Comparison of a forest process model (3-PG) with growth and yield models to predict productivity at Bago State Forest, NSW

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Summary

In this paper predictions from a process model, based on the Physiological Principel Predicting Growth (3-PG) model, are compared with those of two conventional growth and yield models. A number of forest growth variables are compared including the standing volume, mean diameter at breast height (DBH), and stocking over 50 000 ha of native eucalypt forest in south-eastern Australia. Stand variable predictions at 22 permanent plot locations, using a locally calibrated empirical growth model and 3-PG were highly correlated with field estimates derived from plot data. 3-PG predictions of standing volume, diameter at breast height (DBH) and stocking explained 86%, 59% and 89% of the variance respectively, compared to the local empirical model which explained 84%, 59% and 78% of the variance in predictions of the same variables. A generic forest growth model explained only 6% of the variance in standing volume predictions. A number of methods of estimating maximum potential standing volume across the landscape were also compared. The estimates over an 80-year rotation varied by as much as 24% for a forest stratum, and by as much as 40% at the stand level. Results suggest that significant improvements in local and regional prediction of forest growth may be gained by augmenting information derived from aerial photography and limited field inventory, with predictions made from process models such as 3-PG. The utility of process models to predict forest growth variables at specific stand ages, and their capacity to be extrapolated across the landscape using geographic information system (GIS) technology, now offer operational potential for use in routine forest management and planning.

Keywords: Forest growth model; physiological processes; forest productivity; site index; spatial; GIS; landscape scale

Introduction

A key variable in the sustainable management of both native and plantation forests is an accurate projection of growth and timber yield at a range of spatial and temporal scales. Landsberg and Coops (1999) suggest three main types of models have been developed to deal with different aspects of, and approaches to, forest productivity. These are conventional growth and yield models, based on statistical relationships derived from long-term measurements on trees (Ek and Monserud 1979; Campbell *et al*. 1979; West and Mattay 1993); gap models (Shugart 1984; Bugmann *et al*. 1996) concerned with species succession and dynamics; and carbon balance or biomass models (Landsberg and Gower 1997) which predict net primary productivity (P_N) using climatic and edaphic variables.

Growth and yield models, which are statistical descriptions of patterns of tree growth, determined by measurements made in forests over time have been the conventional tools used to predict forest production. In Australia, these estimates are traditionally extrapolated across the forest estate using aerial photo mapping of appropriate strata (Skidmore *et al*. 1987; Black 1996; Victorian Department of Natural Resources and Environment 1999).

The past two decades have seen considerable progress in developing process-based models to predict current and potential forest productivity. These process-based models aim to simulate the growth of stands in terms of the underlying physiological processes and the way stands are affected by the physical conditions to which trees are subject and with which they interact. Process-based models have the potential to be far more flexible than empirical relationships and can be used in a heuristic sense to evaluate the consequences of change and the likely effects of stimuli (Landsberg and Gower 1997). In general, these models have proved useful for integrating different processes and scales of knowledge, for honing research hypotheses, and for making broad predictions of relative productivity regionally or under different environmental change scenarios (Coops and Waring 2000). Despite the potential for process-based models to contribute to forest management goals, there has been little operational adoption by forest management agencies. This may be largely attributed to the fact that process-models have focused on producing estimates of total biomass production, rather than variables of interest to forest managers such as basal area (BA), stem volume and stocking (Landsberg and Waring 1997). In addition, until recently, the detailed information and powerful computing systems required to run complex process models has not been commonly available at the forest management level, and the models have not generally been available in user-friendly forms.

In this paper, we detail the use of 3PG-SPATIAL, a Geographic Information System (GIS) based implementation of the 3-PG model (Landsberg and Waring 1997) to make fine-scale, spatially explicit predictions of standing volume, mean diameter at breast height (DBH) and stocking over 50 000 ha of native eucalypt forest in south-eastern Australia. These predictions are then compared, at a series of plots (Ryan *et al*. 2000), to conventional forest growth and yield predictions. These conventional approaches utilise yield prediction curves developed either by Lindsay (1939) from regional yield and volume data for *Eucalyptus delegatensis* (alpine ash) or a set of equations developed by West and Mattay (1993) from national datasets for a number of species including *E. delegatensis*. In addition, comparisons are made using regional forest type information derived from 1:25 000 scale mapping to extrapolate empirical yield prediction curves.

Conventional growth and yield models

Forest managers and operational planners require predictive tools to project growth rates and productivity on varying land units. The tools often used are mensuration-based growth and yield models, which are essentially statistical descriptions of patterns of tree growth, determined by repeated measurements of forest plots made over time. These growth models may be tabular, graphical or expressed as suites of mathematical functions. The latter may also include a series of inter-related sub-models that comprise an overall simulation system. There is much of literature about such models, which are generally developed for specific areas, forest types or species. Well-known examples are the individual tree growth model of Ek and Monserud (1979) and, in Australia, the STANDSIM model (Campbell *et al.* 1979). Rayner and Turner (1990a, 1990b) provide a comprehensive review of these model types.

Lindsay (1939)

Even-aged eucalypt forests occur naturally in a number of regions of Australia, usually following regeneration from wildfires or burning after clear felling. An early approach to yield estimation in such forests involved the preparation of yield tables to provide estimates of the current forest estate, and the basis for extrapolation of yields from natural to managed stands. One of the first was that of Lindsay (1939) who undertook a comprehensive study of the growth of alpine ash (*E. delegatensis*) at Bago State Forest in NSW. The technique employed a strip survey covering about 5% or the area. Once the initial survey was completed, plots were selected along the strips. The strips were divided, on a grid system, into 1/5-acre sections and the diameters of all trees measured along with a number of representative heights. In all, 104 plots were established ranging in ages from 2 to 134 years with an elevation range of 976-1340 m. Tree age was estimated for a sub-sample of trees using dendrochronology.

The technique used to prepare the yield tables was based on Behre (1927) involving the graphical fitting of growth functions as curves of stand volume and basal area over age or height. This principle is used in similar yield tables in New Zealand and Britain (Bradley *et al.* 1966; Rayner and Turner 1990a). The Lindsay (1939) yield tables were expressed in the form of 7 site indices (1 being the highest) based on tree height at 10-year age intervals from 10-130 years. Tables for stem volume, stocking and basal area were then a function of site index and age.

West and Mattay (1993)

West and Mattay (1993) developed a series of generic yield prediction models for a number of eucalypt species based on datasets from the major Australian forestry organizations. The equations were developed for several of key eucalypt species including *E. regnans*, *E. obliqua* and *E. delegatensis* using datasets of fully stocked, monospecific stands that had received no major natural or unnatural disturbance throughout their lifetimes.

Various measurements were taken at each of the forestry plots used in the analysis. In all cases, DBH had been measured, and total heights had been measured for most plots. From these measurements, the organisation concerned made an estimate of total stand volume using a range of techniques. The most precise estimates involved summing tree volumes estimated from individual tree DBH and height measurements. The least precise method involved use of existing stand volume functions to estimate total volume from BA and dominant height.

From the plot data, a site index equation was developed for each species. As a measure of the potential forest growth at a particular site, site index (SI) was defined as the dominant height of the trees at a given age. Given the SI the second step was to develop stand volume yield prediction models by establishing relationships between stand volume and stand SI age. A Schumacher yield model was used to develop the stand volume yield prediction models (Clutter *et al.* 1983).

Methods of areal extrapolation

Regional estimation of wood volume or potential productivity using conventional growth and yield models requires accurate area estimates of each forest type (or stratum) being modeled. In the case of forest plantations, compartment areas are generally well known, allowing standing volume to be easily and accurately estimated from ground-based inventories. In native forest there is often poor or inappropriate spatial coverage or information on disturbance history and stand age. Public forest agencies in Australia, without exception, rely on medium-scale aerial photo interpretation (API) (Sun *et al.* 1998) to provide information on the location and extent of forest resources. The resource is often mapped based on a variety of forest attributes including species or species associations, crown cover and crown form which is used as surrogate for mapping age (often into categories of regrowth, mature or senescent), and a number of height classes (Black 1996; Sun *et al.* 1998; Victorian Department of Natural Resources and Environment 1999). Volume and potential site productivity are then inferred as a function of these variables using relationships developed from limited field inventories which usually involve the establishment of temporary plots. Stand age is often available only for areas of known fire regeneration or harvesting. These techniques generally produce estimates of standing volume to within +/-30% at the forest type level over large regions, with estimates of site productivity produced at similar or lower levels (State Forests of NSW 1999). At the finer scale of individual compartments or stands, predictions are generally much poorer.

