Description of the 3PG+ forest growth model

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APPENDIX B. Descriptions of the subroutines within 3PG+.

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1. Introduction

There have been considerable developments made to the original 3PG forest growth model developed by Landsberg and Waring (1997). The most recent has resulted in the incorporation of 3PG+ (Morris and Baker (2002) into the Catchment Analysis Tools (CAT) modelling framework (Beverly et al. 2005; DSE, 2007) as described by Feikema et al. 2008 and in Feikema et al. (submitted).

This report describes these developments in more detail, and specifically how they are currently represented within 3PG+. This is done with reference to the Fortran source code. Two appendices provide additional information, namely, Appendix A lists the symbols used in this report with respective labels in the source code, units, and descriptions, and Appendix B provides brief descriptions of all the subroutines within the 3PG+ source code.

There is a collection of supporting references that relate to the background development of 3PG, and that describe other developments and various applications. The reader is therefore referred to a number of key references that provide a more comprehensive background to the development of the 3PG forest growth model.

The model was first described by Landsberg and Waring (1997).

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

Sands and Landsberg (2002) added modificatrions to the original version, as well as providing species parameters for *Eucalyptus globulus*.

> Sands, P.J. and Landsberg, J.J. 2002. Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. Forest Ecology and Management 163, 273-292.

Two workshops edited by Williams (1999) and Williams (2000) were held in which 3PG researchers, collaborators and model users discussed model applicastions and developments.

> Williams, K.J. (ed) 1999. Workshop on the forest model 3-PG. Its use, evaluation, the wide-scale versions and matters arising. Forest Ecosystem Research and Assessment Technical Papers 99-8, February 1999. Queensland Departments of Natural Resources and Primary Industries, Brisbane.

> Williams, K.J. (ed) 2000. 3PG 2000: A workshop on the forest model 3-PG. New developments in calibration, performance, spatial inputs and practical applications. Forest Ecosystem Research and Assessment Technical Papers 00-18, August 2000, DNRQ00126. Queensland Departments of Natural Resources and Primary Industries, Brisbane.

A sensitivity analysis was undertaken by Esprey et al. (2004).

> Esprey, L.J., Sands, P.J., Smith, C.W. 2004. Understanding 3-PG using a sensitivity analysis. Forest Ecology and Management 193, 235-250.

A comprehensive set of guidelines for parameterising 3PG for new species is provided by

Sands, P. 2004. Adaptation of 3PG to novel species: guidelines for data collection ad parameter assignment. Cooperative Research Centre for Sustainable Production Forestry and CSIRO. Technical report 141, 34 pp.

2. 3PG overview and development

2.1 The 3PG forest growth model

The 3PG forest growth model is a process-based generalised stand-level model developed by Landsberg and Waring (1997). The model calculates dry mass production from the photosynthetically active radiation (PAR) absorbed by the forest canopy (APAR), modified by environmental factors including temperature, vapour pressure deficit, available soil water, stand age and site fertility, that reduce the efficiency with which the canopy converts radiation into carbohydrates. The modified, or 'utilisable' PAR ($APAR_u$) is multiplied by the canopy quantum efficiency (α_c) to give gross primary production (GPP). Net primary production (NPP) is taken to be a constant fraction of GPP (≈ 0.47), an assumption strongly supported by experimental data (see Waring et al. 1997). NPP is partitioned between roots, stems and leaves using a relationship which reflects the fact that the amount of carbon allocated to roots increases when growing conditions are poor, and equations based on the allometric relationships between stem size, stem mass and foliage mass.

While 3PG is not constrained by statistical relationships, parameter values and the constants and coefficients in various equations are empirically-based. The model now runs on a daily time step, can be run to any age, and produces monthly and/or annual values of stem number, stem diameter, stem mass, leaf area index (LAI). A complete description is given by Landsberg and Waring (1997) with modifications described in Sands and Landsberg (2002).

In 3PG, fixed carbon is allocated to foliage, stems, branches and roots using allometric relationships of biomass with tree diameter. Stemwood biomass (and volume) is calculated from stemwood carbon and stemwood volume from biomass and wood basic density. Monthly transpiration 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 soil water stress.

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) and Tickle et al. (2001) applied the model to large areas using remotely sensed spatial data or geographic information systems. Dye et al. (2004) used 3PG to predict growth and transpiration of *Eucalyptus* species in South Africa. Landsberg et al. (2000) 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 parameters for *E. cladocalyx* and *Corymbia maculata* plantations in lower rainfall regions of Australia.

2.2 3PG+ development

Developments to the original 3PG model, described in Morris and Baker (2002) and referred to as the 3PG+ model, include enhancements to the early stage radiation interception, mortality function, and salinity and drought responses. Notwithstanding the advances made in the development of the 3PG+ module, one of the shortcomings of the Landsberg and Waring (1997) model remained; the root zone water balance is calculated

on a monthly time step, and is 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 has recently been integrated into the Catchment Analysis Tool (CAT) framework (Beverly *et al*., 2005). The aim was to create a robust system for predicting the impacts of plantation or forest location, design and management on water balances of catchments. The integration of 3PG+ with PERFECT in CAT primarily required developments to provide a more dynamic representation of the root zone, as a multiple-layer soil with water balance calculated on a daily basis.

2.3   Model structure

The underlying principle of 3PG is the carbon balance approach (see Mäkelä et al., 2000) in which gross primary production is partly lost to respiration and the remainder allocated to different tree parts. 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 transpiration from monthly values for solar radiation, modified by other climate, soil and management factors. The model essentially comprises five submodels: (1) biomass production is predicted by environmental modification of radiation-use efficiency; (2) allocation of biomass between foliage, roots, stems and branches which are influenced by growing conditions and tree size; (3) tree density as determined using the self-thinning rule; (4) calculation of conventional stand growth parameters (e.g. basal area, volume) from stemwood biomass (e.g. basal area and stem volume from stemwood biomass); and (5) water balance where evapotranspiration is calculated using the Penman-Monteith equation. The basic structure of 3PG and the causal influences of its variables and processes are the same as presented by (Sands, 2004) and shown in Figure 2.1.

Biomass is produced via calculations of interception of radiation, gross primary product (GPP) from photosynthesis, estimation of net primary product (NPP) and is then allocated to above-ground and to below-ground (i.e. roots) tree components. Above-ground biomass is then allocated to foliage and to stems plus branches using allometric (power function) relationships of component biomass with tree diameter. Stem plus branch biomass is then divided among branches, stembark and stemwood using empirical relationships. Stemwood volume is calculated from stemwood biomass and wood basic density. Monthly transpiration is calculated using the Penman-Monteith equation with mean monthly canopy conductance affected by leaf area, vapour pressure deficit and soil water stress.

3PG requires monthly climate data (air temperature, vapour pressure deficit, solar radiation, rainfall, and frost days) either as long term averages or as actual or estimated values for the period of interest, site factors (latitude, soil texture, maximum available soil water storage, and soil fertility rating), initial conditions of biomass and stocking (planting density), and management inputs (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.

The 3PG+ module still runs on a monthly time step, as does 3PG. However, the water balance component runs on a daily time step. On the first day of each month, monthly growth in 3PG is calculated as usual. Values of leaf area index (LAI) and root biomass, are then used for daily calculations of light interception,

rainfall interception, transpiration, and water uptake. On each day, the modifiers, canopy conductance and daily transpiration are calculated.

More detailed descriptions of the submodules are provided in the remainder of this report.

2.4   Subroutine structure

This section still requires refinement of the suboutine structure. An updated version will be provided as soon as this is complete.

A more detailed description of each subroutine is provided in Appendix B, and this section provides a description of the order in which the subroutines are activated.

For each day:

- [NEW ROUTINE] Calculate initial root distribution. Initial soil water distribution is already known from initialisation or previous day's call to waterbalance.
- [NEW ROUTINE] For each layer calculate fulrootfrac(i) and soilwatA(i) taking root growth/decline into account.
- [NEW ROUTINE] Aggregate layer values for overall fulrootfrac and soilwatA, calculate ftheta
- If it's the first day of the month:

  - Calculate monthly growth (requires a call to monthly hydrocalcs and Penman for monthly transp to arrive at ftheta; the monthly transp estimate isn't accurate but could be saved for a later check against summed daily transp)
  - Update WF, WS and WR; calculate average daily root growth for the daily transp calculations below.
  - Standfacs
  - Monthly data output

- Get daily climate and modified daily 3PG parameters
- Canopycond
- Daily hydrocalcs/Penman for daily transp including gc correction as necessary. Note this is an overall profile calculation using ftheta derived from the aggregated soilwatA.
- [NEW ROUTINE] Allocate transp to layers
- Waterbalance
- Output daily data

Next day

Outlines of the four new routines that seem to make sense and should give a reasonably realistic depiction of the distribution of water removal from the root zone.

Structure of ThreePG.exe source code

Initialisation:

assignDefaultParameters

Set default values of all parameters and default monthly mean climate

readinfiles

readrunfile

Read $$3PGinp run control and site parameter file

If multi rotation mode:

getfallow

Read fallow file with inter-rotation parameters

getclimate

Read monthly climate data from specified file

aligncltable

Start climate table from selected planting month

getspecies

Read specified species parameter file

checkinputs

Report missing/out of range parameters etc

standinit

Set initial values of stand variables for this rotation

standfacs

Calculate current fertility, SLA, LAI, DBH, basal area, sapwood area, branch fraction, dominant height

diamdist

Calculate current diameter distribution parameters

For each year:

yearcalcs

Get 12 months climate data

For each month:

monthcalcs

calcMortality

6

calculate mortality this month

test for thinning trigger condition and apply type 1 or 2 thinning if appropriate

adjust for early growth before canopy is complete

allow for canopy light transmission

Calculate gc from modifier product, using daytime temperature

Calculate capillary rise into root zone, drainage, soil moisture, salinity, cumulative transpiration

calculate daylength from date and latitude

Calculate transpiration, correcting gc and ftheta if available soil water is insufficient

Apply simple product of modifiers to absPAR

Allow for fertility effect and respiration

get root allocation fraction

stemfac

get stem allocation fraction, allow for fertility effect

calculate leaf allocation as difference

litterfall

Calculate litterfall, allow for drought effect

updatebiomass

Calculate new stocking, biomass components, effective root zone moisture content

standfacs

Calculate current fertility, SLA, LAI, DBH, basal area, sapwood area, branch fraction, dominant height

diamdist

Calculate current diameter distribution parameters

monthlyoutput

Write monthly values of all variables to output file

If end of rotation (multi rotation mode):

harvest

Calculate end of rotation values of annual variables

annualoutput

Store end of year values in array for later print to file

If spatial mode:

gridoutput

Write end of year values of selected variables to grid file

Initialise fallow period conditions

Next month

Calculate annual variables (volume, CAI, MAI, transpiration efficiency)

annualoutput

Store end of year values in array for later print to file

If spatial mode:

gridoutput

Write end of year values of selected variables to grid file

If a new rotation (multi rotation mode):

standinit

Re-initialise stand variables

Next year

chartem

Display chart of CAI and MAI vs time

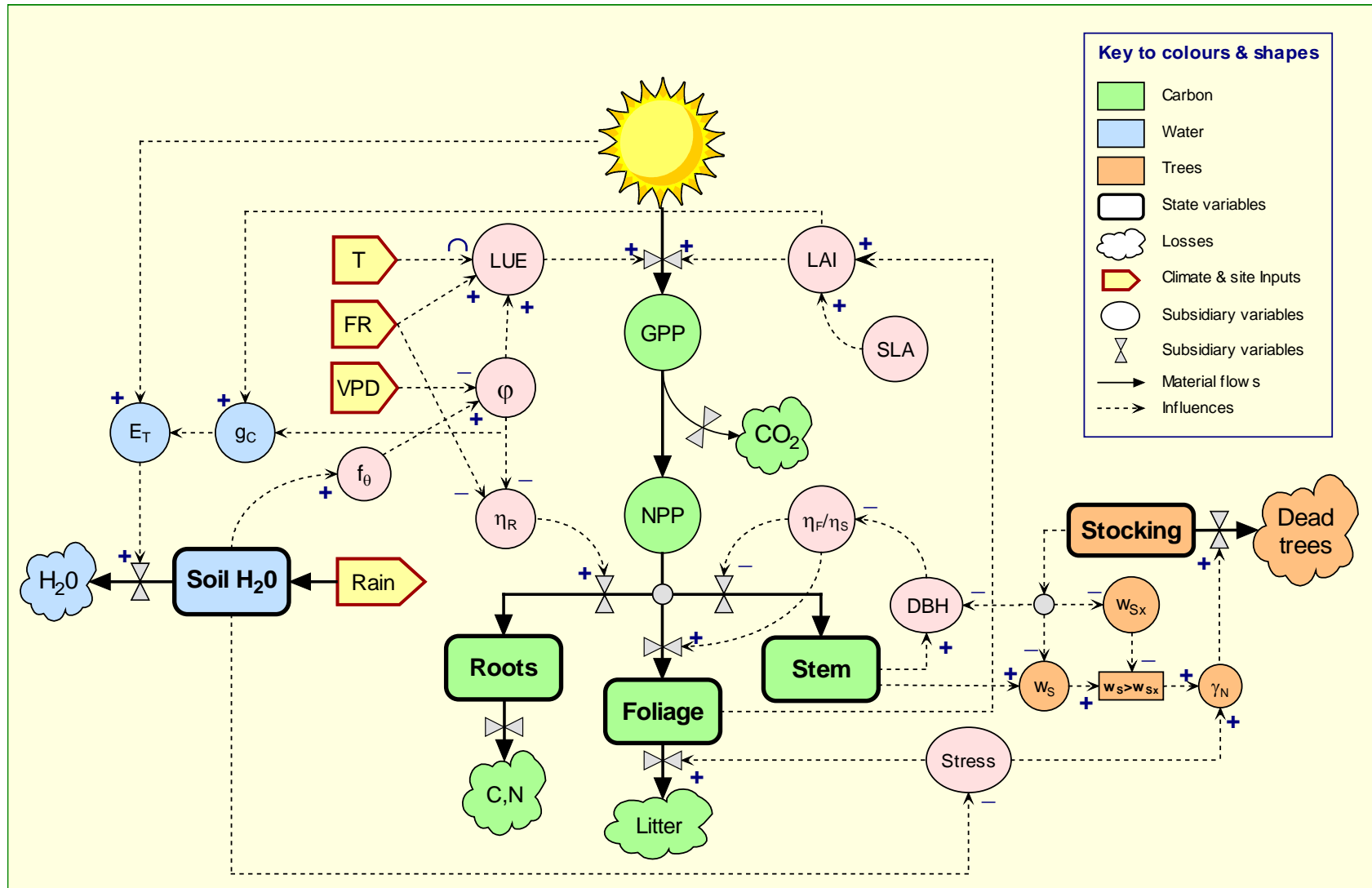Print annual outputs to file

End

Figure 2.1. Basic structure of 3PG and the causal influences of its variables and processes (Sands, 2004). Symbols are not always comparable to 3PG+.

3. Biomass production and allocation

Radiation intercepted by the canopy is determined from total incoming solar radiation and LAI through Beer's law. Gross primary production (GPP) is proportional to intercepted photosynthetically active radiation. The proportionality factor, called canopy quantum efficiency, takes into account environmental effects through multiplicative modifiers based on atmospheric VPD, available soil water, mean air temperature, frost days per month, site nutrition, and stand age.

3.1 Radiation interception

Incoming solar radiation is modified to account for position in the landscape. Radiation read in from the input climate file is modified by a radiation coefficient based on calculating the radiation incident to a plane of given slope and aspect at a given latitude on a given day. The slope, aspect and latitude are all read from the input data files. Calculations are in **subroutine calcrcoef**.

As in the original 3PG (Landsberg and Waring, 1997), photosynthetically active radiation (ϕ_p) is assumed to be 0.5 of incoming solar radiation. The amount of ϕ_p that is absorbed (ϕ_{pa}) is calculated by Beer's law by

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

where k_φ is the species specific extinction coefficient, which depends on the angle of inclination of leaves (θ) and can be approximated by

$$k_\phi \approx \cos MTA \tag{2}$$

where *MTA* is the mean tilt angle of leaves relative to horizontal, in radians. Photosynthetically active radiation (ϕ_p; abspar) calculated in the source code in **subroutine absorbedpar**.

```
abspar(itr3pg) = par * (1 - exp(-kphi(itr3pg) * lai3pg(itr3pg)))
```

As in the original 3PG (Landsberg and Waring, 1997), utilisable absorbed photosynthetically active radiation (ϕ_{pau}) is calculated in 3PG+ as the product of absorbed photosynthetically active radiation (ϕ_{pa}) and a series of modifiers, each of which takes a value between 0 and 1:

$$\phi_{pau} = \phi_{pa} \min\left(f_\theta, f_{VPD}\right) f_{age} \ f_{temp} \ f_{frost} \ f_{salt} \tag{3}$$

where f_θ is a function of soil water availability; f_{VPD} is a function of species stomatal response to daytime vapour pressure deficit (VPD); f_{age} is a function of tree age; f_{temp} is a function of species optimum, minimum and maximum temperatures for growth; f_{frost} is a function of monthly climate; and f_{salt}, which is an additional modifier in 3PG+ that provides for the effects of root-zone salt on tree growth, and is a function of species salinity tolerance. 3PG+ uses the temperature modifier (f_{temp}) described by Sands and Landsberg (2002), which takes into account the effects of temperature on canopy quantum efficiency.

This function is in the source code under **subroutine utilisablepar** as

```
phipau(itr3pg)  =  abspar(itr3pg)  *  ffrost  *  fage(itr3pg)  *
ftemp(itr3pg) * fsalt(itr3pg) * min(fd(itr3pg), ftheta(itr3pg))
```

The soil water (f_{soil}) and vapour pressure deficit (f_{VPD}) modifiers are not multiplicative relative to each other. 3PG uses the lower value of these, on the assumption that if stomata are closed by VPD, limiting transpiration rate (and CO_2 uptake) so that the rate of water movement to the roots is fast enough to maintain the transpiration rate even in relatively dry soil, then soil water content is not a limiting factor. The reverse holds: if water cannot move to roots fast enough to meet transpiration demand then g_c must be reduced to a value appropriate to the supply rate, even if that is below that determined by VPD, otherwise the trees would become desiccated. In this case soil water is the limiting factor, and not canopy conductance.

Landsberg and Waring (1997) recognised, but did not address, that modelling young stands requires attention to the absorption of radiation by unclosed canopies. At low values of LAI prior to canopy closure, the assumption that the leaf area of a stand is evenly spread across the ground area leads to overestimation of absorbed radiation. In 3PG+ two species-specific coefficients, ($early_{co}$ and $early_{exp}$), limit early growth in stands with unclosed canopies by limiting incident photosynthetically active radiation (ϕ_p) to ϕ_{early}

$$\phi_{early} = \frac{\phi_p}{\left(1 + early_{co}\ e^{\left(-early_{exp}\ LAI\right)}\right)} \qquad \text{when} \qquad \left\{early_{co}\ e^{\left(-early_{exp}\ LAI\right)}\right\} > 0.1 \qquad (4)$$

This limitation on absorbed radiation is distinct from that of leaf area index and the extinction coefficient (k_ϕ) in Beer's law. An example of the effect of implementing this function on radiation interception by *E. grandis* is shown in Figure 3.1.

Figure 3.1. Effect of early growth reduction parameters on radiation interception by *E. grandis* canopy ($early_{co} = 2$, $early_{exp} = 1.2$, $k_\phi = 0.45$).

This modification is located in the source code under **subroutine getpar** as

```
par = 0.5 * csolarrad(monno)

val = earlyco(itr3pg) * exp(-earlyexp(itr3pg) * lai3pg(itr3pg))

if(val.lt.0.1) earlypar = .false.
adjust for early growth before canopy complete

if(earlypar) then par = par / (1.0 + val)
```

3.2   Growth modifiers

3.2.1   Soil modifier

The soil water balance is obtained as the difference between daily transpiration (mm), calculated using the Penman-Monteith equation, and daily precipitation. The water available to trees is dependent on the water holding characteristics of the soil and the rooting depth of the trees. The moisture ratio for the stand is calculated as

$$r_\theta = \frac{\text{current soil water content} + \text{water balance}}{\text{available water}} \tag{5}$$

The water balance is negative if transpiration exceeds precipitation, and vice versa. If the numerator of this expression exceeds the maximum available water (θ_{max}), it is set to θ_{max}, i.e. the excess water is assumed to have run off or drained out of the system. If it is negative, $r_\theta = 0$. Total available water is calculated by intrinsic water holding capacity of the specific soil texture, the thickness of the soil layer, and the total depth of the soil profile available to roots. The effect of water on tree growth is defines by the soil water modifier (f_θ) by

$$f_\theta = \frac{1}{\left(1 + \left[(1 - r_\theta)/c_\theta\right]^{n_\theta}\right)} \tag{6}$$

where c_θ and the power n_θ take different values for different soil types depending on their clay content. Landsberg and Waring (1997) suggested values for four different soil types, and 3PG+ now incorporates values for 10 texture classes as listed in Table 3.1 and the relationship between f_θ and r_θ for the 10 texture classes is shown in Figure 3.2.

