV by 3, 6 and 5% for Eu, U6 and W5 respectively but 50% decrease in rainfall decreased SV by 15, 15 and 12% respectively.

Figure 7 shows that fertility and salinity particularly affected stand volumes for each genotype. Fertility has a positive response to SV, with increasing soil fertility resulting in more biomass partitioning to stems and less to roots (Landsberg & Waring 1997). On the contrary, salinity showed markedly negative response to SV with increasing soil salinity which improved the osmotic pressure in soil solution, severely hindering water uptake and reducing growth of trees. Thus, 3-PG was capable of estimating potential growth in new areas and separating the effects of soil and climatic factors.

DISCUSSION

This study established a set of parameter values for each genotype by subjectively matching 3-PG outputs and observational data as the basis for varying from a set of default parameter values. The process-based 3-PG model can be validated at the level of its submodels or submodel parameters. Dye (2001), Landsberg *et al.* (2003), Dye *et al.* (2004) and Morris & Collopy (2001) have tested various submodels in a number of species from widely differing climate and site conditions. Fitting the model to three species at Jijia has demonstrated that it can reproduce good quality forest growth data sets. Good

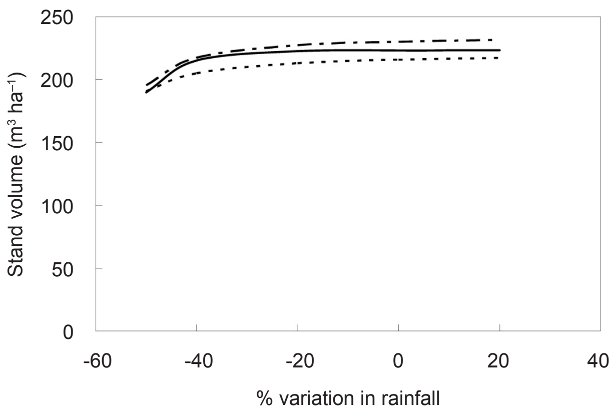

Figure 6 Predicted stand volumes as a function of monthly rainfall for three *Eucalyptus* genotypes: *Eucalyptus urophylla* (———), *E. urophylla* Clone U6 (---------) and *Eucalyptus* ABL12 Clone W5 (— - —) at age 10 years.

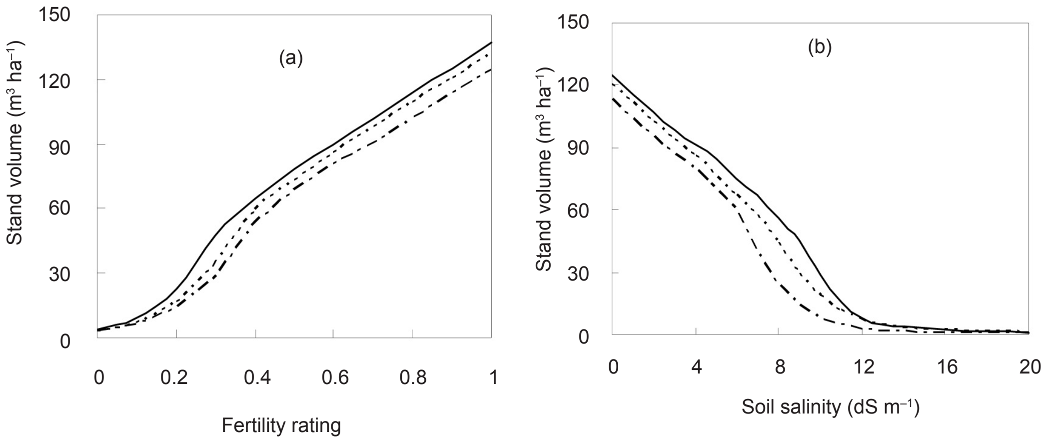

Figure 7 Predicted stand volumes as a function of the site factors: (a) fertility rating and (b) soil salinity for three *Eucalyptus* genotypes: *Eucalyptus urophylla* (———), *E. urophylla* Clone U6 (--------) and *Eucalyptus* ABL12 Clone W5 (— - —) at age 5 years

data sets obtained from stand measurements are indispensable for calibrating and testing the model, although some measurements are destructive, e.g. stem and root biomass measurements and, therefore, often confined to a relatively small number of trees.