The 3PG-SPATIAL Model

3PG-SPATIAL provides a common spatial framework for the Physiological Principles Predicting Growth (3-PG) (Landsberg and Waring 1997) and 3PG-S (Coops *et al.* 1998) models and operates under a GIS environment using the ESRI(TM) suite of software. 3PG-SPATIAL generates spatially and temporally explicit outputs at the scale of the input surfaces. It runs for a nominated period of years in monthly timesteps. The model requires climate and soils data, and can use satellite data to provide estimates of leaf area index (L) which drives the model. Spatial outputs include variables such as above and below ground biomass, BA, DBH, stocking, L, stem volume, current annual increment (CAI) and maximum CAI. The advantages of a spatial modeling framework are twofold. Firstly, spatial inputs to the model may capture aspects of spatial variability which influence forest productivity, for example, slope and aspect patterns which can provide topographically corrected fine scale climate data, or management and environmental disturbance information captured in imagery. Secondly, outputs from the model can potentially be scaled up from local and regional analysis to national levels and incorporated into other spatial datasets. 3-PG is based on established biophysical relationships and constants (Fig.1). It requires parameters related to tree physiology derived from literature or field measurements and the following input data: average daily short-wave and net radiation for each month, monthly temperature extremes, total monthly precipitation and estimates of soil water storage capacity and fertility.

In the model, absorbed photosynthetically active radiation ($\Phi_{p.a}$) is estimated from global solar radiation. Global solar radiation can be derived, if necessary, from an established empirical relationship based on average maximum and minimum temperatures. The utilized portion of $\Phi_{p.a}$ ($\Phi_{p.u}$) is obtained by reducing $\Phi_{p.a}$ by an amount determined by a series of modifiers (Landsberg and Gower 1997). These are derived from constraints imposed by: (a) stomatal closure, associated with high day-time atmospheric vapor pressure deficits (D) (see Landsberg and Waring 1997); (b) soil water balance, which is the difference between total monthly rainfall, plus available soil water stored from the previous month, and transpiration, calculated using the Penman-Monteith equation with canopy conductance (maximum value is set at 0.02 m s^{-1}) (Kelliher *et al.* 1995) modified by projected L of the forest and constrained by monthly estimates of D; (c) the effects of sub-freezing temperatures using a frost modifier calculated from the number of frost days per month; and (d) a temperature quadratic function that regulates the photosynthetic capacity seasonally.

Modifiers take values between 0 (system 'shutdown') and 1 (no constraint) (see Landsberg 1986; McMurtrie *et al.* 1994; Runyon *et al.* 1994). Gross primary production (P_G) is calculated by multiplying $\Phi_{p.a}$ by the canopy quantum efficiency (α). 3-PG assumes that total net primary production (P_N) in temperate forests is approximately a fixed fraction (0.45 ± 0.04) of P_G (Landsberg and Waring 1997; Arneth *et al.*1998; Waring *et al.* 1998; Law *et al.* 1999). The model partitions P_N into below (P_B) and above-ground biomass (P_A), the latter being subdivided into stems (P_S) and foliage (P_F). The fraction of P_N allocated to root growth increases from 0.2 to 0.6 as the ratio $\Phi_{p.a}/\Phi_{p.a}$ decreases from 1.0 to 0.2.

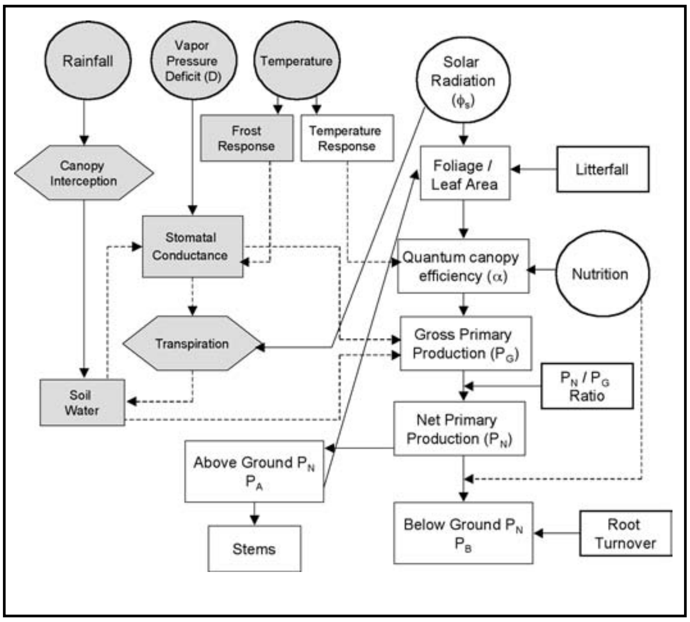


Figure 1. Flow diagram of 3-PG. The left hand side of the model, grey, contains components affecting predominately the hydrologic balance. Through stomatal control the hydrological components affect the carbon balance of the forests (right side of diagram).

Variations of 3-PG have been applied in Australia and New Zealand (Coops 1999; NSW CRA/RFA Steering Committee 2000), South America, South Africa, U.K. (Waring 2000) and North America (Law *et al.* 2000, Landsberg *et al.* 2000a; Coops and Waring 2001). Landsberg *et al.* (2001b; 2000c) provide a detailed review of the use of 3-PG as a forest modeling tool.

Methods

Study area

The Bago-Maragle study area (E148º15', S35º45') is adjacent to the Snowy Mountains in southern New South Wales (NSW), Australia and covers an area of approximately 50 000 ha of publicly owned State Forest (Fig. 2). The study area is largely composed of gently undulating plateau topography, falling off into deeply incised valleys and escarpments with tall eucalypt forests containing *Eucalyptus delegatensis* (alpine ash), *E. dalrympleana* (mountain gum) and *E. radiata* ssp. *robertsonii* (narrow-leaved peppermint). At high, exposed elevations *E. pauciflora* (snow gum) and *E. stellulata* (black sallee) become dominant.

Altitude varies from 400 m in the north-east to a maximum of 1438 m at Granite Mountain. It has a cool to cold moist sub-alpine climate characterised by cold winters with mean daily maximum and minimum temperatures for July of 8.2°C and –0.5°C and warm summers, 26.0°C and 10.6°C, respectively in January. Mean annual rainfall varies across the region from 680-1800 mm, with most of the area receiving approximately 1400 mm. Snowfalls are common in winter; snow may cover the ground for 3-4 weeks, but the soil never freezes. The plateau is composed of Paleozoic sedimentary and igneous rocks with a sporadic capping of Cainozoic basalt on the old erosional surface comprising the western extension of the Kosciuzsko highlands and forms the eastern part of the Upper Murray Province.

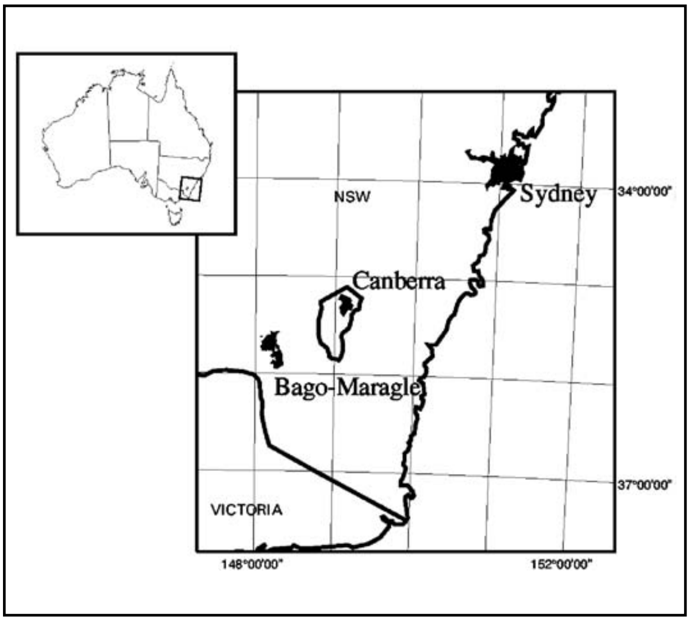


Figure 2. Geographic location of the Bago-Maragle State Forests in Southern N.S.W., Australia (taken from McKenzie and Ryan 1999)

Sources of data

Digital elevation model (DEM)

A digital elevation model (DEM) with a grid size of 25 m was obtained for the area from digital contours, streamlines and spot heights from 1:25 000 topographic map sheets using the ANUDEM program (Hutchinson 1989a). The DEM was used to calculate soil variables and to topographically correct radiation and temperature data (see following sections). A number of additional terrain attributes were modelled from the DEM using the TAPESG program (Gallant and Wilson 1997) including slope, upslope catchment area and curvature parameters, as well as the compound topographic index (CTI) (Ryan *et al.* 1996), which can be a useful guide to water and sediment movement in particular landscapes and were used in the modelling of soil properties.

Climate

Spatial surfaces of mean monthly rainfall and temperature extremes were obtained from the program ANUCLIM (Hutchinson 1989b; McMahon *et al.* 1995) which utilises the DEM to spatially extend long-term meteorological records. SRAD was used to produce topographically correct radiation and temperature surfaces based on slope, aspect and topographic shadowing effects (Wilson and Gallant 2000). In order to simulate the monthly variation in actual rainfall, as opposed to mean monthly rainfall over a 30-year period, the long-term mean monthly rainfall surfaces derived from ANUCLIM were re-scaled using actual monthly rainfall records from nearby weather stations. This was undertaken for the years where rainfall data were readily available (1970 – 1998) from two nearby stations, Tumbarumba Post Office, (E148.01° S35.78°) and Cabramurra (E148.38° S35.93°). For every month from 1970-1998, the actual monthly rainfall at the weather stations were compared to the long-term average calculate for the same locations in the monthly rainfall surfaces using ANUCLIM. For every month, the differences were used to calculated ratios (on-the-fly) between the long-term average rainfall surfaces and the mean monthly rainfall of the two stations. The simple ratio was then used to re-scale the entire average monthly rainfall surface to reflect the actual rainfall that fell in any month between 1970 and 1998. So instead of using the same monthly rainfall surfaces every year, a new surface was calculated every month based on the actual rainfall. Simulations performed for those years prior to 1970 use the long-term mean monthly rainfall surfaces repeatedly regardless of year.

