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Predicting wood quality to improve sawlog value in radiata pine

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Predicting wood quality to improve sawlog value in radiata pine

Prepared for

Forest & Wood Products Australia

by

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Executive Summary

A new model of tree growth and xylem formation, which provides explicit predictions of wood property variation, is presented in this report. The work is the outcome of a three-year FWPA-funded project with the key objective to: “develop and validate a software tool to predict variation in commercially important wood properties of *Pinus radiata* as a function of variation in growing conditions and management”. This was achieved with the development of a software tool called *e*-Cambium that predicts the following variables, at a daily time step, from basic site, climate and silvicultural inputs:

- Wood density,
- Tracheid cell size and wall thickness
- Microfibril angle (MFA)
- Modulus of elasticity (MOE) and wood stiffness
- Virtually sawn boards of user-prescribed dimensions in terms of number and grade

The model is process-based. It predicts growth and wood properties, effectively simulating the kind of data that the SilviScan® system generates, by mathematically describing known and hypothesized processes in tree biology and wood formation. The development of the code was based on a synthesis of the scientific literature as well as detailed measurements of tree growth across a six contrasting sites over the 3 year project. Preliminary validation was against data from previous FWPA studies in which the model performed well. The FWPRDC Resource for Profit study (2003-2005), provided the relationship between SilviScan data and actual sawlog out-turn, allowing us to calibrate the virtual sawing simulator. The model is unique in that it contains the first known process-based attempt to predict MFA, a major determinant of wood stiffness, in a complete modelling framework. As such, it encapsulates fundamental biological processes about which there is still much scientific debate.

The project has shown that the 18 key model parameters (which function to limit and restrict simulations for a particular genotype) can be held constant and describe wood property variation for very diverse sites and silvicultural regimes. Testing was undertaken across 18 scenarios, from 16 different sites from various radiata growing regions. The model was able to explain about 80% of the variation in mean core wood density (the average wood density of a hypothetical sampled core of wood) and 60 – 70% of the variation in outerwood wood density. Similarly, the model explained 60 – 70% of the variation in mean core and outerwood MOE. These results show that the model can be expected to be broadly applicable to *P. radiata* plantations across quite different regions, grown under a wide variety of conditions, without the need for re-parameterisation. In this sense it differs from, and is thus complementary to, empirical models that are easily applied but require regional calibration. In effect the model encodes decades of knowledge into a predictable form that allows industry to efficiently utilize this information. Industry workshops were conducted in Hobart, Melbourne and Mt Gambier where industry representatives from a range of growers and some processors were given detailed presentations on, and trained in the use of, the industry-testable version.

Users can explore the effect of age, site and climate variation on predicted sawn product against which economic values can be readily assigned. Some utilities of a process-based tool such as e-Cambium are as follows:

- Growing a site “on”: growers can explore the possible growth and wood property implications and potential of a site into the future

- Exploring the effects of uncertain climate or environmental variation not just on growth and stand volume, but on properties like wood density and stiffness
- Exploring the effects of altered silvicultural regimes on wood properties like density or MOE. This is particularly valuable when possible management regimes are unprecedented
- As a tool complementary to regular sampling or empirical models of growth, wood density or other wood properties.

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Introduction

Since the first establishment of *Pinus radiata* in Australia, there have been substantial improvements in the management of commercial log production from this important plantation species. Greater volumes achieved by improvements in breeding and silviculture have frequently resulted in commercially harvestable volumes being achieved at younger ages. Unfortunately, however, this has in many cases resulted in logs that produce a less valuable sawn-product distribution. This is not a simple problem to solve, as it is difficult to quantify how age, site, climate and forest management interact to affect log value. Certainly, the application of silviculture can make significant positive or negative differences. For example, mid-rotation fertilisation and thinning of radiata pine may increase the proportion of non-juvenile wood without affecting the value recovery (Downes et al. 2002a; Nyakuengama et al. 2003; Nyakuengama et al. 2002). Faster growth rates, a larger juvenile core and shorter rotations are recognised as key variables. Processed logs have proportionately more juvenile wood with quality issues related to lower stiffness, strength and poor dimensional stability. As a result, there is an increasing shift in the management and breeding of radiata pine towards wood quality improvement in addition to volume and form. Extensive investment to identify wood trait heritability has produced genetic gains. Increasingly the focus is on the nexus between genetics, management, site and the value of products. Under constantly changing climatic and management conditions, however, the prediction of site, genotype, management and climatic interactions, is beyond the scope of empirical approaches. A more enduring investment is likely to be in models that utilise knowledge of tree biology (often called process-based models), designed as single tools, or suites of tools, useable across the radiata resource.

Process-based models of forest stand growth have improved considerably in recent years, to the point where they have become useful management tools (Almeida et al. 2004; Battaglia and Sands 1997). The value of the process-based approach is that it theoretically makes scenario exploration possible beyond the bounds of existing data and field experience. That is, stand growth responses and tree performance can be forecast under hypothetical future conditions for which they may not be any precedent (e.g. increasing average temperatures, or a new silvicultural intervention). Inasmuch as it is valuable to understand how tree growth may vary (i.e. how big trees will get, or volume of wood expected from a stand), it is also of importance to understand what changing conditions or management might do to wood quality. To this end, the process-based approach is useful.

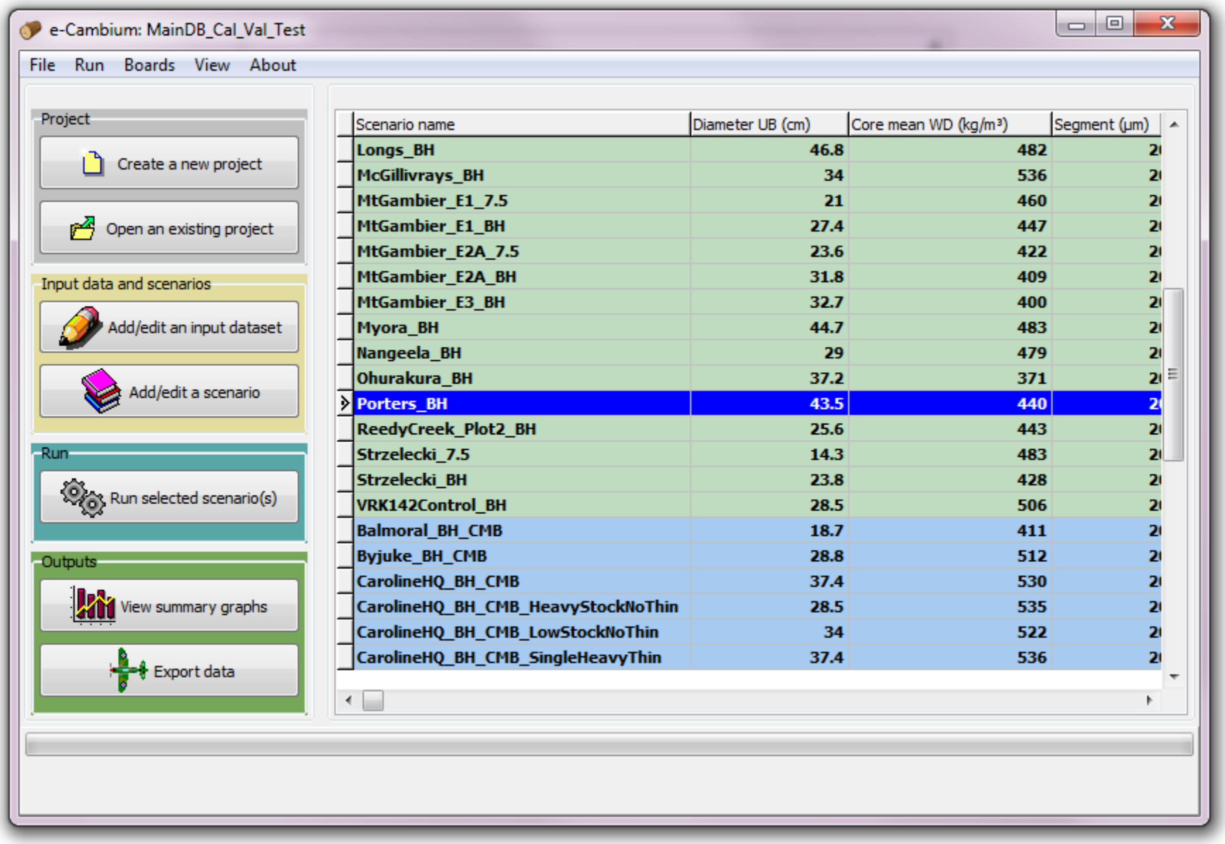
A number of process-based models, designed to simulate cambial activity and ultimately wood property variation, have also been described by various authors (Deckmyn et al. 2006; Deleuze and Houllier 1998; Fritts et al. 1999b; Hölttä et al. 2010; Kramer 2002; Meicenheimer and Larson 1983; Vaganov et al. 2006; Wilson 1964; Wilson and Howard 1968). A prototype model of cambial activity and xylem development called CAMBIUM was developed for *Eucalyptus* spp. (Drew et al. 2010). The eucalypt version of the model was developed for short-rotation situations and was specifically, and uniquely, able to cope with varied xylem cell types (fibres and vessels).

