Predicting the Impacts of Plantations on Catchment Water Balances Using the 3PG Forest Growth Model

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EXTENDED ABSTRACT

Forest plantations for wood production are an increasingly important land use in Australia. It is important to be able to predict the impact of this expansion on surface water and groundwater resources which are under significant stress in many regions. A modelling approach is essential to account for the many interacting environmental and management factors which may influence plantation growth and water use.

The 3PG forest growth model is a radiation driven, process-based, generalised, stand-level model developed by Landsberg and Waring (1997). Shortcomings of this model include the representation of the (one-dimensional) soil water balance in the root zone on a single layer, monthly time step basis, and that the maximum plant available water and the water-potential water-retention relationship are somewhat subjectively specified by the modeller.

We used an enhanced version of 3PG (designated 3PG+) that interfaces with a more detailed multi-layered, daily time-step representation of the soil water balance. This was achieved by migrating the 3PG+ model into the Catchment Analysis Tool (CAT) framework (Beverly *et al*. 2005).

The CAT framework comprises a suite of farming systems models, and allows more complex representation of the spatial extent and location of plantations, and their effect on catchment water balance, while also including agricultural land uses.

Three validation catchments, having a variety of land uses across a wide geographic distribution, were studied. Within each of the catchments, tree water use (sap-flow) was measured in one or two sample plots using heat-pulse devices.

For each plot, the 3PG+/CAT model was calibrated against observed stand growth (volume) at the age corresponding to the period of tree water use measurements. Subsequently 3PG+/CAT predicted stand water use at daily time scales with acceptable accuracy.

The CAT (incorporating 3PG+) was then applied at the catchment scale to investigate scenarios where land use was altered to reflect different species and extent of plantation establishment.

The resulting water balance components of the catchment (e.g. evapotranspiration, streamflow) under each of these scenarios were then compared to the 'current' scenario. Predictions suggest that conversion of catchments from trees to pasture leads to an increase in streamflow of between 6% to 79% over a 20 year period. The increase in streamflow is proportional to the percentage of the catchment covered by pasture. Furthermore, the simulations suggest that relative increases in streamflow resulting from changes from trees to pastures may be more pronounced in catchments where evapotranspiration processes represent a larger proportion of the catchment water balance.

The 3PG+/CAT was capable of predicting stand water use at daily time scales with acceptable accuracy. Nonetheless, the model requires additional parameterisation and validation for both growth and water use from a wider range of species and field sites. Such work for the main plantation species in southern Australia (*Eucalyptus globulus*, *E. nitens* and *Pinus radiata*) is underway. This will lead to a more robust model for predicting the likely impacts of plantation extent, location, design and management on catchment water balances in a range of environments.

1. INTRODUCTION

Australia's forest plantation area totals 1.74 million hectares (Parsons *et al.* 2006). A rapid expansion in the past decade has arisen primarily from planting short-rotation hardwood species for pulpwood production on formerly agricultural land. While plantation forestry has environmental benefits, particularly where plantations replace agricultural land uses (e.g. soil erosion protection and improved water quality, carbon storage, habitat for biodiversity), there are important hydrologic consequences that must be recognised and understood. Strategically located, plantations may have beneficial hydrologic impacts in some catchments to reduce dryland salinity. On the other hand, water resources are under significant stress in many regions of Australia and it is essential that we determine and plan for the impact of plantation development on these resources.

Biophysical modelling approaches that integrate vegetation, climatic and edaphic variables are essential given that experimental empirical approaches are difficult to conduct at the catchment scale, and may not adequately deal with land use and climate change. Process-based forest growth models have become more widely used to predict the growth of plantations and native forests in Australia and in other countries. These models also provide predictions of tree water use. However, they must be validated so that they can be used confidently under varying site conditions.

To investigate the effects of plantation establishment on catchment water balances, forest growth models must be able to accurately represent tree water use, and be incorporated into a spatial modeling framework that is inclusive of the effects of other land uses within the catchment.

Catchment water balances are driven by complex interactions between rainfall, climate, soils, geology and land cover. All these factors must be considered in any modelling approach to assess the hydrological effects of plantation development in a particular region. It is also important that social and economic implications are considered so that impacts, if any, on other water resource users can be weighed against the socio-economic benefits of increased timber production.