Spatial soil models

A soil survey of the Bago and Maragle region was undertaken using quantitative soil survey methodology (Gessler *et al*. 1995; Ryan *et al*. 1996; Ryan *et al*. 2000) to predict key soil properties affecting forest management. GIS, DEM, terrain analysis, global positioning systems (GPS), gamma radiometric and magnetic remote sensing, and spatial statistics were used in this new quantitative approach to soil and land survey (Ryan *et al*. 1996; McKenzie and Ryan 1999; Ryan *et al*. 2000). From this program several spatial soil models for soil fertility indices and a spatial model for soil water-holding capacity were developed. One of the soil fertility indices was the prediction of the amount soil phosphorus (t ha^{-1}) to 1 m or impeding layer across Bago-Maragle (Ryan *et al*. 1996). This model was represented as a linear regression equation with independent variables of gamma radiometric potassium, Prescott Index (Ryan *et al*. 1996), near infrared band of a Landsat TM scene, and the airborne geo-magnetic signal (R^2 = 0.619). For the purposes of the 3-PG modeling, this soil phosphorus layer was re-scaled to between 0 and 1 to provide a spatial soil fertility index. The canopy quantum efficiency (α) was modified as a function of soil fertility based on the work of Coops and Waring (2000) and Waring (2000). Canopy quantum efficiency was increased linearly from 1.8 – 4.2 g C MJ^{-1} $\Phi_{p.a}$ over the range of fertility index.

Direct measurements of plant available water capacity were not available, so the spatial soil model predictions of profile water holding capacity were modified using the Williams *et al*. (1992) 'pedo-transfer functions'. These relationships allow prediction of parameters of the soil water retention curve. When these are totaled with estimates of the combined thickness of soil layers, estimates can be made of plant available water capacity for each of the survey sites. These estimates were then used to generate a surface for the complete study area by developing a tree regression model (Breiman *et al*. 1984).

Forest survey data

The status of growth, inventory and yield information for the region has been detailed by Hatich *et al*. (1996). Twenty-four plots were established in 1997 representing variations in stand age, disturbance and environments and were accurately positioned using GPS. The 24 plots comprise 12 pairs, identified by the plot number (e.g. 1 and 1A are paired). The paired plots are within a few hundred metres of each other and were selected as replicates, that is, they are as homogeneous as possible with respect to forest productivity. The majority of the plots were located in regeneration stands with ages ranging from 16 to 80 years and all occurred in *E. delegatensis* although other species may also occur on the plot. Core sampling and dendrochronology was undertaken across all sites to provide an estimate of mean stand age. A number of trees were selected within each plot in order to obtain a robust measure of stand age at each site. The field program, field measurements and coring techniques are detailed in Ryan *et al*. (2000). Table 1 provides details on the plot locations, age, height, dbh, stocking and volume.

Table 1. Summary of field variables for the 24 permanent plots used in the study.

Plot no.	X	Y	Age (yr)	Tree height (m)	Measured mean DBH (mm)	Measured live stocking (stems/ha)	Measured live stand volume (m^3/ha)
1	603511	6057252	85	48.8	680	142	801
1A	603614	6057185	85	43.5	332	705	774
2	602427	6054645	54	43.5	557	235	840
2A	602418	6054844	53	40.5	522	260	705
3	606785	6055049	82	47.6	449	410	955
3A	606753	6055153	82	47.7	417	450	913
4	604035	6058587	42	42.3	447	310	606
4A	604048	6058516	40	39.2	388	510	707
5	609183	6048605	58	37.1	391	360	513
5A	609200	6048659	51	33.9	337	480	520
6	611610	6046190	38	38.5	337	510	485
6A	611695	6046190	30	37.6	326	470	422
7	611735	6043738	45	39.7	423	230	431
7A	611685	6043739	37	40.9	309	660	561
8	601835	6048590	65	38.5	449	350	677
8A	601803	6048549	55	42.7	429	360	670
9	617043	6034004	52	50.1	506	415	1228
9A	617069	6034095	55	48.3	545	400	1330
10	617055	6033915	16	25.3	151	1820	264
10A	617095	6033844	16	24.5	145	2170	293
11	617215	6030795	22	29.8	250	450	222
11A	617167	6030753	21	28.4	238	640	279
12	621066	6023771	24	27.9	205	1120	353
12A	621074	6023737	24	28.1	221	790	330

Derivation of stand variables from conventional growth and yield models

The Lindsay (1939) yield tables (7 site indices with predictions every 10 years from 10 – 130 years) were input to a spreadsheet package. Using the field measured mean dominant tree height and mean stand age, the appropriate site index was read from the Lindsay (1939) site index graph. Forest stand variables were then extracted from the Lindsay (1939) yield tables, including estimated standing volume, stocking and mean DBH in 1998, given site index and current age. It is important to note that Lindsay (1939) used stocking rates at 10 years of age, which varied depending upon the site index.

To extract estimates of standing volume from West and Mattay (1993) it was necessary to normalize all plots to a mean stand height at 20 years. To do this, equation 3 of West and Mattay (1993 : page 215) was applied using parameters for *E. delegatensis*. Once the mean stand height at 20 years was predicted at each of the 24 stands, the West and Mattay (1993) site index could be established from the dominant height and age graphs. Using the Schumacher yield model, West and Mattay (1993) developed an equation that relates stand volume to site index and age, allowing 1998 mean stand volume to be estimated for each plot.

Existing forest type mapping

Forest type mapping of the region was completed as part of the Comprehensive Regional Assessment (CRA) program undertaken jointly between the Commonwealth and the State of NSW (NSW CRA/RFA Steering Committee 2000). The mapping was undertaken using the Baur (1968) forest

classification at 1:25 000 scale using colour aerial photography. The majority of the Bago study area was classified into one of three forest strata: Bago Alpine Ash (Stratum 21); Maragle Alpine Ash (Stratum 22) and Bago/Maragle Mixed Hardwoods (Stratum 23). For the purposes of wood scheduling and sustainable yield calculations undertaken during the CRA, each stratum had been assigned a single set of attribute data including merchantable volume and site height. These estimates were based on 31 temporary plots randomly located within Stratum 21, and a further 25 located in Stratum 22. Results indicated that the inventory reached a target precision of +/-30% for total merchantable volume at the stratum level (State Forests of NSW 1999) over the entire region.

Due to the subjective nature of the site height variable used in the strategic inventory (height of the tallest mature tree within 100 m of the plot) we chose to maintain the API forest type mapping, and to assign an appropriate site index based on the permanent plots used in this study, rather than the temporary plot data. To compare the predictions from 3PG-SPATIAL with that obtainable from a strategic inventory, we extracted the forest stratum (Bago Ash, Stratum 21) that incorporated the greatest number of permanent growth plots (n=16). For this single forest stratum which covered in excess of 12 000 ha, we calculated an average site index based on the 16 plots by simply averaging the Lindsay (1939) site indices assigned to each of the plots, as had been done using the 31 temporary plots. Potential standing volume for the forest strata was then estimated using the Lindsay (1939) yield tables.

Simulations

Calibration of the 3PG-SPATIAL model for *E. delegatensis* forests has been detailed in Tickle *et al*. (2001). Landsberg *et al*. (2000b) describe the procedure for development of calibration parameters for the 3-PG model based on experience gained when modelling over 50 forest stands in a range of environments.

For completeness, an abridged description of the calibration is included below. In this study, 8 of the Bago plots were selected as calibration plots from which to obtain the optimum 3PG-SPATIAL parameters. The minimum number of plots as selected to cover the full range of mean DBH and ages recorded in the field study and to maintain as many plots as possible for validation purposes. Climate and soils data at each of the plots was extracted from the coincident GIS cell and 3-PG run in a point mode to determine the most appropriate allometric parameters. All parameters were initially set to Landsberg and Waring (1997). First, the stem mass/stem diameter ($w_s = a_s B^{n_s}$) was determined using standard forest inventory data. Once set, the constant (a_f) and coefficient (n_f) in the equation describing foliage mass in terms of stem diameter ($w_f = a_f B^{n_f}$), and the value of α_c (canopy quantum efficiency) were varied to ensure that 3-PG predicted the correct mean DBH of the plot at the appropriate age while maintaining plausible values of leaf area index (L). Due to the fact that 3PG-SPATIAL requires a single set of model parameters for each model run, a set of allometric parameters was developed to best fit the DBH data from the 8 calibration plots. The one set of allometric parameters was then utilised across the entire study area. Initial stocking was set to 10 000 seedlings ha^{-1}, with initial biomass of foliage, roots, and stems set at 1, 2.5, and 3 Mg ha^{-1} respectively. Table 2 lists the 3PG-SPATIAL parameters used in this study.