From this base, a new project was developed to improve and streamline wood property modelling in plantation trees, and specifically adapt it for use in radiata pine. The three year project was a collaboration between the FWPA, CSIRO, Scion, HVP and ForestrySA. Its key objective was to: "Develop and validate a software tool to predict variation in commercially important wood properties of Pinus radiata as a function of variation in growing conditions and management”. Here we describe the final version of the model, called *e*-Cambium. It is process-based, capable of running completely independently or in conjunction with other models (currently, the CaBala model (Battaglia et al. 2004)) and is designed primarily as a tool by which forest managers could conceivably predict tree stem growth as well as wood density (and stiffness) responses under a range of conditions

Software and GUI

The prototype *e*- Cambium model described in this report has been developed as easy-to-use software, installed on the user's computer. It uses a project-based approach to setting up hypothetical modeling scenarios, and users can create multiple projects depending on their need or interest. See Appendix 3 for detailed instructions on using the software.

The main user interface



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
Longs_BH	46.8	482	2
McGillivrays_BH	34	536	2
MtGambier_E1_7.5	21	460	2
MtGambier_E1_BH	27.4	447	2
MtGambier_E2A_7.5	23.6	422	2
MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

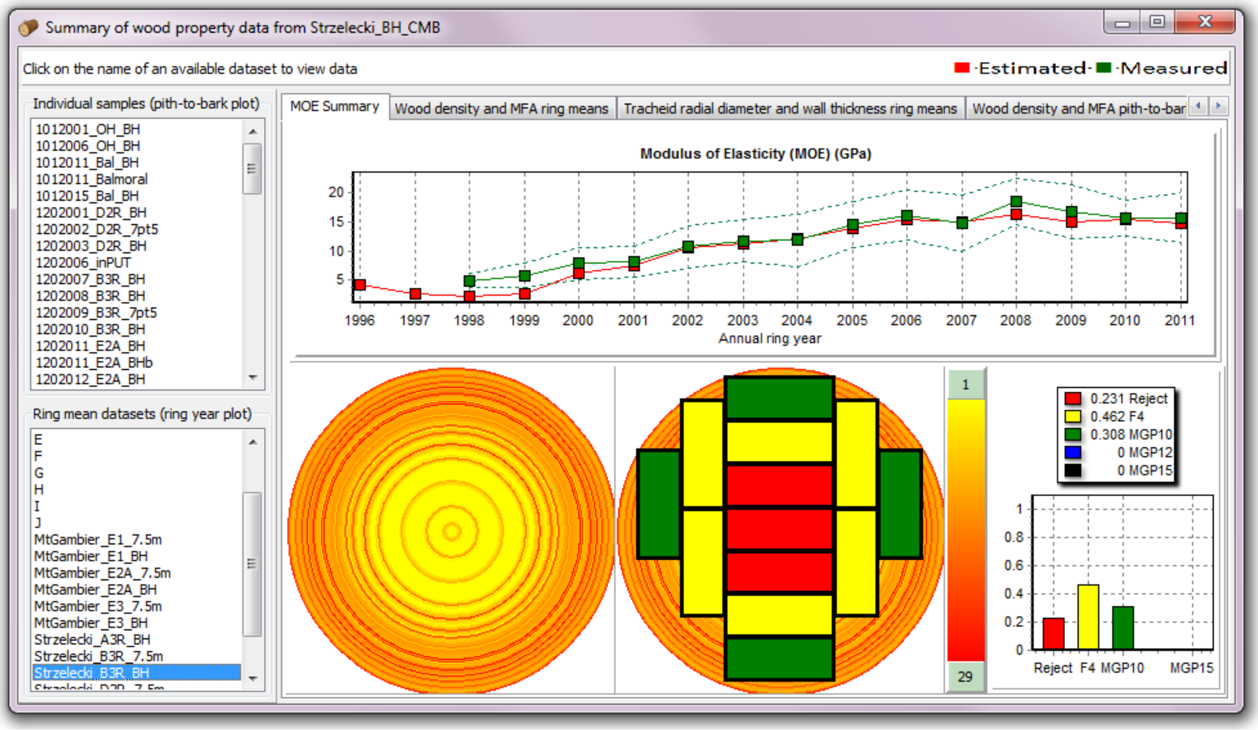
Figure 1: The cambial model GUI. A range of scenarios can be set up to be run as a batch.

The software is operated by means of a simple graphical user interface (Figure 1). The user is presented with four main options for managing a project:

1. Project management tools, including the ability to create a new project, or to open and work with an existing, saved project
2. Data management tools, including the ability to create and edit datasets (e.g. weather data or a hypothetical management regime) and the ability to combine these datasets into "scenarios" which can be run
3. A button to start or stop model runs, with associated options available through a menu list
4. Data output tools, including graphics windows, data summaries and a data export tool