2. 3PG FOREST GROWTH MODEL

The 3PG forest growth model is a process-based generalised stand-level model developed by Landsberg and Waring (1997). It is driven by intercepted radiation with radiation-use efficiency for carbon fixation limited by temperature, vapour pressure deficit, available soil water, stand age and site fertility. 3PG predicts monthly net carbon fixation (from gross fixation after allowance for respiration), stand development, biomass (stem, foliage and root) and water use from monthly values for solar radiation, modified by other climate, soil and management factors. Additional description of the model can be found in Sands and Landsberg, (2002).

Fixed carbon is allocated to foliage, stems and roots using allometric relationships for foliage and stem biomass with tree diameter. Stemwood biomass (and volume) is calculated from stem carbon after allowance for branches and bark. 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 water stress, and other factors of the plantation environment.

The model essentially comprises five submodels: (1) biomass production is predicted by environmental modification of light use efficiency; (2) allocation of biomass between foliage, roots and stems (including branches and bark) which are influenced by growing conditions and tree size; (3) tree stocking rates as determined by the probability of death and self-thinning; (4) conversion of stem biomass into variables of interest to forest managers (e.g. leaf area index (LAI), basal area (BA), stem volume, mean annual stem volume increment (MAI)); and (5) water balance of a single soil layer where evapotranspiration is calculated using the Penman-Monteith equation.

3PG requires either long-term average, or actual, monthly climate data (air temperature, vapour pressure deficit, solar radiation, rainfall, and frost days), site factors (latitude, soil texture, maximum available soil water storage, and soil fertility rating), initial conditions of biomass and stocking rates, and management conditions (e.g. irrigation and thinning). Species specific parameters in 3PG characterise canopy structure and canopy quantum efficiency, relationships affecting partitioning of biomass, basic wood density, litterfall and root turnover rates, and various environmental modifiers.

There has been growing interest worldwide in using 3PG as a forest management tool in part because is relatively simple to run, and it is freely available. It has been applied successfully for different purposes and across different forest types under differing climatic and edaphic regions across the globe. For example, (Coops *et al.* 1998) (Coops and Waring 2001; Tickle *et al.* 2001) applied the model to large areas using remotely sensed spatial data or geographic information systems (GIS). Dye *et al.* (2004) used 3PG to predict growth and water use of *Eucalyptus* species in South Africa. Landsberg *et al.* (2001) and Landsberg *et al.* (2003) evaluated the model's performance using data from experimental and commercial plantations from several countries.

Several researchers have also undertaken work to enhance the capabilities of 3PG, and thereby make it more widely applicable for new environments and new species. For example, Sands and Landsberg (2002) provided a detailed procedure for parameterising the model for *E. globulus* in Tasmania and Western Australia, while Paul *et al.* (2007) provided species paramaters for *Eucalyptus cladocalyx* and *Corymbia maculata* plantations in low rainfall regions of Australia.

3. 3PG+/CAT MODEL DEVELOPMENT

We used an enhanced version of 3PG (referred to as 3PG+, Morris and Baker 2002; Morris 2003) that incorporates several developments on the model described by Landsberg and Waring (1997). These developments include enhancements to the temperature modifier, early stage radiation interception, mortality function, and salinity and drought responses. In this paper, an additional modification concerns the representation of the soil water balance. A shortcoming of the original Landsberg and Waring (1997) 3PG model is the representation of soil water. The root zone water balance is calculated on a monthly time step, and was represented as a single layer, with the maximum plant available water specified by the modeller, along with two empirical parameters that describe the relationship between relative transpiration rate and volumetric water content published by Denmead and Shaw (1961) for different soil texture classes.

The 3PG+ model was migrated into the Catchment Analysis Tool (CAT) framework (Beverly *et al.*, 2005). The CAT framework is an enhancement of the one-dimensional crop production PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) model (Littleboy *et al.* 1989).

PERFECT is a biophysical model that simulates the plant – soil – water - management dynamics in agricultural systems, and uses daily weather inputs to simulate the major effects of management and environment to predict the water balance (runoff, soil evaporation, transpiration, soil water storage, redistribution and deep drainage), crop growth (leaf area development, biomass accumulation phenology and yield), soil erosion and surface crop residue. This model has been extensively modified when integrated into CAT to include phenological pasture growth modules, 3PG+, salinity impacts and nutrient dynamics.