Table 3.1. Values for 10 different texture classes given by Ward *et al.* (2000) with approximate percentage clay.

Soil texture class	% clay (approx.)	c_θ	n_θ
Sand	3	0.75	10
Loamy Sand	7	0.7	9
Sandy loam	10	0.65	8
Loam	18	0.6	7
Silt loam	18	0.55	6
Silty clay loam	35	0.5	5
Clay loam	35	0.45	4
Sandy clay	40	0.4	3
Silty clay	50	0.35	2
Clay	65	0.3	1

Figure 3.2. Relationship between the soil water modifier (f_θ) and the soil moisture ratio (r_θ) for the 10 texture classes in Ward *et al.* (2000).

The curves in Figure 3.2 resemble those for relative transpiration rate vs. volumetric water content published by Denmead and Shaw (1961). The curve shift from sand to clay, causing f_θ to fall earlier in clay, but not as rapidly as in the sand, reflects the differences in the hydraulic characteristics of soils with different proportions of clay. At a given soil water content the water potential of clay, soils is significantly lower than in sandy soils. It should be noted that values of *c* and *n* are chosen without specific empirical justification. If appropriate experimental results become available, these values may need to be altered.

Detail of how values for c_θ and n_θ are assigned to the whole profile, and how water available to trees is estimated, is provided in Section 7.

The calculations for r_θ are in **subroutine theta3pg** as

```
rtheta(itr3pg) = soilwata / thetamax
```

and f_θ is calculated in **subroutine soilwatermod** as

```
ftheta(itr3pg) = 1.0 / (1.0 + ((1.0 - rtheta(itr3pg)) / ctheta) **
ntheta)
```

3.2.2 VPD modifier

The effects of vapour pressure deificit (VPD) on ϕ_{pau} in Eq (4) and on g_c in Eq (46) are implemented by a VPD modifier (f_{VPD}) described by

$$f_{VPD} = e^{\left(-k_g . D\right)} \tag{7}$$

where k_g is a coefficient (species parameter) based on well-established relationships between stomatal conductance and vapour pressure deficit (D) (see, for example, Dye and Olbrich, 1993; Leuning, 1995; Granier et al., 1996). Relationships between f_{VPD} and D for *E. globulus* and *P. radiata* are shown in Figure 3.3.

Figure 3.3. Example of the VPD modifier for *E. globulus* (k_g =0.45) and *P. radiata* (k_g =0.5).

The calculation for f_{VPD} is in **subroutine vpdmod** as

```
fd(itr3pg) = exp(-kg(itr3pg) * cvpd(monno))
```

3.2.3 Age modifier

As a forest ages, its above-ground net primary production and maximum stomatal conductance decreases. The age modifier (f_{age}), is given by an equation that mimics the changes in (normalised) above-ground wood production shown by data collated by Ryan et al. (1996).

$$f_{age} = \frac{1}{1 + \left(age / \left(0.95.age_{max} \right) \right)^{n_{age}}}$$
(8)

where the constant (age_{max}), the maximum stand age to calculate relative age, and power (n_{age}) are species parameters and *age* is tree age in years.

Either of these parameter values can be varied as seems appropriate by users. The expression is not sensitive to the maximum age specified for a forest, although it will clearly cause large differences in growth rates of stands that are, say, 20 years old, if the maximum age is specified as 80 years, as may be the case for some plantations in sub-tropical areas, or 300 years, which would be a normal age for a mature forest in many parts of the world.

Regardless of growing conditions, Eq (8) results in patterns of biomass production that decrease at rates comparable to the reported decrease in above-ground production published in forestry yield tables appropriate for a given region.

Figure 3.4. Example of the age modifier for *E. globulus* and *P. radiata*.

The age modifier can be located in the source code under **subroutine agemod** as

```
fage(itr3pg) = 1.0 / (1.0 + (ageyrs / (0.95 * maxage(itr3pg))) **
nage(itr3pg))
```

3.2.4 Temperature modifier

The initial version of 3PG did not include the effect of temperature canopy quantum efficiency (α_c). However, it is known that photosynthetic rate in *E. globulus* declines with declining ambient temperature below an optimum of about 20^oC (Battaglia et al., 1996; Sands, 1996). In an application of 3PG, Sands and Landsberg (2002) presented a clear relationship when the best-fit values of α_c for a range of sites were plotted against annual mean temperature. Those results suggested α_c is related to monthly mean temperature, so Sands and Landsberg (2002) introduced an additional environmental modifier to take into account effects of temperature on quantum efficiency. The temperature modifier $f_t(T_a)$ has been included in 3PG+ and is defined as

$$f_T(T_a) = \left(\frac{T_a - T_{\min}}{T_{opt} - T_{\min}} \right) \left(\frac{T_{\max} - T_a}{T_{\max} - T_{opt}} \right)^{(T_{\max} - T_{opt})/(T_{opt} - T_{\min})} \qquad \text{where } f_T \geq 0 \qquad (9)$$

and $f_T(T_a) = 0$ if $T_a > T_{\max}$ or $T_a < T_{\min}$

The parameters $T_{\min}$, T_{opt} and $T_{\max}$ are minimum, optimum, and maximum, or cardinal, temperatures for net photosynthetic production. Initial values for *E. globulus* were set at $T_{\min} = 8.5^o$C, $T_{opt} = 16^o$C and $T_{\max} = 40^o$C because *E. globulus* does not grow under high temperatures, but its value affects $f_t(T_a)$ at all T_a, not just at high temperatures. Note that monthly temperatures span a range on both sides of T_{opt}. The relationships of $f_t(T_a)$ (or **ftemp**) with temperature as presently parameterised for several species are shown in Figure 3.5. The temperature modifier can be located in the source code under **subroutine tempmod**.

Figure 3.5. Example of the temperature modifier for *E. globulus*, *P. radiata, E. grandis* and *E. nitens*.

The calculation for $f_t(T_a)$ is in **subroutine tempmod** as

```
ftemp(itr3pg)  =  ((ctav(monno)  -  tminpar(itr3pg))  /  (toptpar(itr3pg)  -
tminpar(itr3pg)))  *  ((tmaxpar(itr3pg)  -  ctav(monno))  /  (tmaxpar(itr3pg)  -
toptpar(itr3pg)))  **  ((tmaxpar(itr3pg)  -  toptpar(itr3pg))  /  (toptpar(itr3pg)
- tminpar(itr3pg)))
```

3.2.5   Frost modifier

The present version of 3PG+ accounts for the occurrence of frosts by assuming there is no photosynthesis on any day that temperatures fall below zero. This can easily be altered, on the basis of appropriate empirical evidence, to more than one day. The frost modifier (f_{frost}) is given by

$$f_{frost} = 1 - \frac{\text{frost days in month}}{\text{total days in month}} \tag{10}$$

and because the number of frost days per month is not readily supplied in climate data and is related to the minimum daily temperature, 3PG+ calculates the number of frost days by

$$\text{frost days in month} = 15 - 3 \times T_{min} \tag{11}$$

where T_{min} is the daily minimum temperature. The frost modifier is located in the source code under **subroutine frostmod** as

```
ffrost = 1.0 - float(cfrostdays(monno)) / daysinmon(month)
```

3.2.6   Biomass conversion (radiation conversion efficiency)

Gross primary production (*GPP*; pgross) is calculated by multiplying ϕ_{pau} (phipau) by the canopy quantum efficiency coefficient (α_c) in the **subroutine netpsyn**. Note that α_c converts MJ m^{-2} to g c m^{-2}.

$$GPP = \phi_{pau} \times (\alpha_c + ff \times F_t) \tag{12}$$

```
pgross(itr3pg) = phipau(itr3pg) * (alphac(itr3pg) + fertfac(itr3pg) *
mnfert)
```

where fertfac is factor (species parameter) for the effect of soil fertility (mnfert, the fertility rating) on ϕ_{pau} for the calculation of *GPP*.

Net primary production (*NPP*; pnet) is then calculated by

$$NPP = GPP \times 0.47 \tag{13}$$

```
pnet(itr3pg) = pgross(itr3pg) * cpp(itr3pg)
```

where cpp is a constant fraction (~0.47) of *GPP* which is assumed to be lost in respiration to give *NPP* (Waring et al. 1998).

Carbon allocation is calculated monthly, and LAI for one month is derived using the foliage mass at the end of the previous month. 3PG initially used a 'universal' canopy quantum efficiency coefficient (α_c; `alphac`) with a value of 1.8 g C MJ^{-1} but this is now species specific. Several studies have shown that α_c has a value for forests near 1.8 g C MJ^{-1} (or 0.03 mol C (mol photon)$^{-1}$) and does not vary widely about that value. However, on severely nutrient deficient soils, α_c will decrease below the maximum.

3.3 Biomass allocation

Carbon derived from leaf photosynthesis is transported to different parts of trees, where they are used for respiration and as structural material. The mechanisms determining the amount of carbon allocated to any part of a tree are not well understood. In models aimed at simulating the growth of real forests, as opposed to exploring the mechanisms that influence growth patterns, carbon allocation is some times estimated using allocation coefficients (η_i) derived from allometric equations that relate the observed mass or size of different plant parts (see, e.g. McMurtrie; Landsberg, 1992).

3.3.1 Belowground allocation

The first step in carbon allocation is to define that which is above ground (stem, branches, leaves) and that which it below ground (roots). Two important generalisations have emerged from analyses of carbon allocation in trees: i) there is a strong inverse relationship between stem growth and the fraction of NPP allocated below ground (Beets and Whitehead, 1996), and ii) as environmental conditions become harsher, the fraction of NPP allocated annually to fine root growth increases from about 25% to nearly 60% (Santantonio, 1989; Runyon et al. 1994; Beets and Whitehead, 1996). In 3PG+, the environmental modifiers provide a measure of the 'harshness' of the environment, and so under zero-stress conditions, the modifiers, f_{soil}, f_{temp} and f_{frost} are equal to one, and so $\phi_{pau} = \phi_{pa}$. Operationally, it is possible to define the harshness of the environment in terms of the ratio of ϕ_{pau} to ϕ_{pa} i.e. the smaller the proportion of radiation absorbed by foliage that could be utilised, the more the harsh the environment. The allocation coefficient for roots (η_r) that defines the allocation of NPP to roots is determined by

$$\eta_r = \frac{rootco1}{1 + rootco2 * F_t * \left(\phi_{pau.}/\phi_{pa}\right)} \tag{14}$$

where *rootco1* and *rootco2* are species specific coefficients. Relationships using values of 0.6 and 8 for *rootco1* and *rootco2* respectively (for *E. globulus*) and different levels of nutrition (fertility rating, F_t) are shown in Figure 3.6.

Figure 3.6. Variation of the fraction of NPP (carbon) allocation to roots (η_r) with decreasing site harshness (represented by higher ϕ_{pau}/ϕ_{pa}) and nutritional status (fertility rating; F_t).

The allocation to roots is calculated in **subroutine rootfac** by

```
netar(itr3pg) = rootco1(itr3pg) / (1.0 + rootco2(itr3pg) * mnfert *
phipau(itr3pg) / abspar(itr3pg))
```

3.3.2 Aboveground allocation

Once belowground carbon has been allocated, aboveground carbon is partitioned between stems and foliage. Allometric relationships for single trees can, almost invariably, be described by equations of the form

$$w_i = a_i w^{n_i} \tag{15}$$

where w is the total mass of the plant and i denotes any component part. It is reasonable to assume that the parameter values (particularly n_i) reflect the genetic characteristics of species. There are many examples in the literature of improved descriptions of data by fitting equations of other forms, but almost all data sets can be described, with high statistical r^2 values by Eq (15), which is a very tractable and useful form. Foresters generally use stem diameter at 1.3m height D_{OB} (diameter over bark) as a measure of stem size, and this can be used as a surrogate for w so that

$$w_s = a_s D_{OB}{}^{n_s} \tag{16}$$

where w_s is the stem mass (i.e. stem + branch + bark; kg). The ratio of the stem and leaf allocation coefficients (applicable to NPP) can be obtained from Eq (15) with numerical values of a_i and n_i appropriate to each tree component of the tree(s) and species of interest to give

$$p_{f.s} = \frac{dw_f / dD_{OB}}{dw_s / dD_{OB}} \tag{17}$$

where $p_{f.s}$ is the ratio of the growth rates of foliage (f) and stems (s) in terms of their relation to D_{OB}.
Given that $\eta_s + \eta_f + \eta_r = 1$ and that η_r is calculated by Eq.(14), then η_s and η_f can be derived by

$$\eta_s = \frac{(1 - \eta_r)}{(1 + p_{f.s})} \quad \text{and} \quad \eta_f = 1 - \eta_s - \eta_r \tag{18}$$

Operationally, in 3PG, average stem mass is calculated from total (stand) stem mass and stem number. Eq.(15) is inverted and solved for D_{OB} to provide the value for use in Eq. (17). Foliage and stem mass are never calculated directly from Eq. (15). This procedure has proved remarkably stable. If *NPP* is reduced by poor or harsh growing conditions, η_r is increased (see Eq. (14) and stem and foliage growth are reduced in a way that conserves the allometric balance of trees.

Stem biomass (kg m^{-2}) at time (t) is calculated in 3PG+ in the **subroutine updtbioms** by

$$W_{s(t)} = W_{s(t-1)} - stemloss + \eta_s (NPP - ma\,\text{int}\,resp) \times \frac{2.2}{1000} - mortality \times w_s \times \frac{20.4}{10000} \tag{19}$$

where *stemloss* is the weight of stems removed through thinning (if any), *maintresp* is maintenance respiration (currently not used; i.e. =0), *mortality* represents the monthly stem deaths to keep stocking below self thinning rule. The constant 2.2 (derived from drymass which is ~45% carbon) converts carbon to biomass (**ctobiomass**), 20.4 represents the fraction of mean stem biomass lost when a tree dies (**mortfac=dyingfrac**).

```
wswood = wswood(itr3pg) - stemloss(itr3pg) + netas(itr3pg) *
(pnet(itr3pg) - maintresp(itr3pg)) * ctobiomass(itr3pg) / 1000 -
(mortality(itr3pg) * meanstemkg(itr3pg) * dyingfrac(itr3pg)) / 10000
```

$$W_{f(t)} = W_{f(t-1)} - folloss + \eta_f (NPP - ma\,\text{int}\,resp) \times \frac{2.2}{1000} - litter \tag{20}$$

where folloss is the weight of foliage removed by thinning (if any), and *litter* is the weight of litterfall per month.

```
wfwood(itr3pg) = wfwood(itr3pg) - folloss(itr3pg) + netaf(itr3pg) *
(pnet(itr3pg) - maintresp(itr3pg)) * ctobiomass(itr3pg) / 1000.0 -
litter(itr3pg)
```

3.4   Litterfall

Litterfall is an important process in plantations and forests and the rate of litterfall tends to be in the order of 25% per year. Landsberg and Waring (1997) calculated litterfall as a proportion of foliage mass and as a function of age for young stands that increases asymptotically to the maximum 'standard' litterfall rate from near zero at 1 year to the maximum at about 5 years by

$$\gamma_f = \frac{\gamma_{f\,max}}{1 + c_\gamma . e^{(-k_\gamma t)}} \tag{21}$$

where γ_f is the foliage litterfall rate per month c_γ is an empirical constant, k_γ is an empirical coefficient, $\gamma_{f\,max}$ is the maximum (or constant) monthly litterfall rate, and t is time in months. An example of this function with current parameterisations for several species is shown in Figure 3.7.

While Landsberg and Waring (1997) noted that this appears to work well, experimental results show that litterfall is better represented as a variable function of water availability (e.g. Pook, 1986). In 3PG+, drought increases the rate of leaf senescence and litterfall, which also depends on the drought tolerance of a particular species. When the soil water modifier (f_θ) falls below a critical species-specific value (l_{thresh}), then the litterfall fraction per month (γ_f) is calculated by

$$\gamma_{f(drought)} = \gamma_f + (0.5 - \gamma_f)\frac{(l_{thresh} - f_\theta)}{l_{thresh}} \tag{22}$$

The maximum leaf fall in response to drought is set to 0.5 by default, and sets an upper limit to the increase in monthly litterfall induced in drying soil when f_θ falls below the threshold value (l_{thresh}). The value of l_{thresh} is defined in the species parameter file, and allows differentiation between drought tolerant and intolerant species. Setting l_{thresh} to 0 disables this function. Example of the change in litterfall in response to different levels of l_{thresh} can be seen in Figure 3.8. The litterfall subroutines can be found in the source code under **subroutine litterfall**. where γ_f is calculated by

```
gammaf(itr3pg) = gammafmax(itr3pg) / (1 + cgamma(itr3pg) * exp(-
kgamma(itr3pg) * ageyrs))
```

and `litter` (the weight of litterfall per month) is calculated by

```
litter(itr3pg) = gammaf(itr3pg) * wfwood(itr3pg)
```

Examples of the effect of changes in the three litterfall parameters in Eq (21) on the simulated LAI and stand volume are provided in Figure 3.9, Figure 3.10 and Figure 3.11. While the predictions of LAI are quite sensitive to changes in the three litterfall parameters, the predictions in stand volume are less sensitive in the first 10 years. The changes in predicted volume become greater as the simulation progresses, and so care should be taken when assigning new parameters, particularly when simulations run beyond 15 years since planting.

Figure 3.7. Functions of γ_f (`gammaf`) with age for current parameristations for different species.

Figure 3.8. Functions of γ_f (`gammaf`) for different values of l_{thresh} (with $\gamma_{f\,max} = 0.05$).

Figure 3.9. Effect of different values of $\gamma_{f\max}$ (`gammafmax`) between 0.4 and 1.0 on a) LAI and b) volume predictions of *E. globulus*.

Figure 3.10. Effect of different values of c_γ (cgamma) between 4 and 10 on a) LAI and b) volume predictions of *E. globulus*.

Figure 3.11. Effect of different values of k_γ (kgamma) between 1.0 and 2.5 on a) LAI and b) volume predictions of *E. globulus*.

3.5 Branch fraction

In 3PG, the proportion of stem mass (defined as stemwood plus stembark plus branch mass) that is not stemwood and therefore not (conventionally) potential wood yield was termed 'branch fraction' (*BF*), and was either constant or calculated as a linear decline with stand age (see Sands and Landsberg (2002). In 3PG+, an exponential decline with age, together with an adjustment for effects of tree density, is provided to better match trends in observed biomass component data

$$BF = BF_{init} - \left(BF_{init} - BF_{adj}\right)\left(1 - e^{BF_{dec} \cdot age}\right) \tag{23}$$

where BF_{init} is the initial branch fraction, BF_{dec}, is an exponential decline factor, *age* is stand age (years), and BF_{adj} is the value of BF_{final} (the final branch fraction for older stands) adjusted for N (the current tree density; trees ha^{-1}) given by

$$BF_{adj} = 0.1 + \left(BF_{init} - 0.08\right)e^{\left(N/z_{fac}\right)} \tag{24}$$

where

$$z_{fac} = \frac{1500}{\log\left[\dfrac{\left(BF_{final} - 0.12\right)}{\left(BF_{init} - 0.12\right)}\right]} \tag{25}$$

The BF (branch and bark fraction; `bfrac`) stocking response factor, z_{fac} (`zfac`) contains defaults 1500 and 0.12 which are used in an empirical estimate of the effect of tree stocking on the branching habit of trees. Trees at wide spacing usually develop larger and longer branches than closely spaced trees. The species parameter file specifies an initial and final value for `bfrac` (`initbf` and `finbf`), and a parameter `bfdec` which determines how quickly `bfrac` declines from the initial to the final value. To introduce a response to stocking, we assume that the value given for `finbf` is relevant to a stocking of 1500 trees ha^{-1} (the first default factor) and that the smallest believable value of `finbf` at very close tree spacing is 0.12 (the second default factor). The branch and bark fraction; `bfrac`, is calculated in subroutine `standfacs` via calculations of `zfac` and `adjbf` in the following functions

```
zfac = 1500 / log((finbf(itr3pg) - 0.12) / (initbf(itr3pg) - 0.12))

adjbf = 0.1 + (initbf(itr3pg) - 0.08) * exp(stocking(itr3pg) / zfac)

bfrac(itr3pg) = initbf(itr3pg) - (initbf(itr3pg) - adjbf) * (1 -
exp(bfdec(itr3pg) * ageyrs))
```

3.6 Specific leaf area

For a model such as 3PG which calculates growth on the basis of intercepted radiation, the relation between leaf area and foliage mass is of central importance. In 3PG specific leaf area (*SLA*; kg m^{-2}) was initially specified as a fixed value, although known to generally decrease with age from planting over the first few years (Landsberg and Gower, 1997) and markedly so where foliage morphology changes (e.g. Medhurst et al., 1999). In 3PG+, *SLA* declines between specified initial (SLA_{init}) and final values (SLA_{final}) according to an exponential decline factor (SLA_{dec}) in:

$$SLA = SLA_{init} - \left(SLA_{init} - SLA_{final}\right) * \left(1 - e^{SLA_{dec}\,age}\right) \tag{26}$$

Values of SLA_{dec} of -0.6 and -0.3 result in *SLA* approaching SLA_{final} after about 5 and 10 years respectively.

