

Technical Report No. 29

**3PGpjs – a User-Friendly Interface to 3-PG, the
Landsberg and Waring Model of Forest Productivity**

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Productivity

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3-PG was developed by Joe Landsberg and Dick Waring. Enquiries concerning 3-PG should be directed to Joe Landsberg (email: joe.landsberg@landsberg.com.au).

Enquiries or suggestions concerning the **3PGpjs** interface are welcome and should be directed to the author.

Summary

3PGpjs is a user-friendly interface for 3-PG, a model of forest productivity (Landsberg and Waring, 1997). It was designed primarily to facilitate the use of 3-PG in a research setting, e.g. the adaptation of 3-PG to novel species or situations, although it is ideally suited to perform production runs at a single site or across a moderate number of sites. The interface is via MicroSoft Excel worksheets and is coded in Visual Basic. Normal spreadsheet operations can be combined with **3PGpjs**, and **3PGpjs.xls** includes examples of the use of these facilities to compare observed and predicted stand development, and to perform a sensitivity analysis of 3-PG output with respect to selected parameters.

3PGpjs presumes some structure to input worksheets, yet is flexible enough to facilitate easy modification of site factors and default parameter values. The interface allows either a single site or a series of sites to be run.

- In a single-site run, climatic data, site-specific factors and user-selected 3-PG parameter values are specified on a worksheet. Annual details of stand development are written to that worksheet.
- In a sensitivity analysis, worksheets for specific sites are named, the user can supply values for site factors or 3-PG parameters for each site, and the sites are run in sequence. Selected output from all sites is written to a single worksheet.

3PGpjs permits selected site factors to be age-dependent. This aids the study of consequences to temporal changes in site conditions, e.g. due to fertilisation or irrigation, or a natural run-down of site conditions.

The code for 3-PG embedded in **3PGpjs** includes changes from the model as originally published (Landsberg and Waring, 1997) and made in agreement with Joe Landsberg. Modifications to 3-PG are documented in the Appendix and include:

- corrections have been made to ensure the model is consistently state-determined,
- temperature-dependent and site nutrient status modifiers have been applied to canopy quantum efficiency, and the frost modifier has been generalised,
- the manner in which the various modifiers are applied has been improved,
- specific leaf area declines with stand-age for young stands,
- loss of production because the canopy is not closed during early growth is taken into account,
- stand volume is based on basic density and an age dependent branch and bark fraction,
- daylength for each month is computed from site latitude and mid-month date,
- the allometric relationships assume DBH is given in cm rather than mm,
- the way in which various functions are parameterised has been changed to give the parameters greater intuitive meaning.

1. Introductory remarks

3-PG is a dynamic, process-based model for forest growth developed by Landsberg and Waring (1997). This report documents **3PGpjs**, a simple and flexible spreadsheet-based interface to 3-PG. It provides the user considerable flexibility with out need to modify computer code. The advantages of working in a worksheet environment are available as the user is free to use worksheet features to transform 3-PG output. Examples are: to compute variables not provided by 3-PG, to graph stand development as a function of age with observed data superimposed, or to graph how stand characteristics depend on specific 3-PG parameters.

The interface allows two distinct modes of operation. In a single-site run, all data required and subsequent output is confined to a single worksheet for that site, the *single-site data sheet*. This comprises climatic data and site-specific factors, and optional changes to 3-PG parameters or age-dependent management factors. **3PGpjs** can also be used to run a series of single-site data sheets by listing their names, optional values for 3-PG parameters and a list of required output variables on a single worksheet, the *sensitivity data sheet*. Sample data sheets are included in the file **3PGpjs.xls**.

2. Running 3-PG

When the **3PGpjs.xls** file is loaded into memory, **3PGpjs** displays a disclaimer to the effect that neither I, nor CSIRO nor CRCSPF accept any responsibility for your use of this software. If you agree, press **Y** or click on the **Yes** button, otherwise you can not run 3-PG. If you press **Yes**, the **3PGpjs** "About" form is displayed. Pressing any key removes this and **3PGpjs** can then be used.

If a work sheet in **3PGpjs.xls** can be run with 3-PG, a cell near its top left hand corner contains the keyword **Run**. To run 3-PG then type **Ctrl_Shift_r** (hold down the Ctrl- and Shift-keys and press the r-key) with a single-site or sensitivity data sheet active. Alternatively, press the **Run** button displayed on the sheet. This button can be freely moved any where on the sheet, and is linked directly to the **3PGpjs** main program. The type of run associated with the work sheet is indicated by the contents of the cell to the right of the keyword **Run**. This can be either **SingleSite** or **Sensitivity**.

A single-site run writes a summary of stand development to the single-site data sheet. An optional detailed listing of monthly values of variables in 3-PG can be written to a worksheet named **3-PG_results**. Output from a sensitivity analysis is totally under user control, and can be a few basic results or a full summary of stand development for each site.