Outputs and graphics

Pith-bark wood property profiles



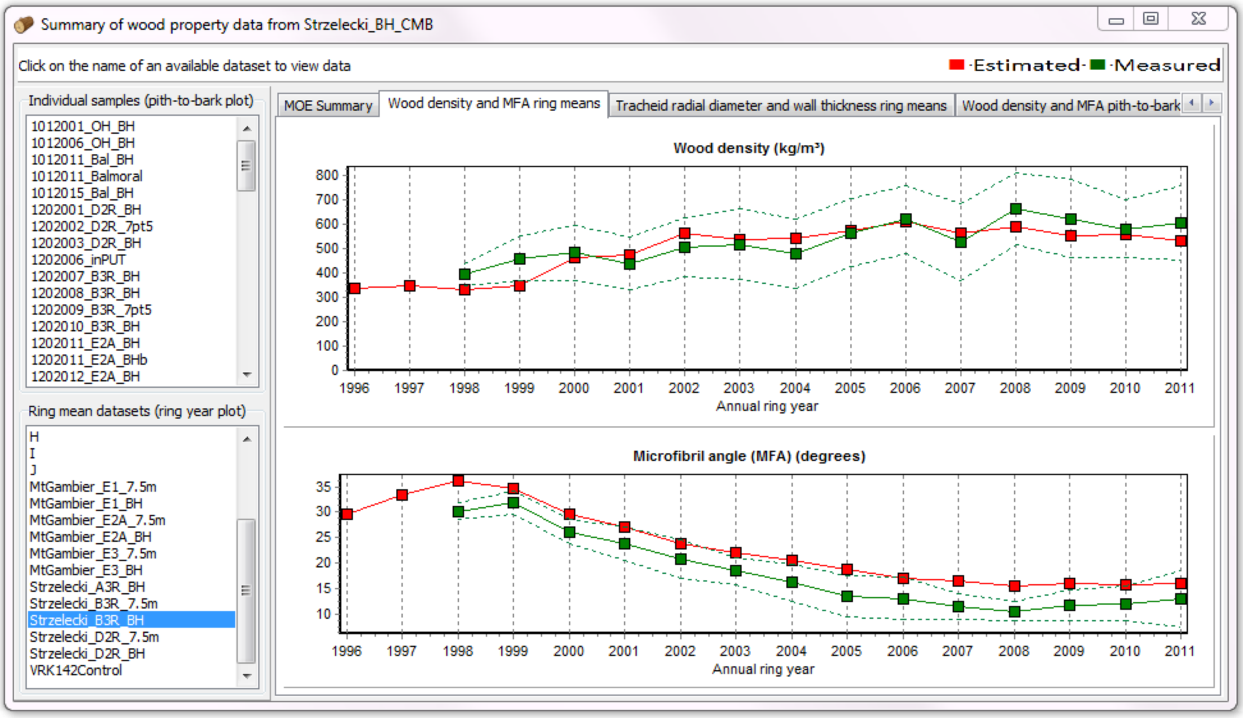


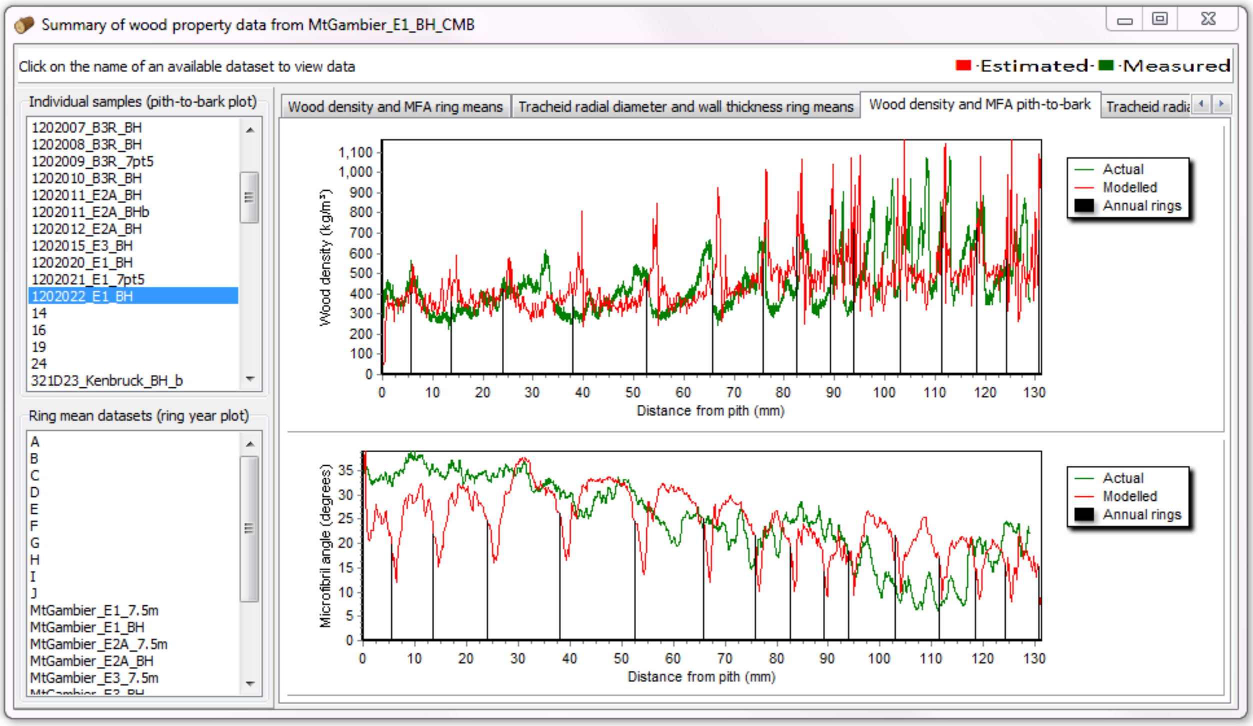
Figure 2: Cambium output graphics showing predicted annual mean MOE, wood density, MFA, tracheid radial diameter and wall thickness (red points and lines) for the rings formed at breast height. In the top window (with the MOE prediction) is shown an image of hypothetical boards which might be expected to be produced from clear wood with the predicted properties. It is possible to overlay measured data if available (green points and lines) of means and standard deviation.

Ring averages

The main output window for viewing predicted wood property profiles shows data averaged on an annual ring basis (Figure 2). Outputs are shown for average modulus of elasticity (MOE), wood density, microfibril angle (MFA), tracheid radial diameter and wall thickness. In addition, a graphic is produced of the log base, showing annual rings (the colour scheme indicates variation in MOE), and a second graphic which overlays an indication of the types of boards that could be expected from the model simulation, assuming a bole of entirely clear wood. The e-Cambium model does not take into account the effects of defects like knots. These data are summarised as a simple histogram showing the relative number of boards of different classes which could be produced from the hypothetical tree.

Pith-to-bark profiles

It is also possible to view the data in more detail, similar to the kind of information available when processing sampled cores through the CSIRO SilviScan® system (Evans et al. 1995). Data are presented on a distance from pith basis (in mm), showing average wood density, MFA, tracheid radial diameter and wall thickness averaged over a segment of size that can be specified by the user. These data represent a simulation of a single hypothetical cell file whereas in a system like SilviScan, the properties of possibly hundreds of cells (in a tangential direction) on a strip 2-mm wide are averaged.



Summary of wood property data from MtGambier_E1_BH_CMB

Click on the name of an available dataset to view data

Figure 3: Cambium output graphics showing predicted (red) and actual (green) (from a single SilviScan strip) wood density and MFA on a distance-from-pith (mm) basis for 100 µm segment averages.

Daily tree-level information

In addition to wood property information, Cambium also provides graphical outputs of predicted growth and physiological data (Figure 4). If the Cambium run utilised a Cabala simulation, Cabala outputs are shown (along with a Cambium predicted underbark diameter prediction). If e-Cambium's internal growth model (IGM) is used, all physiological and growth data presented is that which was simulated by the Cambium-IGM complex. Variables that are presented are daily estimates of:

- Stem diameter at the modelled position (cm)

- Tree height (m)
- NPP (stand and tree level) (T Ha^{-1} and kg $tree^{-1}$)
- Component biomass (T Ha^{-1})
- LAI
- Stand density (stems Ha^{-1})
- Pre-dawn (maximum) leaf water potential (MPa)
- Soil water availability (mm)
- Minimum and maximum temperature (°C)
- Number of cells in the cambial, enlarging and secondary thickening zones (# cells)
- Duration of the cell cycle, tracheid enlargement and secondary thickening (days)

Summary statistics

On the main table, visible on the GUI, information is provided for completed runs (Figure 1). This includes the predicted under-bark stem diameter (cm) and a mean wood density or MOE of the whole "core" or of the inner or outer core. The length over which the mean is calculated can be adjusted by the user.