Specific leaf area (`sla3pg`) is calculated in subroutine `standfacs` by

```
sla3pg(itr3pg) = initsla(itr3pg) - (initsla(itr3pg) - finsla(itr3pg))
* (1 - exp(sladec(itr3pg) * ageyrs))
```

Leaf area index (LAI) is then calculated by

$$LAI = SLA \times w_f \tag{27}$$

where w_f is the foliage mass (kg m^{-2}; see section 3.3.2).

```
lai3pg(itr3pg) = sla3pg(itr3pg) * wfwood(itr3pg)
```

Both SLA and LAI are calculated within the **subroutine standfacs**.

3.7 Root distribution and density function

A selection of four different root distribution and root density functions are available to describe the proportion of root biomass within each soil layer, and subsequently used to calculate plant available water and water uptake in the root zone. The four root distribution functions available are

- generic root penetration and root density equation ($K_{R3}=0$)
- the Ritchie root distribution function ($K_{R3}=1$)
- an exponential decay function based on Gale and Grigal (1987) ($K_{R3}=2$).
- depth weighted distribution function ($K_{R3}=3$)

and are schematically shown in Figure 3.12. The root depth and percent soil profile occupied by roots calculated by 3PG+ is used to weight the functions describing the root distribution architecture shown in Figure 3.12. The root distribution is then used to allocate transpiration demand through the soil profile. The generic function ($K_{R3}=0$) for `dfac` is currently set as the default in the **subroutine rootf**.

Figure 3.12. The four available root distribution functions.

3.8 Stem mortality and self thinning

Competition-induced tree mortality in 3PG is predicted according to the –3/2 power self thinning law (a theoretical function/'curve' describing an upper limit of tree density) using mean stem mass as a measure of tree size. The model requires stem density (or numbers) because the allometric equations (see section 3.3.2) used to allocate carbon to tree parts are invariably determined for single trees. Furthermore, forest managers are generally interested in stem growth rates and final stem volumes. 3PG utilises the (virtually universal) relationship between stem populations and maximum achievable individual stem mass to calculate changes in stem populations (p) by

$$w_{s\,max}k_{s}\,p^{-3/2} \tag{28}$$

where k_{s} is a species specific coefficient. Landsberg and Waring (1997) suggested this can be obtained either from empirical data, the average mass of individual stems in stands near the end of their life cycle, or a value can be obtained from 3PG by running the model through an appropriate rotation length with low stocking 100-150 trees ha^{-1} with the mortality function 'switched off', to estimate maximum achievable stem mass for the environmental conditions and allometric ratios used in the simulation.

Eq (28) is also known as the self thinning rule that describes plant mortality due to competition in even-aged stands (where all trees are of the same age) and is shown graphically in Figure 3.13. If mean stem mass (w_s) is less than $w_{s\,max}$ (point 1), the population remains unchanged. If $w_s > w_{s\,max}$ (point 2), p is reduced by the number necessary to conform to the relationship.

Figure 3.13. Diagrammatic representation of the stem population submodel (or self thinning rule) (Landsberg and Waring,1997)

In 3PG, initial stem mass is provided as an input, and from the end of year 1, predicted mean stem mass (w_s) is tested against $w_{s\,max}$ for the current population. If $w_s > w_{s\,max}$ then Eq (28) is solved for p, and stem numbers are reduced by Δp (i.e. stem mortality) so that $w_s \leq w_{s\,max}$. By the end of the following year, mean stem mass will have increased and the procedure is repeated. It has the disadvantage that stem numbers fluctuate above the $w_{s\,max}/p$ line, instead of below it (see Landsberg, 1986).

However, in plantations typically established at planting densities around 1000 trees ha^{-1}, the self thinning rule Eq (28) does not predict any early mortality (although typically some occurs), and then simulates a

sharp increase in mortality once stem mass reaches the limiting curve (see Sands and Landsberg, 2002). Plantation growth data (e.g. Wang and Baker, 2007) indicate that tree density approaches the curve gradually, and at a rate dependent on initial density. Therefore, mortality in 3PG+ has been modelled by combining the -3/2 power function with a parabolic function (with intercept set by the planting density, and the parameter set so as the function touches the power function) to describe the upper limit of tree density as a function of mean stem mass. The relationships have been rewritten in terms of tree density rather than average stem mass as in previous versions of 3PG, thereby avoiding the need for iterative application of the self thinning rule to ensure it is satisfied.

The parabolic function describing the maximum tree density for dense young plantations (N_{early}) is

$$N_{early} = N_0 + \beta_{early} \times w_s^2 \times \frac{\left(N_0 / 1000\right)^{3.5}}{100} \tag{29}$$

where N_0 is the tree density a planting (trees ha^{-1}), β_{early} is the mortality function factor for the initial parabolic phase, and w_s is the mean stem mass (kg). The power function defining the maximum tree density for mature stands (N_{mature}) is

$$N_{mature} = \beta_{mature} \times N_0^{0.56} \times w_s^{\left(-1/n_N\right)} \tag{30}$$

where β_{mature} is the mortality function factor, and n_N is a power parameter, for the -3/2 function phase.

N_{early} is used from the start of the simulation, and N_{mature} is invoked at the point when $N_{early} > \left(N_{mature} - 1\right)$ or $N_{early} \leq 0$. Mortality is then calculated as the difference between the current tree density (N_t) when it exceeds the respective value for the maximum tree density (N_{early} or N_{mature}). The mass of the stems that die must be discarded from standing biomass. Stem mortality largely occurs among the smaller stems in a population so in 3PG and in 3PG+, Δp is divided by 3 and stem mass loss is calculated as

$$\left(\Delta p/3\right) \times w_s \left(1/3 + 1/6 + 1/9\right) \tag{31}$$

which numerically relates to approximately 20.4% of the biomass of the average stem and is specified by the species parameter, **mortfac**. Leaf mass is not reduced, on the assumption that dying stems would have few leaves, and that the stand foliage mass is distributed among the living stems. The calculations for stem mortality can be found under **subroutine calcmortality** in the source code where N_{early} is given by

```
stempara(itr3pg) = stockinit(itr3pg) + afact(itr3pg) *
meanstemkg(itr3pg) ** 2 * ((stockinit(itr3pg) / 1000.0) ** 3.5) /
100.0
```

and N_{mature} is given as

```
stem32(itr3pg) = (p32fac(itr3pg) * stockinit(itr3pg) ** 0.56) *
meanstemkg(itr3pg) ** (-1.0 / thinpower(itr3pg))
```

Figure 3.14. Predicting maximum tree density for mortality calculations based on mean individual stem mass. Parabolic approach (N_{early}; dashed lines) to a -3/2 law curve (N_{mature}; solid lines) in mature stands. Examples are for two different planting densities of $N_0 = 1000$ and $N_0 = 2000$ trees ha^{-1} with current parameters for *E. globulus*.

3.9 Stand characteristics

Stand level characteristics of importance, such as stem volume, diameter at 1.3m (*DBH*), basal area (*BA*), and mean annual increment (*MAI*) are calculated from the biomass pools and tree density. The branch-and bark-fraction are explicitly age and density related. Stand-level variables such as stem diameter *DBH* (cm), basal area *BA* (m^2 ha^{-1}), height *H* (m), and stem volume V_S (m^3 ha^{-1}) can be predicted in 3PG from predicted stem mass and stocking using simple empirical relationships.

3.9.1 DBH (diameter over bark)

To calculate diameter over bark at 1.3 m above the ground (*DBH*; dbh), the mean stem weight (w_s; `meanstemkg`) is first calculated by

$$w_s = W_s \times \frac{10000}{N} \tag{32}$$

where W_s is the total stem biomass (kg m^{-2}) and N is the tree density, and then

$$DBH = \left(\frac{w_s}{a_s}\right)^{\left(\frac{1}{n_s}\right)} \tag{33}$$

where a_s and n_s are species parameter representing allometric stem coefficients.

These calculations occur in the `subroutine standfacs` as

```
meanstemkg(itr3pg) = wswood(itr3pg) * 10000.0 / stocking(itr3pg)

dbh(itr3pg) = (meanstemkg(itr3pg) / asfac(itr3pg)) ** (1 /
nsfac(itr3pg))
```

3.9.2 Volume

Total stand volume (V_s; `newvol`) is calculated as

$$V_s = (1 - BF) \times W_s \times \frac{10000}{\rho} \tag{34}$$

where BF is the bark fraction, W_s is the total stem biomass (kg m^{-2}), and ρ is the basic density of wood (kg m^{-3}), a species parameter.

```
newvol(itr3pg) = (1.0 - bfrac(itr3pg)) * wswood(itr3pg) * 10000.0 /
denwood(itr3pg)
```

The current annual increment (or current year volume growth; CAI; m^3 ha^{-1}) is calculated as the difference between the current standing volume (V_s) and that of a year ago (V_{st-1}) by

$$CAI = V_s - V_{st-1} \tag{35}$$

```
cai(itr3pg) = newvol(itr3pg) - monvol(itr3pg,month)
```

The mean annual increment (or mean annual volume growth; MAI; m^3 ha^{-1} year^{-1}) is calculated as the current standing volume (V_s) divided by the *age* (years) since planting as

$$MAI = \frac{V_s}{age} \tag{36}$$

```
mai(itr3pg) = (newvol(itr3pg) - initvol(itr3pg)) / ageyrs
```

3.9.3 Basal area

Basal area is calculated for trees younger than 18 months as

$$BA_1 = N \times \pi \times \left(\frac{DBH}{200}\right)^2 \tag{37}$$

Need to resolve the difference between `dbh` and `meandiam`?

```
ba(itr3pg) = stocking(itr3pg) * pi * (dbh(itr3pg) / 200.0) ** 2
```

and for trees older than 30 months using a Weibull function

$$BA_2 = weibullBA(N)$$ (38)

```
ba(itr3pg) = weibullba(stocking(itr3pg))
```

For trees between 18 and 30 months, BA is a weighted average of BA_1 and BA_2

$$BA = (age_{mon} - 18) \times \frac{BA_2}{12} + (30 - age_{mon}) \times \frac{BA_1}{12}$$ (39)

```
ba(itr3pg) = (agemon - 18) * ba2 / 12 + (30 - agemon) * ba1 / 12
```

Note that the Weibull function applied to diameter distributions and basal area is untested.

3.9.4 Height

Height is calculated from empirical functions that relate stem volume (V_s) and basal area (BA) to height (H) described in Wong and Baker (2001) by

$$H = \frac{Vol - (0.3983 \times BA)}{(0.35366 \times BA) - 0.0661}$$ (40)

```
heightvpgm = (standvol(itr3pg) - 0.3983 * ba(itr3pg)) / (0.35366 *
ba(itr3pg) - 0.0661)
```


3.9.5 Sapwood area

Measurements of forest stand transpiration derived from the widely-used sapflow techniques usually estimate transpiration as the product of sapwood cross-sectional area and sap flux density (SFD; L m^{-2} day^{-1}). Although 3PG+ does not need to estimate sapwood area to model tree growth, it is of interest to include this function so that SFD can be derived from transpiration predictions. Additionally, an estimate of sapwood area over time helps facilitate the reconstruction of the physiological development of forest stands and this may provide considerable insight into the dynamics of forest ecosystems.

In order to estimate the sapwood area over time, it must be related in some way to the growth of the tree, and ideally, be a function of the stem basal area. Preferably, it should also be defined by species-specific relationships.

Sapwood area is calculated in 3PG+ by subtracting previous basal area growth at a fixed (user-specified) time, from current basal area. This time frame, which represents the time at which sapwood is converted to heartwood (notionally set at 60 months) is set as a species parameter. This generally agrees with field observations for eucalypts, although these can be between 6-8 for unirrigated and 3-4 for irrigated trees (Feikema, 2000). The sapwood in trees younger than the age specified by the user at which time heartwood forms, is estimated by

$$SA = SA_{frac} \text{ x } BA \tag{41}$$

where SA is the sapwood area (m^2), BA is the basal area (m^2), SA_{frac} is the fraction of BA that is SA before the development of heartwood, and for trees greater than $month_{SA}$ months of age

$$SA_{age} = BA_{age} - BA_{age-month_{SA}} \tag{42}$$

where age is tree age, or time since planting, in months. Both SA_{frac} and $month_{SA}$ are set as species-specific parameters. Sapwood area is calculated in **subroutine standfacs**.

3.10 Carbon decay

The decay rates factors for litter, dead roots and dead trees in 3PG+ are relevant only where the model is applied for long term carbon sequestration calculation of the mass of carbon in the soil, litter and standing dead trees. The default values are 0.02 (litter), 0.04 (dead roots) and 0.004 (dead tree stems) remove carbon from these pools as CO_2 lost to the atmosphere at a rate of 25%, 50% and 5% respectively. In a more developed C sequestration model, these rates should be made dependent on temperature and moisture conditions.

The decay rate of C in the soil (`soildecay`) is used in the calculation of the soil C pool (`csoil`) in **subroutine updtbioms**. The decay rate for tree stems (`treedecay`) is used in the calculation of the dead tree stem pool (`cmort`) in **subroutine updtbioms**. The decay rate for leaf litter (`littdecay`) is used to calculate litter carbon pool (`clitt`) in the **subroutine litterfall**.

4. Water balance

Rainfall (including irrigation) is balanced against evapotranspiration calculated using the Penman-Monteith equation. A proportion of the rainfall is intercepted by the tree canopy, and depends on canopy LAI. Soil water in excess of the intrinsic soil-water holding capacity for the site is lost as runoff (or deep drainage). Canopy conductance is determined from canopy LAI and stomatal conductance. It increases with increasing LAI up to a maximum conductance, and is affected by VPD, available soil water and stand age.

The original 3PG model had a single soil-layer root zone, and ran on a monthly time step. The migration with CAT has resulted in a multi-layered soil water balance that runs on a daily time step.

4.1 Evapotranspiration

The rate of water loss from a dry canopy is determined by the transpiration rates of leaves within the canopy. Evaporation from leaves, or evapotranspiration, is calculated in **subroutine penman**. Potential daily evaporation (E; mm day^{-1}) in 3PG+ is estimated using the Penman-Monteith equation (Monteith, 1965) in the form given in Landsberg and Gower (1997) as

$$\lambda E = \frac{\varepsilon R_n + \lambda \rho D_q g_a}{\varepsilon + 1 + g_a / g_c} \tag{43}$$

where ε is the dimensionless rate of change of saturated specific humidity with temperature (estimated as 2.2 at 20°C), R_n is net radiation, D_q is specific saturation deficit (calculated as 0.00622.VPD), λ is the latent heat of evaporation of water (2460000 J kg^{-1}) and ρ is air density, g_a is aerodynamic conductance, g_c is canopy conductance (assumed to be infinite for a wet canopy). Daily net radiation is estimated from solar radiation as: $R_n = 0.8R_s - 90$W m^{-2} and aerodynamic conductance 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. The Penman Monteith equation also takes into account the fact that transpiration occurs only during daylight hours, and the day length h (s d^{-1}) is calculated for the time of year and site latitude.

Calculated transpiration is checked against available water such that if transpiration is not less than the sum of soil water and rain water, f_θ (ftheta) is reduced until it is. The soil water balance is then performed, and then *NPP* is calculated.

In the source code, tree transpiration (ttransp) is calculated by

```
ttransp(itr3pg) = convert * (netrad(itr3pg) + defterm(itr3pg)) /
div(itr3pg)
```

where

```
convert = daylength(month) * 3600.0 / lambda
```

To convert energy units to mass units (kg water m^{-2} s^{-1}; 1 kg m^{-2} = 1 mm depth) by division by **lambda** (=2.46×10^6) and integrated to monthly values by multiplication by `daylength` (average monthly daylight length) and the number of days in the month, and where

```
netrad(itr3pg) = e20 * (qb * rad3pg * 1000000.0 / (3600.0 * xdim3pg *
daylength(month)) + qa)
```

and

```
defterm(itr3pg) = ga * rhoair * lambda * vpd3pg * vpdconv
```

and

```
div(itr3pg) = 1.0 + e20 + ga / gc(itr3pg)
```

Definitions for the remaining terms can be found in the source code.

4.2   Rainfall interception

Interception and evaporation of rainfall from the forest canopy were not calculated in the original version of 3PG, and in early stand-alone versions of 3PG+, rainfall interception was simply calculated as a constant fraction of rainfall. For the daily time-step water balance for 3PG+, interception (I_R, mm) is calculated after Battaglia et al. (2004)

$$I_R = \min\{I^*R, I_L L - R_C + E_C\} \tag{44}$$

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. I^* is assigned a value of 0.75 (after Kirschbaum, 1999). Values for I_L are approximately 0.3 mm per unit LAI for eucalypts (Leuning, 1991) and 0.5 mm per unit LAI for *P. radiata* (McMurtrie et al., 1990). A value of 0.3 for I_L for eucalypts resulted in relatively low predicted annual interception rates, and a value of 0.45 mm per unit LAI provided more realistic estimates. If the canopy is wet, evaporation from the crown (E_c) is calculated:

$$E_c = 0.8 \times E_P \tag{45}$$

where E_P is pan evaporation (mm). If the canopy is wet, daily pan evaporation is first used in the evaporation of any intercepted precipitation. The remainder is then used for transpiration.

The module calculating interception of rainfall is located in the **subroutine intercept** with terms **crownfrc** (the term linking crown storage to LAI) or **crownppt** (the fraction of incoming rainfall that can be intercepted).

4.3   Canopy conductance

Canopy conductance (g_c; m s^{-1}) is the canopy transpiration rate divided by potential rate of evaporation from bare saturated soil and is a measure of the ease at which water vapour escapes from plants to the air.

It is an important parameter that controls gas and heat exchanges between vegetation and the atmosphere. Canopy conductance in 3PG+ is calculated in the **subroutine canopycond**. Canopy conductance (g_c; m s^{-1}) is derived from the maximum canopy conductance ($g_{c_{max}}$; a species-specific parameter), five of the six modifiers in (3), and the leaf area index (LAI):

$$g_c = g_{c_{max}} \ f_\theta \ f_{VPD} \ f_{age} \ f_{gtemp} \ \min\left\{1, \tanh \frac{LAI}{3}\right\} \tag{46}$$

Landsberg and Waring (1997) initially suggested a threshold value of 3 above which increasing LAI does not increase canopy conductance. This formulation tends to develop instabilities as LAI approaches 3. In 3PG+, it is no longer a sharp threshold value, but a continuous function defined by the hyperbolic tangent (tanh).

This definition of g_c differs from that in 3PG (Landsberg and Waring, 1997; Sands, 2000) in that it includes the f_{temp} modifier, and assumes that the effects of f_θ 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 water, 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 water, salinity and temperature, it is essential to include them in the calculation of g_c.

The g_c is calculated in the **subroutine canopycond**. A special temperature modifier (different to ftemp), known as gcftemp and based on the approximate daytime mean temperature, is used in the calculation of g_c, where

```
gcftemp = ((daymeantemp - tmin3pg(itr3pg)) / (topt3pg(itr3pg) -
tmin3pg(itr3pg))) * ((tmax3pg(itr3pg) - daymeantemp) /
(tmax3pg(itr3pg) - topt3pg(itr3pg))) ** ((tmax3pg(itr3pg) -
topt3pg(itr3pg)) / (topt3pg(itr3pg) - tmin3pg(itr3pg)))
```

and

```
tav3pg = daymeantemp= (ctmax(monno) + ctav(monno)) / 2.0
```

which is the average of maximum and average (and not minimum) daily temperatures. The resulting value of g_c is then calculated by

```
gc(itr3pg)  =  gcmx3pg(itr3pg)  *  ftheta(itr3pg)  *  fd(itr3pg)  *
fage(itr3pg) * gcftemp
```

and then adjusted for LAI by

```
gc(itr3pg) = gc(itr3pg) * tanh(lai3pg(itr3pg)/3.0)
```

4.4   Soil water balance

The soil water balance sub-model operates on a daily time step and is a balance between rainfall and evapotranspiration, which is calculated using the Penman-Monteith equation; Eq (43) using the appropriate g_c value from Eq (46). Water movement is simulated as a one-dimensional (vertical) water balance. The solution scheme calculates for each day of the simulation in the following order of operation: subsurface lateral flow, runoff, soil evaporation, plant transpiration and finally water redistribution and deep drainage. The functions related to these processes are presented and described in DSE (2007).

5. Species-specific parameters

5.1 Introduction

The proposed use of 3PG as a tool for forest and land use management is predicated on the ability to reliably assign values for parameters characterising novel species. There is potential for incorrect model predictions due to a general lack of suitable data to properly test or parameterise the 3PG, especially both above- and below-ground biomass data. Furthermore, testing and parameterisation might not be done with a proper understanding of the subtleties of the various parameters. In only a few cases have parameters characterising a species been rigorously determined, and even then this has been largely by a process of trial and error, e.g. for *E. globulus* by Sands and Landsberg (2002).