Limited error checking is performed, and the interface exits gracefully with a meaningful error message, at least under those circumstances I contrived! Pressing Ctrl-Pause interrupts execution.

3. Provision of data

The minimum data required to run 3-PG comprise the following:

- a) *Climate data*. Monthly means of temperature, solar radiation, rainfall, VPD, and frost days.
- b) *Site factors*: Site-latitude, maximum available soil water storage, soil fertility rating.
- c) *Initial conditions*: Stem, root and foliage biomass, and stocking, at some initial age.
- d) *3-PG parameters*. A set of parameters characterising the performance of 3-PG.

In addition the following data are optional:

- e) *Site-specific changes to default parameters*: These can be made as required.

- f) *Management factors*: Annual variation in fertility rating, irrigation and minimum available soil water can be specified.

All data is provided in data blocks on worksheets, and **3PGpjs.xls** contains worksheets of climatic and site data in different formats, and a sheet providing 3-PG parameters; see Sec. 5.

The location of data blocks are determined by *keywords*, and some basic restrictions on the structure of data blocks must be adhered to. Keywords must be spelt as shown on the **3PGpjs.xls** data sheets. The textual format (case, font, size, colour, etc) of keywords and all input is ignored, and the “=” or “:” seen in some keywords in the sample worksheets are for aesthetic purposes only and are ignored. Climatic data can be provided in various formats, and parameter values are specified by the name of the parameter with its value in the cell to the right.

3.1 Default parameter values

A set of 3-PG parameter values is provided as part of the 3-PG code. These are the basic defaults.

However, if a worksheet named **3PG_Parameters** exists, **3PGpjs** reads values for all parameters from it. This sheet must be in the specific format shown in the file **3PGpjs.xls**. Parameter values are contained in the columns to the right of the **Units** column, and the heading of each of these columns is used to identify a species. The species to be used is determined from a cell identified by the keyword **Species** on the single-site data sheet (see Sec 3.2). Sections 3.3-4 show how parameter values can also be supplied on single-site and sensitivity analysis data sheets.

3PGpjs assigns parameters in the following steps:

- The internal, coded values are assigned.
- The **3PG_Parameters** worksheet, if present, is read.
- These values are updated by any parameter values specified on the single-site data sheets.
- If the run was initiated from a sensitivity analysis worksheet, parameters are then read from that worksheet.

In this way, the parameters actually used are those found on the active worksheet.

3.2 Specification of single-site data

A worksheet is a *single-site data sheet* if the cell to the right of the **Run** keyword contains the keyword **SingleSite**.

A single-site data sheet must contain a cell with the keyword **Site**, to the right of which is a name or code for the site. It must also contain a cell with the keyword **Species**, to the right of which is the name of the species. If the species name can not be identified as a species on the **3PG_Parameters** sheet, or that sheet is not present in the workbook, the default parameter values coded into 3-PG are used.

Site-related input data comprises three mandatory data blocks, i.e. *Climate data*, *Site factors*, and *Initialisation*, and two optional data blocks, i.e. *Parameters* and *Management*. The structure of these data blocks is fixed, but not the textual format, or their precise or relative locations.

Climate data block

Three formats for the climate data block are recognised: (a) the original 3-PG format, and formats based on data used by the model PROMOD (Battaglia and sands, 1997) with data for each month given in (b) columns or (c) rows. Format (c) is recommended. The keyword identifying the climate

data block is **Climate data**. The cell below or to the right of this contains the keyword indicating the format: **Radiation** below for format (a), **Tmax** below for (b), and **Tmax** to the right for (c).

Note that if format (b) or (c) is used, mean temperature and VPD are computed from maximum and minimum temperatures, and pan evaporation and rain days are ignored.

If format (c) is used, monthly data can be given for multiples of 12 months, and 3-PG cycles through this data as required. This enables the use of realistic sequences of climatic data. The file **3GPpjs.xls** includes sample single-site worksheets; see Sec. 5.

Site factors data block

The site factors block is identified by the keyword **Site factors** and its format must be as in the sample worksheets. The data required are as follows

- site latitude (-ve for the S hemisphere),
- site fertility rating, on a range of 0 for concrete to 1 for a highly fertile site,
- the soil class, which is used to specify the parameters c_q and n_q in accordance with Table 1,
- the maximum available soil water (mm),
- the minimum allowed available soil water (mm).

If actual soil water falls below a non-zero minimum available soil water, it is assumed that the shortfall is made up by irrigation. **3PGpjs** totals this added water.

Initialisation data block

The *Initialisation* block is identified by the keyword **Initialisation**, and its format must be as in the sample worksheets. The data required are as follows

- the starting and terminating stand age for the run,
- the biomass (t/ha) in the foliage, root and stem biomass pools at the starting stand age,
- the stocking (trees/ha) of the stand at the starting stand age,
- the initial available soil water (mm), constrained to be between the minimum allowed and maximum available soil water,
- the calendar year in which the stand was planted (from which stand age is measured).