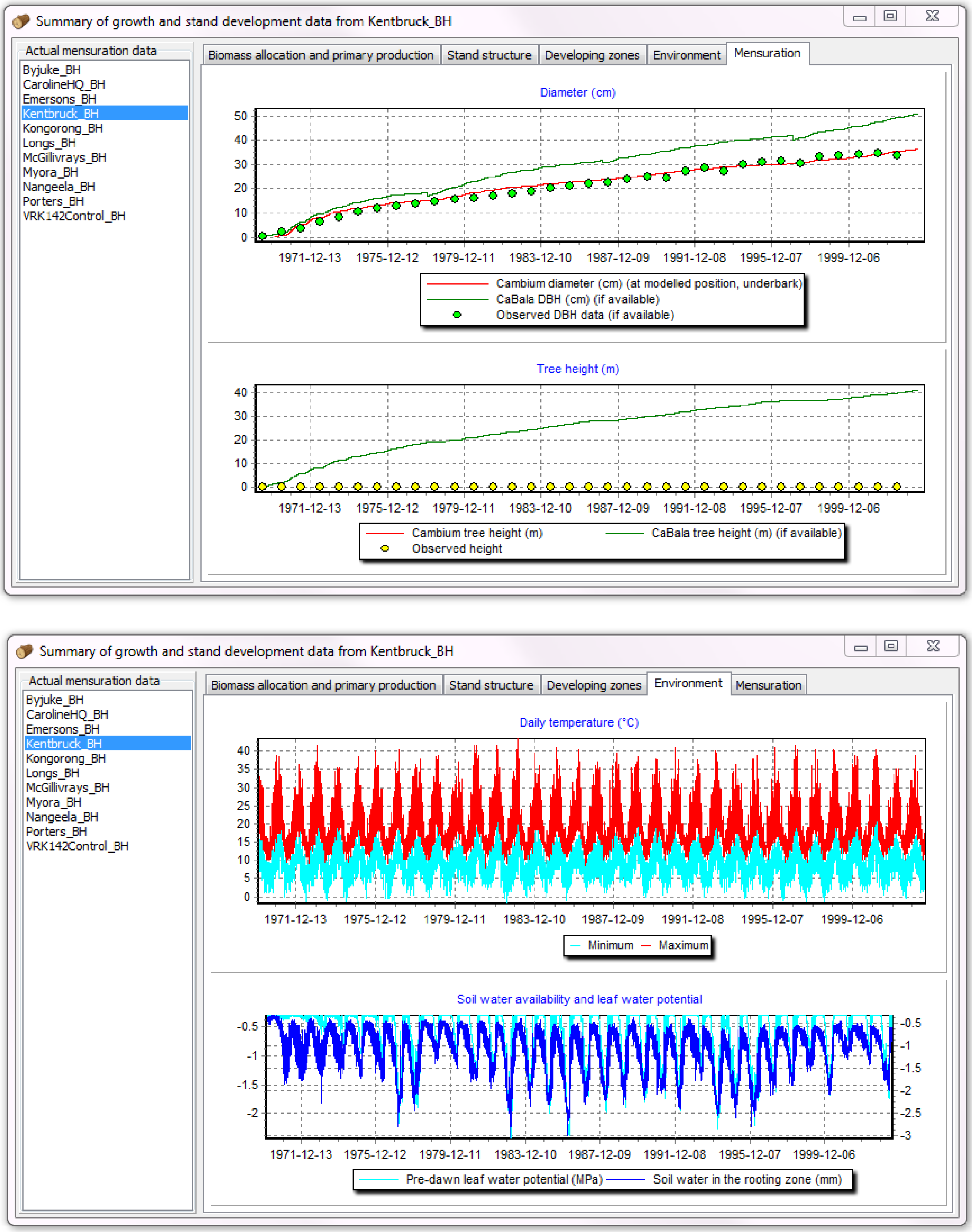


Figure 4: Cambium output graphics showing simulated growth and other physiological data.

Model description

The e-Cambium model

Model organisation

The e-Cambium model operates on a daily time-step, using either inputs from pre-existing stand level simulations from the CaBala model (Battaglia et al. 2004) or from the internal growth model (IGM); a modified version of the 3PG stand growth model (Landsberg and Wareing 1997) later modified and released widely as “the Excel version” by Peter Sands (Sands 2004).

At the onset of a model run, an initial set of hypothetical cells is created, all assigned meristematic status. Thereafter, for each daily time step, stand-level data are read in, and where necessary re-calculated to a tree level (see below). Thereafter, variables are calculated applicable at the level of the stem position for which the simulation is being run. Once the tree- and stem position-level variables have been calculated, the software considers each cell in the increasingly large hypothetical population and performs the following operations for day *d* on cell *c*:

(a) The allocation of daily carbohydrate to each cell
(b) The determination of cell fate
(c) The determination of cell division (only for meristematic cells)
(d) Cell enlargement
(e) Cell secondary thickening and microfibril angle calculation
(f) Cell death

Each cell is tracked until it exits the zone of secondary thickening, after which it ceases to be considered in the daily loop. Once the full modelling period is completed, all cells are considered in the calculation of average wood properties for user-defined radial segments. These data are used by the software to calculated board stiffness.

The main code loop

A summary of the model logic encoded in the software is shown in Figure 5. At the beginning of a model run, all variables are initialized (some values of which can be set by the user, and others of which are hard-coded assuming “seedling” properties). Then, an initial cell simulated population is created for two stem positions. The first is created at the base of the stem (5 cm above ground level) and the second at the position specified for the modeling exercise. If e-Cambium is being run based on pre-existing CaBala simulations, all the data from each simulation is read in prior to the model run. If the IGM is being used, the weather data and site and regime information is read in. Thereafter, the stand growth and development is calculated each day, followed by the Cambium simulation for that day, and so on.