A detailed procedure for assigning species-specific parameters is provided by Sands (2004) and the reader is advised to consult that document when attempting to assign species parameters. As a first general rule, parameters for new species should always be assigned by direct and independent measurement or by analogy with others species. Failing this, their values can be adjusted in order to optimise the fit of selected outputs to corresponding observed values.

Sands (2004) emphasised that:
(a) in the first instance parameters should be assigned values based on direct measurement or by analogy with other species
(b) estimation of parameters by fitting model output to observed data should be done with care and a sound understanding of the structure of the model
(c) it is necessary to check that the final parameter values and all model outputs are biologically reasonable
(d) predictions based on the assigned parameters should be always validated against independently observed data.

The reader is also referred to Esprey et al. (2004) and Sands (2004) who provide a guide to the sensitivity of model outputs to various species parameters.

5.2 Current species parameter sets

3PG relies on sets of species parameters that describe physiological and morphological characteristics of a given species. The use of 3PG is based on ability to assign reliable values for parameters characterising new species. Here, we provide a listing of the current species parameter sets for 3PG+, and a brief description on their respective development.

Table 5.1. Species parameter sets used for 3PG+.

Description[a]	Symbol	Code name	Units	P. radia.	E. glob.	E. nitens	E. regn.	E. grand.	E.camal.	E. obliq.	E. salig	C. macul	E. clado
Beer's law constant for radiation[1]	k_ϕ	kphi	-	0.5	0.55	0.55	0.55	0.55	0.55	0.55	0.45	0.4	0.55
Constant in VPD modifier[1]	k_g	kg	-	0.5	0.45	0.45	0.45	0.45	0.45	0.45	0.58	0.48	0.45
Maximum canopy conductance[1]	$g_{c\,max}$	gcmax	m s^{-1}	0.02	0.018	0.018	0.018	0.018	0.018	0.018	0.02	0.024	0.018
Mortality function factor (parabolic phase)[3]	β_{early}	afact	-	-0.2	-0.45	-0.45	-0.45	-0.45	-0.35	-1	-0.3	-0.42	-0.45
Mortality function factor (power phase)[3]	β_{mature}	p32fac	-	650	78	78	62	78	84	42	8	145	75
Fraction of mean stem biomass lost when tree dies[3]		mortfac	-	0.2037	0.2037	0.2037	0.2037	0.2037	0.2037	0.2037	0.2037	0.2037	0.2037
Constant for age effect on growth[1]	max_{age}	MaxAge	years	80	80	80	80	80	80	80	80	80	80
Power for age effect on growth[1]	n_{age}	nAge	-	1.8	2	2	2	2	2	1.8	2	2	2
Canopy quantum efficiency[1]	α_c	alphaC	-	1.85	2.3	2.3	2.3	2.3	2.2	1.6	4.4	4.6	1.6
Fertility effect on photosynthesis[3]	ff	fertfac	-	1.0	1.5	1.5	1.5	1.5	1.1	1.5	0	0.2	1.5
Ratio of net to gross primary productio[1]	c_{pp}	cpp	-	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Maintenance respiration[1]	-	maintfac	-	0	0	0	0	0	0	0	0	0	0
Initial mass (above+below-ground) of a single tree[1]	w_{init}	initwt	kg	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Root turnover fraction per month[1]	γ_r	gammaR	-	0.02	0.1	0.1	0.1	0.1	0.04	0.09	0.015	0.015	0.05
Parameter for root allocation[1]	r_a	rootco1	-	0.8	0.6	0.6	0.6	0.6	0.6	0.9	0.58	1	0.8
Parameter for root allocation[1]	r_b	rootco2	-	3	8	8	8	8	2.4	5	2.3	7	6
Maximum litterfall fraction per month[1]	$\gamma_{f\,max}$	gammafmax	-	0.03	0.05	0.045	0.045	0.05	0.066	0.04	0.02	0.017	0.08
Constant in litterfall function[1]	c_γ	cgamma	-	5	6	6	6	6	3	5	15	15	10
Constant in litterfall function[1]	k_γ	kgamma	-	0.5	0.5	0.6	0.6	0.6	0.5	0.5	1.5	1.1	0.3
Allometric foliage co-efficient[1]	a_f	afco	-	0.06	0.05	0.05	0.05	0.05	0.055	0.05	0.04	0.06	0.055
Allometric foliage co-efficient[1]	n_{f_base}	nfbase	-	2.2	2.3	2.3	2.3	2.3	2.4	2.2	1.83	1.92	2.3
Allometric foliage co-efficient[1]	n_f	nffac	-	0	0	0	0	0	0	0	1.95	2.04	0
Allometric stem coefficient[1]	a_s	asfac	-	0.06	0.05	0.05	0.05	0.05	0.05	0.083	0.058	0.063	0.05
Allometric stem coefficient[1]	n_s	nsfac	-	2.65	2.75	2.75	2.75	2.75	2.75	2.47	2.68	2.7	2.75
Factor to convert C mass to biomass[1]	$C_{biomass}$	ctobiomass	kg kg^{-1}	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Mean stemwood basic density[1]	ρ	denwood	kg m^{-3}	380	525	510	500	550	525	525	475	550	600

Description	Symbol	Code	Units										
Maximum temperature for growth[2]	T_{max}	tmaxpar	°C	32	32	32	32	35	35	32	36	38	32
Minimum temperature for growth[2]	T_{min}	tminpar	°C	5	5	3	3	7	5	5	5	2	5
Optimum temperature for growth[2]	T_{opt}	toptpar	°C	19	19	19	19	24	22	21	24	22	19
Branch fraction initial value[3]	BF_{init}	initbf	-	0.5	0.4	0.7	0.4	0.4	0.6	0.45	0.6	0.6	0.4
Branch fraction final value[3]	BF_{final}	finbf	-	0.27	0.25	0.3	0.2	0.25	0.36	0.25	0.25	0.212	0.2
Branch fraction exponential decline factor[3]	BF_{dec}	bfdec	-	-0.08	-0.6	-0.6	-0.6	-0.6	-0.2	-0.6	-0.4	-0.4	-0.6
Salinity in soil water for zero growth[3]	sal_0	maxsal	dS m^{-1}	15	13	13	13	13	30	15	20	20	20
Coefficient to limit early growth[3]	$early_{co}$	earlyco	-	3	1.5	1.5	1.5	1.5	1.5	1	2	1.5	1.5
Coefficient to limit early growth[3]	$early_{exp}$	earlyexp	-	1.5	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Specific leaf area for younger trees[3]	SLA_{init}	initsla	m^2 kg^{-1}	15	16	11	7	16	16	16	16	16	16
Specific leaf area for older trees[3]	SLA_{final}	finsla	m^2 kg^{-1}	5	4	4.5	4	4	4	4	7.5	4	5
Specific leaf area exponential decline factor[3]	SLA_{dec}	sladec	-	-0.4	-0.8	-0.4	-0.025	-0.8	-0.8	-0.8	-0.5	-0.4	-0.8
Fraction of initial tree mass that is foliage[1]	fol_{frac}	folfrac	-	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.5
Fraction of initial tree mass that is stem[1]	$stem_{frac}$	stemfrac	-	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4
Fraction of initial tree mass that is root[1]	$root_{frac}$	rootfrac	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1
Mortality function power (power phase)[3]	n_N	thinpower	-	1.5	3.5	3.5	3.5	3.5	3.5	4.5	300	2.5	3.5
Threshold value of f_θ for enhanced litterfall during drought[3]	l_{thresh}	lthresh	-	0.1	0.1	0.15	0.1	0.1	0.3	0.6	2.93	0	0.4
Term linking crown storage of rainfall to LAI[3]	I_L	crownfrc	mm (LAI)$^{-1}$	0.5	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Maximum fraction of rainfall intercepted per day[3]	I^*	crownppt	-	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

[a] Parameters as defined (= 1) / modified (= 2) for 3PG (Landsberg and Waring 1997, Sands and Landsberg 2002); or modified / additional (= 3) for 3PG+

5.2.1 E. globulus

Parameters for *E. globulus* (and *E. grandis*) have largely been assigned from unpublished data obtained from a series of biomass studies undertaken at a wastewater-irrigated eucalypt biomass trial established by CFTT (the former forest research group within DSE) at Shepparton. Results from this study (provided by courtesy of Drs Tom Baker and Michael Duncan of CFTT) were averaged over all diameter classes, which was used as a basis for parameter estimation. No objective parameter optimisation procedure has been applied. Rather, the approach taken was to progressively adjust individual parameters within the bounds of values expected from the field observations, published values and previous experience with the model. The final sets of parameters arrived at lead to growth predictions in good agreement with the trial data and sensible predictions for other sites. However there is undoubtedly scope for further improvement and this will be obtained as the model is tested against detailed field observations from a wider range of age, climate and growing conditions.

Most of the parameters are not known with complete certainty, and so a degree of 'tuning' is acceptable and may prove necessary or desirable to optimise the model when further data becomes available. The sensitivity of the volume growth and other outputs to any of the parameters is readily tested. In general the model is reasonably robust and its predictions appear likely to be within 20% or better of actual performance (e.g. a predicted MAI of 20 $m^3 ha^{-1}$ year$^-$1 means 16 to 24 $m^3 ha^{-1}$ year^{-1}).

The Beer's law constant (canopy extinction coefficient) is often assumed to be approximately 0.5 in eucalypt canopies, although differences in leaf angle, albedo and canopy structure could cause significant species differences. The value of k_g has been reduced substantially from the value adopted by Landsberg and Waring (1997), to conform with field observations of eucalypt plantation transpiration in relation to vapour pressure deficit (VPD) in northern Victoria which indicate peak transpiration at 1-2 kPa.

The tree age effect incorporated in 3PG+ to reflect the long-term decline in hydraulic conductivity of stems and branches is of little importance in the context of short rotation (e.g. 10- 25 years) plantations, unless an unusually short physiological maximum lifetime is assumed. The possibility of including a small maintenance respiration factor (e.g. 0.1% of stand biomass per month) was explored, compensated by a small increase in c_{pp} (which was based on an assumption that respiration is a constant proportion of gross photosynthesis in Landsberg and Waring's development). This also leads to a decline in growth with stand age, noticeable as early as age 10-20. This variant of the model has theoretical appeal but data to confidently set the values of c_{pp} and maintenance respiration are not available, so maintenance respiration has not been included and c_{pp} is left at a 'universal' value shown to be appropriate for eucalypt plantations in Tasmania and W.A.

The root turnover fraction of 1.5% per month is largely a guess of an inaccessible parameter. It leads to reasonable values of root biomass as a proportion of stem biomass under most circumstances. Parameters for allocation of photosynthate to root growth are as suggested by Landsberg and Waring (1997). The monthly litterfall fraction is derived from measurements of litterfall and foliar biomass in irrigated *E. globulus* at Shepparton, and for *E. globulus* at Cann River, and the values of c_γ and k_γ are designed to increase litterfall up to this value by age 5. The allometric foliage and stem coefficients are also derived from detailed annual biomass assessments of irrigated *E. globulus* trees at Shepparton.

The conversion factor from photosynthetic carbon fixation to plant biomass assumes dry biomass is 45% carbon, a factor which depends mainly on the proportions of cellulose-like and lignin-like compounds

present. A common approximation is 50%; adopting this would lead to slightly lower predicted growth than obtained in our analysis. The value assumed for mean wood density also directly affects the predicted volume growth, though not the modelled biomass. The values of maximum, minimum and optimum temperatures are approximations derived from controlled environment studies (Morris, 1977) and from the natural occurrence of the species (Booth, 1995). The `branchfrac` parameter, is dependent on a number of growth factors including tree form and branch persistence as well as the small end diameter limit of the harvested product. Clearly it has a direct influence on the volume production predicted by modelling.

A set of parameters for *E. globulus* was published by Sands and Landsberg (2002). Differences between that parameter set and the one reported here for 3PG+ can largely be explained by differences in the model version (Sands and Landsberg used 3PGpjs) and that data from different was used for validation. The parameter set currently used has undergone considerable development and is dated December 2005.

5.2.2   E. grandis

Parameters for *E. grandis* were developed from recommendations by Landsberg and Waring (1997), together with growth, litterfall, transpiration, salt tolerance and biomass data from irrigated and groundwater-dependent *E. grandis* plantations in northern Victoria and some published data for plantations in NSW (Bradstock, 198).

Specific leaf area of *E. grandis* was estimated from biomass studies at Shepparton. The value of k_g has been reduced substantially from the value adopted by Landsberg and Waring, to conform with field observations of eucalypt plantation transpiration in relation to vapour pressure deficit (VPD) in northern Victoria which indicate peak transpiration at 1-2 kPa.

Parameters for allocation of photosynthate to root growth are as suggested by Landsberg and Waring (1997). The monthly litterfall fraction of 3% is derived from measurements of litterfall and foliar biomass in irrigated *E. grandis* at Shepparton, and the values of c_γ and k_γ are designed to increase litterfall up to this value by age 5. The allometric foliage and stem coefficients are also derived from detailed annual biomass assessments of irrigated young *E. grandis* at Shepparton.

The conversion factor from photosynthetic carbon fixation to plant biomass assumes dry biomass is 45% carbon, a factor which depends mainly on the proportions of cellulose-like and lignin-like compounds present. A common approximation is 50%; adopting this would lead to slightly lower predicted growth than obtained in our analysis. The value assumed for mean wood density also directly affects the predicted volume growth, though not the modelled biomass; the value of 500 kg/m^3 adopted here and consistent may prove to be low for *E. grandis*, again tending to cause an overestimation of volume growth. The values of maximum, minimum and optimum temperatures for *E. grandis* are approximations derived from controlled environment studies (Morris, 1977) and from the natural occurrence of the species (Booth, 1995). The `branchfrac` parameter, estimated as 25%, is dependent on a number of growth factors including tree form and branch persistence as well as the small end diameter limit of the harvested product. It has a direct influence on the volume production predicted by modelling.

Early growth of the plantation (before canopy closure) is parameterised by the `earlyco` and `earlyexp` parameters. The values adopted are derived from biomass measurements of irrigated *E. grandis* at Wodonga.

Parameter sets for *E. grandis* have been published by Almeida et al. (2004) and by Esprey et al. (2004) using the 3PGpjs version of the model. Both those studies used data from fast growing *E. grandis* plantations in South Africa. The most current parameter set has undergone very little development and is dated February 2004.

5.2.3 Pinus radiata

Initial species parameters were obtained from Dye (2001). Leaf and stem allocation parameters were adjusted following allometric biomass functions from Madgwick (????). Initial specific leaf area was set at 15 according to values in the literature for *P. radiata*. Values for `alphac` and `fertfac` were varied to fit both Rennick and Scarsdale data. Values for branch fraction (`bfrac`) were varied to balance height and diameter growth. The most current parameter set has undergone some development and is dated May 2005.

5.2.4 E. camaldulensis, E. obliqua and E. cladocalyx

Parameter sets for *E. camaldulensis* and *E. obliqua* were assigned during the Carbon Tender project aimed at predicting the amount of carbon that could potentially be stored by trees on agricultural land. The focus of 3PG+ was to develop a map of predicted carbon stored in native vegetation (defined by EVC). The main or dominant species was selected from the most common EVC groups. Data from research trials and from the literature were then used for parameterisation. The parameterisation was such that the model could simultaneously predict the growth of these species at a variety of sites.

Plot data from Nathalia (2-8 years), Appin South (2-6 years), Yarrawalla (2-6 years), Shepparton (2-6 years), Tatura (2-7 years) and Kyabram (4-18 years) were used to assign parameters for *E. camaldulensis*. The most current parameter set has undergone little development and is dated February 2006.

Plot data from Narbethong (32 years), Irrewillipe (12.6 years), Buffalo River and Tostaree (3 years) together with allometric relationships from Keith et al. (2000) were used to assign parameters for *E. obliqua*. The most current parameter set has undergone little development and is dated April 2004.

Plot data from Nathalia (2-9 years), Appin South (2-6 years), Yarrawalla (2-6 years), Shepparton (2-6 years), were used to assign parameters for *E. cladocalyx*. The most current parameter set has undergone very some development and is dated February 2006. A different parameter set for *E. caldocalyx* has been published by Paul et al. (2006).

5.2.5 E. nitens and E. regnans

Species parameters for *E. nitens* and *E. regnans*, for the most part, were assigned by direct and independent measurements from the literature, and by analogy with others species. The parameter set for *E. globulus* was adopted, and selected parameters were altered based on valid experimental data. The parameters re-assigned include those describing, specific leaf area, species response to temperature, stemwood density, and drought tolerance. The most current parameter sets have undergone little development and are dated April 2008.

5.2.6 Other species

Parameter sets for *E. tricarpa* (August 2004), *Corymbia maculata* (October 2004) and *E. saligna* (June 2001) have undergone little if any development. They were developed with minimal growth data. A different parameter set for *C. maculata* has been published by Paul et al. (2006).

6. Fertility

6.1.1 Fertility rating

The original 3PG by Landsberg and Waring (1997) considered nutrition, or fertility, only though a mechanism of carbon allocation to below ground. Evidence suggests that nutrition affects the amount of carbon allocated to roots with a greater proportion going to the roots of trees on infertile sites than those on fertile sites. Climatic constraints generally override nutritional limitations and trees in the most fertile soil will not grow without adequate water, or in very cold conditions. But, when water is adequate, improved nutrition usually results in increasing the proportion of net photosynthesis allocated above ground. Quantifying the relationship is difficult and our understanding of nutrient dynamics and uptake processes is not yet good enough, at the tree or stand level, to allow formulation of definitive, deterministic relationships, and so Landsberg and Waring (1997) implemented a simple scaling procedure, whereby the allocation of carbon below ground is minimised on fertile sites and increases as fertility decreases.

It is a general finding from physiological ecology that, particularly in broad-leaved species, there is a positive relationship between the nutritional status of foliage and canopy photosynthesis rates (see Landsberg and Gower, 1997, Ch.5). Trees also tend to allocate a greater proportion of their carbon to foliage when water and nutritional status are favourable (Landsberg and Gower, 1997; Kriedemann and Cromer (1996) provide explicit evidence of this in eucalypts). Sands and Landsberg (2002) made two adjustments to the way in which 3PG reflects soil nutritional status:

- Canopy quantum efficiency (α_c) increases linearly with fertility rating ($0 \leq F_t \leq 1$)
- The power in the allometric equation relating leaf mass to stem diameter (n_f) increase linearly with F_t

Because F_t is applied to α_c, and not in the calculation of ϕ_{pau} from ϕ_{pa} (see Eq (3)) F_t does not affect the ϕ_{pau}/ϕ_{pa} ratio and hence root allocation through Eq (14), and is therefore included explicitly in the denominator of Eq (14).

At present, in 3PG+, fertility influences tree growth in three ways; through the fertility rating (F_t)

1. In the calculation of below ground carbon allocation (η_r) in section 3.3.1
2. As a fertility modifier to derive *GPP* from α_c in section 3.2.6

and through factor $m_f \left(= F_t/F_0\right)$

3. As an effect on biomass allocation to foliage (*pfs*) in section 6.1.2

6.1.2 Fertility effect on foliage allocation

The original 3PG model allows for the effects of site fertility on allocation of carbon to above- and below-ground, and we also now enhance this to allow site fertility to effect foliage-stem carbon allocation to reflect the effects of fertility on the allocation of carbon to foliage and stems. The derived ratio of foliage to stem allocation (*pfs*) is described by Eq (17) factors related to fertility to yield

$$pfs = \frac{x_{af} \; x_{nf} \; D_{OB}^{\left(x_{nf}-1\right)}}{a_s \; n_s \; D_{OB}^{\left(n_s-1\right)}} \tag{47}$$

where D_{OB} is mean tree diameter over bark at 1.3m from the ground (cm), a_s and n_s are species specific allometric stem coefficients defined by the user, and x_{af} and x_{nf} are respective values of a_f and n_f (both species specific allometric foliage parameters) as a function of fertility and given by

$$x_{af} = a_f \times m_f^{\,4} \tag{48}$$

and

$$x_{nf} = n_{f.base} + n_f \left(1 - m_f^{\,2}\right) \tag{49}$$

where m_f is a fertility multiplier in Eq (51), and $n_{f.base}$ is a species specific base for age-related allometric foliage coefficient. As fertility declines, x_{af} decreases and x_{nf} increases. The stem allocation factor (η_s) is then defined by Eq (18) and reproduced here.

$$\eta_s = \frac{\left(1 - \eta_r\right)}{\left(1 + p_{f.s}\right)} \tag{18}$$

where η_r is the root allocation factor.