The 3PG-SPATIAL simulations were completed on a UNIX workstation with climate and soil data described earlier at 25 m cell resolution. 3PG-SPATIAL was simulated for 100 years and we extracted standing volume, stocking and mean DBH for 1998 for comparison with other model results.

Results

Comparison of three models' predictions of standing volume

Identification of data outliers

Figures 3a-d highlight two significant outliers that have a major impact on the results for all three models being used. Lindsay (1939), 3PG-SPATIAL, and West and Mattay (1993) all significantly under-predict standing volume by 30% or more and inclusion of the outliers significantly affects both correlation coefficients and slopes of relationships. Both plots 9 and 9A exhibit exceptional levels of stand volume, atypical of other stands of similar age (see Table 1.). While the reason is unknown, it is possible that both the management history (e.g. timing of thinning event) and the physical environment at the

Table 2. Parameter values for the 3PG-SPATIAL model used in this study.

Variable	Functions and parameter values	Reference
Light conversion efficiency of photosynthesis	Maximum α_c ranges from 1.8 - 4.2 g C MJ^{-1} $\phi_{p.a.u}$, increases linearly with soil fertility	Landsberg 1986 Waring 2000 Linder and Murray 1998
Constraints of light conversion efficiency associated with temperature	T_{opt} was set at 15°C, T_{min} -2°C, and T_{max} 25°C	This study
Fraction of radiation absorbed by canopy	1-(exp (-0.5* L)	Landsberg and Waring 1997
Specific Leaf Area	6.0 m^2 kg^{-1}	Specht and Specht 1989
Allometric equation for stem mass	Stem mass, kg =0.00007 * dia., $mm^{2.65}$	This study
Allometric equation for foliage mass	Foliage mass, kg = 0.00005 * dia., $mm^{2.26}$	This study
Wood density in stands	500 kg m^{-3}	Kingston and Risdon 1961
Foliage turnover	2% $month^{-1}$	Landsberg and Waring 1997
Maximum leaf stomatal conductance	0.005 m s^{-1}	This study
Maximum canopy stomatal conductance	0.02 m s-1	This study
Fraction of production allocated to roots, monthly	$0.8/(1 + \phi_{p.a.u}/\phi_{p.a.})*2.5*$highest f_i Selects the most restrictive environmental constraint (*fi*), e.g., with value nearest zero; includes soil fertility.	Landsberg and Waring 1997

Symbols: L = leaf area index, m^2 m^{-2}; g_{cmax} = maximum stomatal conductance, m s^{-1}; $\phi_{p.a}$ = photosynthetically active solar radiation, MJ m^{-2} $month^{-1}$; D = monthly mean daily vapor pressure deficit, kPa; $\phi_{p.a.u}$ = photosynthetically active solar radiation utilized, MJ m^{-2} $month^{-1}$; dia. = average stem diameter, mm; T_{opt} = optimum temperature for photosynthesis; g_c = stomatal conductance, m s^{-1}

site are ideal, and the site is likely to represent an example of the best productivity over the region (Philip Ryan CSIRO, *pers. comm.*). However, the modelled climate and soil inputs from the GIS layers do not reflect this exceptional status. The site is among the highest in rainfall and among the coolest, but it has less than average radiation. Both the soil water and fertility status at the site are thought to be very high, but the fertility ranking used as input to the 3PG-SPATIAL model (based on phosphorous alone) falls within a standard deviation of the mean fertility. The available soil water holding capacity of the cell is among the lowest of all the sites. Consequently neither the inputs nor model outputs indicate exceptional productivity.

Given that field-estimated standing volume for these stands was more than double stands of similar age, and that none of the models, including the locally empiricised Lindsay (1939) model, were able to make reliable predictions, it was decided to remove these two plots from any further analysis. One might suggest that since 2 of the 24 plots had extremely high productivity that perhaps 8% of the area might be of similar productivity, which could greatly affect the reliability of area-wide predictions. The 24 plots, however, were not established on the basis of proportional representation, but rather to cover the total range of productivity known to occur in the area. Extensive local knowledge confirms that stands of this quality are in fact rare occurrences that are unlikely to make up more than 1 percent of the area. Research is still ongoing (Philip Ryan *pers. comm.*) which may help resolve the issue and allow these stands to be more accurately modelled.

Lindsay (1939) standing volume

The relationship between the 1998 standing volume predicted by Lindsay (1939) and the field-estimated volume at the 24 Bago plots is shown in Figure 3(a). Table 3 provides the statistical significance of the relationships presented in the figure excluding the two outlier plots. The relationship is significant at the 0.001 level (using an F test), explaining 84% of the variation in the observed volume with a standard error (SE) of 94 $m^3 ha^{-1}$ or 17% of the mean observed value. A *t* test of the slope of the relationship indicates it is not significantly different from the 1:1 line (at the 0.05 confidence level), although predictions were consistently higher with an intercept of 114 $m^3 ha^{-1}$.

West and Mattay (1993) standing volume

The relationship between the 1998 standing volume predicted by West and Mattay (1993), and the field-estimated volume at the 24 Bago plots is shown in Figure 3(b). Table 3 again provides the statistical significance of the relationships presented in the figure excluding the outlier plots excluded from further analysis. The relationship is not significant at the 0.05 level (using an F test) explaining only 6% of the variation in the observed volume with a large standard error (SE) of 166 $m^3 ha^{-1}$.

3PG-SPATIAL standing volume

Figure 3(c) shows the relationship between the 3PG-SPATIAL predicted volumes at the calibration plots (including outlier plot 9) and the field-measured volume. Excluding the outlier plot, the relationship is significant at the 0.01 level (using an F test) with the calibrated predictions explaining 80% of the variation with a SE of 78 $m^3 ha^{-1}$ or 13% of the mean observed value (Table 3.). Figure 3(d) shows the relationship between the 3PG-SPATIAL predicted volume at all 24 plots against the field-measured volume. The relationship excluding the outlier plots is significant and explains more variation than the relationship for the calibration plots alone, with an adjusted r^2 of 86% and SE of 82 $m^3 ha^{-1}$ (14% of mean). However the relationship is biased, with the slope being significantly different from the 1:1 line with an intercept of 62 $m^3 ha^{-1}$.

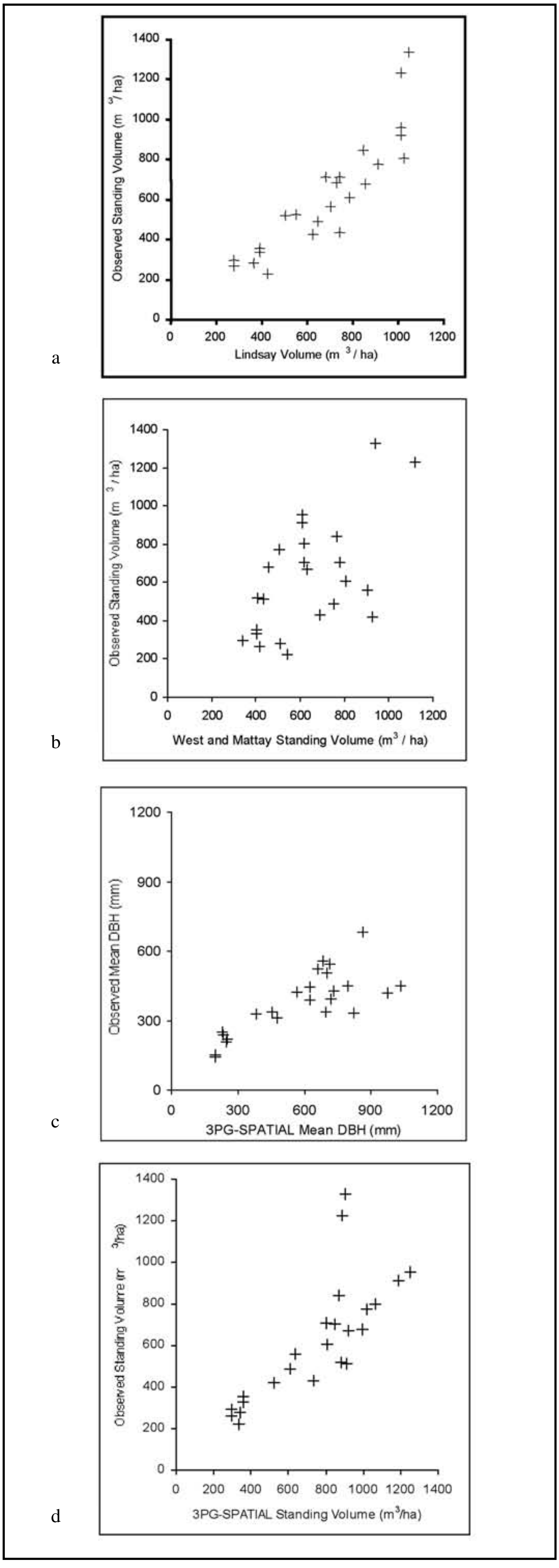
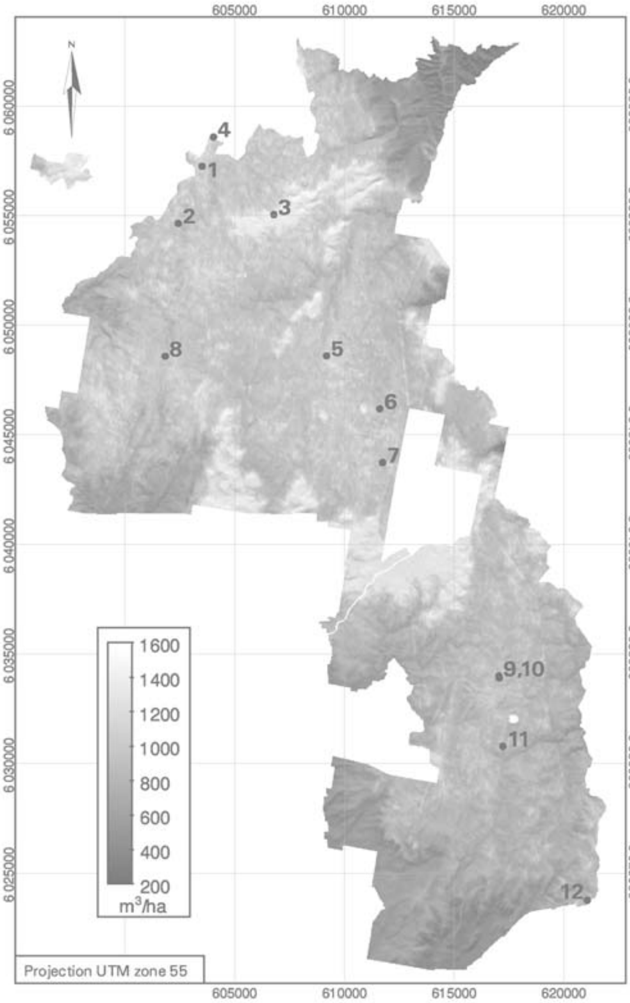


