Validating Plantation Water Use Predictions from the 3PG Forest Growth Model

J. D. Morris and **J. J. Collopy**

Forest Science Centre, Heidelberg Victoria 3084 (jim.morris@nre.vic.gov.au)

Abstract: The 3PG forest growth model is becoming widely used in both research and management contexts as a convenient means of predicting the productivity of tree plantations in relation to climate and site conditions. The model is based on the absorption of photosynthetically active radiation by a forest canopy, and includes functions to modify carbon fixation influenced by temperature, nutrition, vapour pressure deficit, stand age and soil water availability. The last of these requires a simple sub-model of soil water storage and canopy evaporation. Although the growth predictions of 3PG have been validated in a number of species from widely differing climate and site conditions, little attention has been given to testing the accuracy of the water use predictions or optimisation of the hydrological sub-model. Research directions to address this need include (1) modifying 3PG to generate water use variables amenable to field measurement, including sap flux density and sapwood area; (2) deriving monthly mean canopy conductance estimates from existing plantation water use datasets, for comparison with model outputs; and (3) field studies at a range of locations to estimate monthly water use at different times of year in stands with a well-documented growth history. These validation studies are in progress for plantations of *Eucalyptus globulus*, *E. grandis* and other commercial eucalypts in south-eastern Australia. The validated model is expected to provide a useful tool for assessing the catchment scale impacts of land use change involving forest establishment or clearing.

Keywords: Process-based model; canopy conductance; transpiration; Eucalyptus

1. INTRODUCTION

There is a well-established need for a means of tree water use estimation or prediction to assess the impact of large scale plantation establishment on surface water and groundwater resources. A modelling approach is essential as a means of accounting for the many environmental and management factors which may influence water use. In recent years process-based forest models have become more widely used as a means of predicting the growth of plantations and native forests. Unlike the empirical models they are replacing, these models of necessity make estimates of key physiological and environmental factors in order to allow for their influence on stand growth. Tree water uptake is one such factor, but it cannot be assumed that this and other intermediate variables of a process-based growth model are accurately estimated even when the growth predictions themselves are well validated. Opportunities exist for compensating errors both in the model structure and its parameter values, so caution is required in accepting predictions of any variable until they are separately validated against direct observations. More precisely, it is advisable to parameterise a model against observations of all the variables to be predicted before applying it in a multivariate manner.

2. THE 3PG MODEL

The 3PG forest growth model [Landsberg and Waring, 1997] predicts monthly net photosynthesis by forest stands from monthly solar radiation, modified by other climate, soil and management factors. The predicted monthly carbon fixation is allocated to foliage, stems and roots using allometric relations of foliage and stem biomass with tree diameter. Stem carbon is converted to wood biomass and, with an allowance for branches and bark, to an estimate of stemwood volume production. Monthly water use is calculated using the Penman-Monteith equation with a monthly mean canopy conductance estimate which takes into account the effects of leaf area, vapour pressure deficit and/or soil moisture stress, and other factors of the plantation environment.

The version of 3PG used for this study has been modified from the original model described by Landsberg and Waring [1997]. Changes pertinent to the prediction of stand water use include

(a) addition of a root zone salinity modifier
(b) inclusion of shallow groundwater as a source of plantation water uptake
(c) a revised definition of canopy conductance.

Utilisable absorbed photosynthetically active radiation (PAR) within 3PG is calculated as the product of absorbed PAR and a series of modifiers, each of which takes values between 0 and 1:

$$\Phi_{pau} = PAR_{absorbed} \times \min(f_{soil}, f_{VPD}) \times f_{age} \times f_{nut} \times f_{salt} \times f_{temp} \times f_{frost} \quad (1)$$

where f_{soil} is a function of soil moisture availability, f_{VPD} is a function of species stomatal response to VPD, f_{age} is a function of tree age, f_{nut} is a function of site fertility, f_{salt} is a function of species salinity tolerance, f_{temp} is a function of species optimum, minimum and maximum temperatures for growth, and f_{frost} is a function of monthly climate.