3.3 Specification of site-specific parameters and management options

The format of the *Parameters* and *Management* data blocks on a single-site data sheet must be as given in the sample data sheets, but their location, size and content is flexible.

Parameters data block

The parameters data block is optional, and is identified by the keyword **Parameters**. Parameter names are listed in cells immediately below the **Parameters** keyword, and their values in the cells to the right. The number of parameters specified is arbitrary. A blank cell in the column of parameter names terminates parsing of parameters. The names to be used to identify parameters are given in Table 4, and in the *Names* column on the “**3PG_Parameters**” worksheet.

Management data block

The management data block is optional, and is identified by the keyword **Management**. It comprises small tables of data specifying how site fertility, minimum available soil water, or annual total irrigation vary with stand age. Keywords that identify these tables are **Fertility**, **MinASW** and **Irrigation**, respectively, and are located in the row below the keyword **Management**.

Each table is two columns wide and of an arbitrary depth. The left-hand column contains its keyword, below which is “Age” and a series of stand ages. The column to the right contains the values of the relevant variable that pertains up to the age given in that row. A blank cell in the “Age” column terminates parsing of that table.

Tables must be adjacent, and their tops aligned. Adjacent tables are parsed by scanning the row below the **Management** keyword for the keywords **Fertility**, **MinASW** or **Irrigation**, starting with the cell below **Management** and moving right. Alternate cells in that row contain the keyword for a table, and parsing for tables is terminated when a blank cell is found instead of a keyword.

3.4 *Specification of sensitivity analysis data*

A sensitivity analysis data sheet is identified by the keyword **Sensitivity** in the cell to the right of the **Run** keyword. This data sheet comprises a single data block identified by the keyword **Sheet** in its top left-hand corner, and fields determining whether a summary of stand growth should be generated for each site and where that data will be located on the sensitivity analysis sheet. An example is the “**Sensitivity**” worksheet in **3GPpjs.xls**.

The sensitivity analysis data block comprises adjacent columns of data. The first row contains column headings used to interpret the data in the columns. The first column (the only mandatory column) has the keyword **Sheet** as its heading. This lists the names of the single-site worksheets for sites to be run. Sheet names are parsed by scanning down this column to a blank cell. Columns to the right of the *Sheet* column are optional and are headed by the names of 3-PG parameters, site factors, or output variables. Valid parameter names are those listed in table 4 or on the “**3PG_Parameters**” worksheet. Names for site factors are given in Table 2, and name of available output variables are in Table 3.

The first columns to the right of the *Sheet* column are assumed to contain 3-PG parameters or site factors, and have parameter or site factor names as their headings. The values in these columns are the values of the corresponding parameters or site factors for each site. Names are parsed by scanning column headings to the right. A blank cell terminates parsing, as does a cell that does not contain a known parameter or site factor name. The remaining columns are for 3-PG output variables, and have names of output variable as their headings. Output variable names are parsed by scanning the column headings to the right, and a blank cell terminates parsing.

4. Output data

4.1 *Single-site runs*

A single-site run writes a summary of stand development on the site-data worksheet. The number of the first row to be used for output is specified in the cell to the right of the cell “**First output row**” in the *Site factors* data block. Detailed monthly and annual data are written to a worksheet called “**3PG_Results**” if the cell to the right of the cell “**Monthly output?**” in the *Site factors data block* contains “Y” (or “y” or “yes”).

4.2 *Sensitivity analyses*

When a sensitivity analysis is performed, all output is directed to the sensitivity analysis worksheet. No output is written to individual site-data sheets, or to the “**3PG_Results**” worksheet. By default only output is selected as in Section 3.4 is displayed. If a summary of stand development is required for each run, a “Y” should be placed in the cell to the right of the cell “**Show site output (Y/N)?**”. The row number for the first row of the stand summaries should be placed in the cell to the right of the cell “**Output row**”.

5. Comments on the example worksheets in 3PGpjs.xls

Following are brief notes on the worksheets in **3PGpjs.xls**. Climate and site data are realistic data for a site in SE Queensland, and the observed stand growth data are actual observations from that site. However, the analysis and parameter values are only meant to be illustrative and should not be assumed to be realistic for the species used. No discussion of the results is given.

5.1 The 3PG_Parameters worksheet

The **3PG_Parameters** worksheet has the standard name and format for the worksheet giving default 3-PG parameters. The parameter set for the species named *Default* are the values hard-coded into this version of 3-PG; they are the values used if the **3PG_Parameters** worksheet is absent. The column headed *Species 1* contains the nominal parameter values to be used for the species for which observed data is used in the examples in **3PGpjs.xls**.