Figure 3(a)-(d). Relationships between Lindsay (1939), West and Mattay (1993), 3PG-SPATIAL and field-estimated 1998 volume at the permanent plots.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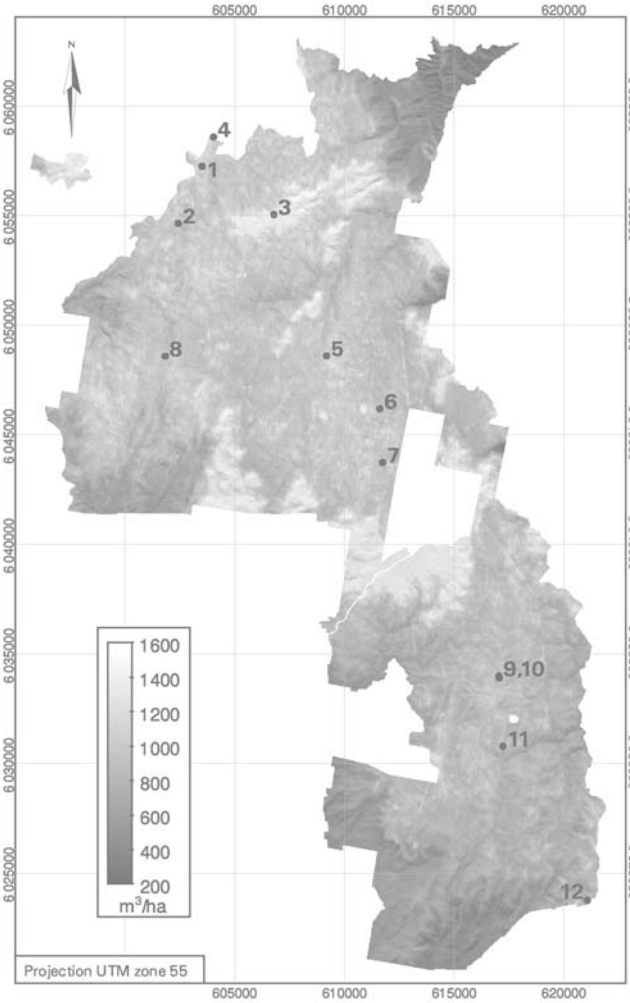
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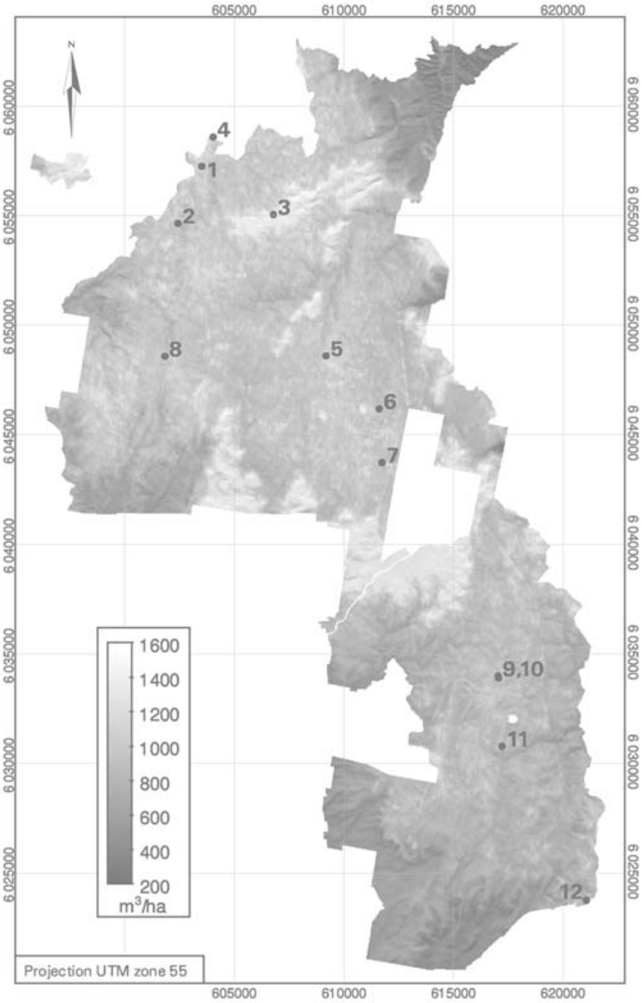

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Table 3. Summary of statistical relationships between model predictions and observed field variables.

Variable and model	Adjusted r^2	Standard Error	Significance (p)	N	Intercept	Slope
Volume (m^3 ha^{-1})						
Lindsay (1939)	0.84	94	< 0.001	22	114	0.98
West and Mattay (1993)	0.06	166	0.13	22		
3PG-SPATIAL (calibration)	0.80	78	0.04	8	66	0.61
3PG-SPATIAL (full dataset)	0.86	82	< 0.001	22	62	0.68
Mean DBH (mm)						
Lindsay (1939)	0.59	85	< 0.001	22	140	0.57
3PG-SPATIAL (full dataset)	0.59	84	< 0.001	22	138	0.42
Stocking (stems ha^{-1})						
Lindsay (1939)	0.78	233	< 0.001	22	143	0.59
3PG-SPATIAL (full dataset)	0.89	188	< 0.001	22	163	0.96

Figure 3(a)-(d) indicates that the Lindsay (1939) and the 3PG-SPATIAL predictions of volume are very similar and correspond well with the field-measured values, with adjusted r^2 values in-excess of 0.8. Both models exhibit linear behavior and both require outputs to be re-scaled due to general over-estimation of stand volume. The 3PG-SPATIAL predictions at the validation plots is actually better than the calibration plots alone, implying the model is well suited to extrapolation over the landscape. It is important to note that the Lindsay (1939) predictions of standing volume required both an estimate of stand height and stand age (to provide the relevant site index curve) to allow 1998 volume to be extracted from the curves. In the case of 3PG-SPATIAL an estimate of only stand age is required for calibration, and no age information is required for model extrapolation (in terms of potential volume at maturity).

Normally one might expect that a proper 3PG-model calibration should provide an un-biased scatter of points about the 1:1 line. The reason this was not achieved relates to the inclusion of an 'outlier' in the development of the single set of allometric parameter values. During calibration, the model was tuned for each plot individually, and then a single set of parameter values was generated using the mid-point of the range used for each variable. Since we did not have information to justify the exclusion of plot 9 at the calibration stage it was retained. Had this plot been excluded in the derivation of the single set of parameter values, predictions would have fallen around a 1:1 line. This issue is discussed in greater detail in Tickle *et al.* (2001).

As one of the objectives of the study was to produce fine-scale, spatially explicit predictions of potential forest production across the entire 50 000 ha region, any bias in model predictions had to be removed. This could have been achieved by excluding the outliers from the calibration and re-running the model, or by simply re-scaling the model outputs. We chose the latter and used the regression parameters derived from the validation data fitted against the predictions (excluding plots 9 and 9A) to re-scale the spatial model outputs. The re-scaled model predictions across the entire study area for potential stem volume at 100 years of age are presented in Figure 4.