The CAT framework comprises a suite of farming systems models ranging in complexity, which allow the user the flexibility to select the appropriate model based on the available data and data source. CAT provides users a range of modelling water balance tools. The CAT framework allows more complex representation of the spatial extent and location of plantations, and their effect on catchment water balance, while also including agricultural land uses which are often the dominant land use in catchments of interest.

The migration of 3PG+ into the CAT framework has facilitated a significant enhancement on the soil-water-plant interactions within 3PG+, including:

1. Soil layering through depth that accounts for soil water redistribution and transfers between soil layers.
2. Evaporation from bare soil.
3. Runoff and run-on processes.
4. Residue impacts on evaporation and infiltration processes.
5. A root distribution and root density function to account for the mass of roots within each soil layer.

With the exception of the 3PG+ module which operates on a monthly timestep, all other elements of the model adopt a daily timestep. That is, in the case of 3PG+, the canopy cover (e.g. used to calculate interception losses and transpiration) is assumed constant over the month whereas the water balance (including transpiration, soil evaporation, infiltration, drainage), erosion and residue modules are calculated daily.

4. VALIDATION OF TRANSPIRATION

4.1. Data collection and field measurements

Three validation catchments were selected based on availability of data and wide geographic distribution. They are: Clem Creek (Vic.), Pine Creek (Vic.) and Delegate River (Vic/NSW). Data sets from each of these catchments were assembled from public domain information and previous studies (see first column in Table 2 for catchment area and mean annual rainfall).

Within each of the validation catchments, one or two plots (between 30 and 100 trees) in plantations were identified for targeted ('snapshot' over approximately one month) measurement of plantation water use, and for measurement of tree growth. Tree water use measurements using heat-pulse sapflow measurement devices were made on 2 or 3 trees in each plot.

A weather station was established at one site (Delegate River) to measure daily temperature (maximum and minimum), radiation, vapour pressure deficit, rainfall, relative humidity and wind speed to coincide with the period of water use measurements. Spatially interpolated daily climate sequences for each site (1980 to 2000) were obtained from Data Drill (http://www.nrw.qld.gov.au/silo/datadrill/; Jeffrey *et al*., 2001), and the data from the local weather station (where present) were superimposed onto the Data Drill data for the period of transpiration measurements.

4.2. Model validation

For each plot, the one-dimensional 3PG+/CAT model was calibrated against observed stand volume at the age corresponding to the period of tree water use measurements. Predicted and measured daily plot water use (mm/day) were compared at each location (example shown in Figure 1).

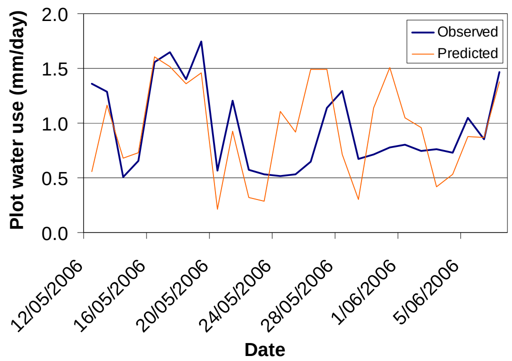

Figure 1. Measured and predicted daily plot water use (mm) for *E. nitens* (at age 12.8 years) at Delegate River.

Across species and sites, observed and predicted plot water use for the targeted measurement period (Table 1) were relatively well correlated ($r = 0.94$). This was a particularly promising result given that 3PG+ was initially developed to run on a monthly time step, and its application within the CAT framework is on a daily time step.

Under prediction of water use at Clem Creek A occurred for part of the monitoring period only, and is largely unexplained. Under prediction of water use at North Esk was due to effects of very low temperatures during the monitoring period, and further refinement of species parameters in light of this is continuing.

Table 1. Plot water use validation summary. (Species PR= *P. radiata*, EN = *E. nitens*; Meas. = measured average daily plot water use; Pred. = predicted plot water use using 3PG+/CAT; % error = difference between measured and predicted water use).