Except for soil moisture and VPD, the effects of the modifiers on growth are assumed to be independent so their combination as a simple product is appropriate. The soil moisture and VPD modifiers are assumed to act through effects on stomatal conductance, and to interact such that only the more limiting of the two is significant.

The f_{salt} modifier declines linearly from 1 at zero root zone soil solution salinity, to 0 at a maximum tolerance level defined as a parameter for the species. In the absence of this modifier, growth reduction on saline sites can only be modelled through the fertility parameters controlling f_{nut} and will not be sensitive to temporal changes in root zone salinity. The simple water balance calculation of the original 3PG model has been extended to include a monthly root zone salt balance. Transfers of water and salt between the root zone and shallow groundwater are estimated, but the watertable depth is a constant value. Capillary rise from the groundwater into the root zone is calculated by an empirical function of soil moisture content, soil texture and watertable depth. The salt concentration of this influx is assumed equal to the constant groundwater salinity. If the monthly additions and losses of water to and from the root zone result in a moisture content greater than its maximum retention capacity, the excess is drained to the groundwater with salt concentration equal to the current root zone soil solution salinity.

Transpiration in 3PG is estimated using the Penman-Monteith evaporation equation with a surface conductance (g_C) derived from maximum canopy conductance, some of the modifiers from (1) and a leaf area index (LAI) factor. The function adopted for this study is

$$g_C = g_{Cmax} \times f_{soil} \times f_{VPD} \times f_{age} \times f_{salt} \times f_{temp} \times LAI/3 \quad (2)$$

(to a maximum LAI of 3)

LAI is a function of foliage mass and specific leaf area, which is allowed to reduce with increasing tree age. This definition of g_C differs from other implementations of 3PG [e.g. Landsberg and Waring, 1997; Sands, 2000] in that it includes the f_{salt} and f_{temp} modifiers, and assumes that the effects of f_{soil} and f_{VPD} are independent. The rationale for these changes is that g_C, unlike stomatal conductance, includes a series of conductances through the canopy, stem and root system into moist soil. It is reasonable to assume, a priori, that elements of this conductance chain are influenced by soil moisture, salinity and temperature independently of any effects of these factors on stomatal conductance. Hence, for transpiration by the modelled stand to be responsive to site differences or temporal changes in soil moisture, salinity and temperature it is essential to include them in the calculation of g_C.

Table 1. Site parameters for three irrigated plantations in northern Victoria.

	Shepparton	Kyabram	Nathalia
Soil texture	Clay loam	Clay loam	Sandy loam
Maximum soil moisture	250 mm	250 mm	350 mm
Annual irrigation rate	1200 mm	720 mm (to age 6)	720 mm
Irrigation salinity	0.5 dS m^{-1}	0.5 dS m^{-1}	3.3 dS m^{-1}
Watertable depth	2.5 m	3 m	3 m
Fertility	1	0.5	0.8
Stocking (stems ha^{-1})	2666/1333	747	1173 *E. globulus* 853 *E. grandis*

3. METHODS

3.1 Modelling Sapwood Area and Sap Flux Density in 3PG

Measurements of forest stand water use derived from the widely-used sapflow techniques usually estimate transpiration as the product of sapwood cross-sectional area and sap flux density (SFD). Mean SFD tends to be constant for trees in uniform stands, in some cases even between species. It has also been found to be remarkably constant between trees subjected to different degrees of salinity stress but otherwise similar soil and climate conditions. Although 3PG does not need to estimate sapwood area to model tree growth, it is of interest to add this function to the model so that SFD can be derived from the monthly water use predictions. For this study, sapwood area was assumed to be equal to the increase in tree cross-sectional area during the previous 60 months, i.e. in effect the outermost 5 annual growth rings. This is in general accord with field observations, although in a more refined model the number of rings might be allowed to vary with growing conditions or tree age.

3.2 Canopy Conductance

Canopy conductance (g_C) is not routinely calculated in the course of tree water use measurements, but in comparing observed and modelled water use it is clearly of interest to derive this value on the monthly time scale of 3PG, as a more direct basis for comparison. The close relationship between g_C and the modifiers in (2) may then allow ready identification of the factors responsible for deviations of modelled from observed water use. For this study, daily mean g_C was calculated from daily stand water use measurements, solar radiation, mean wind speed and mean daytime VPD using an inverted form of the Penman-Monteith function from 3PG. Daytime VPD was derived from half-hourly observations of temperature and relative humidity recorded by a weather station in the vicinity of the plantations.