The West and Mattay (1993) predictions of standing volume (Fig. 3b) are not as good as those of Lindsay (1939), with a very poor relationship shown between the standing volume as measured at the Bago plots and that predicted by the West and Mattay (1993) curves. This lack of correspondence may be attributed to the fact that the West and Mattay (1993) curves for *E. delegatensis* were compiled from data for the entire range of the species in NSW, Victoria and Tasmania to provide generic curves for the species. In the original study a correlation coefficient (r^2) of 0.79 was reported. The hypothesis of the West and Mattay (1993) study was, however, that generic empirical growth curves could be used across the range of the species being modelled with reasonable precision. This study suggests this may not be the case.

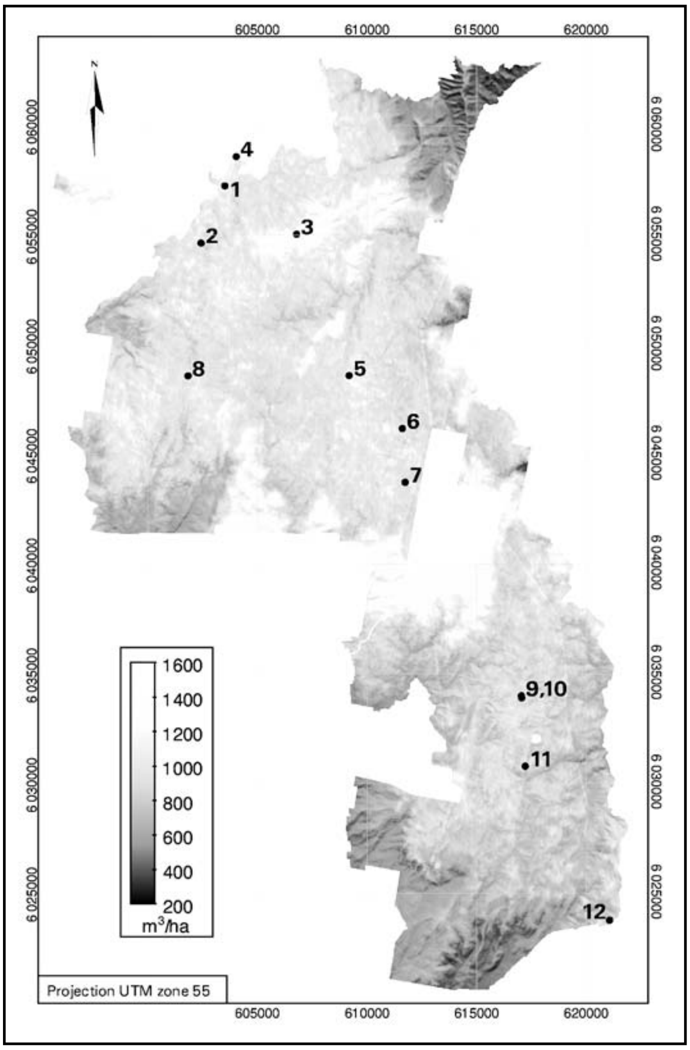


Figure 4. 3PG-SPATIAL –Potential stand stem volume (m^3 ha^{-1}) at 100 years (grid represents 5 km spacing) with paired Bago plot locations

Comparison of Lindsay and 3PG-SPATIAL predictions of DBH and stocking

Lindsay (1939) mean DBH

The relationship between the 1998 mean DBH predicted by Lindsay (1939) and the field estimated DBH at the 22 Bago plots is shown in Figure 5(a). The relationship is significant at the 0.001 level (using an F test), explaining 59% of the variation in the observed DBH with a SE of 85 mm or 23% of the mean observed value. A *t* test of the slope of the relationship indicates it is not significantly different from the 1:1 line (at the 0.05 confidence level).

3PG-SPATIAL mean DBH

Figure 5(b) shows the relationship between the mean DBH predicted by 3PG-SPATIAL at all 22 plots against the field-measured DBH. The relationship explains the same variation as the Lindsay (1939) relationship, and is significant, with an adjusted r^2 of 59% and SE of 84 mm (23% of mean). A *t* test of the slope of the relationship indicates it was significantly different from the 1:1 line (at the 0.05 confidence level).

Lindsay (1939) stocking

The relationship between the Lindsay (1939) predicted 1998 stocking and the field measured stocking at the 22 Bago plots is

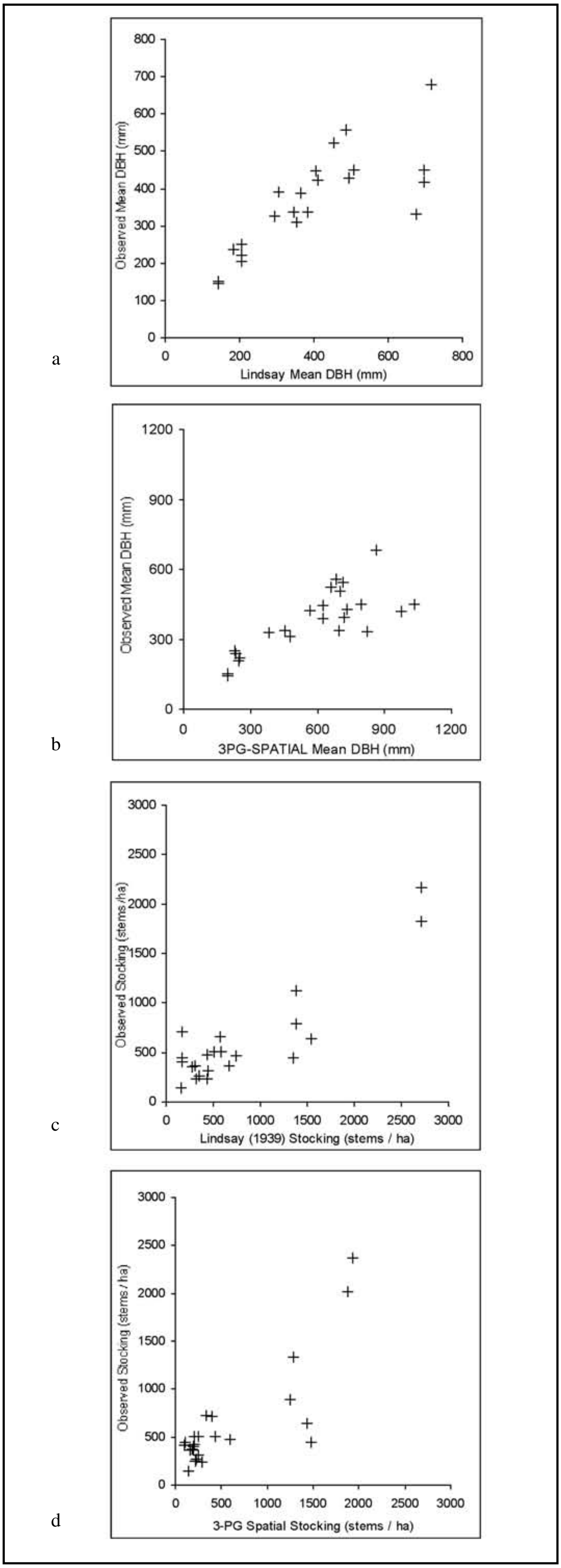


Figure 5(a)-(d). Relationships between Lindsay (1939), 3PG-SPATIAL and field-estimated 1998 stocking and mean DBH at the 22 Bago plots

shown in Figure 5(c). The relationship is significant at the 0.001 level (using an F test) explaining 78% of the variation in the observed volume with a SE of 234 stems/ha or 38% of the mean observed value. A *t* test of the slope of the relationship indicates the trend line is significantly different from the 1:1 line (at the 0.05 confidence level) signifying a bias in the relationship.

3PG-SPATIAL stocking

Figure 5(d) shows the relationship between the stocking predicted by 3PG-SPATIAL at the 22 plots against the field-measured stocking. The relationship is significant with an adjusted r^2 of 89%, SE of 188 stem ha^{-1}, and the slope of the relationship is not significantly different from the 1:1 line.

The mean DBH and stocking relationships between predicted and observed are similar for both the Lindsay (1939) and the 3PG-SPATIAL simulations. The mean DBH relationships both explain 60% of the variation in the measured data, but the Lindsay (1939) dataset is less biased than the 3PG-SPATIAL data with a trend line not significantly different from the 1:1 line. The 3PG-SPATIAL results, however, whilst similar in accuracy, have a distinct bias with DBH values being over-predicted compared to the field data.

The stocking relationships indicate that that both the Lindsay (1939) estimates and the 3PG-SPATIAL relationships are close to the measured values with r^2 values of 0.78 and 0.65 respectively. The Lindsay (1939) values, whilst explaining more variation than the 3PG-SPATIAL predicted values, are significantly biased whereas the 3PG-SPATIAL ones are not significantly different from the 1:1 trend line.

