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Application of *Macaque* and *3PG+ in CAT* catchment-scale hydrological models: limitations and opportunities

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Abstact: Forest management, fire and climate change can have profound and lasting effects on catchment water balances and water yields. This is because significant changes in the growth and structure of forests can lead to changes in evaporation, rainfall interception and transpiration, and in resulting streamflow.

Process-based models that incorporate the major environmental influences on the growth and water use of forests and vegetation, and on the consequential effects on streamflow, allow us to explore the likely effects of the change in forest structure on resulting catchment water balances. Results from these models are being used, to underpin the development of water and forest management strategies and policies. In this paper we describe and discuss the application of two catchment-scale process-based models, their assumptions and limitations, and provide some guidance for the further development and future application of these models.

Macaque, a process-based model, was used to develop models for several forested catchments that supply water to Melbourne. They were used to investigate the likely effects of various bushfire scenarios and climate change projections on catchment water balances. A limitation of this approach is the absence of a growth module that allows for the effects of climate and edaphic factors on the development of forests. The model uses a set of empirical functions that describe the time course of leaf area index (LAI) for a range of forest types.

Changes in the LAI can have relatively large effects on resulting evapotranspiration (ET) and streamflow. Adjustments in the LAI empirical functions based on field measurements led to a decrease in mean catchment average LAI by nearly 14%, with a consequential decrease in ET of over 6%, and an increase in streamflow of over 18%. This highlights the value in collecting LAI data for model parameterisation.

Recent work incorporating the 3PG+ forest growth model into the CAT (Catchment Analysis Tool) framework (*3PG+ in CAT*) allows for the investigation of catchment-scale responses in mixed-landuse catchments, as well as having a forest-growth module that characterises the effects of management and environmental influences on forest growth and on water use.

3PG+ in CAT is able to take into account the effects of a changing climate (but at least presently, not CO_2 concentrations) on growth and water use. Not only is the growth and LAI influenced by topography and location within a catchment, but changes in the environment over time will lead to responsive changes in LAI and ET. For example, invoking a step change in rainfall (-7.1%) and temperature (+1.5^{o}C), both considered ‘moderate’ climate change projections, led to an increase in LAI (3.4%) and a decrease in ET (-7.1%) for a plantation in Eastern Victoria.

While 3PG has been widely applied to single-species plantations and even-aged, relatively homogenous forests, it has had limited application to more species rich forest systems. The challenge now is to enhance *3PG+ in CAT* and apply it to these more complex systems.

As in most physically-based models, LAI is a major control of all evapotranspiration processes. With the influences of climate change, the past can no longer be considered a reliable predictor of the future. If we want to be able to represent possible changes in rainfall and temperature on catchment hydrology, it is essential we take into account these effects on vegetation growth and ET.

Keywords: *catchment, hydrology, forest growth, modelling, 3PG, CAT, Macaque*

1. INTRODUCTION

Water resources in many river basins across southern Australia are already highly committed and increasing demands and climate change can be expected to put further pressure on these resources. Because of their location in higher rainfall areas, forested catchments are important for water supplies. However, losses through evapotranspiration (ET) are also relatively high in forested catchments (~65-80%+ of rainfall), and these losses are influenced by a range of catchment characteristics (e.g. rainfall, soil type and depth, aspect) and forest characteristics (e.g. species or forest type, age, and density which, in turn, are influenced by forest management).

The effects of forest management, fire and climate change can have profound and lasting effects on resulting catchment water balances and on water yields. This is because they may lead to significant alterations in the growth and structure of forests and other vegetation, which in turn results in changes in evapotranspiration (ET). In south-eastern Australia, climate change has the potential to both further reduce rainfall and increase evapotranspiration, resulting in streamflow becoming an even smaller proportion of a decreasing total water balance.

There is a clear need to integrate knowledge from both forestry and hydrology disciplines, to link the carbon and hydrologic cycles, to advance our understanding of forests in the broader context. Models that incorporate the major environmental influences on the growth and water use of forests and vegetation, and on the resulting streamflow, allow us to examine and explore the likely effects of the change in forest structure on resulting catchment water balances.