3.3 Model Validation against Field Data

The 3PG model was parameterised against tree growth data from research plantations of two species at three locations where water use observations were also available. At Shepparton, growth of effluent-irrigated *E. grandis* and *E. globulus* planted at densities of 1333 and 2666 stems ha^{-1} has been intensively studied by annual destructive biomass sampling since 1994. At Kyabram, a plantation of *E. grandis* and other species was established in 1976 and irrigated with channel water for 6 years, after which the plantation became dependent on shallow saline groundwater [Silberstein et al., 1999]. At Nathalia, *E. grandis* and *E. globulus* are among four eucalypt species planted in one of a series of well-replicated and regularly monitored research plantations testing various options for disposal of saline wastewater or pumped groundwater. The site parameters which differed among the three plantations are listed in Table 1.

Water use studies were carried out at all three sites between 1994 and 1998, using sapflow measurement devices to monitor stand water use over periods of 5 months to 2 years. Morris [1999] described a previous application of 3PG to the Shepparton growth data, and the species parameters reported there for *E. globulus* and *E. grandis* were adopted as a starting point for a more comprehensive parameterisation including the other two sites. Selection of parameter values was essentially subjective, aided by a scenario generator linked to the model, which allowed many combinations of possible parameter values to be efficiently explored. When a satisfactory set of values for each species was identified, i.e. one which simultaneously gave an acceptable approximation to the growth observations from all three sites and both high and low tree densities at Shepparton, the monthly transpiration estimates generated by the model during the period when water use of each stand was monitored were compared with observed values. Monthly climate data for input to 3PG were derived from spatially interpolated daily data from the Silo Patched Point Dataset (Queensland Department of Natural Resources) for Tatura, which is within 40 km of the three plantations.

4. RESULTS

4.1 Sapwood Area and Leaf Area Index

Monthly stand sapwood area values from 3PG were similar to estimates from field observations of tree diameter and sapwood width, indicating that the assumption of 5 growth rings is not unreasonable for these sites. Figure 1 shows sapwood area and LAI modelled for *E. grandis* at Kyabram, displaying a sharp response to the cessation of irrigation at age 6. The leaf area:sapwood area ratio derived from these data declines from an initially high level to an equilibrium at approximately 3500 m^2 m^{-2} after age 10, comparable with field observations.

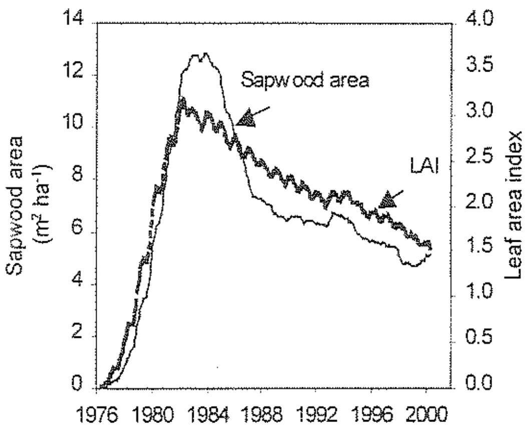

Figure 1. Modelled sapwood area and LAI growth of *E. grandis* at Kyabram.

4.2 Canopy Conductance Observations

Daily and monthly mean daytime VPD observations from Shepparton in 1995-96 are shown in Figure 2, emphasising the narrower range of variation on the monthly timescale.

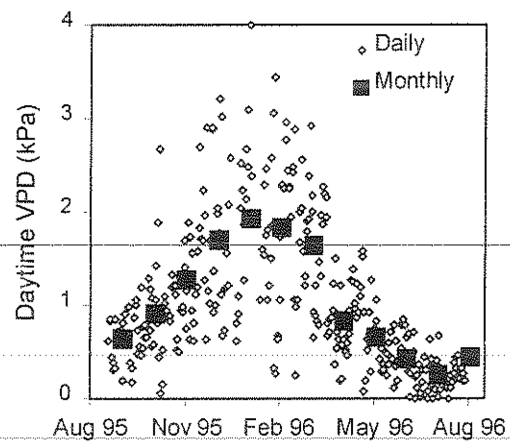

Figure 2. Mean daytime VPD at Shepparton in 1995-96.