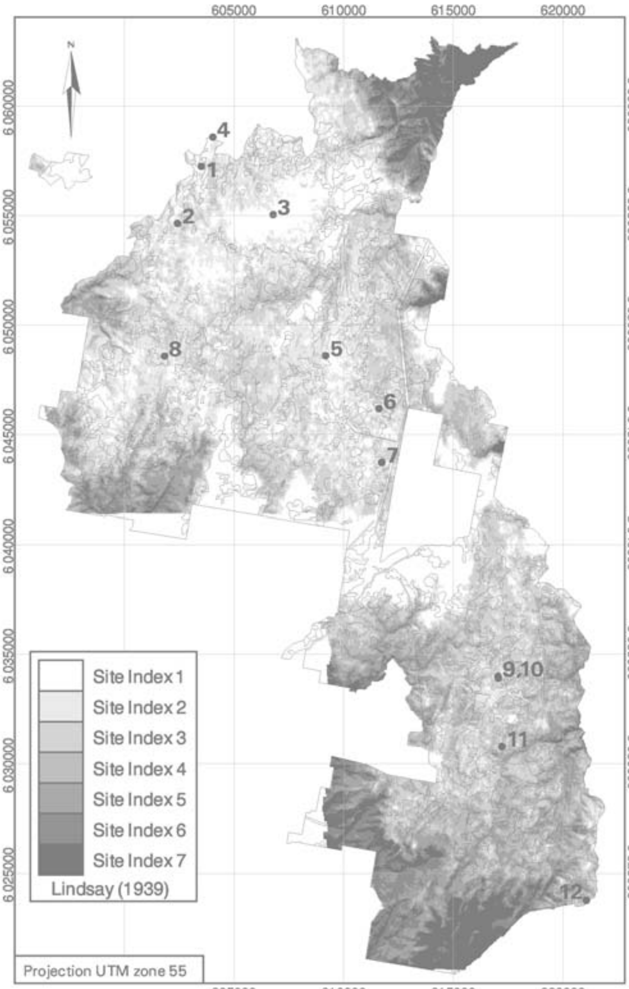
Comparison of methods of productivity prediction across the landscape

The mean site index of the 16 field plots (Hatich *et al.* 1996) within the Bago Alpine Ash forest stratum (Stratum 21) defined by the forest type mapping was 3, with eight plots having this site index. Site indices 2, 4 and 5 were each represented at two plots, and site indices 1 and 6 at one plot each. Using the Lindsay (1939) yield tables, at a stand age of 100 years the predicted volume over the 16 plots varied from 691-1243 m^3 ha^{-1}. Utilizing current strategic inventory practices (State Forests of NSW 1999), this forest stratum would be assigned a single site index (such as 3 with a predicted average volume of 1013 m^3 ha^{-1}) resulting in discrepancies of up to 30%-40% at each plot location.

To demonstrate the utility of the 3PG-SPATIAL approach, the Lindsay (1939) site index was computed for each 25 m^2 cell in the study area. After the bias in the 3PG-SPATIAL predictions was removed by calibration with the volume measurements shown in Figure 3(d), the un-biased predictions (intercept of zero and slope of 1) of volume at 100 years were classified into site index classes according to the Lindsay (1939) yield tables. This spatial layer of Lindsay site index was then intersected with the existing forest type mapping.

Figure 6 shows the proportions of each site index as predicted by 3PG-SPATIAL within the 12 259 ha Bago Alpine Ash forest stratum (Stratum 21). The figure shows that the area-based estimate of site index is significantly different from the average site index calculated using the field plots. Site index 3 only occupies 5% of the forest stratum, while site index 5 occupies 43%. A weighted average site index based on the spatially explicit area of each site index is also 5, indicating that the permanent plots do not completely represent the range of forest productivity within the Bago Alpine Ash.

The difference between the averaged plot estimates of site index and a spatially explicit surface has a major impact on the estimated potential volume over the entire stratum. By multiplying each 3PG-SPATIAL derived site index by its area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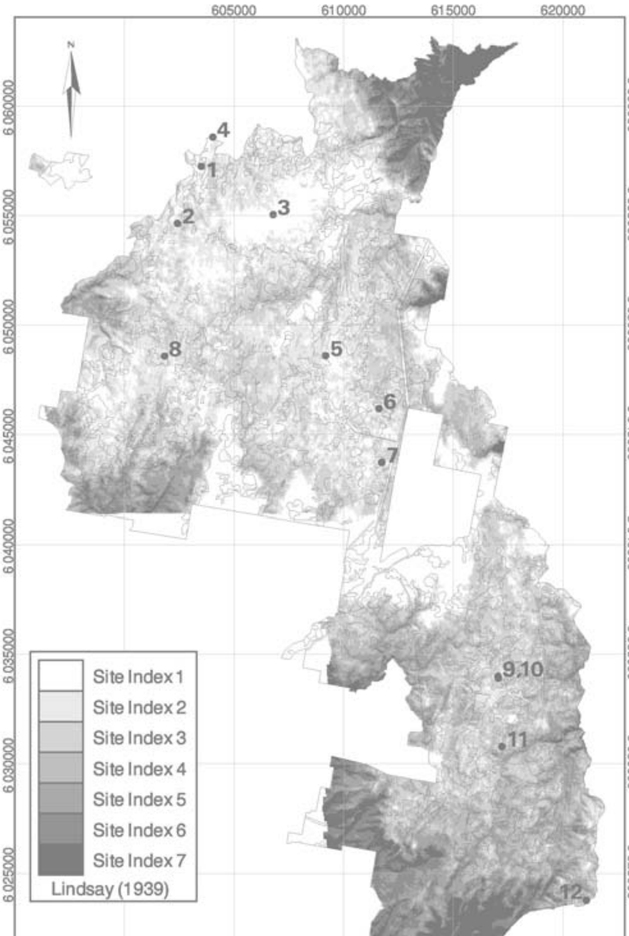
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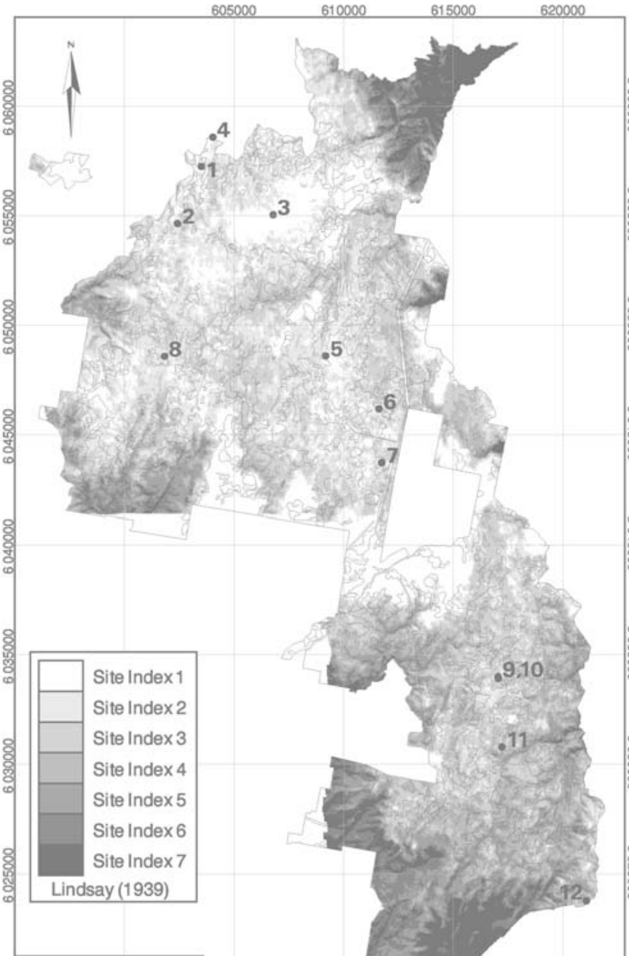

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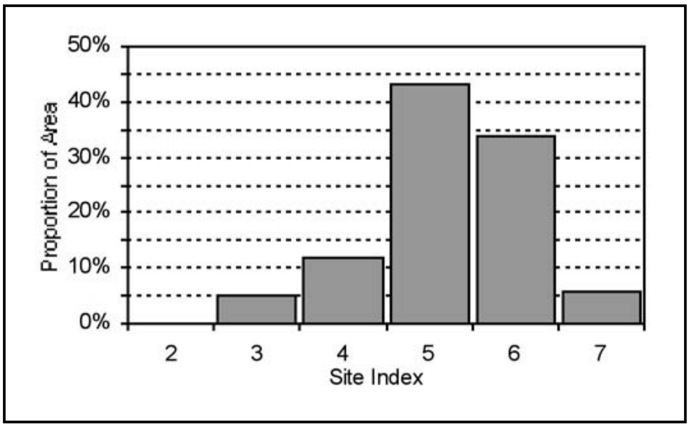

Figure 6. Proportions of each site index as predicted by 3PG-SPATIAL within the Bago Ash forest stratum (Stratum 21).