Results from process-based models are being used, *inter alia*, to underpin the development of policies addressing the development of management strategies for Melbourne’s water catchments specifically to increase water yields. Model results are also being used in the development of a State-wide framework for accounting for and managing the impacts of land use change on water resources. It is important for stakeholders to have confidence in the ‘numbers’ being generated by these models if we are going to be able to progress the debate beyond what the numbers are to consideration about an appropriate policy response. It is also be important for policy makers to understand the assumptions built into the modeling processes, and to recognise, and allow for, the inherent uncertainties associated with model outputs.

Here we describe and discuss the application of two catchment-scale process-based models to examine the effects of land use change on hydrology at the catchment scale. Assumptions, limitations, and comparisons of both applications are discussed, with a view to improving future application of catchment-scale hydrological models to landscape change.

2. MODEL DESCRIPTIONS

2.1. Macaque

Macaque is a physically-based model developed to assess the long-term impacts of forest disturbance in large catchments (Watson 1999, Watson et al., 1999). Model parameters are assigned values based on direct measurements of physical properties within a catchment, or from the literature. A few parameters, particularly those relating to soil properties, are used for calibration of the model against observed water yield. These parameters are unlikely to change with forest disturbance.

The catchment is discretised spatially into hillslopes, and hillslopes into smaller areas known as elementary spatial units (ESUs). Each ESU is modelled separately, and are linked together by subsurface water flow pathways. Hillslopes are linked together by a stream network, which sums the flow from all the hillslopes to get the total catchment flow. The model runs on a daily time-step and requires a daily time series of precipitation and maximum and minimum temperature as input. A detailed climate sub-model is used to convert precipitation and temperature range inputs into required climate variables such as radiation and humidity for the estimation of evapotranspiration.

Within each ESU, two layers of vegetation are represented: overstorey and understorey. Precipitation interception and throughfall are modelled for both these layers. Solar radiation is propagated through, and absorbed by these layers. The Penman-Monteith equation (Monteith and Unsworth, 1990) is used to calculate evapotranspiration (ET) using leaf area index (LAI) and canopy conductance for each of the layers, as well as to calculate evaporation from the soil. LAI and leaf conductance are specified to the model as a series of LAI with age and conductance with age relationships for each forest type (e.g. Mountain Ash, Mixed Species, Rainforest, Heath).

Predictions of water yield are sensitive to climate, vegetation water use, the amount of water stored within the soil, and the rate at which this water moves into and out of the soil and into the streams. Therefore, spatial changes in climate, vegetation, soil, and topography cause changes in water yield.

2.2. 3PG+ in CAT

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 affected by temperature, vapour pressure deficit, available soil water, stand age and site fertility. 3PG calculates monthly net carbon fixation (from gross fixation after allowance for respiration), stand development, biomass (foliage, stems and branches) 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). It has been applied successfully for different purposes and across different species under differing climatic and edaphic regions across the globe (for example, Coops et al., 1998;Landsberg et al., 2003).

Enhancements to the original 3PG, resulting in the 3PG+ model, include a revised definition of canopy conductance, reduced radiation interception before canopy closure, incorporation of fertility decline over time, increased litterfall in response to drought, and incorporation for effects of salinity on growth (Morris and Baker, 2002). Recent (Feikema et al., 2007) and continuing work has integrated the 3PG+ forest growth model into the Catchment Analysis Tool (CAT). CAT (Beverly et al., 2005) comprises a suite of farming system models linked in a spatial framework that accounts for runon-runoff processes and sub-surface lateral flow and simulates plant-soil-water dynamics in agricultural systems and the major effects of management and environment on the water balance (runoff, soil evaporation, water use, soil water storage, redistribution and deep drainage), crop growth, soil erosion and surface crop residue. A key development in the integration of 3PG+ with CAT is a more dynamic representation of the root zone, as a multiple-layer soil with water balance calculated on a daily basis. Soil layering through depth allows accounting for soil water redistribution and transfer of water between soil layers. It allows more complex representation of the spatial extent and location of different landuses, and their effect on catchment water balances.

3. APPLICATIONS, LIMITATIONS AND OPPORTUNITIES

In this section, we present some of the main issues and limitations that have arisen in application of *Macaque* and *3PG+ in CAT*. We discuss these under broad headings and suggest possible solutions.

