International Environmental Modelling and Software Society (iEMSs)
2010 International Congress on Environmental Modelling and Software
Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, Canada
David A. Swayne, Wanhong Yang, A. A. Voinov, A. Rizzoli, T. Filatova (Eds.)
http://www.iemss.org/iemss2010/index.php?n=Main.Proceedings

Using 3PG+ to simulate longterm growth and transpiration in *Eucalyptus regnans* forests

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Abstract: The amount of water derived from forested water supply catchments depends largely on forest evapotranspiration, which in turn depends on forest age and structure. There is increasing interest to predict the effects of forest disturbance (e.g. fire) and management (e.g. thinning) on streamflow. One approach is to incorporate present knowledge of water use into process-based models that simultaneously predict water use and growth of forests. We take 3PG+, an enhanced version of the 3PG forest growth model with a daily multi-layered water balance, and validate it for multi-species *Eucalyptus regnans* forests. The model has to date been applied to single-species forests or plantations, and adaptation to native forest systems with multiple canopy layers required the vertical distribution of radiation propagation, rainfall interception, humidity gradients, canopy conductance and evapotranspiration, and soil water uptake. Assigning species parameters for complex forest systems presented a challenge. We assigned the overstorey and an understorey component each with a set of species parameters. Simulations of over 230 years were able to capture well the trends and magnitude of forest structure (stocking, leaf area index) and water balance components (transpiration, evapotranspiration, rainfall interception and runoff). Further validation across additional sites is required before the model is used to predict the likely effects of changes in forest age and structure and catchment water balances arising from disturbances such as fire, land use change, and climate change.

***Keywords**:* 3PG+, process-based model, water balance, native forest, mountain ash

1. INTRODUCTION

In Australia and in many other countries, catchments dominated by native forests provide a major source of water for many cities. 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. Process-based models that can simulate carbon and water cycles in forests in response to seasonal variation in climatic conditions, provide a way to assess likely effects of these changes on forest growth and water balances which is otherwise very difficult through space and time.

The 3PG forest growth model [Landsberg and Waring, 1997] has been widely used to simulate the growth of forests, and recent developments to 3PG, resulting in 3PG+, have improved its ability to simulate water use by forests [Morris and Collopy, 2001; Feikema et al. submitted]. These developments involved incorporation of 3PG+ into the Catchment Analysis Tool [CAT; Beverly et al., 2005], a modelling framework that allows for the application of 3PG+ at catchment scales with multiple landuses.

The application of 3PG has been limited to single-species plantations and even-aged, relatively homogenous stands (for example, Sands and Landsberg, 2002; Landsberg et al., 2003]. It has had few applications 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].

There are many fundamental differences between plantations and native forest systems; shorter *cf.* longer timeframes, and differences in growth rates, nutrient status, and management. Inclusion of an understorey component allows for competition for water and can therefore affect overstorey productivity. The understorey component may contribute significantly to stand biomass, and therefore be important in estimations of carbon storage of forests. In this paper, we describe developments to the 3PG+ to allow the simulation of the growth and water use of native *Eucalyptus regnans* forests with an overstorey and understorey component. We provide a more detailed parameterisation of both components against measurements of growth, LAI and transpiration.

2. MODEL DEVELOPMENT

Structural changes to allow for overstorey and understorey components were made to 3PG+, and allow for two competing species to co-exist. Inclusion of an understorey component required representation of the vertical distribution of i) radiation interception, ii) rainfall interception, iii) humidity gradients canopy conductance and evapotranspiration, and iv) soil water uptake.