Columns of parameter values for additional species can be added to the right of the *Units* column. The headings of these columns contain the names of the corresponding species, and these should be used with the **Species** keyword on single-site data sheets to select a set of parameter values. If parameters for a named species are not found on the **3PG_Parameter** worksheet, the internally coded values are used. Do not edit the parameter names.

5.2 The Site (a) worksheet

This example shows the most basic use of **3PGpjs**. No other worksheet is required to run this example.

The climate data is in format (a), and comprises long-term monthly mean data. No species has been specified, so the parameters for the *Default* species are used. No site-specific parameters are provided, and no management options are selected. The original stand grown on this site was fertilised; hence $FR=1$. Initial soil water was set to 999 mm; **3PGpjs** resets this to **MaxASW**, i.e. 300 mm. The predicted time-course of stem volume (red curve) and canopy LAI (green curve) are shown in the graph.

5.3 The Site (b) worksheet

This example uses the climate and site data on worksheet **Site (a)**. However, climate data is now in format (b), i.e. the PROMOD format with monthly data in columns. Standard parameters for the species *Species 1* are now used, but some of these have been overwritten with site-specific values chosen so as to reproduce early growth by the stand. The graph now compares predicted stem volume and canopy LAI with corresponding observed values at this site.

5.4 The Site (c) worksheet

Time dependent management options have now been specified. This site was fertilised for the first three years, and site fertility was then allowed to run down. Accordingly, the 3-PG fertility rating was reduced as the stand ages so that 3-PG output reproduces the observed stem volumes. The stand was also irrigated with about 10 MI ha^{-1} of water applied in each of the first 6 years, but was then subject to a mild drought. The latter is simulated by a negative irrigation of 1 MI ha^{-1} for years 7 onwards.

Because irrigation increased early growth, it was necessary to reduce α slightly in order to reproduce early growth. This was because the 3-PG soil-water modifier f_{SW} was no longer limiting growth.

5.5 The Site (d) worksheet

This example uses the actual rainfall data for this site, including applied irrigation, for the entire period of the trial. The climate data is therefore presented in format (c), i.e. with monthly data in rows. As before, site fertility runs down over the life of the stand, but irrigation is no longer specified as a management option.

5.6 The Site (e) worksheet and the 3PG_Results worksheet

This example is a repeat of the example on the **Site (c)** worksheet. However, irrigation is not specified as a management option. Rather, a non-zero value has been assigned to the minimum available soil water (**MinASW**) so that rainfall is supplemented by irrigation whenever soil water would fall below this value.

This example also requests output of monthly data and a more comprehensive summary of stand development. This is written to the **3PG_Results** worksheet, which is created if a sheet of that name does not already exist. Reference to this worksheet shows that in the first four years of growth rainfall was supplemented by 200, 250, 250 and 70 mm of irrigation, respectively.

5.7 The Sensitivity analysis worksheet

The **Sensitivity** worksheet shows how the sensitivity of canopy development to different patterns of litterfall can be examined by running the same site for a range of parameter values. The worksheet includes results from two distinct runs, in each of which a different parameter controlling litterfall was varied over a range of possible values.

Once the first set was run, its input and output data were copied to another location on the worksheet and its **Sheet** keyword removed to hide it from **3PGpjs**. The parameter values in the original block were then edited, and a second run generated new results.

The graphs were constructed using normal spreadsheet techniques. The objective was to find combinations of parameters so that a peak LAI of about 5 occurred at a stand age of 2-3. The results suggest $\gamma_{Fx} > 0.075$ and $t_{gF} < 15$.

5.8 The Conversions and Tools worksheets

These two worksheets are not required by **3PGpjs**, but are often useful.

The **Conversions** worksheet provides a form for converting between new and old parameter sets. Edit any of the parameter values shown in red and the corresponding old (or new) parameters are updated to reflect the changes.

The **Tools** worksheet graphically illustrates many of the relationships in 3-PG. It is used to explore consequences on the form of a relationship of changes in the parameters that characterise that relationship. Change the value of a parameter and the graph of the associated relationship is updated to reflect the change in the parameter.

6. Notes on the 3PGpjs code

A detailed discussion of the code for **3PGpjs** is inappropriate in this report, so I will confine my comments to the following:

- **3PGpjs** is coded in Visual Basic, coupled to MicroSoft Excel.

- I have used **Option Explicit** so all variables are, and must be, explicitly defined.
- I have made a serious attempt to isolate code for distinct aspects of the user interface into the distinct modules described below.
- I have attempted to ensure that the interface can be easily modified. For instance, the code in the **Generic_IO** module avoids the need to count exactly which row or column number a particular item of data is being read from, or written to. The insertion of new input or output items between existing items is thus very easy.