These calculations can be found in **subroutine stemfac.**

```
xaf = afco(itr3pg) * fertmult ** 4

xnf = nfbase(itr3pg) + nffac(itr3pg) * (1.0 - fertmult ** 2)

pfs(itr3pg) = (xaf * xnf * dbh(itr3pg) ** (xnf - 1.0)) /
(asfac(itr3pg) * nsfac(itr3pg) * dbh(itr3pg) ** (nsfac(itr3pg) - 1.0))

netas(itr3pg) = (1.0 - netar(itr3pg)) / (1.0 + pfs(itr3pg))
```

6.1.3   Fertility decline

The 3PG+ model is therefore sensitive to fertility in three respects: net photosynthesis, root allocation, and foliage-stem allocation. When combined with a capacity to impose a decline in fertility through time, this has allowed excellent results in fitting the model to sample plot growth data from plantations on the Leizhou Peninsula in China (Morris, 2003). At this stage, no attempt has been made to implement a feedback through which stand growth or litterfall may affect the rate or extent of fertility decline. Johnsen et al. (2001) noted that soil and nutritional interactions remain the most difficult components for development of process-based forest growth models. Apart from the shortage of reliable data to construct such a link, a more compelling reason for maintaining fertility decline as an imposed change in the tree environment is the fact that it is likely to result to a large degree from other biological and physical factors outside the influence of the trees.

A feature of *Eucalyptus* plantations in many (particularly tropical) areas is rapid early growth followed by a rapid decline of leaf area and growth rate. There is some evidence that this is nutritionally, related to loss of nitrogen and possibly other key nutrients from the upper soil profile by physical and biological

processes. Irrespective of the mechanism, in 3PG, this is evidently a decline in 'fertility', that is, an external site factor and not a physiological change in the trees themselves. The sharp decline in leaf area with age leads to a strong shift in the relation between foliage mass and tree diameter, violating the 3PG assumption of a constant relationship which is at the core of the model's carbon allocation and hence growth predictions. Morris and Baker (2002) showed that this change with age cannot be adequately explained as a result of litterfall, and suggested modelling the foliage mass – diameter relation as an explicit function of age. However, if it is accepted that the cause of the change is external then it can be more usefully modelled as a function of fertility with the important difference that fertility may or may not decline through time, depending on soil conditions and stand management. The fertility rating (F_t, *mnfert*) for any given month in 3PG+ is now defined through time by

$$F_t = m_f \times F_0 \qquad (50)$$

where F_0 is the site fertility index at the start of the rotation (0 to 1) and F_t is the monthly value of F_0, allowing for decline, and

$$m_f = e^{\left(-dec_f.age\right)} \qquad (51)$$

where m_f is a fertility multiplier used in calculating *af* (constant of the foliage mass;) in Eq (48) and *nf* (the power of the foliage mass) in Eq (49), dec_f is a fertility decline parameter representing the decline rate of initial fertility, 0 to >1 (although 1 is extreme), and *age* is the time since planting (in years). Figure 3.5 provides an example of change in monthly values of fertility rating (F_t) with age for different values of m_f and dec_f. The fertility rating or modifier (`mnfert`) can be located in the source code under **subroutine standfacs.**
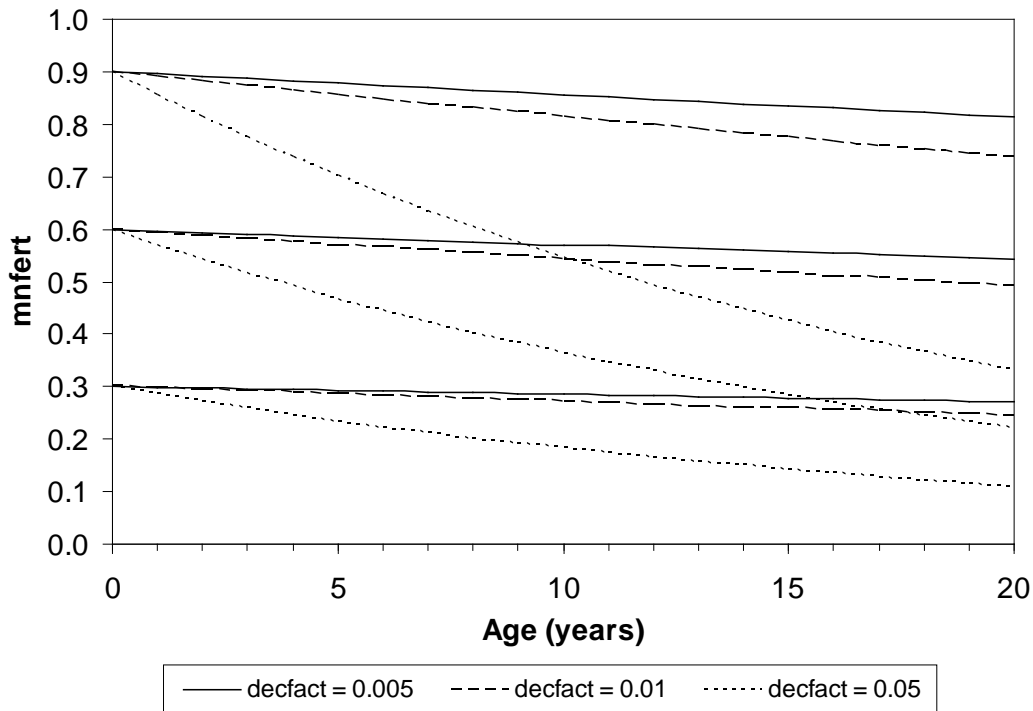

Figure 6.1. Resulting values of `mnfert` (monthly value of `mfert` allowing for decline) with tree age for different values of `mfert` (0.3, 0.6, 0.9) and `decfact` (0.005, 0.01. 0.05).

7. Representation of the soil

7.1.1 Soil layering through depth

The soil profile is characterised as a series of soil layers, each assigned a thickness, texture class, bulk density, proportion of coarse fragments, and soil water characteristics (air dry, wilting point, field capacity and saturation volumetric water contents), and vertical saturated hydraulic conductivity. These variables are used to calculate plant available water capacity for each layer and a total to a specified maximum rooting depth. Layering of the soil in 3PG+ provides a more appropriate spatial resolution for water movement given the daily time step hydrology. Layering also allows for more accurate estimation of water uptake from the lower root zone

Water is redistributed through the soil profile using either a cascading bucket approach. At the end of each month, the available soil water in each soil layer is partitioned based on root depth and occupancy (both of which are derived using 3PG+) into the 'zone' occupied by roots, and that zone which is unavailable to water uptake by roots. The extent of occupancy as a function of 'zone' is then used to define the root distribution within the root zone. That is, 50% zone occupancy, for example, translates to 50% extraction within the root zone. Transpiration demand is sourced from all soil layers in contact with roots, regardless of distribution. At the end of each month, 3PG+ updates the vegetation response including LAI, stemwood volume and root biomass.

7.1.2 Parameterisation of n_θ and c_θ with depth

In 3PG, the growth modifier f_{soil} is a function of (relative) soil water content, and two empirical parameters, n_θ and c_θ, are used to reflect differences in the relationship between transpiration rate and soil water content for different soil textures (Landsberg and Waring, 1997 after Denmead and Shaw, 1962). For 3PG+ values of n_θ and c_θ are first assigned to each soil layer according to soil texture class. From these, single representative values of n_θ and c_θ are calculated:

$$\overline{n}_\theta = \frac{\sum_{i=1,L} \left(n_{\theta_i} ASW_i \right)}{\sum_{i=1,L} ASW_i} \tag{52}$$

and

$$\overline{c}_\theta = \frac{\sum_{i=1,L} \left(c_{\theta_i} ASW_i \right)}{\sum_{i=1,L} ASW_i} \tag{53}$$

where L is the number of soil layers to the specified maximum rooting depth; ASW_i is the available soil water capacity, n_{θ_i} is the value of n_θ and c_{θ_i} is the value of c_θ for soil layer i; and $\overline{n}_\theta$ and $\overline{c}_\theta$ are weighted average values of n_θ and c_θ.

This approach retains from 3PG the empirical basis of representing the soil water retention curve as it affects transpiration, but provides an objective basis for estimation of the parameters for multi-layered soils. Landsberg and Waring (1997) provided indicative values for four broad soil textures, but here we use values of n_θ and c_θ that range from 1 to 10, and from 0.3 to 0.75 respectively for a greater number of

soil textures from clay through to sand by Ward et al. (2000). Values for n_θ and c_θ applied to each texture are listed in Table 3.1. These values result in relationships between the soil water modifier (f_θ) and the soil moisture ratio (r_θ) as shown in Figure 3.2.

7.1.3 'Rooted' and 'unrooted' soil

The initial 3PG model did not include soil layering and that the available water within the total soil profile was available to trees from the start of the rotation. The relatively simple 3PG simple hydrology has limitations because, in reality;

- roots may not have access to the whole root zone
- trees cannot 'borrow' water from one month to the next
- rain may not enter the 'rooted' part of the soil

In 3PG+, the soil is divided into layers (see sections 7.1.1 and 7.1.2) and additionally into two zones (*A* and *B*) defined by the fraction exploited by roots (Figure 7.1). Zone A (Z_A) is the fraction exploited by roots and from which water uptake and transpiration can occur. Zone B (Z_B) is the remainder of the root zone that is not exploited by roots. The sum of Z_A and Z_B is the total root zone as defined as a fixed depth of soil or maximum root depth (`dwemax;` species parameter). As root biomass increases, Z_A becomes larger, and the root zone is fully exploited to the full soil depth when root density reaches the maximum or full root density (`fulrootden`), currently set at a default value of 0.1 kg m^{-3}. Additionally, the root density required to intercept all of the effective rain water (`fulrain`) is also set at a value of 0.1 kg m^{-3}. The `fulrootden` and `fulrain` factors are of primary importance in 3PG+ modelling of root water availability. `fulrootden` is the density (kg m^{-3}) that roots must reach in order to access all the soil in the root zone. `fulrootfrac` is the current root density as fraction of `fulrootden`. `fulrain` on the other hand represents the density of roots (kg m^{-2}) that must be reached before it is assumed that roots spread laterally throughout the soil to a sufficient extent to intercept all the infiltrating rain water. Therefore, the fraction of effective rainfall that enters zone A logically increases with root biomass. Increasing either or both `fulrootden` and `fulrain` will reduce the ability of roots to reach and take up water from the soil, and hence will increase water stress.

Transpiration comes only from Zone A, hence it is usually dryer than Zone B. If root biomass increases, Zone A expands and soilwatA increases as it takes in some of Zone B. If root biomass decreases, Zone B expands and soilwatB decreases as it takes in some of Zone A. In stressed conditions, trees can improve their water supply by allocating more carbohydrate to roots. Species differences in drought tolerance can be modelled in terms of root allocation and root turnover.

Figure 7.1. Conceptual diagram of compartmentalising the root zone into zone A, the fraction exploited by roots, and zone B, the remainder of the root zone.

Figure 7.2 provides a conceptual diagram of how the amounts of water (mm) in Zones A (SW_A) and B (SW_B) are calculated by

$$SW_A = \frac{\left[\left(SW_{At-1} \times Z_{At-1}\right) + \left(BtoA \times SW_{Bt-1}\right) + \left(AtoB \times SW_{At-1}\right)\right]}{Z_A} \tag{54}$$

$$SW_B = \frac{\left[\left(SW_{Bt-1} \times Z_{Bt-1}\right) + \left(AtoB \times SW_{At-1}\right) + \left(BtoA \times SW_{Bt-1}\right)\right]}{Z_B} \tag{55}$$

where SW_{At-1} and SW_{Bt-1} are amounts (mm) of existing soil water in the previous month (t-1) in zones A ad B respectively, Z_{At-1} is the fraction of the root zone exploited by roots in the previous month, and Z_{Bt-1} is the is the remainder of the root zone that is not exploited by roots in the previous month, $AtoB$ and $BtoA$ describe the change in fractions between zones A and B between the previous and current month, and Z_A is the root zone fraction exploited by roots and Z_B is the remainder of the root zone that is not exploited by roots in the current month.

```
soilwata = (oldsoilwata * oldafrac + btoa * oldsoilwatb - atob *
oldsoilwata) / zoneafrac
soilwatb = (oldsoilwatb * oldbfrac + atob * oldsoilwata + btoa *
oldsoilwatb / zonebfrac
```

The value of r_θ (rtheta) is then calculated as

$$r_\theta = \frac{SW_A}{\left(\left[SW_A + SW_B\right] \times \text{FC}\right)} \tag{56}$$

where SW_A is the amount of water in Z_A, $SW_A + SW_B$ is the maximum amount of water in the whole soil profile, and FC is the field capacity of the soil.

```
rtheta(1) = sumzwata / sumzwatamax
```

where `sumzwatamax` ($SW_A + SW_B$) x field capacity of the soil. So, `rtheta` is derived from the sum (of all layers) of water in the rooted (zone A) part of the profile.
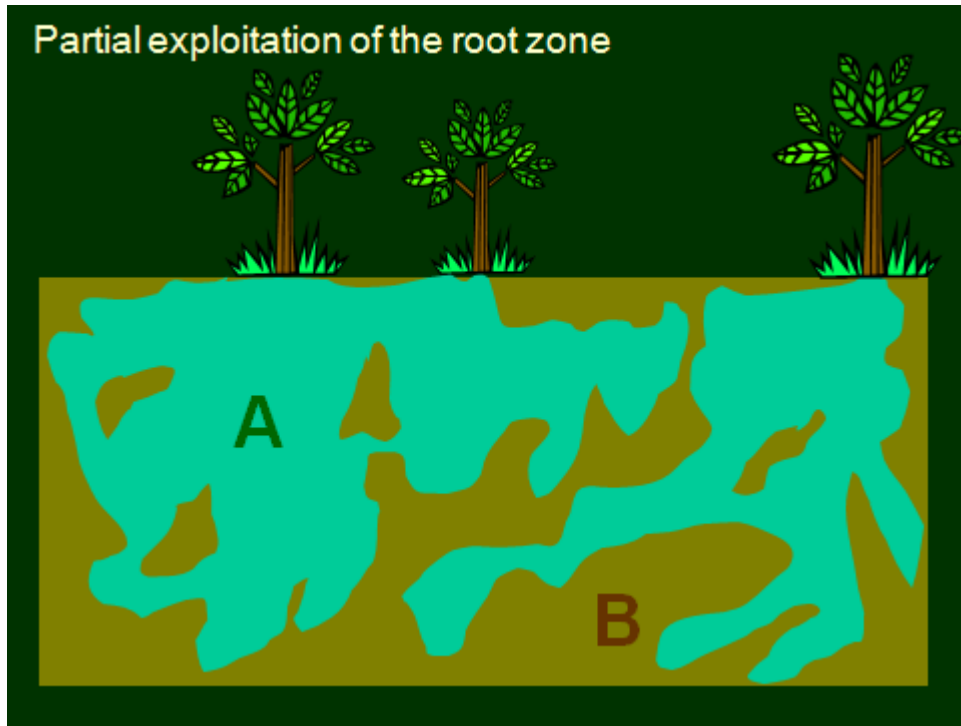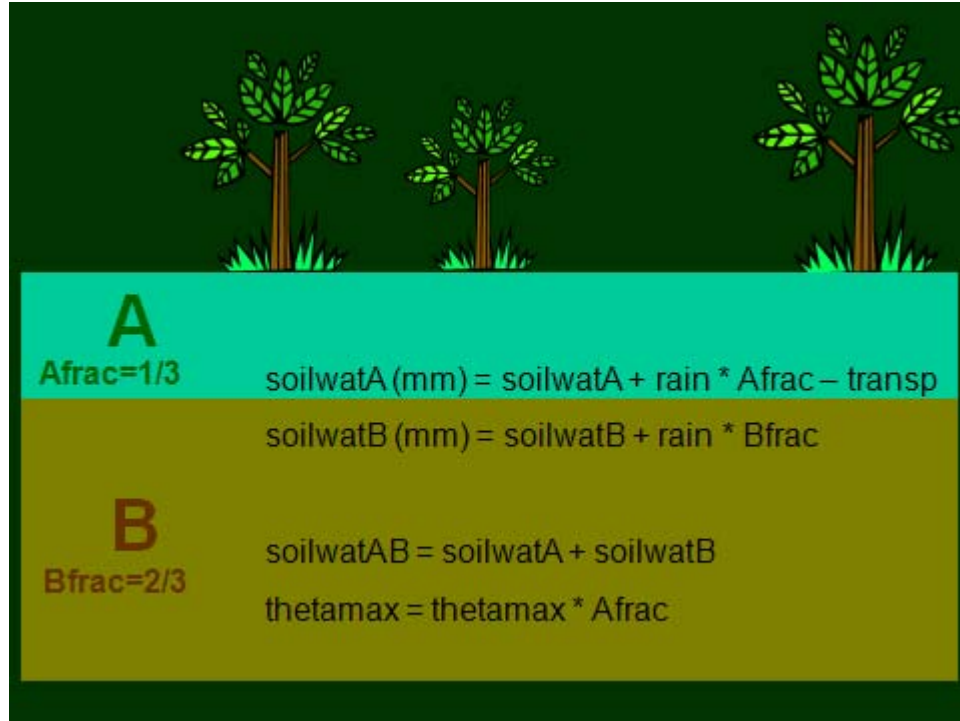

Figure 7.2. Conceptual diagram of calculating the amount of water in zone A, the fraction exploited by roots, and zone B, the remainder of the root zone.

In the original 3PG, trees could 'borrow' water. The modifiers are calculated and then used to calculate NPP, canopy conductance and then transpiration is calculated. The soil water balance was then updated (where the soil water = previous soil water + rain – transpiration). But if soil water is < 0, the soil water is reset to = 0. For example, if the maximum available water is 5mm in a very shallow root zone, then it can be easily saturated so that r_θ (`rtheta`) if often equal to 1 (i.e. soil water is not limiting for growth or canopy conductance). If monthly transpiration is calculated as 50 mm, and only a maximum of 5 mm is available in the soil, then transpiration and growth are significantly overestimated for the month.

In 3PG+, the modifiers are calculated and then used to calculate canopy conductance in the same way, but calculated transpiration is checked against available water such that if transpiration is not less than the sum of soil water and rain water, f_θ (`ftheta`) is reduced until it is. The soil water balance is then performed, and then NPP is calculated. Transpiration is allocated to layers from the top down.

8. Continued model validation

Several components of the mode, while appearing to work well, require further attention and validation that they are capturing the main processes and that they have been adequately parameterised. These include i) components of the model that calculate transpiration, ii) soil parameters, and iii) the fertility rating.

8.1 Transpiration

The prediction of transpiration both in plantations and in native forests is an important area of research. How much water do trees transpire? How does climate and site affect this? How do management options such as species selection, spacing, thinning affect this? The problem in addressing the first question has always been, which trees? located where? on what day? Transpiration on hourly, daily or longer timescales varies greatly with tree, site and climate factors; so the relatively small number of combinations of these variables that we can actually measure in the course of a field research program can never be sufficient to provide empirical answers for all real world situations. There is a need to identify functional relations for predicting transpiration, and this has led to the development of stand models such as Waves and 3PG+. These and similar models explicitly or implicitly impose a relation between transpiration and growth that may be tested by comparisons with field data, though there appears to have been little effort to do this so far.

The approach to answering these questions can be either (a) through making many point measurements of transpiration spanning a range of sites, stand and climate conditions, and manually interpolating between these with empirical data to estimate transpiration in a given real-world situation; or (b) by incorporating present knowledge of transpiration into physically/physiologically based, process or hybrid models that simultaneously predict transpiration and growth of forest stands. The more discrimination that is required between site, climate and stand conditions, the less satisfactory is approach (a), and the more effective is the process/hybrid modelling approach.

In the terms of the 3PG+ hybrid model, transpiration is estimated using the Penman-Monteith evaporation equation with canopy conductance (g_C) derived from a maximum canopy conductance and a series of modifiers for the limiting effects of soil moisture, vapour pressure deficit, tree age, salinity, temperature and leaf area index. This is similar to the derivation of utilisable absorbed photosynthetically active radiation within 3PG, i.e. the driver for growth.

These functions are being applied to predict stand growth and transpiration with promising results, yet we don't know with confidence:
- Are the parameter values right?
- Are the functions right?
- Is the combination of modifiers as a simple product right?

Until we learn by wide experience what are the "right" values and functions, the model will tend to be used as an extension of the empirical approach to prediction of stand growth and transpiration: that is, it will usually require calibration against observed data for each distinctly new combination of tree, site and climate circumstances it is applied to. This is equally true of other available models which differ in their detail but not so much in their data inputs and outputs; for example Waves uses a different but no more tractable set of functions and parameters for calculations similar to those in 3PG+.

In summary:

- We should be moving towards applying models to predict stand transpiration, taking into account the relation between transpiration and growth.
- 3PG+ offers a suitable framework for this purpose at a monthly timescale, with realistic data requirements.
- Existing transpiration data sets could be usefully applied to improve the functionality of 3PG+ for some key species.
- Additional transpiration data is also needed, and should be collected from short term studies in species trials and other monitored/characterised stands.

While 3PG+ currently simulates water uptake from each layer of the soil profile, the accuracy of this in relation to patterns of temporal soil water profiles through time requires testing. Current research within DFES in mixed native species forests involves measurements on water balance components, including tree transpiration and soil water profiles over time. These data provides a valuable resource for validation of the uptake of water at depth over time.