2.1 Solar radiation

As in the original 3PG [Landsberg and Waring, 1997], photosynthetically active radiation (ϕ_p) is assumed to be 0.5 of incoming solar radiation. Solar radiation is intercepted, absorbed or transmitted by the two vegetation layers in succession, and the remainder is absorbed by litter and the soil at the forest floor. The amount of ϕ_p that is absorbed (ϕ_{pa}) is calculated using Beer's law [Monteith and Unsworth, 1990] which states that radiation decreases exponentially through the canopy, and makes assumptions about the random distribution of leaves within a canopy. The canopy intercepts the incident radiation in non-linear proportion to its LAI and an associated radiation extinction coefficient. Some of the intercepted radiation is reflected back upward and some is transmitted through the canopy to the understorey layer. Absorbed photosynthetic radiation (ϕ_{pa1}) by the overstorey is represented by

$$\phi_{pa1} = \phi_p\left(1 - e^{(-k_{\varphi 1}.LAI)}\right) \quad (1)$$

and understorey absorbed solar radiation is modelled in a similar way, except that the understorey photosynthetic radiation is that which is left over after canopy interception, and so radiation absorbed by the understorey (ϕ_{pa2}) can be calculated by

$$\phi_{pa2} = \left(\phi_p - \phi_{pa1}\right)\left(1 - e^{(-k_{\varphi 2}.LAI)}\right) \quad (2)$$

2.2 Rainfall interception

Rain falling on the overstorey and understorey are partially intercepted and evaporated back into the atmosphere. Each vegetation layer can intercept and store water up to a maximum level scaled by the LAI of the vegetation. Excess water falls through the layer to the layer below. Secondly, the amount of stored water which is evaporated back to the atmosphere depends on potential evaporation.

Understorey interception is modelled in the same way as overstorey interception except that the input to the understorey is the throughfall from the canopy.

$$I_{R1} = \min\left\{ I_1^{*} R, I_{L1} L_1 - R_{C1} + E_{C1} \right\} \qquad (3)$$

Where the subscript *1* refers to the overstorey, and where I_L is an empirical term that links maximum crown storage of rainfall to leaf area index (L), i.e. mm per unit LAI, R_C (mm) is existing crown-stored rainfall, and E_C (mm) is evaporation of crown-stored rainfall. The equation provides that at most a fraction I^{*} of rainfall (R) can be intercepted; that is some proportion of rainfall always reaches the ground through gaps in the canopy or as stemflow. Interception by the understorey is given by

$$I_{R2} = \min\left\{ I_2^{*}\left(R - I_{R1}\right), I_{L2} L_2 - R_{C2} + E_{C2} \right\} \qquad (4)$$

where the subscript *2* refers to understorey. Total interception by the forest canopy is then given by the sum of I_{R1} and I_{R2}.

2.3 Evapotranspiration

The model includes a three layer (canopy, understorey and forest floor) Penman-Monteith representation of ET. Controls of ET by canopy LAI and understorey LAI are separated. This occurs through mechanisms of LAI control of rainfall interception, transpiring surface area, as well as LAI control of the amount of radiation intercepted by the canopy and understorey, and hence the amount of energy available for ET.

In calculating potential transpiration for overstorey and understorey layers, the vapour pressure deficit at the overstorey canopy surface (VPD_1) is modified to reflect the effective deficit at the understory canopy surface [*sensu* Grantz and Meinzer 1990]; this modified deficit (VPD_2) is calculated using the omega decoupling coefficient (Ω_c) proposed by Jarvis and McNaughton [1986]:

$$VPD_2 = \Omega_c VPD_{eq} + \left(1 - \Omega_c\right) VPD_1 \qquad (5)$$

with

$$VPD_{eq} = \frac{\gamma \varsigma R_n \left(c_p / r_s\right)}{\varepsilon + 1} \qquad (6)$$

$$\Omega_c = \frac{\varsigma + 1}{\varsigma + 1 + r_s / r_a} \qquad (7)$$

Where VPD_{eq} is the equilibrium saturation deficit, and ζ is s/γ, and ε is the dimensionless rate of change of saturated specific humidity with temperature (estimated as 2.2 at 20^{o}C), γ is the psychometric constant, R_n is net radiation, c_p is the specific heat of air, r_s is the surface resistance and r_a is the aerodynamic resistance. Daily net radiation is estimated from total solar radiation as: $R_n = 0.8R_s - 90\text{W m}^{-2}$ and aerodynamic conductance is estimated as 0.1 times wind speed in m s^{-1} [Landsberg, 1986]. The default values of 0.8 and -90 are consistent with empirical estimates from studies in several forest types, and actual values will depends on local climate as well as forest structure and species.