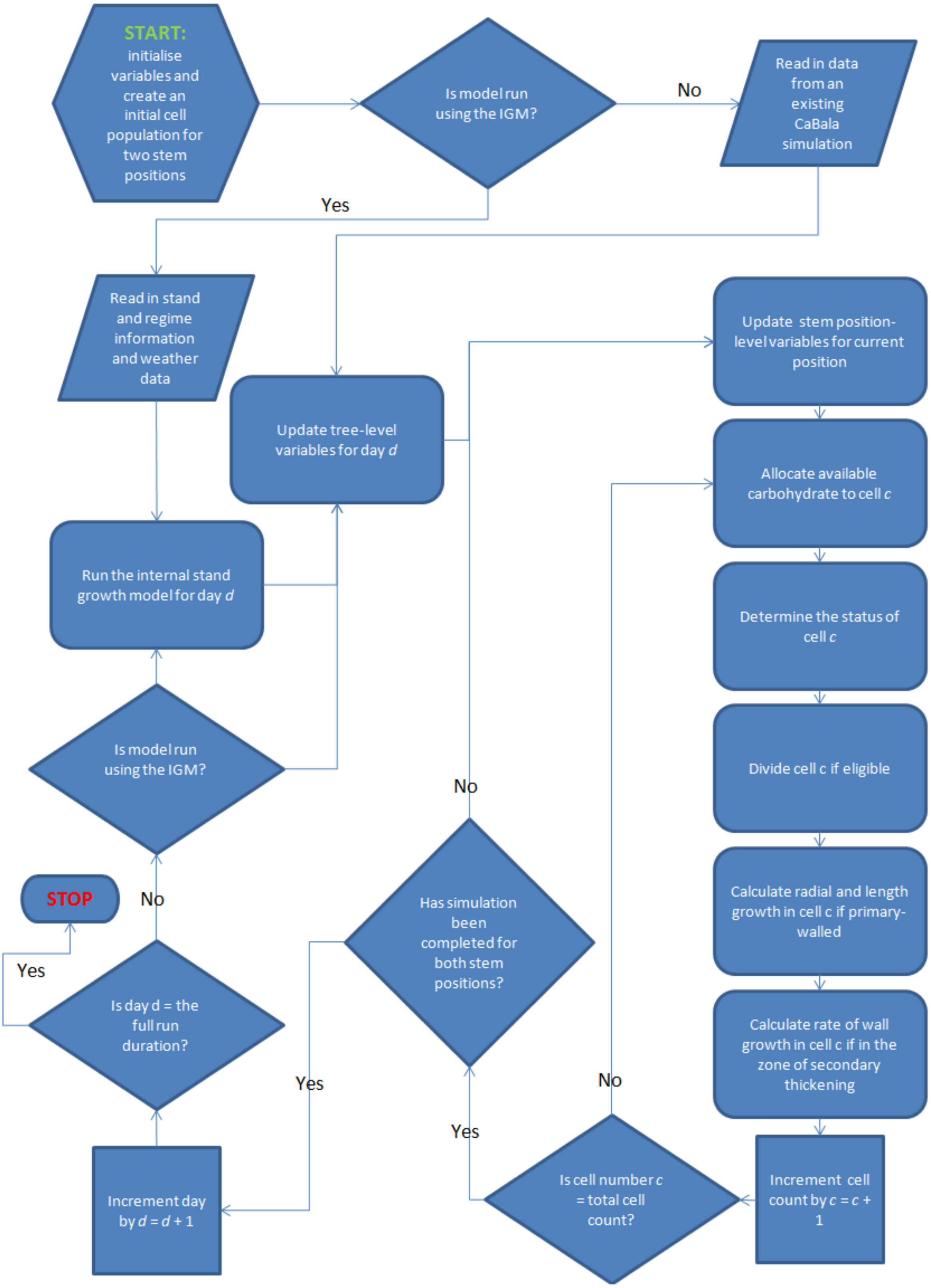


Figure 5: The logic of the Cambium model software

Parameters

Cambium uses a set of 21 parameters that the user must define for the species or ‘genotype’ to bound predictions. A working parameter set, with ranges of values that could be expected to capture a majority of *P. radiata* trees, is presented in Table 1. These parameters represent a function set of model constraints, indicative of what would broadly be expected of “*Pinus radiata*” at a range of sites, but should not be seen as final or even, necessarily, as complete.

There is scope to adjust these parameters for different genotypes, or as understanding of xylem response to environmental conditions improves. Some of these parameters are more important, or “sensitive” than others, and following a comprehensive sensitivity analysis, it is likely that this existing parameter set could be reduced.

Table 1: Cambium parameters with recommended initial ranges

Parameter symbol used in the text	Parameter description and units	Estimate parameter value ranges
$\gamma_{SUC_{CD}}$	The critical concentration of carbohydrates for the cessation of secondary thickening (g/ml)	0.05 - 0.15
α_L	The proportion of cell length after a cell division	0.88 – 0.93
$\alpha_{EZ/CZ_{max}}$	The target ratio of enlarging to cambial cells (# EZ cells/# CZ cells)	0.2 – 0.35
θ_{max}	Maximum wall extensibility (µm/MPa/d)	8 – 12
MFA_{max}	The maximum angle of microfibrils in the S_2 wall layer (degrees)	60 – 66
L_{max}	The maximum length of a mature tracheid (µm)	2000
$\varnothing_{max}$	The maximum diameter of a mature tracheid (µm)	50 – 55
$\alpha_{wall_{max}}$	The maximum ratio of wall area to cell cross sectional area (μm^2 / μm^2)	0.65 – 0.85
$\Delta V_{wall_{max}}$	The maximum rate of wall thickening (μm^3/d)	10000 - 12000
f_{MFA}	Factor determining MFA responsiveness to carbohydrate allocation across the differentiating zones	0.35 – 0.45
$t_{div_{min}}$	The minimum time required between successive cell divisions (cell cycle) (d)	5 - 7
$\varnothing_{div_{min}}$	Minimum radial diameter for periclinal division (µm)	16 – 18
$\Psi_{\pi_{min}}$	The minimum osmotic potential achievable by differentiating cells in the cambial zone (MPa)	-4 - -4.5
T_{min}	The lower air temperature at which metabolic activity in the developing xylem is inhibited (deg C))	0 - 2
$\Psi_{p_{crit}}$	The target turgor for growing cells (MPa)	1 - 1.3
$\propto_{\Delta\varnothing L}$	Ratio of tracheid length/radial growth (µm/µm)	9 – 12
f_{vac}	Scaling factor to adjust from lumen volume to the “effective” volume for osmotic adjustment	0.045 – 0.055
ρ_{CW}	Density of the cell wall (g/cm^3)	1.5
$\Psi_{p_{YT}}$	The cell wall yield threshold (MPa)	0.2 – 0.4
f_{juv}	Distance from crown apex at which juvenile production completely ceases (m)	8 – 10
$\alpha_{alloc_{min}}$	The minimum rate of carbohydrate extraction per cell (%)	0.15 – 0.35

In addition to the parameters listed in Table 1, to calculate board stiffness, or modulus of elasticity (MOE) (GPa), two additional parameters are defined: f_{MOE_0} and f_{MOE_1}. These were estimated at values of -11.03 and 24 respectively for the model runs discussed in this paper, calculated from regression analysis of SilviScan (Evans 1994; Evans 1997; Evans et al. 1995) using data from 12 *P. radiata* sites studied as part of a previous FWPA study (see FWPA report PN03.3906: Resource Evaluation for Future Profit).

Tree-level variables

Although input data from CaBala or the IGM are at a stand-level, *e*-Cambium performs calculations at an individual tree level (conceptually, the "average" tree in the stand). As a result, stand level data must first be converted to the appropriate unit. Most critically, the daily NPP allocated to the stem for the individual "average" tree *X* (kg) on day *d* is calculated (Equation 1).

$$NPP_{stem_t} = \left(\left({NPP_{stand}}/{SPH}\right) \times 1000\right) \times alloc_{stem} \text{.......Equation 1}$$

Where NPP_{stand} is the NPP for the stand (t/Ha), *SPH* is the stand density (trees/Ha) and $alloc_{stem}$ is is the allocation to stem (%) on day *d*.

The calculated value of NPP_{stem_t} utilised for further calculations in *e*-Cambium is then smoothed using a 5-day moving average, under the assumption that availability of carbohydrate in the phloem at the modeled position will buffer fluctuations in sequestration and allocation from the crown. Cambial surface area on day *d* is calculated assuming a stem that is 3-dimensionally parabolic in shape. This calculation requires the diameter of the tree at the base. For this reason, the model needs to run at two positions in parallel: the position of interest to the user, and at the base of the tree (nominally assumed to be 5 cm above the ground level), for a basal diameter estimate. An area specific available carbohydrate value (g/µm^2) is then calculated for tree *X* on day *d* (Equation 2).

$$ASC_{stem} = {\left(NPP_{stem_t} \times 1000\right)}/{\left(SA_{stem} \times 10^{12}\right)} \text{.......Equation 2}$$

Where NPP_{stem_t} is defined in Equation 1, and SA_{stem} is the surface area of the stem (underbark) (m^2).

Stem position-level variables

The e-Cambium model is capable of simulating xylem development at any point in a hypothetical tree above the nominal "base" position of 5 cm. In order to achieve this, a number of "position-level" variables are calculated at each time step. First, the total carbohydrate available for the modeled developing cell file *f* (g) is calculated (Equation 3):

$$Carbs_f = \left(ASC_{stem} + StoredCarbs_f\right) \times TanArea_{tracheid} \text{.......Equation 3}$$

Where ASC_{stem} is defined in Equation 2, $StoredCarbs_f$ is the amount of non-structural carbohydrates in addition to new allocation available for the modeled cell file *f* (g), and $TanArea_{tracheid}$ is the area of the tangential face of the average tracheid in the cell file (µm^2).

Each day a critical osmotic potential ($\Psi_{\pi_{crit}}$) (MPa), is calculated (Equation 4), below which the model tries to maintain the average osmotic potential of the dividing and enlarging cells in the modeled cell file (so that cells can maintain turgor). $\Psi_{\pi_{crit}}$ is assumed to be, in large part, determined by ambient conditions, particularly xylem water potential (Ψ_x). It is assumed in the model that xylem growth occurs predominantly at night when water potentials are recovering (Downes et al. 1999c; Downes et al. 2004b), and therefore only pre-dawn xylem water potential (a measure of effective water availability at the site) is used in calculations in the model. The calculation has two components. First, the need to maintain the target turgor potential (a parameter, $\Psi_{p_{crit}}$) on average in the growing and dividing cell population. Target turgor is modified at positions less than f_{juv} (a parameter, in m) from the top of the tree, to a minimum of 0.9 X $\Psi_{p_{crit}}$. Second, the need to protect the cambium against very cold temperatures. This effect only becomes operational in near- or below-freezing conditions, if temperatures drop below the minimum temperature for cambial activity (T_{min}) reaching a maximum at -5 °C.

$$\Psi_{\pi_{crit}} = min\begin{cases} \Psi_{x_{max}} - \Psi_{p_{crit}} \\ (T_{min} - (-5))\Big/ (T_{crit} - (-5)) \times \Psi_{\pi_{min}} \end{cases} \text{.......Equation 4}$$

Where $\Psi_{x_{max}}$ is maximum (pre-dawn) daily xylem water potential and $\Psi_{p_{crit}}$, T_{min}, and $\Psi_{\pi_{min}}$ are parameters. -5°C is assumed to be the base temperature below which cells fully protect against frost damage.