8.2   Soil parameters

The empirical relationships that represent the availability of water in different textures, and that relates the soil water content to the soil water modifier, requires further investigation. There has been little attention given to the empirical nature of the soil parameters c_θ and n_θ. A more thorough examination of these parameters and the functions to which they apply may help improve the accuracy of the soil water balance component of the model.

Another avenue may be to explore the relationship between c_θ and n_θ, and to determine appropriate values for these parameters based on the texture classes given in McDonald et al. (1990). This may include establishing guidelines for ascribing one of the field textures to the root zone represented in the model.

8.3   Fertility rating

The fertility rating is a model parameter with great uncertainty and many model developers and users ask how does one assign objective values? Deriving a number for the fertility rating is generally a matter of local knowledge and intelligent guesswork. Suggested quantitative measures have included base exchange capacity of the upper soil layers, or total N content of the foliage. It may also be inferred from growth of vegetation on similar sites. At present, there is no objective process to estimate the fertility rating based on foliar or soil nutrient status. While the fertility rating may be perceived as related solely to soil nutrient availability, it actually reflects the complex soil conditions that influence growth and that are not specifically included elsewhere, such as the effects of soil pH, aeration and strength.

The fertility rating in 3PG provides a means of varying the effect of fertility on canopy quantum efficiency. However, this parameter is often used in the calibration procedure where it is altered to enable the model output to fit the observed data. While this provides information about how the model is performing, the results are not a test of the accuracy with which the model represents the real data. If the model is to be used in a predictive sense, then parameter values need to be assigned on the basis of the best available knowledge about the site and species.

It is generally thought that the growth of fertilised trees should not be limited by nutrition, and therefore FR would be set to 1. However, even with considerable research in this area, it is still difficult to accurately predict the effect of a given soil fertility on tree growth.

It has been suggested that a more objective mechanism for estimating the fertility rating could be developed by parameterising 3PG+ with comprehensive tree growth and nutritional data from fertiliser trials where clear fertiliser responses have been observed. The magnitude of changes in the fertility rating could be related to observed differences in tree growth due to the nutritional status of the trees, where the effects of climate and other soil factors do not differ significantly between different fertility treatments. While this may provide greater confidence in applying a value of the fertility rating based on site characterisation, the issue of applying values spatially across catchments, is still problematic. In the absence of any objective way to do this, it may be beneficial to relate the value of the fertility rating to a known soil attribute that describes the harshness of a site, such as soil depth for example. This is clearly an area where further research is required.

9. Future research, model development and application

While 3PG has been applied internationally for a variety of purposes, most have focussed on questions related to production of single-species plantations. With increased pressure on limited water supplies, there is increasing interest to apply the model to catchments to assess the variety of impacts that changes in vegetation cover can have on catchment water balances. This will require scenarios that can adequately represent multiple species forests, and will have to account for issues such as climate change.

While this report has focused on describing the 3PG+ model in the one dimensional sense, its real strengths lie in the possibilities to be applied at catchment scales. The ability to represent a mosaic of forest types and ages across a catchment, or forests and different agricultural land uses, provides many opportunities to simulate and examine key processes, and likely outcomes, of changes in climate and disturbances on the carbon and hydrological cycles within catchments.

Applying 3PG+ in this way will require further development, parameterisation and testing. Here we describe and provide possible avenues for further development of 3PG+ to address application to i) native forest ecosystems with overstorey and understorey components; ii) plant response to elevated carbon dioxide concentration, iii) groundwater uptake and salinity and iv) thinning.

9.1 Multi-species forests

9.1.1 General

Previous applications of 3PG have generally been 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 though, it 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 development of forests in new areas is largely dependent on quality of the input data (Mummery and Battaglia, 2002). Models may be calibrated 'successfully' against data from controlled experiments or where conditions are relatively uniform. Native forest systems, when compared to managed plantations, are generally more complex in vegetation structure and topography (and therefore also climate). So the prediction of growth and transpiration 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 large areas of native forest, than they have across many of the agricultural areas in which plantations have been established. The availability and quality of input data is likely to impose a limit to the ability for 3PG+ to simulate forest development of native forests.

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+ 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 transpiration, 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. The main fundamental differences between plantations and native forest systems in relation to simulating the main processes are listed in Table 8.1. The inclusion of an understorey component is also important given that the understorey can compete for water and therefore affect overstorey productivity. It is also true that the understorey component may contribute significantly to stand biomass, and therefore be important in estimations of carbon storage of forests.

Table 8.1. General differences between plantations and native forest systems relevant to 3GP+ modelling.

Plantations	Native forests
Ecology	
Monocultures	often Multi-species
Overstorey only	Overstorey and understorey
Uniform age	Often multi-aged
Short rotations	Longer timeframes
Faster growth rates (species; management)	Approach equilibrium with site
Competition managed (e.g. weed control)	Competition within system
Longer term changes (e.g. age effects) less important (short rotations)	Contain N-fixing understorey
	Regeneration/recruitment maybe ongoing
	LAI usually less than in plantations
Site characteristics	
High to moderate rainfall (commercial plantations)	High to low rainfall
Relatively high nutrient status (fertilised)	Relatively low nutrient supply (unfertilised)
Initial hydrologic imbalance	Hydrologic equilibrium (more often)
Physiological characteristics	
Selected for relatively fast growth	Often slow growing
High nutrient requirement	Low nutrient requirement
High water demand (generally from mesic sites)	High drought tolerance/avoidance (endemic to water-limited sites)
Limited drought tolerance/avoidance	

We propose that structural changes to allow for overstorey and understorey components should be made to 3PG+, 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.

We provide some guidance as to the main issues with incorporating an understorey component in 3PG+. These relate to the need to provide for the vertical distribution of factors such as i) radiation interception, ii) rainfall interception, iii) humidity gradients, iv) canopy conductance and evapotranspiration, and v) soil water uptake. A conceptual diagram showing these components is shown in Figure 8.1. These are discussed in more detail in sections 8.2.2, 8.2.3, 8.2.4 and 8.2.5.

RADIATION — Interception, absorption, and propagation of solar radiation

EVAPOTRANSPIRATION — Transpiration and soil evaporation into specific atmospheric layers

HUMIDITY — Humidity of specific atmospheric layers and its control of ET

PRECIPITATION — Interception of precipitation

LEGEND

⟹ Downward water flux

⟹ Evapotranspiration

→ Solar radiation

┈┈▸ Functional controls

Solar

Reference level atmosphere

Evaporation

Canopy radiation interception

Radiation control

Humidity control

Canopy atmosphere

Canopy precip. interception

Canopy throughfall

Canopy transpiration

Understorey radiation interception

Radiation control

Humidity control

Understorey atmosphere

Underst. precip. interception

Understorey throughfall

Understorey transpiration

Humidity control

Surface atmosphere

Soil evaporation

Figure 8.1. Main components of the proposed vertical structure for 3PG+ to simulate processes for an overstorey and understorey (modified from Watson, 1999).

9.1.2   Radiation interception

Solar radiation is intercepted, absorbed or transmitted by the two vegetation layers in succession, and the remainder is absorbed by the soil at the forest floor. These processes are modelled 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_{pa}) by the overstorey is represented as before (see section 3.1) by

$$\phi_{pa} = \phi_p \left(1 - e^{\left(-k_\varphi . LAI\right)}\right) \tag{57}$$

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 ($\phi_{pa(under)}$) can be calculated by

$$\phi_{pa(under)} = \left(\phi_p - \phi_{pa}\right)\left(1 - e^{\left(-k_\varphi(under) . LAI\right)}\right) \tag{58}$$

9.1.3   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. The relevant equations are based on Eq (44, 45) (see section 4.2) where interception by the overstorey is

$$I_{RO} = \min\left\{I_O{}^* R, I_{LO}L_O - R_{CO} + E_{CO}\right\} \tag{59}$$

where the parameters have the same meaning as in Eq Eq (44, 45) and the subscript O refers to the overstorey. Interception by the understorey is given by

$$I_{RU} = \min\left\{I_U{}^*\left(R - I_{RO}\right), I_{LU}L_U - R_{CU} + E_{CU}\right\} \tag{60}$$

where the subscript U refers to understorey.

Total interception by the forest canopy is then given by

$$I = I_{RO} + I_{RU} \tag{61}$$

Interception of rainfall by litter is not currently modelled, and this may require revision.

9.1.4   Evapotranspiration

Attention needs to be given to validation of evapotranspiration at different layers within the forest. For example, in the case of an overstorey and understorey component, the model will include 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 in equation (43) for the overstorey and understorey layers, different values of D_q (based on VPD) are estimated for each layer. The vapour pressure deficit at the overstorey canopy surface (VPD_O) is modified to reflect the effective deficit at the understory canopy surface (*sensu* Grantz and Meinzer 1990); this modified deficit (VPD_U) is calculated using the omega decoupling coefficient (Ω_c) proposed by Jarvis and McNaughton (1986):

$$VPD_U = \Omega_c VPD_{eq} + (1 - \Omega_c)VPD_O \tag{62}$$

with

$$VPD_{eq} = \frac{\gamma \varsigma R_n (c_p / r_s)}{\varepsilon + 1} \tag{63}$$

$$\Omega_c = \frac{\varsigma + 1}{\varsigma + 1 + r_s / r_a} \tag{64}$$

where VPD_{eq} is the equilibrium saturation deficit, and ς is s/γ, and ε is the dimensionless rate of change of saturated specific humidity with temperature (estimated as 2.2 at 20°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: $R_n = 0.8R_s - 90W$ 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.

A similar approach is used to reduce the vapour pressure deficit below the understory layer for any additional canopy layers, except instead of using VPD_O in equation (62), the understory canopy value of VPD_U is used.

9.1.5   Soil water availability

In 3PG+, the soil is divided into layers (see sections 7.1.1 and 7.1.2) and additionally into three zones (*A*, *U*, and *B*) defined by the fraction exploited by roots (Figure 8.2). 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 is the fraction exploited by roots from understorey species and from which water uptake can occur. Zone 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 (`dwemax`).
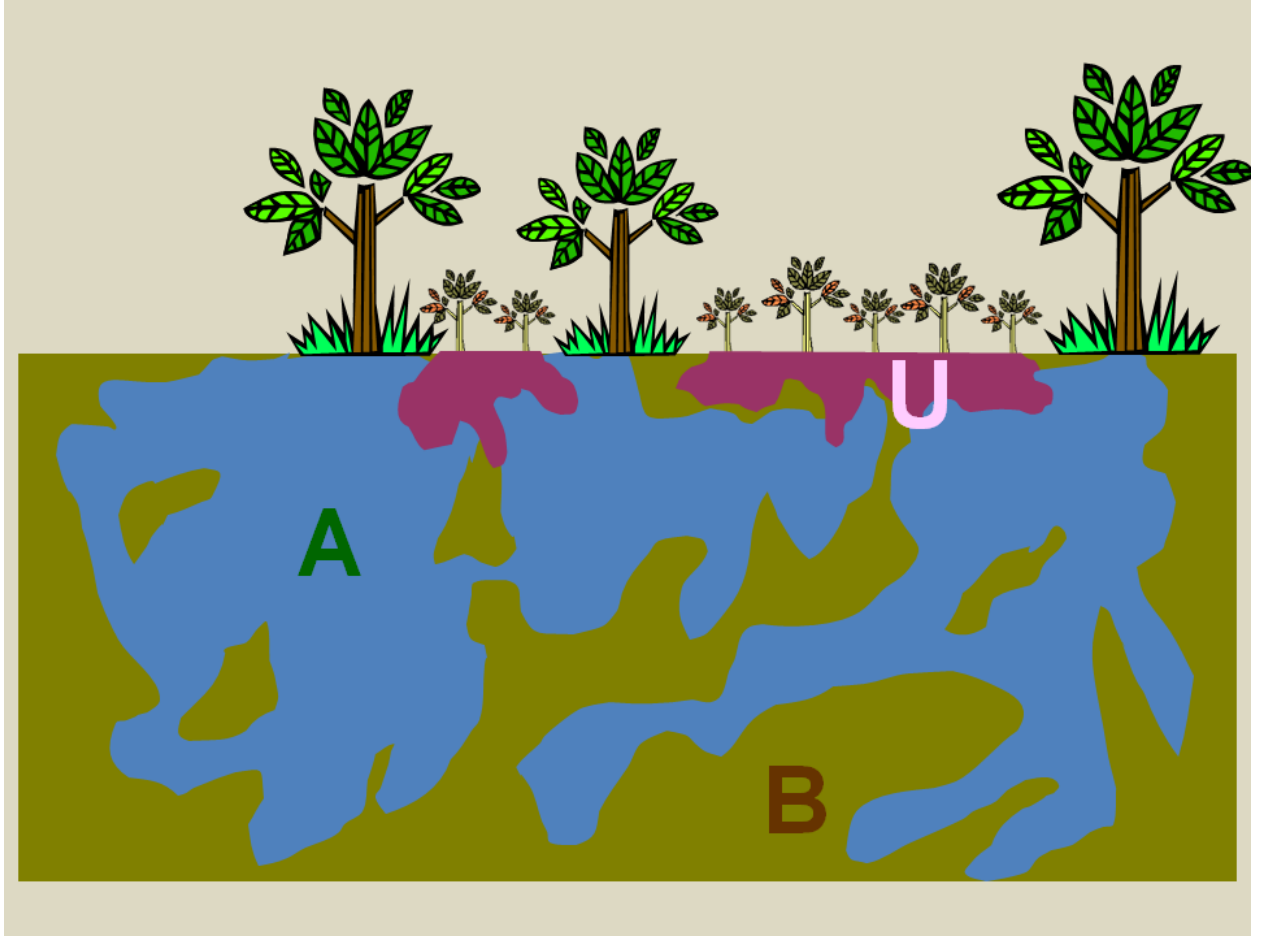
Figure 8.2. Representation of the zones in a single soil layer exploited by roots of the overstorey (A), understorey (U) and the unexploited zone (B).

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

$$Z_{Ai} + Z_{Bi} + Z_{Ui} = SW_i \qquad \text{if } SW_i > 1 \tag{65}$$

where

Z_{Ai} (`zwatA(i)`) = mm of moisture accessible to overstorey roots in layer i

Z_{Bi} (`zwatB(i)`) = is mm of water not accessible by roots in layer i

Z_{Ui} (`zwatU(i)`) = of moisture accessible to understorey roots in layer i

9.1.6 Species parameterisation

Conceptually, species parameters in 3PG apply to a particular species, and is irrespective of site or management. Parameterising for complex forest systems presents a challenge. In the first instance we suggest attempting to model an overstorey and an understorey component, each with its set of species parameters. 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. It may be possible to adequately describe an overstorey component, even though it itself may comprise more than one species, by a single set of parameters. For example, the light extinction coefficient (k_ϕ; see section 3.1) is a function of the angle of inclination of leaves. The angle of inclination of leaves in the understorey is generally lower ($\theta \approx 52^\circ$; i.e. more horizontal) than that of for a eucalypt overstorey ($\theta \approx 65^\circ$; Vertessy et al. 1996).

The current species parameter sets are based on data from plantations typically younger than 12-15 years. Furthermore, functions within 3PG+ have been derived from data from plantations, and it is possible that the model will be less accurate when simulating forest growth beyond 20 years. There will be a need to re-parameterise and even alter existing functions based on longer term simulations and older forests. 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. Investigation is required whether this process is better represented by allowing for decline in the slope of the conductance modifier (k_g) with age, in line with well-established relationships between stomatal conductance and vapour pressure deficit (see, for example, Dye and Olbrich, 1993; Leuning, 1995; Granier et al. 1996).

9.2   Response to elevated carbon dioxide concentration

9.2.1   Representation

Almeida et al. (2009) included effects of changes in atmospheric CO_2 concentration (C_a) on growth in a different version of 3PG (3PG$_2$), by introducing two additional modifiers that affect canopy quantum efficiency (α_C) and canopy (stomatal) conductance (g_C). Separate modifiers were used for α_C and g_C as the effects of atmospheric CO_2 on these are distinct. In 3PG, growth modifiers are bounded by 0 and 1, and act to reduce the potential growth. While the effect of increasing C_a on stomatal conductance results in a reduction of growth, the effect of increasing C_a leads to an increase in photosynthesis, and is therefore not bounded by 1. We propose that the approach taken by Almeida et al. (2009) be incorporated into 3PG+ for further testing.

Experimental and theoretical research suggests that light saturated assimilation rate and light use efficiency increase as C_a increases, and that maximum stomatal conductance decreases with increasing C_a (Ainsworth and Rogers, 2007). Results from gas exchange analyses indicate that the light saturated assimilation rate (and therefore α_C) increases with increasing C_a but at declining rate (Constable and Friend, 2000). Almeida et al. (2009) assume that this relationship saturates at high C_a. The same gas exchange analyses suggest maximum stomatal conductance decreases with increasing C_a, and Almeida et al. (2009) assume it declines to zero for very high C_a.

In the approach by Almeida et al. (2009), growth modifiers applied to the canopy quantum efficiency α_C ($f_{C\alpha}(C_a)$), and canopy conductance g_C ($f_{Cg}(C_a)$) represent the ratios of the variable to its value when $C_a = 350$ ppm. It is presumed that the current parameterisations of 3PG apply to $C_a = 350$ ppm. Almeida et al. (2009) parameterised both modifiers by their values at saturation, when $C_a = 700$ ppm. Growth modifiers are of the form

$$f_{C\alpha}(C_a) = \frac{f_{C\alpha x} C_a}{350(f_{C\alpha x} - 1) + C_a}$$

(66)

$$f_{Cg}(C_a) = \frac{f_{Cg0}}{1 + (f_{Cg0} - 1)C_a/350} \tag{67}$$

where $f_{C\alpha x}$ is the saturated value of $f_{C\alpha}(C_a)$ for large C_a, given by

$$f_{C\alpha x} = \frac{f_{C\alpha 700}}{2 - f_{C\alpha 700}} \tag{68}$$

and f_{Cg0} is the value of $f_{Cg}(C_a)$ when $C_a = 0$, given by

$$f_{Cg0} = \frac{f_{Cg700}}{2 - f_{Cg700}} \tag{69}$$

where $f_{C\alpha 700}$ and f_{Cg700} express values for $f_{C\alpha x}$ and f_{Cg0}, which are assumed to occur at $C_a = 700$ ppm.

It should be noted that parameterisation of these relationships is not based directly on observed data, but rather they were derived from predictions of α_C and g_C made by CABALA (Battaglia et al., 2004) for a range of values of C_a at three contrasting sites. Resulting parameter values of $f_{C\alpha 700} = 1.39$ and $f_{Cg700} = 0.69$ led to the best fit of the relationships (66) and (67) and to the CABALA predictions (Figure 8.2).
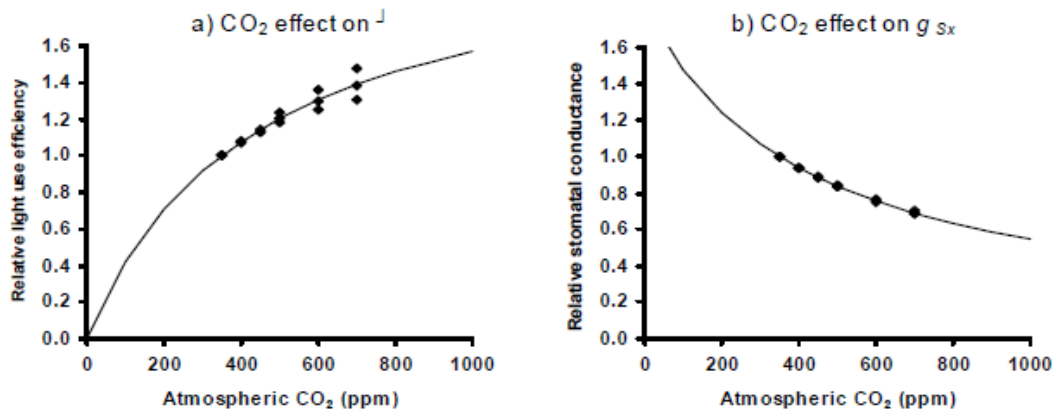
Figure 8.3. Effect of atmospheric CO_2 concentration on (a) light use efficiency and (b) maximum stomatal conductance at three distinct, contrasting sites. Points are output from the CABALA model for *Eucalyptus globulus*, scaled relative to values at $C_a = 350$ ppm for each site. Lines are fits of (66) and (67) to data, with 93% and > 99% variation explained in α and g_c, respectively (after Almeida et al. 2009).

9.2.2 Limitations

9.2.2.1 Parameterisation

While the CO_2 growth modifiers capture the functional form of the dependence of α_C and g_C on C_a, parameterisation is based on outputs from CABALA (Battaglia et al., 2004) process based model rather than directly on observed data. Nonethless, the predictions made by Almeida et al (2009) were consistent with results from FACE (Free Air CO_2 Enrichment) experiments provided by Ainsworth and Rogers (2007) and Buckley (2008). Those two studies reported that, for an increase in atmospheric CO_2 to

approximately 550 ppm, an increase in NPP of 24%-28% and a decrease in stomatal conductance of 16-24% across a range of species can be expected. The data in Figure 8.2 shows for a C_a of 520 ppm, that light use efficiency increases by 25% and conductance decreases by 20%, which is approximately consistent with the FACE observations (Norby et al., 2005).