The results presented in Tables 5 and 6 and Figure 5, show that 3-PG can be calibrated to reproduce observed stand growth accurately in relation to various stand variables. Root biomass was less accurately predicted (Table 6). There are two reasons for this: in both cases of fine and coarse root measurements, root biomass may be underestimated because the root systems actually extend to greater depth than we were able to assess; the other factor to recognize is that we only used a small sample of trees and sampling sites. Nevertheless, our figures provide a useful first estimate of root biomass for the derivation of root allocation parameters in these genotypes. The simultaneous comparison of five output variables with field observations (Figure 5) is a good test of the model performance. The close correspondence between observed and predicted MAI, H, dbh, WU and stand density for Eu at Hetou provides strong evidence that the 3-PG model is robust and credible, and can be used with confidence to predict tree growth and water use in other areas where trees have been grown or in areas considered for new plantation establishment when parameterized for a particular species. Concerns about the water use of *Eucalyptus* plantations have been raised in many countries, including China. This study demonstrates that 3-PG can be applied to explore the impacts of *Eucalyptus* plantations on water resources. This is supported by Almeida *et al.* (2004a) who used the model to explore hypotheses about the way trees function and respond to environmental changes.

The sensitivity of 3-PG outputs, SV, to site and climate changes was also studied. This is crucial in decisions on analyzing risk related to production and improving the quality of the decision-making process. Increased fertility increases SV but an increase in salinity results in a significant reduction of SV. Esprey *et al.* (2004) has shown similar results. SV is not closely correlated with rainfall, but under dry condition, it significantly declines with rainfall decrease. The change of 20% rainfall and even a decrease of 40% had small influence on stand growth, but a decrease of 50% rainfall had extreme constraint on growth (Figure 6) This indicated that soil water was not a main factor limiting growth of *Eucalyptus* plantations and 80% of rainfall, approximately 1200 mm, in this study area was sufficient for good growth.

3-PG can be run for any land unit over any time period to estimate stand growth and yield for forest management and economic evaluation. The present study demonstrates that, at a moderate stand scale, the ability to evaluate the productivity of established *Eucalyptus* plantations can be accurately described by a soundly parameterized process-based growth model.

Storms, especially typhoons have a strong effect on stand production but the model is unable to account for them in the present study. The Leizhou Peninsula is an area where tropical storms and typhoons occur two or three times every year, on average. Sudden storms can give rise to severe physical and physiological damage that has extremely negative influence on forest growth in the long term (He 2001). It is an important reason that 3-PG over predicted stand volume at a specific stand age in the study. Similarly, 3-PG does not take into account the effects of insects, pests, diseases and atmospheric pollution. Our knowledge of a number of physiological processes in trees is still incomplete, and some complicated processes can not be expressed by simplified formulas at present. For example, modelling of fertility dynamics is still rudimentary and there is no nutritional feedback from tree uptake or litter decomposition in 3-PG. Nevertheless, 3-PG has practical advantages in that the software and the complete code are freely available, it is extensively documented, widely used by researchers around the world and much work has been done to improve the model. One way of adding a dynamic soil nutrient and organic matter model in 3-PG is by attempting to quantify soil fertility by laboratory analysis of soil chemical and physical properties for comparison with growth on a number of sites (Landsberg *et al.* 2003).

CONCLUSIONS

It is possible to calibrate 3-PG to reproduce accurately the growth and yield of fast-growing Eu, U6 and W5 in southern China. The results obtained for several 3-PG outputs like SV, dbh, H, stem biomass, leaf biomass and water use demonstrate that the model is robust and balanced. Fertility and salinity are all highly sensitive to SV for each species, but rainfall is an exception, which implies that water is not a main limiting factor on stand growth in this region with enough rainfall. The results obtained from applying 3-PG on the Leizhou Peninsula demonstrate that the 3-PG model has considerable potential as a research tool and practical means of analyzing forest growth and water use to provide a sound and credible basis for decisions by forest managers and planners.

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REFERENCES

Almeida, A. C., Maestri, R., Landsberg, J. J. & Scolforo, J. R. S. 2003. Linking process-based and empirical forest models in *Eucalyptus* plantations in Brazil. Pp. 63–74 in Amaro, A. & Tome', M. (Eds.) *Modelling Forest Systems.* CAB International, Wallingford.

Almeida, A. C., Landsberg, J. J., Sands, P. J., Ambrogi, M. S., Fonseca S., Barddal, S. M. & Bertolucci, F. L. 2004a. Needs and opportunities for using a process-based productivity model as a practical tool in *Eucalyptus* plantations. *Forest Ecology Management* 193: 167–177.

Almeida, A. C., Landsberg, J. J. & Sands P. J. 2004b. Parameterisation of 3-PG for fast growing *Eucalyptus grandis* plantations. *Forest Ecology Management* 193: 179–195.

Campion, J. M., Esprey, L. J. & Scholes, M. C. 2005. Application of the 3-PG model to a *Eucalyptus grandis* stand subjected to varying levels of water and nutritional constraints in KwaZulu-Natal, South Africa. *Southern African Forestry Journal* 203: 3–14.

Coops, N. C., Waring, R. H & Landsberg, J. J. 1998a. Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy productivity. *Forest Ecology Management* 104: 113–127.