3.1. Representation of LAI in Macaque

As in most physically-based models, LAI is a major control of all evapotranspiration processes. *Macaque* represents the time development of vegetation in the form of curves for each species representing changes in LAI and leaf conductance with forest age. For the ash-type species, *E. regnans*, *E. delegatensis* and *E. nitens*, canopy LAI is predicted using the curves developed from experimental data (Watson, 1999). Understorey LAI is then estimated as the difference between total and canopy LAI.

Relationships between forest age and LAI and maximum leaf conductance for *E. regnans* are well known (Watson, 1999, Watson et al., 1999). The LAI curve for *E. regnans* to 100 years of age as represented in Macaque (dashed line) is shown in Figure 1a. For non-ash eucalypts and non-eucalypts, the long-term LAI patterns are less well understood, but are assumed to have constant LAI, following a rapid initial increase from zero in the first 5 to 10 years following disturbance. The LAI curve for non-ash (mixed eucalypt species) vegetation to 100 years of age as represented in Macaque (dashed line) is shown in Figure 1b. These relationships were derived by Watson (1999) from direct measurements as well as allometric and remote sensing data throughout the Maroondah region in southern Victoria. This introduces uncertainty in the representation of these relationships in other catchments, where topographical and climate may result in different growth and LAI development for the same forest type. The variation in LAI for a given forest type will also vary within catchments.

Lane et al. (2007) used *Macaque* to investigate long term effects of the 2003 bushfires on catchment water yield and identified limitations regarding the representation of the LAI of forest types. The LAI development over time specified in *Macaque* for each forest type is independent of topography (slope, aspect and elevation) and climate (rainfall and temperature in this case). The LAI relationships were developed primarily with data from, the relatively wet Maroondah catchment. It is likely that the representation of this forest type under (slightly) drier conditions would lead to an overestimation of LAI, and a consequential overestimation of the effect of any disturbance on catchment streamflow.

To test the applicability of the LAI relationships to other catchments, Mannix (2007) conducted a study which incorporated field measurements of LAI into an existing Macaque model for the Starvation Creek catchment developed by Feikema et al (2006), about 90 km east of Melbourne. These field based measurements were used to update the existing relationship within Macaque. A new relationship was developed for *E. regnans* (Figure 1), mixed *Eucalyptus* species (Figure 1), *E. sieberi* and *E. delegatensis*. The model was rerun, and the changes in average annual ET and annual streamflow were compared (Table 1). Changes in mean catchment LAI over the 30 year period were lower by nearly 14%, with a consequential decrease in ET of over 6%, and an increase in streamflow of over 18%. This highlights the need, when using models such as Macaque where LAI is independent of climate and topography, that effort to collect field data for the catchment of interest is well advised.

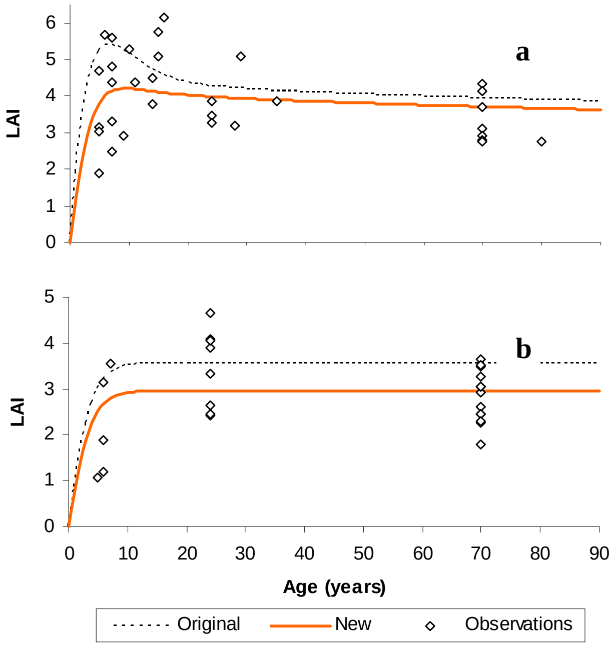

Figure 1. LAI in Macaque for **a)** *Eucalyptus regnans* (Mountain Ash) and **b)** mixed Eucalyptus species in Starvation Creek catchment

Table 1. Summary of changes when using *original* LAI functions (developed by Watson, 1999) for the Maroondah catchment) and *new* LAI functions derived from field measurements(after Mannix, 2007) at Starvation Creek.