The **3PGpjs** code includes the following modules:

- Main_Program** comprises the procedure **run_3PGpjs** which must be run to execute **3PGpjs**. It is linked to the **Ctrl_Shift_r** hot key combination, and to the **Run** button. The mode in which 3-PG is run (single-site or sensitivity analysis) is detected and the appropriate procedure invoked, which in turn runs the actual code for 3-PG.
- The_3PG_Model** contains the code of 3-PG itself. It declares all 3-PG variables and parameters, and includes all functions called by 3-PG. It should be possible to export just this module to use 3-PG in other applications.
- Data_Input** includes the **3PGpjs** input procedures. It reads or assigns default parameter values from **3PG_parameters**; it parses site specific and climatic data from site-data worksheets; and it parses data from sensitivity analysis worksheets. It also converts the climatic data in the various input formats into the data required by 3-PG.
- Data_Output** includes the output procedures required for displaying detailed intermediate results, the annual summary of stand development, and specific output from sensitivity analyses.
- Generic_IO** is a module of generic procedures and functions that assist the implementation of input from, and output to, worksheets.

The code is not protected in any way so the user is free to modify it at will. Unless a user wants to modify 3-PG itself, there should be little need to modify the code of **3PGpjs**. Standard spreadsheet operations can be performed on the **3PGpjs** worksheets.

Neither I, nor CSIRO, nor the CRC SPF, accept any responsibility for the use of this program as supplied or as modified by the end user.

References

- Battaglia, M. and Sands, P.J. (1997). Modelling site productivity of *Eucalyptus globulus* in response to climatic and site factors. *Australian Journal of Plant Physiology* 24: 831-850.
- 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.

Table 1. Soil classes and corresponding parameter assignments

| Soil class index | Soil class code | Predominant character of soil | Soil parameters | |
|------------------|-----------------|-------------------------------|-----------------|-------|
| | | | c_q | n_q |
| 1 | S | Sandy | 0.7 | 9 |
| 2 | SL | Sandy loam | 0.6 | 7 |
| 3 | CL | Clay loam | 0.5 | 5 |
| 4 | L | Clay | 0.4 | 3 |

Table 2. Names and description of site factors that can be controlled during a sensitivity analysis

| Description of site factor | Variable name |
|--|---------------|
| Fertility rating | FR |
| Maximum available soil water capacity | MaxASW |
| Minimum available soil water capacity | MinASW |
| Soil class (S, SL, CL, C) as per Table 1 | Soil |
| Initial foliage biomass | WFi |
| Initial root biomass | WRi |
| Initial stem biomass | WSi |
| Initial stand stocking | StemNoi |
| Initial available soil water | ASWi |

Table 3. Names and description of output variables available during a sensitivity analysis

| Description of output variable | Variable name |
|---|----------------------|
| Name of site, modified by inclusion of parameter values | siteName |
| Stand age at which canopy LAI is a maximum | ageLAIx |
| Maximum canopy LAI during stand development | LAIx |
| Stand age at which MAI is a maximum | ageMAIx |
| Maximum MAI | MAIx |
| Stand stocking | StemNo |
| Foliage biomass | WF |
| Root biomass | WR |
| Stem biomass | WS |
| Total biomass | TotalW |
| Stand basal area | BasArea |
| Stand volume | Standvol |
| Canopy LAI | LAI |
| Mean annual increment | MAI |
| Annual total transpiration by stand | totalTransp |
| Annual total foliage litter fall | CumLittfall |
| Fraction of new biomass allocated to roots | pR |
| Fraction of new biomass allocated to stems | pS |
| Fraction of new biomass allocated to foliage | pF |
| Ratio of foliage to stem allocation | Ratiop |

Table 4. Description of 3-PG parameters, their 3PGpjs names, and values for *E. globulus*