The model then optimizes cambial width and the width of the enlargement zone by trying to ensure that the average osmotic potential of cells in those zones is equal to or slightly below $\Psi_{\pi_{crit}}$.

Allocation of carbohydrates

The model assumes that carbohydrate becomes decreasingly available to cells further from the phloem. Provided the osmotic potential of cell *c* in a radial lineage of cells (a "cell file") is above a minimum value ($\Psi_{\pi_{min}}$) then carbohydrate can be allocated to that cell. An allocation coefficient (α_{alloc}) is calculated for each day *d* using an optimization routine to ensure that the allocation across the zone of cells to which carbohydrate is allocated exceeds 99% of the total available allocation ($Alloc_f$) for cell file *f*, on day *d*, subject to a minimum value ($\alpha_{alloc_{min}}$, a parameter). During earlywood formation, allocation to dividing and enlarging cells is prioritised. Earlywood is defined in the model as the xylem which forms while day length is increasing (provided other factors are not limiting), or while day length is decreasing but greater than 80% of the maximum day length at the site. Thereafter, the priority of direct allocation to cells in which secondary thickening is underway is increased. The allocation of carbohydrate to any cell *c* (g) is calculated as described in Equation 5. The effect of the approach is shown in Figure, where, given the same value of $Alloc_f$, a cell at the same position relative to phloem will receive differing amounts of allocation depending on the width of the zone.

$$Alloc_c = (Alloc_f - Alloc_{c-1}) \times \alpha_{alloc} \text{.......Equation 5}$$

Where $Alloc_f$ is the amount of carbohydrate available for allocation to cell file *f* (g), $Alloc_{c-1}$ is the allocation previously committed to the cell one position closer to the phloem than cell *c* (g) and α_{alloc} (defined above) is the allocation coefficient for day *d*.

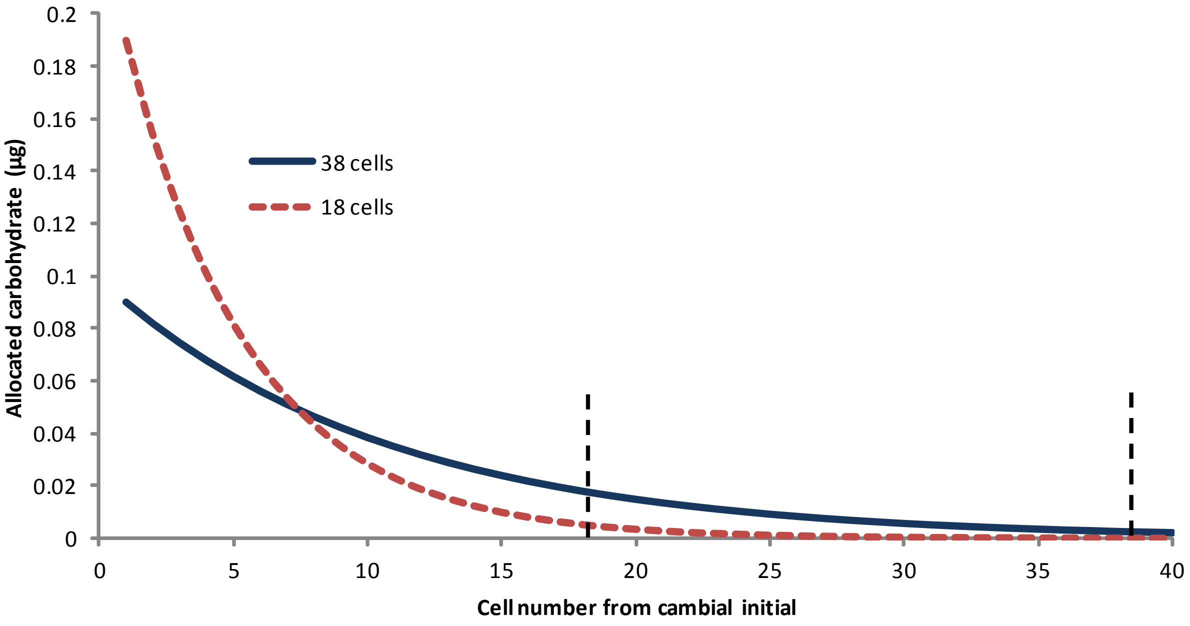


Figure 6: Allocation of the same amount of carbohydrate (in this example, 1 µg per unit cell file) across different numbers of cells. In a shorter cell file, the gradient is steeper. Thickening cells do get some residual allocation once the cambial and enlarging cells have been allocated 99% of the available carbohydrate.

For each cell, a cumulative amount of carbohydrate is monitored. This total carbohydrate content is used to calculate the osmotic potential of the cell *c* on day *d* (Equation 6).

$$\Psi_{\pi_c} = \varphi \times -1 \, {}^{(\gamma_{suc_e} \times R \times T)}\!/_{1000}$$ ….Equation 6

Where φ is the osmotic coefficient of sucrose (assumed to be approximately 1.4), γ_{suc_e} is the effective concentration of sucrose (mol/L) (Equation 7), R is the gas constant (assumed to be 0.0821) and T is the average temperature (K) on day *d*.

$$\gamma_{suc_e} = {}^{Suc}\!/_{(Vol_{lum} \times f_{vac})}$$ …….Equation 7

Where *Suc* is the quantity of sucrose in solution in the osmotically active volume of the cell (mol), Vol_{lum} is the lumen volume (L) and f_{vac} is a parameter scaling to the effective volume.

Tracheid determination

Unlike hardwoods, softwoods produce one main longitudinal cell type in the xylem. As such, xylem cell type is not considered (i.e. in the model, all cells on the pith-side of the cambium are considered merely as “xylem”), but only the stage of cell development. In the present version of the model, only xylem cells are followed through all stages of differentiation. Cells that exit to become phloem cells are immediately removed from the model population and not considered further (to reduce run time), although with some small adjustments, modeling phloem is possible. In the xylem, cells move through three phases: division, enlargement and secondary thickening (Figure 7).

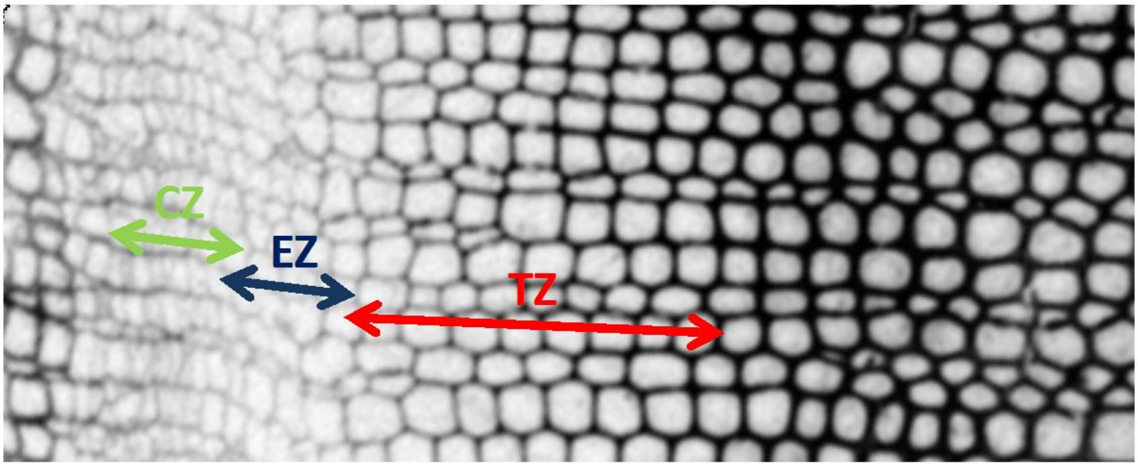


Figure 7: An image (25 X) of a transverse section through the cambial zone (CZ), enlarging zone (EZ) and secondary thickening zone (TZ) of the developing xylem in a *P. radiata* tree, about mid-way through through the growing season. The earliest phloem cells can be seen on the left side of the image.