(Fig. 6, yield tables, an average of 770 m3 ha-1 of stem volume is produced in an 80-year rotation (equivalent to 9 438 000 m^3 over the whole 12 259 ha area of the stratum). This value is a 24% reduction in volume compared to simply multiplying the total area by the volume at 100 years of site index 3. Use of a weighted average site index 5 results in a 22% reduction compared to use of site index 3. Obviously, the site index concept can be completely removed and the estimated standing volume at 100 years can be simply extracted from the 3PG-SPATIAL predictions for the entire stratum. This 3PG-SPATIAL prediction, without using the Lindsay (1939) yield tables,

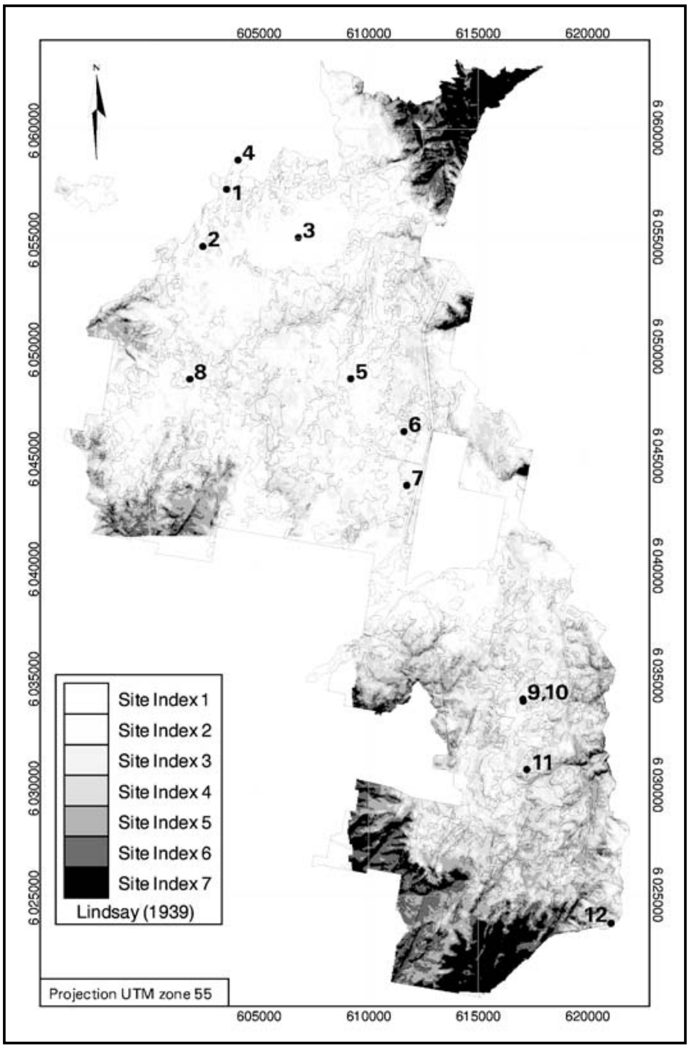

Figure 7. 3PG-SPATIAL predicted Lindsay (1939) site index classes. (grid represents 5 km spacing) with Bago plot locations. Linework is 1:25 000 scale forest type mapping. Plots 1, 2, 3, 4 and 8 are within Bago Alpine ash (Stratum 21)

produces a result within 1% of the estimate calculated using the site index (9 410 000 m^3 total or 768 m^3 ha^{-1}) Figure 7 shows the 3-PG simulations of the Lindsay (1939) site index. This coverage has been developed by using the standing volume ranges of Lindsay (1939) and reclassifying the continuous 3-PG predictions of volume into the 7 discrete Lindsay (1939) site indices. This example demonstrates the potential for combining 3-PG process based-predictions with existing growth curves such as those of Lindsay (1939).

Discussion

The 3PG-SPATIAL predictions presented in this paper suggest that a simplified process model can produce operationally relevant forestry variables such as standing volume and site index, at levels of accuracy comparable to conventional growth and yield models. This work confirms that process-based approaches offer significant potential for improving forest growth predictions at landscape scales, either independently or as a means of refining existing stratifications based on API or other mapping and inventory techniques.

A key assumption of the site index methodology and the 3PG physiological model is that the forest being modeled is fully stocked and even aged, with no distinct age cohorts. This, in fact, is a prerequisite for most yield tables. In the case of managed forests, such as plantations, the age of forest stands is known and the stand has little internal variation, with consistent stocking. Conversely, native forests rarely show absolute uniformity of age, and it has become customary to classify stands showing a variation of as much as 10-15 years as even-aged. The method by which natural regeneration takes place partly determines this variation as well as the added complexity of past disturbances such as selective harvesting. The difficulty in obtaining data on uniform fully-stocked natural stands makes any estimates of growth approximate (Lindsay 1939; Monserud 1988; Wykoff 1990; Wang 1998).

An additional significant limitation of conventional growth and yield models, such as presented in Lindsay (1939), is that in most cases they require as input an assessment of site productivity such as site index. However, as site index is usually expressed in terms of tree height at some standard age – an integral of all the growth processes and limitations of the site, the assessment is circular (Landsberg and Coops 1999). This was the case in this study when using the Lindsay (1939) yield tables to provide an indication of 1998 standing volume. Stand height and age information was used to establish site index, which then allowed a prediction of standing volume. As volume is often computed as a function of dominant height and basal area, the output prediction was a simple function of the input parameters. In this study, we were fortunate to have accurate stand age information based on dendrochronology. If these data had not been available, incorrectly estimating the age of a stand by less than 10 years may have resulted in standing volume errors in excess of 50% at maturity. Furthermore, any regional application of the growth and yield model is dependent on accurately determining the area of each site index through API or systematic survey. It has been shown that API techniques often have low levels of accuracy at the individual stand level (Delaney and Skidmore 1998), and consequently, operational accuracy and precision of growth and yield models can be significantly lower than at individual plots, as was shown here.

To date, there have been few examples of a merging of empirical and process-based growth modeling, with each being largely undertaken independently. Exceptions are Jackson and Gifford (1974) and Turvey *et al.* (1990) who used environmental factors to derive predictions of site index, and Woollons *et al.* (1997) who used environmental data as adjunct variables to growth model equations. While such approaches have demonstrated minor improvements in model predictions, they are still essentially statistical descriptions of observations that provide ittle interpretive power outside the environmental domain in which they were developed. In addition, using simple climatic and edaphic terms fails to recognise that the relative importance of driving variables and their interrelationships may vary from site to site. As a consequence these models require complete re-parameterisation in each region of application.

A key application area of the 3PG-SPATIAL approach is to provide reliable *a priori* spatially explicit estimates of potential forest productivity (in terms of biomass or site index). Using a limited number of well-measured forest inventory plots it is possible to calibrate the model and then use it to either validate data and model assumptions or to obtain information about the forest system. For example, in this study the feedback mechanisms between stem allometrics, L and water balance, were used to ensure that exposed upper slope areas exhibited greater water stresses than sheltered areas, given an absence of knowledge on the absolute accuracy of climatic and soil inputs, and L data. 3PG-SPATIAL offers a platform for exploring the effect of different scenarios across the landscape, such as the effects of drought, changes in fertility and of management practices such as thinning and the use of varying initial stem populations. Predictions of site potential can be assessed using either natural water balance (un-irrigated) regimes, or using additional assumptions such as irrigation or climate change scenarios. Likewise, nutrition can be altered, simulating increased or decreased availability and fixing of nitrogen, and re-translocation within the trees.

In Australia there is a strong move to use treated sewage effluent to irrigate plantations (Myers and Polglase 1996), to ameliorate dryland salinity hazard through large-scale reforestation of catchments (SLWRMC Working Group on Dryland Salinity 2000), and to treble Australia's commercial plantation estate (Plantation 2020 Vision Implementation Committee 1997). The model has been used to assess the potential wood production that will be obtained from such sites (Landsberg *et al.* 2001b) and regions (NSW CRA/RFA Steering Committee 2000). Significant potential also exists to examine the hydrological impacts of large-scale reforestation and to identify the most appropriate location and extent of reforestation while minimising the impacts on domestic and agricultural water supplies (Vertessy and Bessard 1999).

By using observed monthly climate, rather than mean monthly climate as predicted by the ANUCLIM package, it is possible to utilize 3PG-SPATIAL to provide inter-annual estimates of forest growth. Opportunities therefore exist to assess the climatic risk of different regions in relation to investment or insurance decisions, or to audit future carbon trading activities. Research is ongoing to assess the risk of plantation failure due to drought, using a century of actual monthly climate data over a number of regions.

Conclusions

The work presented in this paper demonstrates that a simple process-based growth model can provide accurate and relevant forest productivity information at scales commensurate with, or finer than, conventional forest inventory methods over large areas using readily available information. At the stand level, we have been able to match or better outputs from a locally-calibrated empirical model, and we have shown how a physiological model can be used to significantly improve forest growth predictions at landscape scales, either independently, or by improving on traditional forest mapping. This study has also demonstrated a hybrid approach that can maximise the utility of investments in empirical growth models and take advantage of a process model's capacity to produce spatially explicit outputs using the latest techniques in terrain and climate analysis. The model can be used as an analytical or predictive tool with the capacity to provide *a priori* estimates of forest productivity without relying on site index, and as a monitoring tool when coupled with observed monthly climate and remotely sensed data. With recent advances in spatial modelling capacity, significant opportunities exist for forest management agencies to improve the site-specific management of existing native and plantation forests, to better target reforestation and to assess the climatic risks associated with establishing plantations in low-rainfall areas.

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3PG is available via the 3PG website (www.landsberg.com.au).

For additional information about 3-PG refer to
www.ffp.csiro.au/nfm/mdp.
or contact the author.

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