Coops, N. C., Waring, R. H. & Landsberg, J. J. 1998b. The development of a physiological model (3-PGS) to predict forest productivity using satellite data. Pp. 173–191 in Nabuurs, G., Nuutinen, T., Bartelink, H. & Koorhonen M. (Eds.) *Forest Scenario Modelling for Ecosystem Management at Landscape Level.* European Forest Institute, Joensuu.

Coops, N. C. & Waring, R. H. 2000. Estimating maximum potential site productivity and site water stress in the Eastern Siskiyous using 3-PGS. *Canadian Journal of Forest Research* 31: 143–154.

Coops, N. C. & Waring, R. H. 2001. Estimating forest productivity in the eastern Siskiyou Mountains of southwestern Oregon using a satellite driven process model, 3-PGS. *Canadian Journal of Forest Research* 31: 143–154.

Dye, P. J. 2001. Modeling growth and water use in four *Pinus patula* stands with the 3-PG model. *South African Forestry Journal* 191: 53–64.

Dye, P. J., Jacobs, S. & Drew, D. 2004. Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *Forest Ecology Management* 193: 197–218.

Edwards, W. R. N. & Warwick, N. W. M. 1984. Transpiration from a kiwi fruit vine as estimated by the heat pulse technique and the Penman-Monteith equation. *New Zealand Journal of Agricultural Research* 27: 537–543.

Esprey, L. J., Sands, P. J. & Smith, C. W. 2004. Understanding 3-PG using a sensitivity analysis. *Forest Ecology Management* 193: 235–250.

He, Q. T. 2001. *China Forest Meteorology*. Chinese Forestry Publishing House, Beijing.

Landsberg, J. J. & Waring, R. H. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology Management* 95: 209–228.

Landsberg, J. J., Johnsen, K., Albaugh, T. J., Allen, H. & McKeand, S. E. 2001. Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiment. *Forest Science* 47: 43–51.

Landsberg, J. J., Waring, R. H. & Coops, N. C. 2003. Performance of the forest productivity model 3-PG applied to a wide range of forest types. *Forest Ecology Management* 172: 199–214.

Lane, P. N. J., Morris, J. D., Zhang, N. N., Zhou, G. Y. & Xu, D. P. 2004. Water balance of tropical eucalypt plantations in south-eastern China. *Agricultural and Forest Meteorology* 124: 253–267.

Liang, K. N., Zhou, W. L. & Li, Y. Q. 2002. Research on young seedling plantation fertilizer trial for *Eucalyptus urophylla* at 6 years-old. *Forest Research* 15: 644–653.

Morris, J. D. 1999. Further development of the 3-PG forest growth model and application to young eucalypt plantations in Victoria. Report No. 99/058, Centre for Forest Tree Technology, Melbourne.

Morris, J. D. & Collopy, J. J. 2001. Validating plantation water use predictions from the 3-PG forest growth model. Pp. 437–442 in Ghassemi, F., Post, D., Sivapalan, M. & Vertessy, R. (Eds.) *Proceedings of the MODSIM 2001 International Congress on Modelling and Stimulation*. Australian National University, Canberra.

Morris, J. D. & Baker, T. 2003. Using a process-based forest model to estimate the potential productivity of *Eucalyptus* plantations in southern China. Pp. 325–337 in Wei, R. P. & Xu, D. P. (Eds.) *Eucalyptus Plantations: Research, Management and Development*. World Scientific, Hong Kong.

Morris, J. D., Zhang, N. N., Yang, Z. J., Collopy, J. & Xu, D. P. 2004. Water use by fast-growing *Eucalyptus urophylla* plantations in southern China. *Tree Physiology* 24: 1035–1044.

Olbrich, B. W. 1991.The verification of the heat pulse velocity technique for estimating sap flow in *Eucalyptus grandis*. *Canadian Journal of Forest Research* 21: 836–841.

Qi, S. X. 2002. *Eucalyptus in China*. Chinese Forestry Press, Beijing.

Sands, P. J. & Landsberg, J. J. 2002. Parameterisation of 3-PG for plantation growth *Eucalyptus globulus*. *Forest Ecology Management* 163: 271–292.

Waring, R. H. 2000. A process model analysis of environmental limitations on growth of Sitka spruce plantations in Great Britain. *Forestry* 73: 65–79.

Waring, R. H., Landsberg, J. J. & Williams, M. 1998. Net primary production of forests: a constant fraction of gross primary production? *Tree Physiology* 18: 129–134.

Zhou, G. Y., Morris, J. D., Yan, J. H., Yu, Z. Y. & Peng, S. L. 2002. Hydrological impacts of reafforestation with eucalypts and indigenous species: a case study in southern China. *Forest Ecology Management* 167: 209–222.