Monthly mean g_c of *E. grandis* and *E. globulus* declined with increasing VPD as shown in Figure 3. The slope of the predicted envelope curve for g_c implied by the 3PG parameters adopted in this study may not be steep enough in light of these data; however this function leads to a transpiration envelope curve which reaches a maximum at 1.7 kPa, similar to the observed monthly and daily transpiration data. A steeper g_c curve which more closely fitted the points in Figure 3 would displace this maximum to VPD of around 1.2 kPa.

4.3 Model Validation for Irrigated Plantations

The species parameters which differed between *E. grandis* and *E. globulus* are listed in Table 2.

Table 2. Species parameters which differed between *E. globulus* and *E. grandis* at Shepparton, Kyabram and Nathalia.

	E. globulus	*E. grandis*
Canopy extinction coefficient	0.48	0.45
Canopy quantum efficiency (g MJ^{-1})	3.9	3.7
Root coefficients 1 & 2	0.2, 5	0.3, 4.5
Power in foliage mass vs DBH function	2.15	2.0
Constant in stem mass vs DBH function	0.055	0.052
Optimum temperature	19	24
Maximum salinity (dS m^{-1})	10	20
Final SLA (m^2 kg^{-1})	4	7.5

Apart from these the parameters were similar, as documented by Morris [1999]. Growth predictions from the parameterised model were a satisfactory fit to the field measurements for all combinations of species, site and planting density (e.g. Figure 4), reflecting the flexibility and robustness achievable with 3PG.

Water use predictions for the Shepparton stands of both species were characterised by overestimation during summer (e.g. Figure 5). This could result from insufficient sensitivity of g_c to high VPD, as suggested by Figure 3. However, an examination of the 3PG modifiers in (2) showed a substantial reduction in f_D during summer, to 0.4 or less.

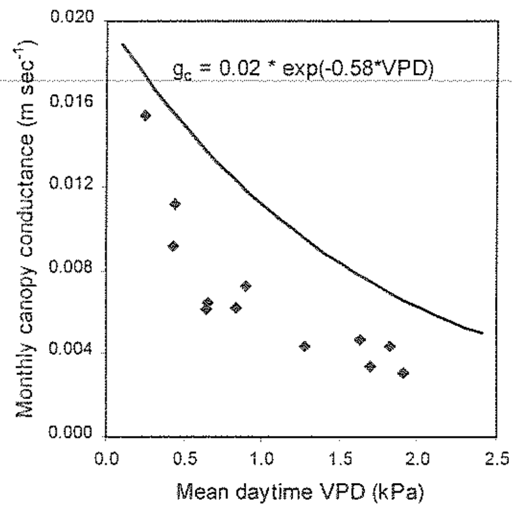

Figure 3. Monthly canopy conductance observed at Shepparton in 1995-96, and the canopy conductance-VPD function predicted by 3PG as parameterised here.

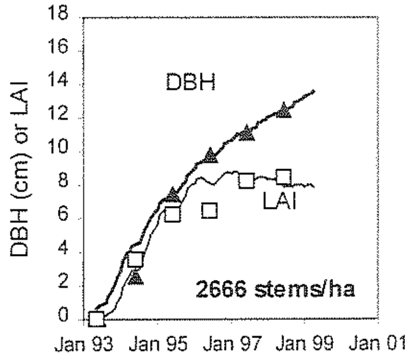

Figure 4. Diameter (DBH) and LAI growth of young *E. globulus* at Shepparton. Symbols are observed values, solid lines are 3PG predictions.

Insufficient sensitivity to high summer temperatures is an alternative possibility. The temperature modifier is a function of monthly mean temperature, which in turn is derived from daily maximum and minimum temperatures. Arguably though, the temperature modifier for g_C should be based on mean daytime temperatures, as it is for VPD. This would reduce predicted water use during summer and increase it slightly during winter, more closely approximating the observed data.