| Meaning/comments | 3-PG symbol | 3PGpjs Name | Value | Units |
|--|--------------|--------------|-------|---------------------------------|
| Allometric relationships & partitioning | | | | |
| Ratio of foliage:stem partitioning at $D = 2$ cm | p_2 | pFS2 | 1 | - |
| Ratio of foliage:stem partitioning at $D = 20$ cm | p_{20} | pFS20 | 0.15 | - |
| Constant in stem mass ν diam. relationship | a_S | stemConst | 0.095 | - |
| Power in stem mass ν diam. relationship | n_S | stemPower | 2.4 | - |
| Maximum fraction of NPP to roots | h_{Rx} | pRx | 0.8 | - |
| Minimum fraction of NPP to roots | h_{Rn} | pRn | 0.23 | - |
| Temperature modifier | | | | |
| Minimum temperature for growth | T_{min} | Tmin | 8 | deg. C |
| Optimum temperature for growth | T_{opt} | Topt | 16 | deg. C |
| Maximum temperature for growth | T_{max} | Tmax | 40 | deg. C |
| Frost modifier | | | | |
| Number of days production lost for each frost day | k_F | kF | 1 | - |
| Litterfall & root turnover | | | | |
| Maximum litterfall rate | g_{Fx} | gammaFx | 0.027 | month ⁻¹ |
| Litterfall rate at $t = 0$ | g_{F0} | gammaF0 | 0.002 | month ⁻¹ |
| Age at which litterfall rate has median value | t_{gF} | tgammaF | 24 | month |
| Average monthly root turnover rate | g_R | Rttover | 0.015 | month ⁻¹ |
| Conductance | | | | |
| Maximum canopy conductance | g_{Cmax} | MaxCond | 0.02 | m s ⁻¹ |
| Maximum stomatal conductance | g_{Smax} | StomCond | 0.006 | m s ⁻¹ |
| Defines stomatal response to VPD | k_g | CoeffCond | 0.05 | kPa ⁻¹ |
| Canopy boundary layer conductance | g_B | BLcond | 0.2 | m s ⁻¹ |
| Fertility effects | | | | |
| Value of m when $FR = 0$ | m_0 | m0 | 0 | - |
| Value of f_N when $FR = 0$ | f_{N0} | fN0 | 1 | - |
| Soil water modifier | | | | |
| Moisture ratio deficit which gives $f_q = 0.5$ | c_q | SWconst | 0.7 | - |
| Power of moisture ratio deficit in f_q | n_q | SWpower | 9 | - |
| Stem numbers | | | | |
| Maximum stem mass per tree at 1000 trees/ha | w_{Sx1000} | wSx1000 | 300 | kg/tree |
| Age modifier | | | | |
| Maximum stand age used to computer relative age | - | MaxAge | 50 | years |
| Power of relative age in f_{age} | n_{age} | nAge | 4 | - |
| Relative age to give $f_{age} = 0.5$ | r_{age} | rAge | 0.95 | - |
| Canopy structure and processes | | | | |
| Specific leaf area at stand age 0 | s_0 | SLA0 | 11 | m ² kg ⁻¹ |
| Specific leaf area for mature aged stands | s_1 | SLA1 | 4 | m ² kg ⁻¹ |
| Age at which specific leaf area = $\frac{1}{2}(s_0 + s_1)$ | t_s | tSLA | 2.5 | years |
| Extinction coefficient for absorption of PAR by canopy | k | k | 0.5 | - |
| Age at full canopy cover | t_{cc} | fullCanAge | 0 | years |
| Proportion of intercepted rainfall evaporated from canopy | - | Interception | 0.15 | - |
| Canopy quantum efficiency | a | alpha | 0.07 | molC mol ⁻¹ PAR |
| Branch & bark fraction | | | | |
| Branch and bark fraction at stand age 0 | p_{BB0} | fracBB0 | 0.75 | - |
| Branch and bark fraction for mature aged stands | p_{BB1} | fracBB1 | 0.15 | - |
| Age at which branch and bark fraction = $\frac{1}{2}(p_{BB0} + p_{BB1})$ | t_{BB} | tBB | 1.5 | years |
| Various | | | | |
| Ratio NPP/GPP | Y | Y | 0.47 | - |
| Basic density | r | Density | 0.5 | t m ⁻³ |

Appendix: Changes incorporated into 3-PG

The 3-PG code embodied in **3PGpjs** differs in several ways from the original version of 3-PG described in Landsberg and Waring (1997). These differences were the result of Joe Landsberg's experience applying 3-PG to numerous data sets, and in response to my attempts to parameterise the model for *E. globulus* and *E. grandis*.

In addition to basic structural changes to 3-PG, I changed how relationships are parameterised to make the parameters in these relationships more intuitively meaningful. The relationships themselves have not been changed, and there is a unique relationship between old and new parameter values. Table 4 lists all parameters, the names by which they are known to **3PGpjs**, and a set of default values. Note that 3-PG uses the conversion factors:

$1 \text{ MJ solar radiation} \equiv 2.3 \text{ mol PAR}$,
 $1 \text{ mol C} \equiv 1 \text{ mol DM} \equiv 24 \text{ g DM}$.

The worksheet **Tools** in **3PGpjs.xls** includes tables for converting between the old and new parameter sets.

The following sub-sections discuss changes made in 3-PG itself, and presume familiarity with Landsberg and Waring (1997).

A.1 New or changed environmental modifiers

Temperature modifier

A new modifier $f_T(T_a)$ that depends on the monthly average daily temperature T_a has been introduced. The definition of f_T is

$$f_T(T_a) = \left(\frac{T_a - T_{min}}{T_{opt} - T_{min}} \right) \left(\frac{T_{max} - T_a}{T_{max} - T_{opt}} \right)^{(T_{max} - T_{opt}) / (T_{opt} - T_{min})}, \quad (1)$$

where $f_T = 0$ if $T_a \leq T_{min}$ or $T_{max} \leq T_a$, and T_{min} , T_{opt} and T_{max} are the minimum, optimum and maximum temperatures for net photosynthetic production.