9.2.2.2 Interactions and feedback

The modifiers do not take into account interactive or feedback effects. The literature suggests that both nutrition and water are likely to interact with CO_2 effects. If the uptake of C by the biosphere increases in response to the increase in C_a, then the rate of increase in atmospheric C_a will decrease. Furthermore, at lower LAI, a large proportion of the response to elevated C_a is through increased light absorption. At higher LAI, the response is wholly caused by increased light use efficiency (Norby et al. 2005). The issues of interaction and feedback become increasingly important when simulating longer rotations (e.g. native forests, as opposed to plantations).

The notion that increases in the concentration of CO_2 in the atmosphere lead to increases in photosynthetic rates implies that carbon is limiting to some degree. At the ecophysical scale, it has been argued that any limitation to carbon at present is only through limitation to soil nutrient cycling (Millard et al. 2007). The key to understanding future responses to climate change are turnover of soil organic matter and nutrient cycling.

There is a consensus in the literature that the nutrient cycle sets the ultimate limit to a carbon-driven, long-term stimulation of plant production (Finzi et al., 2002; Hungate et al., 2006). In studies on non-tree species conducted under conditions in which plant growth was coupled to the nutrient cycle, and particularly those in which plants had reached a steady-state canopy development, revealed far smaller (often zero) influences of elevated atmospheric CO_2 on standing crop biomass and productivity than had been found in systems decoupled from resource supply by either fertiliser application, disturbance or wide spacing.

The regulation of terrestrial carbon (C) sequestration by soil nitrogen (N) availability is a highly controversial issue in global biogeochemistry (Luo et al., 2004) and this controversy translates into great uncertainty in predicting future global terrestrial C sequestration. Luo et al. (2004) proposed a new framework that centres on the concept of progressive N limitation (PNL), in which available soil N becomes increasingly limiting as C and N are sequestered in long-lived plant biomass and soil organic matter. While the PNL-centered framework has the potential to explain diverse experimental results and to help researchers integrate models and data, direct tests of the PNL hypothesis remain a great challenge to the research community.

9.2.2.3 Time scales

There have been hundreds of papers and several reviews describing the responses of trees to elevated atmospheric CO_2 (e.g. Nowak et al. 2004; Ainsworth and Long, 2005). Interpretation of the results of these studies is difficult, as the responses are confounded by the timescales of the study, the stage of and growth (expanding vs closed canopy), and the relative availability of other resources such as nutrients (see Körner, 2006). Most studies are carried out over time scales that are not the time scale of the forest, and generally reflect only a small fraction of the lifetime of a tree (Norby et al., 1999). A common

response to elevated CO_2 in FACE experiments has been faster photosynthetic rates leading to an increase in above-ground and below-ground production (Nowak et al., 2004), although the initial responses in above-ground growth decline over time (Körner, 2006). So, although carbon assimilation increases with increasing atmospheric CO_2, it does so at a diminishing rate.

One reason of this is that the FACE experiments involve a 'priming' of the system with extra C, causing a disruption, and the system is no longer in equilibrium. While the flux of C from the tree into the soil may occur relatively sooner, the feedback between the forest soil and tree may take decades. It is not clear whether any of the experiments have yet reached a new equilibrium or stable state (Körner, 2006). Therefore, it is difficult to know if responses to the abrupt change in atmospheric CO_2 concentrations in FACE experiments would be the same as those to the (comparatively) gradual increase projected over the next 50 years or more. With a gradual rise in CO_2, the C priming effect will be much less and forests may remain closer to a steady state throughout the transition.

A major question still remains as to whether the rate of nutrient supply can meet the demand created by faster tree growth under elevated CO_2. It has been suggested that available soil N may increasingly limit growth as C and N are sequestered in woody biomass and soil organic matter (Luo et al., 2004). There is no evidence that systems within the FACE experiments have reached a new steady state with respect to the interaction between soil C and N cycling. Results generally suggest that, in the medium term, N cycling is unlikely to keep pace with the increases in NPP caused by C priming, resulting in an overall nutrient limitation rather than C limitation to forest growth (Millard et al., 2007).

Ecosystem simulation models suggest a down-regulation of NPP in response to an increase in atmospheric CO_2, when plant uptake of N exceeds the rate of replenishment via mineralisation (Rastetter et al., 1997; Luo and Reynolds, 1999). With a model calibrated to an old growth forest in the north-eastern United States, Rastetter et al. (1997) identified this as happening on a timescale of several decades, which is significantly longer than the duration of any of the FACE experiments.

The weight of evidence suggests that the physiological functioning and growth of individual trees is not limited by the availability of C. Evidence from both the biochemical (leaf) and physiological (whole tree) scales suggests that forest trees have an abundance of C compared with nutrients such as N or P. Where FACE experiments have provided a C priming to a forest system, there has been a faster cycling of C through the trees to the soil and back to the atmosphere because of increased soil autotrophic respiration. But the lack of evidence for an impact on N cycling processes suggest that all this extra labile C entering the soil has little impact on nutrient supply through SOM turnover. This suggests that the faster tree growth that has been observed with FACE has been supported by increased N use efficiency and N cycling, possibly through the interactions of mycorrhizal fungi and leaf litter.

9.2.2.4 Forest age and site conditions

The responses of trees to elevated CO_2 depends on i) whether the forest is expanding or in steady state ii) fertilised or unfertilised, and iii) young or mature (Körner, 2006). This study by Körner looked at the effects of soil type, fertiliser application, CO_2 concentration and showed that soil type and species characteristics were significant in identifying the response of forests to CO_2 concentration.

Altogether, these data warn against overstating beneficial effects of a CO_2-rich world for plant growth, based on inappropriate experimental conditions for such projections or unconstrained models, in essence

based on photosynthesis. Therefore, it may not be accurate to present mean responses, because any such mean would simply reflect the mix of data used (Körner, 2007).

9.3 Groundwater uptake and salinity

The presence and salinity of shallow groundwater has an important influence on tree growth. Trees that have access to groundwater source can grow faster and use more water in otherwise water limited environments (e.g Benyon et al. 2006). Furthermore, the use of saline groundwater may lead to a build up of solutes in the root zone, and potentially reduce growth rates and transpiration. In other cases, plantations may be irrigated with wastewater or pumped groundwater, which may also lead to a build up of solutes in the root zone. Incorporation of the effects of shallow groundwater and salinity into 3PG+ will increase its applicability to areas where these processes affect tree response. 3PG+ currently includes some capability to represent the effects of shallow groundwater and salinity with the following parameters

- Initial soil salt content (kg m^{-2})
- Irrigation water salinity (dS m^{-1})
- Groundwater salinity (dS m^{-1})
- Water table depth (m)
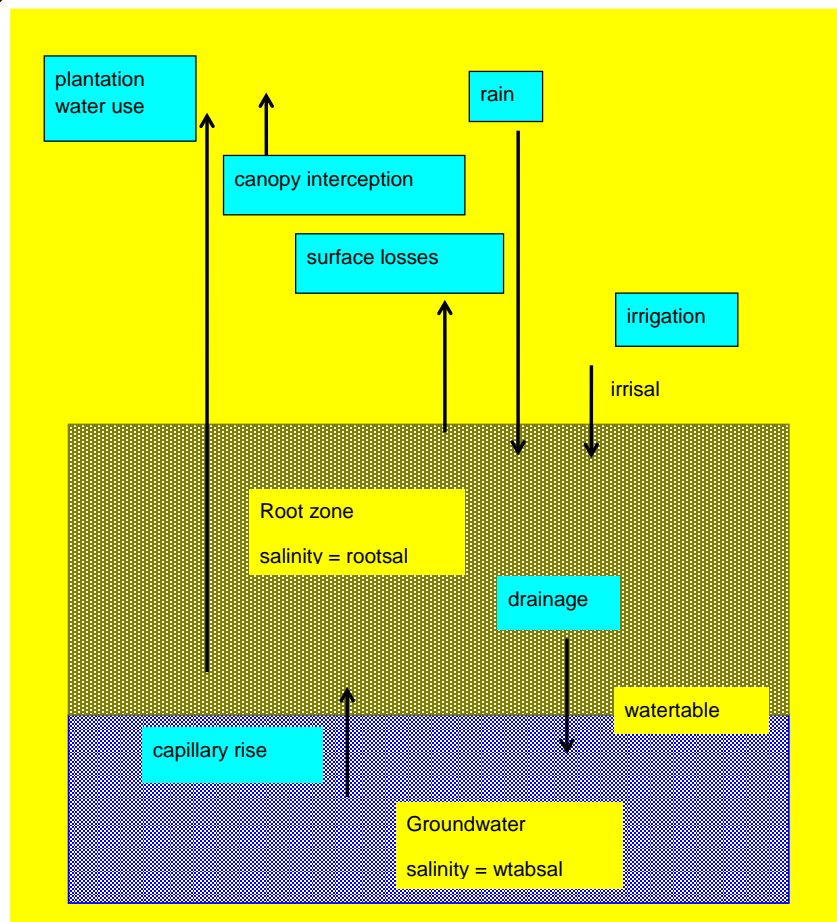- Maximum salinity for tree growth (dS m^{-1})
- Capillary rise factor

Figure 8.4. Conceptual diagram of the rootzone salt balance processes in 3PG+.

The salt stored in the root zone (kg m^{-2}) is given by

$$saltstore = [rootsal \times (soilwatAB + unavailwat)]$$ (70)

Where *soilwatAB* is root zone available soil water content (mm), *unavail* is unavailable soil water content (mm), for salinity calculations, and *rootsal* is the root zone salinity (mg L^{-1}) given by

$$rootsal_{t+1} = \frac{(saltstore + irrisal \times irrig + wtabsal \times caprise - rootsal_t \times drainage)}{(soilwatAB + unavailwat)}$$ (71)

Where *irrisal* is the salinity of irrigation water (mg L^{-1}), irrig is the amount of irrigation water (mm), *wtsal* is the salinity of the watertable (mg L^{-1}), and *caprise* is the daily amount of water in capillary rise from the water table (mm), and *drainage* is the daily amount of water that leaves the root zone (mm). An estimate of unavailable water (water content at wilting point) is required and given by

$$unavailwat = soildep \times 1000 \times \left(0.45 - \frac{c_\theta}{2}\right)$$ (72)

where *soildep* is soil depth (m).

A salinity modifier (f_{salt}) relates the effect of *rootsal* on absorbed photosynthetically active radiation (ϕ_{pau}) and on canopy conductance (g_c) (46) by

$$f_{salt} = 1 - \frac{rootsal}{600 \times maxsal}$$ (73)

and *maxsal* is a user defined species parameter representing the salinity in soil water for zero growth (dS m^{-1}) and reflects the salt tolerance of a particular species. The constant (600) converts values of *maxsal* from dS m^{-1} (usually used for soil salinity levels for plants) to mg L^{-1}. Preliminary values of *maxsal* include 13 dS m^{-1} for *E. globulus*, 15 dS m^{-1} for *P. radiata*, 20 dS m^{-1} for *E. saligna* and 30 dS m^{-1} for *E. camaldulensis*.

One limitation is that it is not possible to simulate a dynamic or variable watertable depth in the 1D version of 3PG+. This behaviour is unrealistic except in conditions of very high saturated hydraulic conductivity. Watertable levels could be read in from a file, but would not be responsive to recharge or discharge processes. It is important that the watertable is responsive to daily groundwater uptake and drainage.

Water entering the soil each month but not transpired or stored becomes drainage, some of which reaches the groundwater and raises the watertable. When roots reach to the watertable depth, groundwater uptake may occur and will tend to lower the watertable. When the watertable beneath the plantation is not at the same level as the external watertable, water will flow from the higher to the lower at a rate determined by the hydraulic conductance of the saturated zone. If the watertable rises above the current rooting depth, the "drowned" roots remain alive but do not take up water, i.e. the soil below the watertable is not included in Zone A.

There is relative large sensitivity of the root zone salt storage to the maximum soil water storage. Root zone salt storage can increase suddenly when moving from a site of low maximum soil water storage to one of high maximum water storage, where leaching is minimised and salinity appears to be independent of the maximum soils water storage.

The ability to simulate recharge to groundwater, and upward flux from (shallow) groundwater into the base of the root zone is possible. The volume of water upward inflow must be calculated using a separate groundwater model that receives recharge estimates from CAT1D simulations.

Application of the water and salt balances to observed field studies of tree growth in relation to shallow saline groundwater will help test the accuracy of this model component, and to more precisely define the parameters values. There is a body of knowledge on the effects of salinity on plantation tee growth for different species from longer term field studies such as that undertaken under the Trees for Profit program (for example, Batey and Morris, 1995; Hamlet and Morris,1995).

Waterlogging of forests is often associated with rising groundwater, and has the potential to reduce growth and transpiration. The 3PG+ model at present takes no account of tree death due to very wet or waterlogged conditions. Depending on the species tolerance to water logging, and site and soil conditions, waterlogging can have a severe impact on tree growth and transpiration. The model could be extended to allow for reduced tree growth and death due to waterlogging. In keeping with the structure of the model, a waterlogging modifier could be developed and included in the derivation of utilisable PAR. This modifier should be a function of the drainage of the site (soil hydraulic conductivity and slope) and the waterlogging tolerance of the species being studied.

Such a relationship should allow for decreased growth and death of trees when the soil water ratio (r_θ) is equal to one for an extended period. The value of r_θ may need to be sufficiently large to reflect a longer period of waterlogging. The next step would be to locate and collate the appropriate data and develop relationships that could be used in calculating the waterlogging modifier.

9.4 Thinning

The 3PG+ model currently includes some capacity to allowing for thinning of a plantation when a specified proportion of the trees reach a given diameter, resulting in a short term reduction of biomass and a change in the diameter distribution of retained trees. This function allows for a removal of stem and foliage biomass, and therefore a reduction in LAI. However, the function is untested and is limited to plantation based scenarios with a single species.

Development of the ability for 3PG+ simulate thinning is also important in the context of native forests and catchment water balances. While the general impact of large-scale forest disturbance on water yield in south east Australia is well-established (Vertessy et al., 1993, 1996, 2001), predicting the impact of thinning remains challenging because the forest is only partially disturbed and a complex structure of overstorey and understorey may remain or develop. Thinning reduces canopy cover and, initially at least evapotranspiration by forests, and it has been put forward as an attractive management option, especially as water becomes more expensive and scarce. The other complexity is that thinning or removal of overstorey species may lead to changes in forest structure, where the understorey responds to newly created gaps (or newly available resources).

Current research within DFES is focussed on
- quantifying changes in water yield from long-term paired catchment studies, and measures current streamflow to determine persistence of these changes.
- investigating post-thinning interaction of vegetation structure and evapotranspiration (ET) through the measurement of leaf area index (LAI).

- quantifying and comparing water yield changes at catchments that have undergone different thinning regimes.
- measurements of streamflow and rainfall to investigate persistence of yield changes.
- correlating vegetation indices retrieved from high resolution satellite images to ground-measured LAI to get LAI spatial distribution at catchment level.

There is great potential to apply, develop and validate 3PG+ so that it can adequately simulate the response of the forest and water balance to thinning regimes.

9.5 Fire

Fire continues to be the most important disturbance in Australia's water supply catchments. The nature and intensity of wildfire is such that it has immediate effects on the physical properties of infiltration and runoff due to enhanced hydrophobicity and the removal of surfaces that would reduce sheet flow along slopes. Catchment responses in the longer term (years to decades) are related to changes in evapotranspiration resulting from changes in forest structure and composition. The effect fire has on forests depends on the fire intensity, and on the age and type of forest affected. The degree to which forests recover depend on these and also on rainfall (and water availability) after the fire.

Experimental studies investigating the hydrologic response of forest disturbance on ET and on catchment water yield have demonstrated that regenerating *E. regnans* forests burnt in the severe 1939 bushfires were using more water than the mature forests they replaced resulting in a reduction in water yield over 21 years following the fires (Langford, 1976). These findings have been supported by a large body of research (eg. Kuczera, 1987, Vertessy et al., 1993, 1996, 2001, *Watson et al.,* 1999, 2001), that have both confirmed the impacts and identified the causal processes. The age/streamflow relationship for *E. regnan*s was generalised by Kuczera (1987) using rainfall and runoff data collected from eight forested catchments that were completely or partially burnt by a wildfire in 1939, and is represented by the well-known 'Kuczera curve' shown in Figure 8.4.
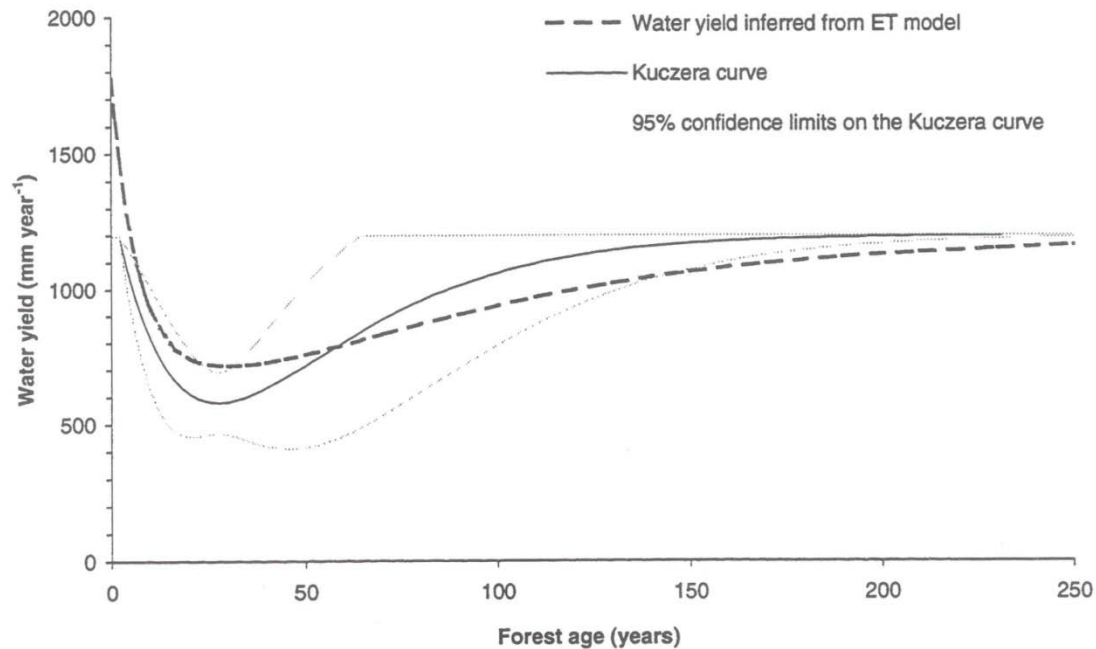
Figure 8.5. Generalised average annual water yield with forest age shown by the Kuczera curve (after Kuczera, 1987), and inferred from evapotranspiration, by Watson *et al.* (1999b). Dashed lines are 95% confidence intervals.

There has not been the same level of research into eucalypt mixed-species age/streamflow relationships, but studies have detected a similar, though subdued, response to clearfell logging (Cornish, 1993; Cornish and Vertessy, 2001; Lane and Mackay, 2001; Roberts et al. 2001). There is a challenge to see whether it is possible, in 3PG+, to distinguish between the ash type and mixed species systems where there are very different ecological responses to fire.

It would be valuable to apply 3PG+ at the catchment scale and examine its ability to simulate the observed response in stream flow to large scale disturbance or fire. To date, the Macaque model (Watson, 1999) has been applied to water supply catchments to investigate the effects on forest ET and catchment streamflow the potential influences of wildfire and changes in rainfall and temperature from climate change projections (Feikema et al. 2008). However, Macaque does not represent the growth of forests as it is affected by environmental conditions and changes in carbon dioxide concentrations. The application of 3PG+ would allow for the effects of changing climate and carbon dioxide concentrations on both carbon and water cycles.

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Appendix A. List of symbols, labels in source code, and descriptions of parameters and calculated values referred to in this report.