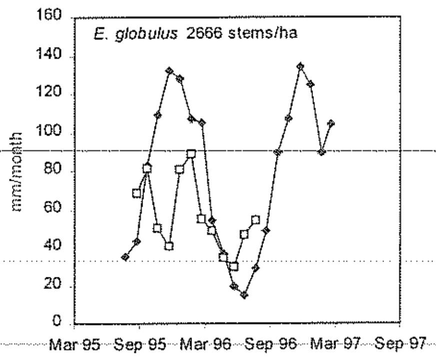

Figure 5. Predicted and observed water use by *E. globulus* at Shepparton.

Diameter growth and annual water use of *E. grandis* at Kyabram are shown in Figure 6, again demonstrating a satisfactory fit with field data, yet the modelled and observed monthly water use (Figure 7) do not match so well. Basing f_{temp} on daytime temperatures as suggested above would be an improvement, but these results probably also reflect two structural shortcomings of the relatively simple 3PG model. Litterfall in 3PG rises to a defined percentage of the leaf biomass per year, and then remains constant. However, severe drought conditions at Kyabram in 1994 caused abnormal leaf shedding in the following summer, such that survival of the plantation was in doubt. The greatly depleted canopy led to low water use throughout the summer and incomplete recovery in the following year, but 3PG is unable to reflect this.

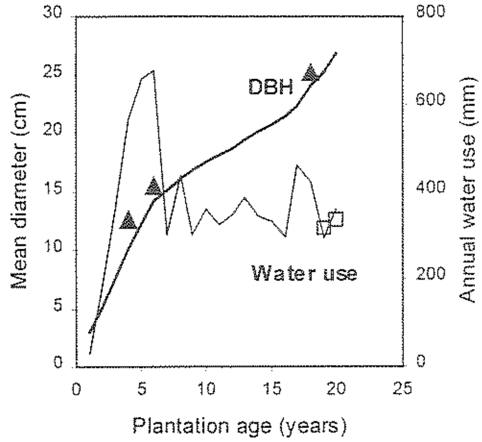

Figure 6. Predicted (lines) and observed (symbols) diameter growth and annual water use of *E. grandis* at Kyabram.

Furthermore, watertable depth in the model remains at a defined level, but watertable depth below the Kyabram plantation increased when the trees became dependent on groundwater after irrigation ceased in 1982. The rudimentary 3PG water balance model is unable to account for the decreasing availability of water which results from this watertable lowering, and hence will tend to overestimate summer water use.

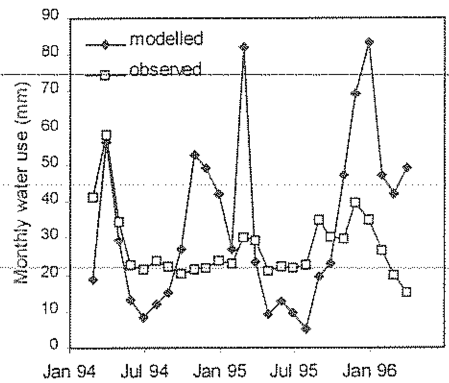

Figure 7. Predicted and observed monthly water use by *E. grandis* at Kyabram.

Growth predictions for Nathalia (Figure 8) correctly predict the observed decrease in growth rate of E. globulus relative to *E. grandis* over 8 years as a result of increasing root zone salinity. Monthly water use of *E. grandis* is also modelled reasonably well at this site, but the predicted water use of *E. globulus* during summer is only half the observed rate (Figure 9). It is most likely that the f_{salt} modifier is the cause of this error. On the basis of these data and the observation that SFD tends to be unaffected by salinity within a given locality, it appears that f_{salt} may not be required as a modifier of g_C. This would mean that the well-established