2.4 Water availability

The soil is divided into layers and additionally into three zones (*A*, *U*, and *B*) defined by the fraction exploited by root. At each soil water balance time step, Zone A (Z_A) is the fraction exploited by roots from overstorey species and from which water uptake can occur. Zone U (Z_U) is the fraction exploited by roots from understorey species and from which water uptake can occur. Zone B (Z_B) is the remainder of the root zone that is not exploited by roots. The three zones comprise the total soil root zone as defined as a specified depth of soil or maximum rooting depth.

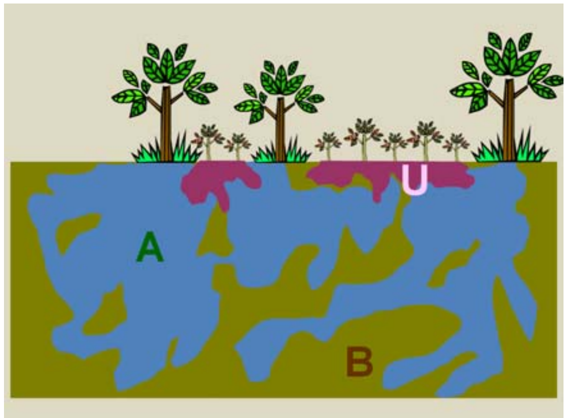

Figure 1. Representation of the zones in a single soil layer exploited by roots of the overstorey (A), understorey (U) and the unexploited zone (B).

Root zone water at the start of the current day (SW_i) is calculated by

$$Z_{Ai} + Z_{Bi} + Z_{Ui} = SW_i \qquad \text{if } SW_i > 1 \tag{8}$$

where Z_{Ai} is the amount (mm) of water accessible to overstorey roots in layer *i*, Z_{Bi} is the amount of water not accessible by roots in layer *i*, and Z_{Ui} is the amount of water accessible to understorey roots in layer *i*.

2.5 Species parameterisation

Parameterising for complex forest systems using two parameter sets presents a challenge. Complex forests may be seen as comprising a combination of groups of species that function similarly in terms of the way they regulate water cycling [Mitchell et al. 2008]. So while plants may display different morphological characteristics such as leaf shape, there is a degree of similarity with respect to resource capture and the traits that govern them, and may be based on a common underlying trait or set of traits. For example, the light extinction coefficient (k_ϕ) is a function of the angle of inclination of leaves. The angle of inclination of leaves in the understorey is generally lower ($\theta \approx 52^o$; i.e. more horizontal) than that of for a eucalypt overstorey [$\theta \approx 65^o$; Vertessy et al. 1996].

Extant 3PG species parameter sets are based on data from plantations typically younger than 12-15 years (e.g. Sand and Landsberg, 2002). Functions within 3PG+ have been developed from plantation based data, where the interest is in simulations generally no longer than 20 years. Re-parameterising is likely to be required for existing species parameters, where the interest in the growth and water use of that species in a native forest is of interest. For example, canopy conductance is known to decline with age in older forests (>50 years) and this process is encapsulated in the f_{age} modifier which has do date been untested on older forests.

We used data in the literature, primarily on partitioning of stems and foliage, specific leaf area, branch fractions and litterfall, to assign a set of parameters for the overstorey (*E. regnans*) and a set for the understorey (*Acacia* spp.based).

3. DATA

3.1 Calibration and validation data

Plot based data for overstorey and understorey components in *E. regnans* forests presented by Dunn and Connor [1993] and O'Sullivan [1999], covering a range of ages from 9 to 235 years, was used to validate the model. A summary, including the type of data available from each study, is provided in Table 1.

Table 1. Summary of data used for calibration and validation.