	Mean LAI	**Mean ET (mm/year)**	**Mean flow (mm/year)**
Original	3.78	1390	440
New	3.25	1300	520
Change in mean	-13.9%	-6.3%	+18.3%

3.2. Vegetation response

Macaque is unable to adapt the time course of LAI across the catchment in response to changes in climate and topography due to the absence of a growth module that simulates growth and water use response of vegetation to changing environmental conditions. While ET will vary with water availability and climate, it may well be over- or underestimated as a consequence of the error in LAI at a given point. While it is possible to redefine the LAI-age relationship with field data for a simulation run, but it is not possible to redefine the relationship of LAI over time due to influences of a changing climate. In a changing environment, the past can no longer be considered a reliable predictor of the future, both biophysically and in the manner in which forests are managed (Battaglia et al., 2007). Growth data collected under current or past environments may not be as valuable as they once were in estimating the future growth potential given changed drought and disease risks.

3PG+ in CAT is able to take into account the effects of a changing climate (but at least presently, not CO_2 concentrations) on vegetation. Changes in the environment over time will lead to responsive changes in LAI and ET. Plant response to rainfall is important is the practice of using long-term average climate data rather than actual climate data if it is available. For example, using the long term average rainfall can lead to overestimation of predicted growth (Figure 2), especially when applied to plantation growth over the past 13 years in southern Australia, where below average rainfall has occurred. In this case, the long term average rainfall is 10% higher than the actual rainfall during the rotation, and using the long term average rainfall leads to predicted increases in stand volume of 5.5%, LAI of 4.6% and ET of 8.4%. As illustrated earlier, (e.g. Table 1) these changes in ET can lead to relatively greater changes to other parts (e.g. streamflow) of the water balance.

Process-based models are increasingly being used to evaluate the effects of climate change on risk and productivity of plantations (Kirschbaum 1999). Applying *3PG+ in CAT* to the same site as in Figure 2, and invoking changes in rainfall (-7.1%) and temperature (+1.5^{o}C), both considered ‘moderate’ climate change projections by Howe et al. (2005), led to an increase in predicted volume (1.9%), increase in LAI (3.4%) and a decrease in ET (-7.1%).

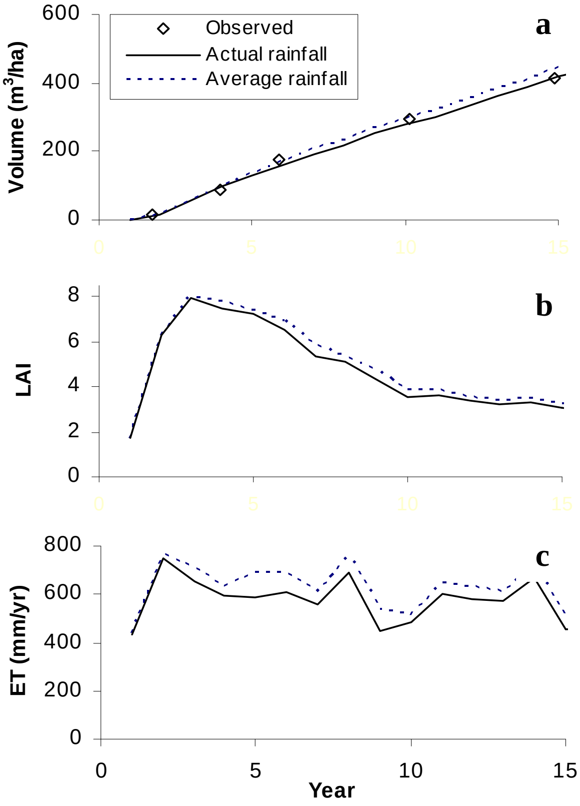

Figure 2. Example of the use of *3PG+ in CAT* to compare predictions of **a)** stand volume, **b)** LAI, and **c)** ET under actual rainfall (solid lines) with those under long term average rainfall conditions (dashed lines) for a *Eucalyptus globulus* plantation planted in 1988 in East Gippsland, Victoria.