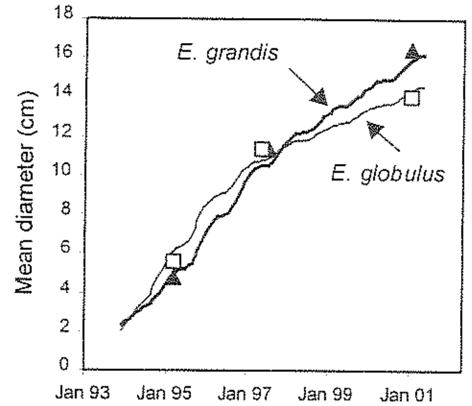

Figure 8. Predicted (lines) and observed (symbols) growth of saline groundwater-irrigated eucalypt plantations at Nathalia.

effects of salinity on water use could only be predicted in 3PG through reduction in leaf area. If leaf area:sapwood area ratio is unaffected by salinity this is reasonable, but if not then a scaled-down f_{salt} modifier might still be required in the g_C function. This result provides an example of how deficiencies in the model structure may be identified by examination of its water use and other intermediate variable predictions.

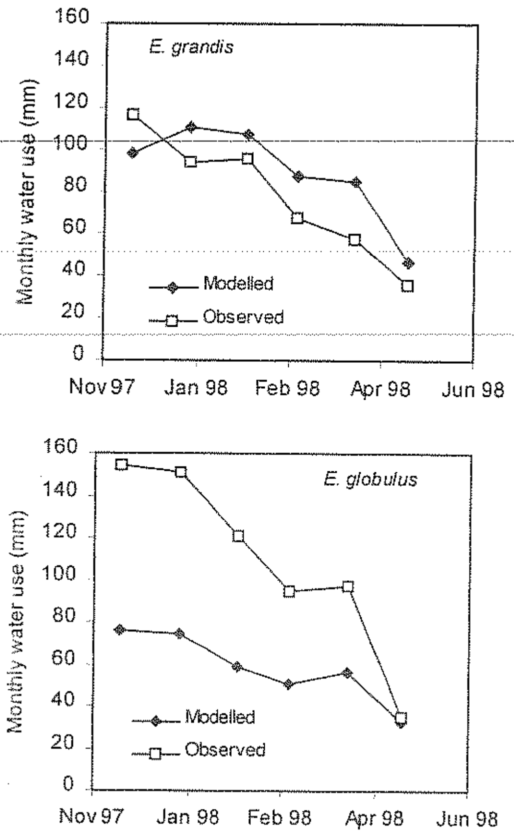

Figure 9. Predicted and observed water use of *E. globulus* and *E. grandis* at Nathalia.

5. CONCLUSIONS

In spite of the shortcomings identified in this study, 3PG appears to be capable of predicting stand water use at annual and probably monthly scales with acceptable accuracy. Obviously when the model is re-parameterised to simultaneously fit both growth and monthly water use observations from a wider range of field sites, its predictive power will be enhanced. The exercise described here is important to identify any structural modifications that may be appropriate, before such a multi-variate parameterisation is attempted. An objective parameterisation of a revised 3PG model for *E. globulus*, *E. grandis* and other species against the water use and growth datasets now being collected from Victorian plantations should lead to a robust model, at least where extreme drought and shallow groundwater uptake are not common.

6. ACKNOWLEDGEMENTS

The work reported here was carried out with the support of RIRDC (Project CSL-9A), ACIAR (Project FST 97/77) and the Private Forestry Unit of the Victorian Department of Natural Resources and Environment, and contributes to CRC for Catchment Hydrology Project 2.3. We are grateful to Richard Stokes, Des Stackpole, Michael Duncan and Tom Baker for collecting and providing access to growth data, and to Louise Mann for water use measurements at Kyabram.

7. REFERENCES

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

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

Sands, P.J., 3PGpjs – a user-friendly interface to 3-PG, the Landsberg and Waring model of forest productivity, Tech. Rep. No. 29, CRC for Sustainable Production Forestry, Hobart, 2000.

Silberstein, R.P., R.A. Vertessy, J.D. Morris and P.M. Feikema, Modelling the effects of soil moisture and solute conditions on long-term tree growth and water use: a case study from the Shepparton Irrigation Area, Australia, *Agricultural Water Management*, 39, 285-315, 1999.