Plot	**Spp.**	**Age (yr)**	**Meas. (mm/d)**	**Pred. (mm/d)**	**% error**
ClemCkA	PR	17.2	4.5	3.6	-20.5
ClemCkB	PR	17.2	3.7	3.5	-5.5
PineCk A	PR	18.6	3.6	3.4	-5.7
PineCk B	PR	18.6	3.5	3.6	+2.7
Del River	EN	8.9	0.95	0.94	-0.6
Nth Esk	EN	12.8	1.7	1.3	-22

5. CATCHMENT SIMULATIONS

5.1. Input Data

Spatial data sets for each of the three example catchments (Clem Creek, Pine Creek and Delegate River) including DEM, landuse, runoff, groundwater and soils information were derived from readily available GIS and internet resources, with the cooperation of Victorian and interstate agencies where necessary.

5.2. Scenarios

The CAT (incorporating 3PG+) was applied to the three example catchments ranging in size from several hundred hectares to several thousand hectares. Using current practice land use, the models represented streamflow (between 1980 and 2000) reasonably well without the need for further parameter fitting. Values for the Nash and Sutcliffe (1970) coefficient of efficiency for monthly streamflow were greater than 0.6 for all catchments (and 0.8 for the Clem Creek catchment). Further work on improving model performance is continuing. The time series of observed and predicted monthly streamflow for the Clem Creek catchment for current land use is shown in Figure 2.

Several scenarios were then run. The scenarios incorporated changes in plantation species (from *P. radiata* to *E. globulus* for example) and changing existing plantation area to annual pasture, and increasing the existing plantation area within specified constraints.

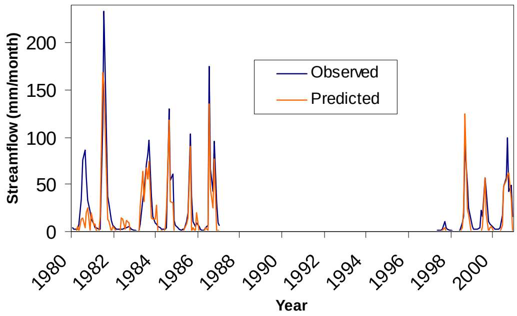

Figure 2. Observed and predicted monthly streamflow for the Clem Creek catchment

The resulting water balance components of the catchment (e.g. evapotranspiration, recharge, streamflow) under each of these scenarios were then compared. A summary of the scenario descriptions and results is given in Table 2. Results represent annual average values over a 21 year simulation period corresponding to 1980-2000 weather conditions.

Predictions made with CAT (incorporating 3PG+) for the Clem Creek catchment suggest that streamflow would be approximately 37% higher if the catchment had been under pasture rather than *P. radiata* plantations (covering 97% of the catchment).

Changes in streamflow between the two plantation species, *P. radiata* and *E. globulus* were more subtle (approximately 7%) and reflect species differences in growth, LAI development and water use.

The results summarised in Table 2 relate to average changes over a 21 year simulation period, and will be different if considered over different time periods because there are species-specific differences in the temporal development of LAI and water use. Particularly, differences in streamflow between plantations and pasture would be greater if compared for years 10 to 21 (as opposed to the entire simulation), because the early development of plantations (when LAI and water use of plantations is lower than those of pastures) is included in the overall differences.

Examples of predicted LAI and annual water use over time (averaged over the catchment) for *P. radiata* and *E. globulus* plantations and for annual pasture are shown in Figure 3 and Figure 4 respectively. The trend shows that in the early years (<4 yrs) pasture LAI and water use is greater than for the *P. radiata* plantation. After this time, LAI and water use is greater for the plantation.

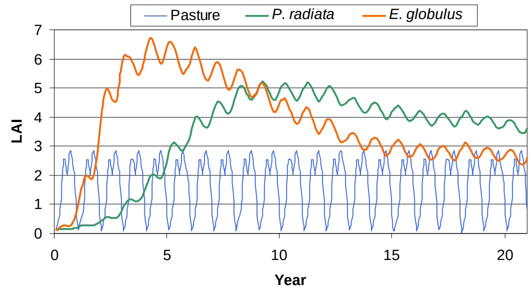

Figure 3. Predicted (average monthly) leaf area index (LAI) for *P. radiata* and *E. globulus* plantations, and for annual pasture in the Clem Creek catchment.