3.3. Native forests

Process-models have been used most in commercial forestry for predicting the potential productivity in new areas where no or little inventory data to establish forest productivity classifications exist (Almeida et al., 2004). Similarly, they may also be useful for predicting the growth of native forests across large areas where little or no growth data exists.

The success for process-based models to predict the growth and development of forests in new areas is largely dependent on quality of the input data (Mummery and Battaglia 2002). In many cases models may be calibrated rather ‘successfully’ against controlled experimental data or where conditions are relatively uniform. Native forest systems, when compared to managed plantations, are more complex in vegetation structure and topography (and therefore also climate). So the prediction of growth and water use of native systems must be done across a wider range of environmental conditions. Furthermore, less is known about those environmental conditions. For example, the spatial variation of soil depth, and the spatial variation of rainfall and temperature, have been much less studied and characterised across vast areas of native forest, than they have across many of the agricultural areas in which plantations have been established.

While 3PG has been widely used, its application has been limited to single-species plantations and even-aged, relatively homogenous forests throughout the world (for example, Coops et al., 1998; Sands and Landsberg, 2002; Landsberg et al., 2003). It has had only limited application to native forest systems with parameterisation and validation of forest productivity based on a limited set of growth attributes (Tickle et al., 2001; Nightingale et al., 2008). If *3PG+ in CAT* is to be used to assess the effects of changes in vegetation structure on the water yield derived from catchments, a more detailed parameterisation, one that includes forest growth measurements, LAI and water use, will be required. The effects of landscape change on the response dynamics of species rich plant communities (forests) is difficult to represent due to their high complexity. There are two approaches in *3PG+ in CAT* that could be taken to deal with this challenge.

1. ***Developing a single set of parameters*****:** The site independent characteristics of a given (plantation) species in *3PG+ in CAT* are represented by a set of ~30 parameters. The challenge is whether an integration of knowledge of the key processes and common ecological patterns of multi-species forests can be captured in a single set of parameters. A limitation of this approach is that it will not be able to represent relative changes in the overstorey and understorey components, or deal with changes in forest structure resulting from disturbance.
2. ***Structural changes to allow for overstorey and understorey components*****:** This would involve making changes to *3PG+ in CAT* to allow for two, competing, species to co-exist. A species parameter set would describe the overstorey, and a separate set would describe the understorey component. The advantage of this is that the model may be better able to represent the competition for resources, and consequential changes in forest structure. One disadvantage of this approach is the doubling the number of parameters and the associated issue to overparameterisation.

4. CONCLUSIONS

While there are future opportunities to apply process-based models in difference regions and different forest types, the greater complexity of vegetation structures, and more variable environments, coupled with the process complexity inherent in responses (to a changing climate for example), present a challenge for models and modellers to provide realistic predictions without making them overly complex. While the application of Macaque to the ash-type forests east of Melbourne may have been sound, doubts may be cast over its application to relatively drier regions, or when changes in climate will affect forest growth. In these instances, a framework such at *3PG+ in CAT* may be more appropriate.

The application of process-based models highlights the knowledge gaps in our understanding of system responses and help us form new questions, and guide our future field-based research. These questions tend to be general ones like; can we better assess soil characteristics spatially, and how do different forest species respond after fire? Applications of Macaque to fire affected catchments has made us question how we represent the development of LAI and water use of different forest types that have been subjected to different fire intensities. In a spatial sense, are we able to better relate tree mortality to species, age, topography and climate? These areas are among broader research programs that investigate catchment response to fire.

The types of models used, and the respective inherent limitations and assumptions that underlie them and therefore the numbers they generate, must be understood by policy makers and catchment managers. While different and contrasting model predictions may provide interesting material for critical review and may indicate new research directions, in many cases a consensus between model estimates may be achieved in the ranking of their predictions and similarities (or sensitivities) between the main influences on vegetation growth, water use, and streamflow. But as with any modelling exercise, those that use them, and those that rely on their results must be aware of the uncertainty, limitations and assumptions that underlie the input data and the models themselves.

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