For each daily time step, a cell *c* will exit the cambial zone and enter the enlarging zone when:

- The ratio of enlarging to dividing cells exceeds a critical value adjusted as a function of the distance from crown (see Anfodillo et al. 2012; Ridoutt and Sands 1993; Ridoutt and Sands 1994) (Equation 8).
- A meristematic cell does not exist between cell *c* and the enlarging zone

$$\alpha_{EZ/CZ} = \alpha_{EZ/CZ_{max}} \times {}^{\left(h_{tree} - h_{modpos}\right)}\!\Big/_{f_{juv}} \text{ ....Equation 8}$$

Where h_{tree} is the height of tree (m) and h_{modpos} is the position on the stem at which the model is operating (m) on day *d* and $\alpha_{EZ/CZ_{max}}$ and f_{juv} are parameters.

Subsequently, after it has exited the cambial zone, a cell *c* will exit the enlarging zone and enter the secondary thickening zone if:

- A growing cell does not exist between cell *c* and the secondary thickening zone and
- The average osmotic potential in the dividing and enlarging cells zone exceeds $\Psi_{\pi_{crit}}$
- The number of growing days exceeds 2 days

Finally, cell *c* will exit the secondary thickening zone and cease to differentiate if:

- A secondary thickening cell does not exist between cell *c* and the functioning xylem and
- A maximum proportion of wall is reached (a parameter, $\alpha_{wall_{max}}$) or
- The cumulative carbohydrate concentration is below a threshold ($\gamma_{SUC_{CD}}$) or

At this point, the cell is assumed to have undergone apoptosis, lost its protoplasm, and become a conductive element.

Cell division

If cells are in the cambial zone, they will have the potential to divide. However, for each daily time step, a cell *c* will only divide if:

- The radial diameter of cell *c* exceed a minimum value, which is affected by distance from the crown (Equation 9)

- The time since a previous mitosis in cell *c* exceeds a minimum duration ($t_{div_{min}}$, a parameter).
- The amount of non-structural carbohydrate accumulated in the cell exceeds the amount required to build a new cell plate and a nominal quantity of new cellular organelles and other protoplasmic material

$$\varnothing_{div} = \varnothing_{div_{min}} + 2 \times \min \begin{cases} \left(h_{tree} - h_{modpos}\right) / f_{juv} \\ 1 \end{cases} \text{……Equation 9}$$

Where h_{tree} is the height of tree (m) and h_{modpos} is the position on the stem at which the model is operating (m) on day *d* and $\varnothing_{div_{min}}$ and f_{juv} are parameters.

Each daughter cell, as well as the newly divided mother cell, is assumed to have a radial diameter equal to half the original diameter of the mother cell. However, the option exists to randomize the diameter of the two cells resulting from a division by between 40 and 60%. Because anticlinal divisions are not explicitly modeled, the length of the daughter cell, as well as the mother cell, following each periclinal division is reduced (Equation 10), assuming a pseudo-transverse division. The daughter cell is the cell which arises on the pith-side of the original mother cell, following a division.

$$L_{c_{postdiv}} = L_{c_{prediv}} \times \alpha_L \text{……Equation 10}$$

Where $L_{c_{prediv}}$ is the length of cell c prior to division (µm) and α_L is a parameter.

Tracheid expansion

The rate of tracheid expansion is a process which is driven by turgor, and adjusted by the extensibility of the cell wall and the yield threshold (Abe and Nakai 1999; Cosgrove 2001; Hölttä et al. 2010; Kutschera 2004). While a cell is in the phase of enlargement, the primary wall is assumed to remain constant at a thickness of 0.2 µm. Radial wall extensibility (µm/MPa/d) in the process is assumed to be predominantly modified by interactions with neighbours (i.e. a physical impedance which becomes greater as cells become larger and fill the available space) and drought severity (assuming that wall extensibility is an additional control of turgor) (Equation 11).

$$\theta_c = \theta_{max} \times \left(1 - \left[\varnothing_c / \varnothing_{max}\right]\right) \times \Psi_{\pi_{crit}} / \Psi_{\pi_{\min}} \text{…….Equation 11}$$

Where $\varnothing_c$ is the radial diameter of cell *c* (µm), $\Psi_{\pi_{crit}}$ is the critical osmotic potential on day *d* (MPa), and θ_{max}, $\varnothing_{max}$ and $\Psi_{\pi_{min}}$ are parameters.

In addition to extensibility control, the development of turgor (MPa) is osmotically adjusted (i.e. by the adjustment of solute concentration and osmotic potential in the vacuole) (Equation 12).

$$\Psi_{p_c} = \min \begin{cases} \Psi_{p_{crit}} \\ \Psi_{xylem} - \Psi_{\pi_c} \end{cases} \text{…….Equation 12}$$

Where Ψ_{xylem} is the mean water potential in the xylem at the modeled stem position (MPa), Ψ_{π_c}, the osmotic potential of cell c (MPa), is defined above and $\varphi_{p_{crit}}$ is a parameter.

Total daily radial growth (µm d^{-1}) in cell *c* for day *d* is then calculated according to Equation 13.

$$\Delta\varnothing_c = \theta_c \times \left(\Psi_{p_c} - \Psi_{p_{YT}}\right) \text{.......Equation 13}$$

Where θ_c is the wall extensibility of cell *c* (Equation 11), Ψ_{p_c} is the turgor pressure of cell *c* (Equation 12) and $\Psi_{p_{YT}}$ is a parameter.

Growth in the length of the tracheid (µm d^{-1}) is assumed to be proportional to the radial growth (Equation 14).

$$\Delta L_c = \min\begin{cases}\Delta\varnothing_c \times \propto_{\Delta\varnothing L}\\ L_{max}\end{cases} \text{.......Equation 14}$$

Where $\Delta\varnothing_c$ is the radial growth rate of cell c on day d (µm d^{-1}) (Equation 13) and $\propto_{\Delta\varnothing L}$ and L_{max} are parameters.

Tracheid secondary thickening

Secondary wall formation utilizes carbohydrate accumulated in the cell during the stages of division and growth, as well as any carbohydrate that is subsequently allocated to the cell directly during the secondary thickening phase. Once secondary thickening commences, the rate of change of wall volume for cell *c*, on day *d*, is calculated (Equation 15)

$$\Delta V_{wall_c} = \min\begin{cases}\Delta V_{wall_{max}}\\ SUC_c \times \left({}^{1}\!/_{\rho_{CW}}\right) \times 10^{12}\end{cases} \text{.......Equation 15}$$

Where SUC_c is the accumulated quantity of carbohydrate (g) in cell *c* on day *d* and $\Delta V_{wall_{max}}$ and ρ_{CW} are parameters.

The lumen volume (µm^3) of cell *c* is then calculated (Equation 16).

$$V_{lum_c} = \max\begin{cases}\left(1 - \alpha_{wall_{max}}\right) \times V_c\\ V_{lum_c} - \Delta V_{wall_c}\end{cases} \text{.....Equation 16}$$

Where V_c is the total volume of cell c (µm^3), V_{lum_c} is the lumen volume of cell *c* (µm^3), ΔV_{wall_c} is the change in wall volume in cell *c* on day *d* (Equation 15) and $\alpha_{wall_{max}}$ is a parameter.