Frost modifier

The functional form of frost modifier $f_F(d_f)$ has been generalised from its original form (Sec. 2.3, Landsberg & Waring, 1997) and is now given by

$$f_F(d_f) = 1 - k_F (d_f / 30), \quad (2)$$

where d_f is the number of frost days in a month and k_F is the number of day's production lost for each frost day, and may be greater or less than 1. Setting $k_F = 0$ essentially switches the frost modifier "off".

Nutrient modifier

A modifier $f_N(FR)$ which depends linearly on the site fertility rating FR has been introduced:

$$f_N(FR) = f_{N0} + (1 - f_{N0})FR, \quad (3)$$

where f_{N0} is the value of f_N when $FR = 0$.

A.2 How environmental modifiers are taken into account

The modifiers f_{VPD} and f_{SW} reduce both canopy conductance (g_c) and “utilisable” PAR (f_{pau}) through a multiplier \mathbf{j} (called **PhysMod** in the 3-PG code) defined by

$$\mathbf{j} = f_{age} \min\{f_{VPD}, f_{SW}\} . \quad (4)$$

Here, f_{age} is the age-dependent modifier simulating possible decline in hydraulic properties with age (Landsberg and Waring 1977, Eqn (3)).

The temperature, frost and nutrition modifiers affect the canopy quantum efficiency (\mathbf{a}_C) multiplicatively because these are assumed to have independent effects on photosynthesis, i.e.

$$\mathbf{a}_C = f_T f_F f_N \mathbf{a} , \quad (5)$$

where \mathbf{a} is the theoretical maximum canopy quantum efficiency. Gross primary production G is then given by

$$G = \mathbf{a}_C \mathbf{f}_{pau} = f_T f_F f_N \mathbf{a} \mathbf{j} \mathbf{f}_{pa} \quad (6)$$

where \mathbf{f}_{pa} is PAR absorbed by the canopy.

Because $\mathbf{f}_{pau}/\mathbf{f}_{pa} = \mathbf{j}$, partitioning to roots is only affected by VPD or soil-water induced stress, and by site fertility through the parameter m (see Landsberg and Waring 1977, Eqn (15) and Eqn (?) below).

A.3 Specific leaf area depends on stand age

Observations from a range of eucalypt stands show specific leaf area σ ($\text{m}^2 \text{kg}^{-1}$) declines with stand age for very young stands. Experience with 3-PG has shown it is unable to reproduce both observed stem biomass and canopy leaf area index of young stands unless σ is age dependent. Accordingly, specific leaf area as a function of stand age t (years) is given by the empirical relationship

$$\sigma = \sigma_1 + (\sigma_0 - \sigma_1) e^{-(\ln 2)(t/t_s)^2} , \quad (7)$$

where σ_0 and σ_1 ($\text{m}^2 \text{kg}^{-1}$) are specific leaf areas at age 0 and for mature stands, respectively, and t_s (years) is the stand age at which $\sigma = \frac{1}{2}(\sigma_0 + \sigma_1)$.

A.4 Loss of intercepted radiation due to non-canopy closure

It is assumed that canopy closure occurs at a stand age of t_{cc} years. Prior to this, intercepted PAR is reduced by the factor t/t_{cc} where t is stand age (in years). This procedure does not work adequately and the default value of the parameter t_{cc} has been set to 0, i.e. by default the canopy is assumed to be closed at all ages.

A.5 Calculation of stand volume

Stand volume V ($\text{m}^3 \text{ha}^{-1}$) is determined from above ground woody biomass W_S (t ha^{-1}) and basic density ρ (t m^{-3}), and is discounted for the fraction p_{BB} of above ground woody biomass as branch and bark:

$$V = (1 - p_{BB}) W_S / \rho . \quad (8)$$

Observations from a range of eucalypt stands show p_{BB} declines with stand age:

$$p_{BB} = p_{BB1} + (p_{BB0} - p_{BB1})e^{-(\ln 2)t/t_{BB}}, \quad (9)$$

where p_{BB0} and p_{BB1} are branch and bark fractions at age 0 and for mature stands, respectively, and t_{BB} (years) is the stand age at which $p_{BB} = \frac{1}{2}(p_{BB0} + p_{BB1})$.