Site	Location	Age (years)	Data*	Source
Dun50	Monda Road	50	S, D, T	Dunn & Connor (1993)
Dun90	Monda Road	90	S, D, T	Dunn & Connor (1993)
Dun150	Monda Road	150	S, D, T	Dunn & Connor (1993)
Dun230	Myrtle 1 catch.	230	S, D, T	Dunn & Connor (1993)
OS9	Myrtle 2 catch.	9	S, D, L, T	O'Sullivan (1999)
OS16	Monda 2-3 catch.	16	S, D, L, T	O'Sullivan (1999)
OS22	Picaninny catch.	22	S, D, L, T	O'Sullivan (1999)
OS55	Ettercon 3 catch.	55	S, D, L, T	O'Sullivan (1999)
OS235	Myrtle 1 catch.	235	S, D, L, T	O'Sullivan (1999)

*S= stocking, D= stem diameter & basal area; L=leaf area index; T=transpiration

3.2 Climate

Daily weather data (Patched Point Dataset; PPD) for the nearest meteorological station to each plot were obtained from the Queensland Department of Natural Resources and Environment's SILO service (http://www.longpaddock.qld.gov.au/silo/). PPD data include total rainfall, minimum and maximum temperatures, total solar radiation, pan evaporation and vapour pressure, and comprise the actual measurements, and interpolated data [Jeffrey et al, 2001] where there are gaps in the record. The daily PPD data were scaled using the ratio of the long-term annual average for the site according to ESOClim [Hutchison, 1999] spatially interpolated data, and the mean of the PPD for the same period.

3.3 Soil

Soil data information was taken from data for the Maroondah catchment by Davis et al. [1999]. Additional information was obtained from the soil database provided by McKenzie et al. [2000]. The soils are approximately 5 m deep, are described as a deep red brown earth, and are classed as Gn3.21 [Northcote, 1979]. The upper 0.5 m of the soil profile is a well structured, dark brown organic clay loam. Between 0.5 and 3 m the soil grades from a well-structured red brown loamy clay to a light clay. Below 3 m the soil typically changes to a yellow brown incompletely weathered soil with a light to medium clay texture. Bedrock or saprolite is generally evident at 5 m.

4. RESULTS AND DISCUSSION

Simulations with 3PG+ were able to capture the decline and general trend in tree stocking fairly well (Figure 2). There was no data available for initial stocking, and stocking rates of 1500 and 5000 trees ha^{-1} were assigned to overstorey and understorey species respectively. Attempts to parameterise the self thinning rule in such a way to reduce final stocking of the overstorey resulted in model instability and requires further attention.

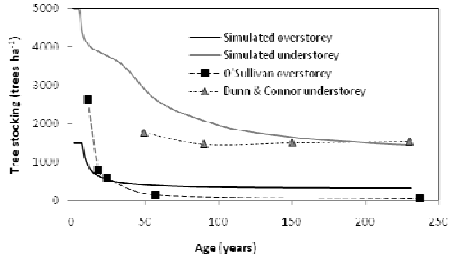

Figure 2. Simulated stocking for overstorey and understorey and data from O'Sullivan [1999].

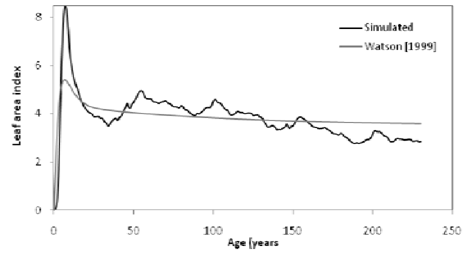

Figure 3. Simulated total leaf area index (LAI) and that based on data from the Maroondah catchment from Watson [1999].

Predicted total leaf area index (LAI) followed the major trend in total LAI estimated by Watson [1999] (Figure 3). Watson [1999] developed a generalised LAI curve based on data from Dunn & Connor [1993], O'Sullivan [1999] and others. While, 3PG+ correctly simulated the timing of the peak in LAI, the magnitude is too high, and resulted from an over prediction of understorey LAI, possibly because simulated litterfall is too low in the first 20 years.