Symbol	Label in code	units	Type	Description
Light interception, production and respiration				
k_φ	kphi	-	Species parameter	Beer's law constant for calculating absorbed radiation
α_c	alphac	G MJ^{-1}	Species parameter	Maximum canopy quantum efficiency
φ_{pa}	abspar	MJ m^{-2}	Calculated	PAR absorbed by canopy
φ_{pau}	phipau	MJ m^{-2}	Calculated	utilisable PAR
Y	cpp	-	Species parameter	Fraction of NPP/GPP
Canopy conductance				
g_c	gc	m s^{-1}	Calculated	Canopy conductance
$g_{c\,max}$	gcmx	m s^{-1}	Species parameter	Maximum canopy conductance
f_{gtemp}	gcftemp	-	Calculated	Modifier based on daytime temp for g_c
Soil water modifier				
f_θ	ftheta	-	Calculated	soil water modifier
r_θ	rtheta	-	Calculated	soil moisture ratio for calculating ftheta
c_θ	ctheta	-	Defined by soil texture	constant term in soil moisture modifier
n_θ	ntheta	-	Defined by soil texture	power term in soil moisture modifier
Temperature modifier				
f_T	ftemp	-	Calculated	Temperature modifier
T_a	ctav	^{o}C	Climate input	mean daily temperature
T_{min}	tminpar	^{o}C	Species parameter	Min temp for ftemp modifier
T_{opt}	toptpar	^{o}C	Species parameter	Optimum temp for ftemp modifier
T_{max}	tmaxpar	^{o}C	Species parameter	Max temp for ftemp modifier
VDP modifier				
f_{VPD}	fD	-	Calculated	VPD modifier
D	cvpd	kPa	Climate input	mean daily VPD
k_g	kg	-	Species parameter	Coefficient for fD modifier
Age modifier				
f_{age}	fage	-	Calculated	stand age modifier
age_{max}	maxAge	years	Species parameter	Constant for age effect on growth
n_{age}	nage	years	Species parameter	Power for age effect on growth

Frost modifier

f_{frost}	ffrost	-	Calculated	frost modifier

Salinity modifier

f_{salt}	fsalt	-	Calculated	root zone salinity modifier

Fertility rating

F_0	mfert	-	Site parameter	Fertility rating (or modifier) at age 0
F_t	mnfert	-	Calculated	Fertility rating (or modifier) at age t years
m_f	fertmult	-	Site parameter	Constant term in mnfert calculation
dec_f	decfact	-	Site parameter	Power term in mnfert calculation
ff	fertfac	-	Species parameter	alphac adjuster for fertility response

Litterfall

γ_f	gammaf	-	Calculated	Litterfall rate per month
$\gamma_{f\,max}$	gammafmax	-	Species parameter	Maximum litterfall rate per month
c_γ	cgamma	-	Species parameter	empirical constant
k_γ	kgamma	-	Species parameter	empirical coefficient
l_{thresh}	lthresh	-	Species parameter	Value of f_θ for drought-enhanced litterfall

Carbon allocation

η_r	netar	-	Calculated	Allocation of NPP to roots
η_s	netas	-	Calculated	Allocation of NPP to stems
η_f	netaf	-	Calculated	Allocation of NPP to foliage

Allometric stem and foliage

a_f	afco	-	Species parameter	used to derive age-related allometric foliage coefficient
$n_{f\,.base}$	nfbase	-	Species parameter	base for age(fertility)-related allometric foliage coefficient
n_f	nffac	-	Species parameter	used to derive age(fertility)-related allometric foliage coefficient
a_s	asfac	-	Species parameter	allometric stem coefficient
n_s	nsfac	-	Species parameter	allometric stem coefficient
x_{af}	xaf	-	Calculated	revised a_f as influenced by fertility
x_{nf}	xnf	-	Calculated	revised n_f as influenced by fertility

Stand characteristics

w_s	meanstemkg	kg	Calculated	Mean stem weight of an individual tree
W_s	wswood	kg m^{-2}	Calculated	Total stand stem weight

V_s	newvol	m³ ha⁻¹	Calculated	Total stand volume
BA_1	ba	m² ha⁻¹	Calculated	Stand basal area (younger than 18 months)
BA_2	ba	m² ha⁻¹	Calculated	Stand basal area (older than 30 months)
H	heightvpgm	m	Calculated	Mean height

Rooted soil

-	dwemax	mm	Site parameter	Maximum root depth
-	fulrootden	kg m⁻³	Default 0.1	density required to access all soil water
-	fulrootfrac	kg m⁻³	Calculated	Current root density
-	fulrain	kg m⁻³	Default 0.1	root density required to intercept all rain effective rain

Tree mortality and self thinning

N_0	stockinit	trees ha⁻¹	Site parameter	Tree density a planting
N_{early}	stempara	trees ha⁻¹	Calculated	maximum tree density for young stands
β_{early}	afact	-	Species parameter	Mortality function factor (parabolic phase)
N_{mature}	stem32	trees ha⁻¹	Calculated	Maximum tree density for mature stands
β_{mature}	p32fact	-	Species parameter	Mortality function factor (power phase)
n_N	thinpower	-	Species parameter	Mortality function power (power phase)
-	mortfac	-	Species parameter	Fraction of stem biomass lost when tree dies

Specific leaf area and LAI

SLA_{init}	initsla	kg m⁻²	Species parameter	initial value of *SLA* for young trees
SLA_{final}	finsla	kg m⁻²	Species parameter	value of *SLA* for mature trees
SLA_{dec}	sladec	-	Species parameter	exponential decline factor
SLA	sla3pg	kg m⁻²	Calculated	Specific leaf area
LAI	lai3pg	m m⁻¹	Calculated	leaf area index
w_f	wfwood	kg m⁻²	Calculated	foliage mass

Branch fraction

BF_{init}	initbf	-	Species parameter	initial branch fraction in young stands
BF_{final}	finbf	-	Species parameter	final branch fraction for older stands
BF_{adj}	bfadj	-	Calculated	value of finbf adjusted for stand density
BF_{dec}	bfdec	-	Species parameter	an exponential decline factor
z_{fac}	zfac	-	Calculated	factor for bfadj calculation

Rainfall interception

I_L	crownfrc	mm LAI⁻¹	Species parameter	term linking crown storage to LAI
I^*	crownppt	-	Species parameter	max. fraction of incoming rainfall that can be intercepted

R_C	crownstr	mm	Calculated	existing crown-stored rainfall
E_C	crownevp	mm	Calculated	evaporation of crown-stored rainfall
I_R	xint	mm	Calculated	rainfall interception by canopy

Appendix B. Descriptions of the subroutines within 3PG+.

===== threepg =====

call grgdaytmp

calculates
1. The declination of the sun based on Julian day number
2. Daylength based on declination of the sun
3. Mean temperature during daylight hours

and is described in DSE (2007) by eqs 3.7.5, 3.7.4 and 3.7.3 respectively.

call init3pg

- initialises control variables including thinning triggers
- initialises control variables (commented out variables not used)
- lists parameter values (based on *E. globulus*)
- contains site parameters
- contains thinning/harvesting
- contains fallow period factors
- contains irrigation regimes
- lists conversion factors
- includes default climate (one year from Shepparton)

These lists are overridden by species and site parameter sets.

call param3pg

This subroutine reads the 3PG input data from a common csv file. Reads in species parameters from type9 file and site parameters from manager file.

[call input3pg

This subroutine reads the 3PG input data from the type9file using the original file formats as used by the VB version.

[call readbuf (idcol,ctwenty,chrlong

Subroutine to read data from a csv file where chrlong is the csv character string and idcol is the column corresponding to the required data which is returned via ctwenty as a character string of length 20.

```
[ call readbuf (idcol,ctwenty,chrlong)
[ call readbuf (idcol,ctwenty,chrlong)
```

[call rootl

Calculates the maximum root length

```
if(rootmx.lt.0.0) then
     dwemax=dwemax*abs(rootmx/100.0)
   else
     dwemax=amin1(dwemax,rootmx)
   endif
```

where `rootmx` = effective rooting depth (mm); `dwemax` = maximum root depth (mm; species parameter), but elsewhere, `rootsmax=dwemax.` <mark>Note sure how this works</mark>

[call rootd

Calculates maximum root depth.

[call standinit

Sets initial values of stand variables for this rotation. It initialises stand factors including
- resets fertility for a new rotation after fallow
- restores saved values of tree parameters
- time since planting
- use correct par absorption for incomplete canopy
- use polynomial mortality at start
- distribute initial seedling weight
- initialise carbon pools assuming
    - retain C pools between rotations
    - dead overstorey C is removed at harvest (but not understorey)
    - dead understorey C pool becomes litter after a harvest
- Initiatlise stand volume and diameter distributions

- set SLA, LAI, meanstemkg(itr3PG), DBH, BA, height, bfrac
- calculates root zones fractions where
    - zoneBfrac = unrooted fraction of root zone
    - zoneAfrac = overstorey fraction of root zone
    - zoneUfrac = understorey fraction of root zone

[call soils3pg

This subroutine calculates the 3PG input soil data based on parameters supplied in the soils.csv file, and it:
- calculates root distribution at maximum extension assuming the Ritchie shape so as to give bias to the topsoil layers when calculating representative values for ntheta and ctheta (the original 3PG assigned ntheta and ctheta based on surface soil texture only)
- it defines depth averaged soil water constant (ntheta) and soil water power (ctheta) texture parameters where

	ctheta	ntheta
Sand	0.75	10
Loamy sand	0.70	9
Sandy loam	0.65	8
Loam	0.60	7
Silt loam	0.55	6
Silty clay loam	0.50	5
Clay loam	0.45	4
Sandy clay	0.40	3
Silty clay	0.35	2
Clay	0.30	1

ctheta and ntheta are calculated based on maximum available soil water content defined as field capacity less wilting point which is equivalent to paramter fc() noting that this parameter has been modified in subroutine soilchara - as such both ctheta and ntheta are volumetric weighted parameters

----
if(iplnt3pg.eq.1) call erosnls

In the event of preceeding crops (eg pasture and fallow) prior to sowing plantation forestry, check 3PG flag to ensure 3PG soil water initialisation calculated on day of planting. `erosnls` is a subroutine to estimate erosion length scale.

call drysw3pg

This subroutine calculates the 3PG input soil data. It defines the depth averaged soil water constant (ctheta)and soil water power (ntheta) texture parameters. ctheta and ntheta are calculated based on maximum available soil water content defined as field capacity less wilting point which is equivalent to paramter fc() noting that this parameter has been modified in subroutine soilchara - as such both ctheta and ntheta are volumetric weighted parameters. (not sure how this is different to soils3pg).

call monthclim (i3pgerr)

Calculates monthly climatic variables from daily data, which is used by 3PG to grow trees.

[call monthmets (i3pgerr)

Initialises key variables and performs various calculations on climate variables.
- calculates saturation vapour pressure
- calculates daily average vapour pressure deficit
- checks climate file backspaced to 1st day of current month
- modifies climate variables
- adjusts daily potential evaporation and solar radiation if site modifiers have been assigned
- modifies climate variables for climate change
- adjusts potential evaporation and radiation to account for landscape aspect
- resets current day's canopy rainfall interception variables

[[call intercept

Calculates interception of rainfall by the tree canopy.

It uses two species parameters, `crownfrc` (term linking crown storage to LAI) and `crownppt` (maximum fraction of daily incoming rainfall that can be intercepted).

It calculates
- maximum crown storage based on lai (`crownfrc*lai`)
- existing crown stored rainfall (`crownstr`)
- daily potential evaporation of crown stored rainfall (`pet`)

and then
- available interception is calculated as the maximum less the previous day's storage plus current day's evaporation
- maximum interception is calculated and assumed to be a fixed fraction of daily rainfall

- current canopy storage is updated
- potential evaporation is modified
- rainfall is modified to derive effective rainfall (to account for interception)

----

call init3pg

as above

call param3pg

as above

call monthcals

Average daily climate parameters are initialised and evapotranspiration is then calculated. The call statements are such that `canopycond` and `hydrocalcs` are calculated before roots. This approach allows for ftheta correction in the event of soil water running out and hence growth is reduced by drought, thin soils or small roots.

[call pjsmortality

Provides an option to calculate tree mortality as described in Sands and Landsberg (2002) and includes the modification for early mortality.

[call calcmortality

Calculate trees mortality for the current month based on a parabolic function for early mortality (`stempara`), and the -3/2 rule (`stem32`) for mortality in older stands. These functions define the maximum density (trees ha^{-1}) for a given mean stem mass (kg) and reduced the number of trees if modelled density exceeds this.

[call thinning

Tests for thinning trigger condition and applies type 1 or type 2 thinning if appropriate. This subroutine is untested.

[call getpar

Calculates PAR from solar radiation and adjusts PAR for early growth before canopy closure.

[call absorbedpar

Allows for canopy light transmission by calculating absorbedPAR from PAR using Beer's Law.

[call modifiers

see below

[call canopycond

Calculates gc for the month from gcmx (species parameter) and a series of modifiers (ftheta, fd, fage, gcftemp). Here, a different version of the temperature modifier is calculated based on average daytime (rather than daily) temperature. Then, gc is modified by LAI using a continuous smooth function (tanh).

[call absorbedpar

as above

[call modifiers

Calls up the growth modifiers, vpdmod, frostmod, agemod, tempmod, soilwatermod and saltmod.

[[call vpdmod

Calculates fd, the VPD modifier using kg (species parameter) and VPD.

[[call frostmod

Calculates ffrost, the frost modifier, using the number of frost days in the month and days in the month.

[[call agemod

Calculates fage, the age modifier using age (years since planting) and two species parameters (maxage and nage).

[[call tempmod

Calculates ftemp, the temperature modifier, using average daily temperature and values for tmin, tmax and topt (species parameters).

[[call soilwatermod

Calculates ftheta, the soil water modifier, using rtheta (calculated) and average values for ctheta and ntheta calculated for the whole soil profile. Values of ctheta and ntheta depend on texture and are read for each soil layer from the soils.csv file.

[[[call rtheta3pg

Calculates rtheta, the relative saturation in the soil zone occupied by roots, namely soilwatA. rtheta is used to calculate ftheta in soilwatermod.

[[call saltmod

Calculates fsalt, the salinity modifier, using the current amount of salt in the rootzone (rootsal), and a species parameter the describes the tree's salt tolerance (maxsal).

[call canopycond

as above

[call irrigcalcs

Calculates irrigation schedule based on `mirrig` (a variant to hold three sets of monthly base irrigation rates), `irriglevel` (a selector for low/medium/high irrigation rates), and `irrifac` (a multiplier times 600 mm/year irrigation). This option is untested and not functional at present.

[call hydrocalcs

Calls subroutine penman and calculates transpiration demand based on penman-montetih equation and adjusts this if there is insufficient available water to meet transpiration. The soil store not occupied by roots is updated in cases where roots do not fully occupy the soil profile (ie `fulrootfrac`<1). Where `fulrootfrac`=1, soilwatB (unrooted part of the soil) is undefined as there is no zone B. Annual transpiration and drainage accumulators are updated.

[call utilisablepar

Applies simple product of modifiers to absorbed PAR to derive absorbed utilisable PAR.

[call netpsyn

Calculates GPP from absorbed utilisable PAR, and NPP from GPP. Allows for maintenance respiration which is currently not activated.

[call allocate

calls `rootfac` – which calculates root allocation fraction (`netar`) from 'harshness index' `phipau/abspar`, fertility, and the two root coefficients (species parameters).

calls `stemfac` – which calculates the stem allocation fraction, allowing for fertility effect,

The foliage allocation is then calculated by difference where it equals `1-rootfac-stemfac`.

[call litterfall

Calculates litterfall asa a function of age and the three litterfall parameters (species parameters), allowing for drought effect if `ftheta` < `lthresh`, and allows for salt enhanced litterfall by `fsalt`.

[call utilisablepar
[call netpsyn
[call allocate
[call litterfall
All as above

----

call updtbioms

- calculates new tree density
- calculates foliage, stem and root mass with error checks

- carbon pools are updated
- stem loss and foliage loss assumed to be removed during thinning (if invoked) whereas root loss stays in the soil
- calculates daily root update (only for daily timesteps
- updates tree age
- updates effective root zone water contents and rooting fractions (soil zones A (overstorey rooted), zone B (unrooted) and (if present) zone U (understorey rooted))

call standfacs

- if fertility decline is invoked, calculates current fertility allowing from decline factor (decfact) and age (ageyrs)
- calculates specific leaf area (SLA) based on 3 species specific parameters and age
- calculates leaf area index (LAI) base on SLA (sla3pg) and foliage mass (wfwood)
- calculates diameter at 1.3 m (dbh) by first calculating mean stem mass (meanstemkg)from total stem mass and stocking, and then dbh from mean stem mass and two allometric coefficients asfac and nsfac (species parameters)
- calculates basal area (ba) by three different methods; if trees <18 months, then ba is a function of dbh and stocking; if trees >30 months, then ba is calculated from weibul distribution; and if tree age is between 18 and 30 months, BA is calculated as a weighted average between the two (note that the calculation of ba is untested)
- calculates sapwood area (sa) as the difference in current ba and ba of 6 years earlier (this is specified in species parameters and can be changed)
- calculates dominant height from stand volume (standvol) and basal area (ba)
- calculates branch fraction (bfrac) from three species parameters, tree age (ageyrs) and stocking or tree density (stocking)

[if(ageyrs.gt.0.0) call diamdist

Calculates current diameter distribution parameters based on a Weibull distribution (untested).

---

if(.not.fallowflag .and. rotmonth.eq.harvmon) call harvest

This applies only multi-rotation simulations and considers harvesting plantation, ie. where two or more tree crops are planted in succession. This calls for a forced harvest. The subroutine harvest calculates calculate final (part)year stand growth and saves values of tree parameters during fallow (if specified).

call roots

Applies a simplistic linear root growth algorithm (outside of 3pg). I need to follow up with CRB as this seems to come from other crop models.

if(markpr.eq.1) call prnt3pg

markpr appears to call several other routines outside of 3PG+ (no idea what it means). Subroutine prnt3pg seems to record outputs.

call dailymods

Defines daily values for modifiers associated with VPD (or D), age, temperature and soil water for subsequent calculation of canopy conductance and transpiration.

[call dvpdmod

Calculates daily values for `fd`, the VPD modifier using `kg` (species parameter) and daytime VPD.

[call dagemod

Calculates `fage`, the age modifier using age (years since planting) and two species parameters (`maxage` and `nage`).

[call dtmpmod

Calculates daily values for `ftemp`, the temperature modifier, using average daily temperature and values for `tmin`, `tmax` and `topt` (species parameters).

[call dwatmod

Calculates daily values for `ftheta`, the soil water modifier, using `rtheta` (calculated) and average values for `ctheta` and `ntheta` calculated for the whole soil profile.

[[call rtheta3pg

As above.

---

call canopycond

As above

call hydrocalcs

As above

[call penman

Calculates transpiration, correcting `gc` and `ftheta` if available soil water is insufficient, using the Penman-Monteith equation.

---

call roots

As above

call transp3pg

- calculates a relative water content (fraction of field capacity) for each soil layer
- evaporative demand/potential evapotranspiration E_0 assumed to be equilivant to pet evaporation (mm)
- LAI explicitly calculated above - as such, back calculate cover
- assign crop cover and LAI
- Calculate potential transpiration (Perfect version)

- assumes transpiration demand sourced from each soil layer independant of available root density/architecture
- currently set so that transpiration demand sourced from each layer until met
- reduce transpiration if total evapotranspiration > daily pet

----
[call rootf

Selects root density distribution scheme, either 1) Ritchie exponential decay function; 2) depth power law decay function; or, 3) proportional depth

----
call dwatmod

As above

[call rtheta3pg

As above

----
call canopycond

As above

call layspenman

As for `subroutine penman`, it calculates transpiration, correcting gC and ftheta if available soil water is insufficient but takes transpiration from each layer into account. Why is it different to `penman` ?

[call day3pg

- Calculates solar declination from day of month
- Adjusts radiation for latitude
- Calculates daylength from solar declination and radiation

```
call dwatmod
call canopycond
call layspenman
call rootf
```

All as above

```
if(jim3pg.ne.2 .and. markpr.eq.1) call prnt3pg
```

When `jim3pg=1`, the current 3PG+ is used, if `jim3pg = 2`, then an older version with monthly time step is used. `markpr` appears to call several other routines outside of 3PG+ (no idea what it means). Subroutine `prnt3pg` seems to record outputs.

Appendix C. Descriptions of solution flags within the 3PG+ source code.

idfmet

Is a switch that relates to the format of the input climate file. If the climate file has multiple header lines, then `idfmet`=2 has multiple header lines, and if the climate file has only one header line, then `idfmet` <>2. `idfmet` can then be assigned the integers 1, 3 or 4 depending on other aspects of the format of the climate file.

idwmet

`idfmet`=0 by default, or `idwmet`=2 when `idfmet`=2. Outside of 3PG+ source code.

jim3pg

The solution flag jim3pg refers to running the current version with daily transpiration components calculated based on LAI equilvant (`jim3PG`=0), or based on penman which requires estimating modifiers and canopy conductance penman (`jim3PG`=1), or the older version with monthly water balance (`jim3PG`=2). The older version has not been used for some time and may be unstable. The default is `jim3PG`=1.

jimpan and **jimten**

jimpan assigns monthly VPD using pan data in weather file (0=no 1=yes), and jimten converts assigned VPD from millibars to kPa (=pan/10) (0=no 1=yes). Note that these switches are only used in the older version (jim3PG=2) of 3PG+.

iplnt3pg

If `iflag` in the manager csv file is = 9, then (`cropflag(icrop)`.= 9 and `iplnt3pg`=1.

If `icrop`>1 and `iplnt3pg`=1 then 3PG+ starts by first calling `init3pg` and `param3pg`.

ntr3pg

The number of species in the current simulation, specified in the type9 csv (species parameter) file. `ntr3pg`=1 for plantations or overstorey, and `ntr3pg`=2 for overstorey and understorey components.