A.6 Litterfall

The relationship for the monthly litterfall rate g_F is now parameterised by the rate of litterfall (g_{F0} , month⁻¹) at age 0, the maximum rate of litter fall (g_{Fx} , month⁻¹), and the age (t_{gF} , months) at which the litterfall rate is $\frac{1}{2}(g_{F0} + g_{Fx})$. Then

$$g_F(t) = \frac{g_{Fx}g_{F0}}{g_{F0} + (g_{Fx} - g_{F0})e^{-k_g t}} \quad (10)$$

$$k_g = \frac{1}{t_{gF}} \ln \left(1 + \frac{g_{Fx}}{g_{F0}} \right), \quad (11)$$

where t is stand age in months. The relationships between the new and old parameters are:

$$\begin{aligned} g_{F0} &= g_{Fx} / (1 + c_g), & t_g &= \frac{1}{k_g} \ln(2 + c_g), \\ c_g &= \frac{g_{Fx}}{g_{F0}} - 1, & k_g &= \frac{1}{t_g} \ln(2 + c_g). \end{aligned} \quad (12)$$

With parameters from Eqn (7) of Landsberg and Waring (1997), $\gamma_{Fx}=0.02$ month⁻¹, $\gamma_{F0}=0.00125$ month⁻¹ and $t_g=23.6$ months.

A.7 Root biomass partitioning

The relationship for the root biomass partitioning ratio h_R is now parameterised by the maximum and minimum partitioning ratios h_{Rx} and h_{Rn} so

$$h_R = \frac{h_{Rx}h_{Rn}}{h_{Rn} + (h_{Rx} - h_{Rn})mf_{pau} / f_{pa}}, \quad (13)$$

where m is given by Eqn (4) above. With parameters from Eqn (15) of Landsberg and Waring (1997), $h_{Rx}=0.8$ and $h_{Rn}=0.23$. The parameter m in Eqn (13), controlling how root biomass allocation depends on site fertility, is assumed to depend linearly on site fertility rating:

$$m = m_0 + (1 - m_0)FR, \quad (14)$$

where m_0 is the value of m for sites of poor fertility, i.e. $FR = 0$.

A.8 Foilage-to-stem biomass partitioning ratio

Landsberg and Waring (1977) expressed the ratio $p_{FS} = h_F/h_S$ of foliage biomass partitioning to stem biomass partitioning as an allometric function of stem diameter D (cm) through observed allometric relationships between foliage and stem biomass and D . As this is the only place where the foliage allometric parameters appear in 3-PG, p_{FS} has been written explicitly as an allometric function of D

$$p_{FS} = a_p D^{n_p}. \quad (15)$$

In terms of the original allometric parameters a_F and n_F , and a_S and n_S , the new parameters are

$$a_p = a_F n_F / a_S n_S, \quad n_p = n_F - n_S . \quad (16)$$

However, when calibrating 3-PG it is more convenient to parameterise p_{FS} in terms of its values p_2 and p_{20} at 2 cm and 20 cm, respectively. In terms of these,

$$n_p = \frac{\ln(p_{20}/p_2)}{\ln 10}, \quad a_p = p_2 / 2^{n_p} . \quad (17)$$

For example, if $p_2=1$ and $p_{20}=0.15$, then $n_p=-0.824$ and $a_p=1.77$.

A.9 Stem mortality

Stem mortality is determined by the self-thinning rule using Eqn (8) in Landsberg and Waring (1977) for the maximum permissible individual tree above ground woody biomass w_{Sx} (kg tree⁻¹) as a function of the current stand stocking N (trees ha⁻¹). This has been rewritten as

$$w_{Sx} = w_{Sx1000} (1000 / N)^{3/2} \quad (18)$$

where w_{Sx1000} (kg tree⁻¹) is the value of w_{Sx} when the stocking is 1000 trees ha⁻¹. (If the stocking is 1000 trees ha⁻¹, then this equation implies that the total above ground woody biomass on the *stand* at which self-thinning commences is about w_{Sx1000} t ha⁻¹.)

A.10 Modifications of the August 1999 3-PG code

Additional modifications to the 3-PG code supplied by Joe Landsberg were made as follows:

- Daylength is computed from site latitude as the daylength on the 15th day of each month.
- The allometric relationships now assume that DBH is given in *cm* rather than *mm*. This requires scaling each allometric constant a by 10^n where n is the power in the allometric relationship. This does not affect the performance of the model.
- An attempt has been made to ensure that the model is properly state-determined. All intermediate variables are determined from the state of the system at the beginning of a time step, output variables are determined from the state at the end of a time step, and all explicitly age-dependent variables are determined from stand age at the beginning of a time step. The resulting numerical changes in output were generally small.
- Although litterfall as expressed by Eq. (7) in Landsberg and Waring (1997) varied monthly, the code used the litterfall rate at the *end* of a year throughout that year. This was corrected, so litterfall is now based on the current stand age. This change had significant effects on predicted canopy development in young stands.
- The annual output from 3-PG included canopy LAI at the end of the year. Because LAI can vary seasonally, this was changed to an annual average of LAI. This change does not affect model performance.
- The start of a growth season is now assumed to January for northern latitudes, and July in the southern hemisphere. This change has a small numerical effect early in stand development.