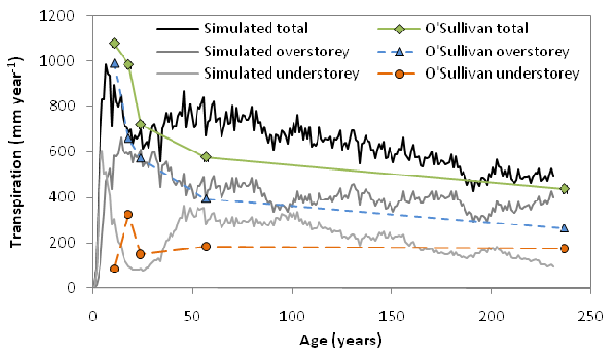

Figure 4. Simulated annual transpiration and that measured by O'Sullivan (1999) in the Maroondah catchment.

Simulated transpiration aged well with the long term trends of overstorey and understorey components as measured by O'Sillivan [1999] (Figure 4). Most importantly, simulations captured the peak in transpiration associated with regrowing *E. regnans* stands following disturbance [Vertessy et al., 2001].

An important capability of 3PG+ and the CAT framework in which it currently sits, is a more refined soil water balance that partitions water into runoff and deep drainage, and that operates at a daily time step [Feikema et al., submitted]. Simulated total ET and runoff were reasonably close to that measured by O'Sullivan [1999] (Figure 5).

The full capability of 3PG+ in CAT in predicting likely effects of differences in forest function arising from, for example, forest management, fire or climate change on runoff, will be realised when applied at catchment scales.

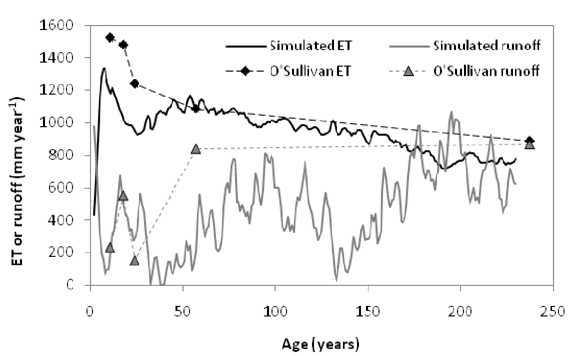

Figure 5. Simulated annual evapotranspiration (ET) and runoff, and that measured by O'Sullivan [1999] in the Maroondah catchment.

Simulated annual total interception (by both overstorey and understorey) is highly variable and is highly dependent on rainfall (Figure 6). It is therefore difficult to compare the predictions with those values presented by O'Sullivan [1999] for the calendar year of 1995. Nonetheless, the model is able to predict annual fairly well.

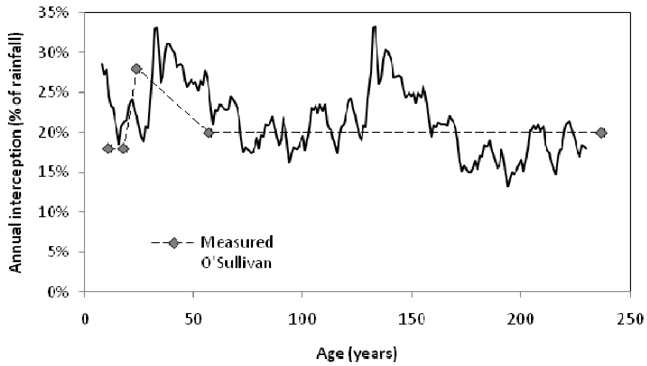

Figure 6. Simulated annual total interception (ET) and that measured by O'Sullivan [1999] in the Maroondah catchment.

5 CONCLUSIONS

We present the first attempt to apply 3PG+ to a two-layered forest stands over long (230 year) time frames. After parameterisation, the model is able to capture the general trends in growth, LAI and ET of overstorey and understorey components of *E. regnans* forests. Continued validation against more datasets is required to have more confidence in the species parameter sets and that the model is adequately simulating long term growth and water balances in *E. regnans* forests.

Further work should be directed at improved parameterisation of understorey species, and other forest types that occur more commonly in water supply catchments in Victoria and Australia, such as mixed *Eucalyptus* forests that occupy drier areas than those in which *E. regnans* forests are found.

ACKNOWLEDGMENT

We acknowledge support from the Victorian Department of Sustainability and Environment.

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