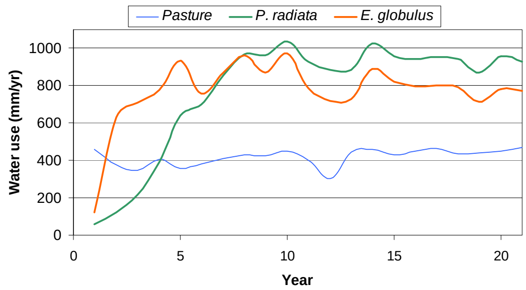

Figure 4. Predicted annual water use (mm/yr) for *P. radiata* and *E. globulus* plantations and for annual pasture in the Clem Creek catchment.

Predicted increases in streamflow between a *P. radiata* and pasture dominated Pine Creek catchment were greater than for Clem Creek (approximately 79%; Table 2). Simulation results suggest that changes in streamflow resulting from changes from trees to pastures may be more pronounced in catchments where evapotranspiration processes represent a larger proportion of the catchment water balance.

Changes in streamflow resulting from land use changes involving plantations and pasture in the Delegate River catchment were lower in magnitude (between 6 and 12%; Table 2). The reason for this is that 44% of the catchment is occupied by native forest (which for the purposes of these scenarios was left unchanged.

6. CONCLUSIONS

The 3PG+/CAT was capable of predicting stand water use at daily time scales with acceptable accuracy across a range of environments. Nonetheless, the model requires additional parameterisation and validation for both growth and water use from a wider range of species and field sites. Such work for the main plantation species in southern Australia (*Eucalyptus globulus*, *E. nitens* and *Pinus radiata*) using observed water use and growth datasets is underway. This will lead to a more robust model for predicting the

Table 2. Predicted water balance components for land use scenarios applied to three example catchments. Values are annual averages over a 21 year period. ET includes transpiration and evaporation. Streamflow includes runoff and subsurface lateral flow (but not deep drainage).

Catchment	Scenario	Land use	ET (mm)	Stream-flow (mm)	% Δ streamflow
Clem Creek	a) Current practice (*P. radiata*)	97% *P. radiata* 3% pasture	843	285	0
Rainfall 1322 mm/yr	b) All plantation area is converted to agricultural pasture	100% pasture	685	390	+37%
Area 50 ha	c) All existing plantation converted to *E. globulus*	97% *E. globulus* 3% pasture	802	305	+7%
Pine Creek	a) Current practice (*P. radiata*)	88% *P. radiata* 12% pasture	628	33	0
Rainfall 755 mm/yr	b) All plantation area is converted to agricultural pasture	100% pasture	558	58	+79%
Area 295 ha	c) *P. radiata* on slopes < 10 degree	72% *P. radiata* 18% pasture	597	43	+30%
	d) *P. radiata* on slopes > 10 degree and < 20 degree	19% *P. radiata* 81% pasture	569	53	+62%
Delegate River	a) Current practice (*P. radiata*)	16% *P. radiata* 44% Native forest 38% pasture	744	148	0
Rainfall 927 mm/yr	b) All plantation area is converted to agricultural pasture	0% *P. radiata* 44% Native forest 54% pasture	748	161	+9%
Area 113,280 ha	c) *P. radiata* on slopes < 10 degree	49% *P. radiata* 44% Native forest 5% pasture	735	131	-12%
	d) *P. radiata* on slopes > 10 degree and < 20 degree	5% *P. radiata* 44% Native forest 49% pasture	746	157	+6%

likely impacts of plantation extent, location, design and management on catchment water balances in a wide range of environments.

Validation of water balance for catchments with multiple land uses remains problematic. Additional application of the 3PG+/CAT model and validation against largely single land use catchments is planned.

The following step involves engagement with industry and water authorities. Results of the scenario modelling will be reported back to CMA's and plantation managers, and to also seek feedback on how the developed modelling system can be made more useful to plantation managers. Reporting and publication of the project results will include recommendations for plantation policy and application of the project outputs as a modelling service for plantation and catchment managers.

7. ACKNOWLEDGEMENTS

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