If wall volume is greater than $\alpha_{wall_{max}} \times V_c$ (where V_c is the volume of cell *c*) then the cell is assumed to have reached the maximum possible wall thickness, and it will exit the phase of secondary thickening. Potential cell lumen surface area of cell *c* (µm^2) (assuming that the cell is a long, narrow rectangular prism) is calculated as (Equation 17):

$$SA_{lum_c} = {}^{V_{lum_c}}\!/_{L_c} \text{.......Equation 17}$$

Where V_{lum_c} is the lumen volume of cell c (µm^3) (Equation 16) and L_c is the length of cell *c* (µm).

Wall thickness (µm) is finally determined using an optimization routine that calculates the wall thickness corresponding to a cell with known tangential and radial diameter with the calculated lumen surface area.

Microfibril angle (MFA)

The mechanism of microfibril orientation in fibres (including tracheids) is still very poorly understood (Donaldson 2008; Donaldson and Xu 2005), but appears to be linked to rates of growth and subsequent wall development (Chan 2011; Donaldson 2008). In the absence of clear evidence for a mechanism, in e-Cambium microfibril angle is calculated as a function of the distribution of carbohydrate across the varying cambial and enlarging zones, and adjusted from tree age (Equation 18), under the assumption that this distribution coefficient provides a good proxy for general vigour and carbohydrate distribution in the differentiating zone. To our knowledge, this is the first attempt to develop an MFA model within the context of a broader xylem development framework.

$$MFA_c = MFA_{max} \times (\alpha_{alloc}{}^{f_{MFA}}) \times \left({}^{\#rings_p}/_{40} \right)^2 \text{ ....Equation 18}$$

Where α_{alloc} is the allocation coefficient on day *d* (see section above: Allocation of carbohydrates) and $\#rings_p$ is the ring count at position *p* on day *d* and MFA_{max} and f_{MFA} are parameters.

The *e*-Cambium internal stand growth model

The *e*-Cambium software provides a built-in stand growth and development model (what we have called the internal stand growth model, or IGM) to produce stand-level estimates of the variables required for input to the xylem development model. The IGM is a modified version of the 3PG stand growth model (Landsberg and Wareing 1997), adapted here from the Microsoft Excel-based version produced by Sands (2004). The biggest change that has been made in the IGM is that the model now runs at a daily time step, with parameters determining maximum losses of leaf litter and root mass, for example, being per day, rather than per month. The model therefore requires weather data (minimum and maximum daily temperature, rainfall and incoming solar radiation) on a daily time step. We detail below only those parts of the original code that have been modified in the *e*-Cambium internal stand growth model, as compared to the earlier versions of 3PG. Readers are referred to Landsberg and Waring (1997) for more information 3PG generally.

Parameters

The *e*-Cambium IGM uses fewer than 40 parameters to limit calculations of stand development, net primary productivity and water availability/tree drought stress (Table 2).

Table 2: Parameters used by the Cambium internal growth model

Parameter symbol used in text	Parameter description	Estimated parameter value ranges
α_{C_x}	Canopy quantum efficiency	0.045 – 0.052
g_B	Canopy boundary layer conductance, assumed constant	0.2

Parameter symbol used in text	**Parameter description**	**Estimated parameter value ranges**
k_g	Determines response of canopy conductance to VPD	0.045 – 0.055
f_{N0}	Value of fN when FR = 0	0.55 – 0.65
t_{FCC}	Age at full canopy cover (Y)	7 – 8
γ_{F0}	Litterfall rate at t = 0 (1/day)	0.00003
γ_{Fx}	Maximum daily litterfall rate	0.0025 – 0.004
γ_R	Root turnover rate per day	0.0004 - 0.0006
K	Radiation extinction coefficient	0.5
L_{gcmax}	LAI required for maximum canopy conductance	5
L_{MaxInt}	LAI at maximum canopy rainfall interception	5 – 7
m_0	Value of m when FR = 0	0
$t_{MaxPhysAge}$	Maximum stand age used in age modifier	250
g_{Cx}	Maximum canopy conductance (gc, m/s)	0.008 – 0.12
$\mathrm{pHD}_{\mathrm{max}}$	The maximum height/base diameter ratio (m/cm)	0.6 – 0.8
I_{max}	Rainfall interception in a canopy with LAI for maximum interception (mm)	0.8 – 1.2
$\mathrm{pHD}_{\mathrm{min}}$	The minimum height/base diameter ratio (m/cm)	0.5
mS	Fraction mean single-tree stem biomass lost per dead tree	0.2
nAge	Power of relative age in function for fAge	3.8 – 4.2
pFS_2	Foliage:stem partitioning ratios for stems with base diameter 2 cm	0.7 - 0.9
pFS_{20}	Foliage:stem partitioning ratios for stems with base diameter 20 cm	0.4 – 0.7
pR_{min}	Minimum root biomass partitioning	0.2 – 0.4
pR_{max}	Maximum root biomass partitioning	0.5 – 0.8
$\Psi_{PD\,\mathrm{min}}$	Minimum achievable pre-dawn leaf water potential (MPa)	-3 - -2
Qa	intercept of net v. solar radiation relationship (W/m2)	-90
Qb	slope of net v. solar radiation relationship	0.8
rAge	Relative age to give fAge = 0.5	0.5
f_{RD}	The rate of root vertical growth per unit root mass (m/kg)	0.5 – 1
SLA_0	Specific leaf area at age 0 (m^2/kg)	5 - 6
SLA_1	Specific leaf area for mature leaves (m^2/kg)	5 - 6

Parameter symbol used in text	Parameter description	Estimated parameter value ranges
$t_{\gamma F}$	Age at which litterfall rate has median value (d)	800 – 1200
$p_{thinning}$	Power in self-thinning law	1.5
T_{max}, T_{opt} and T_{min}	Critical max temp, optimum and minimum temperatures for tree growth and physiological activity (deg C)	40, 20 & 0
t_{SLA}	Stand age (years) for SLA = (SLA0 + SLA1)/2	1.5 – 3
$m_{\mathrm{max}\ 1000}$	Max tree stem mass (kg) likely in mature stands of 1000 trees/ha	160 – 200
Y	Assimilate use efficiency (Ratio NPP/GPP)	0.45 – 0.50

Modification of canopy interception

The calculation of rainfall interception by the canopy (in mm) has been modified to reach a maximum, assumed to be the maximum storage capacity of the canopy (Equation 19). Accordingly, a larger proportion of total rainfall will be intercepted in a small rainfall event, compared to a large rainfall event.

$$I = {}^{I_{max}}\!/_{L_{MaxInt}} \times L_d \text{.......Equation 19}$$

Where L_d is the leaf area index on day *d* and I_{max} and L_{MaxInt} and are parameters.

Introduction of soil depth information

Soil depth is now considered, although in a parsimonious fashion, with an “average” textural class and soil retention characteristics. The soil is set up as a series of 10 cm deep layers, each of which has an independently calculated soil water availability. This is updated daily by considering

- Addition of water following a rainfall event
- Loss of water through evapotranspiration

Water percolation down through the soil profile is calculated by averaging the soil water content of two adjoining 10 cm portions step-wise (Equation 20). That is, a 10 mm rainfall event will not all be allocated to the top 10 cm soil layer, but will be distributed, in decreasing amounts, to all soil layers below the surface.

$$SWC_{l+1} = {}^{(SWC_l + SWC_{l+1})}\!/_{2} \text{.......Equation 20}$$

Where SWC_l and SWC_{l+1} are two adjoining 10 cm thick layers of soil, and SWC_l is above SWC_{l+1}.

Introduction of a root depth term

The model calculates a simple estimate of root depth (m) for each time step, based on the mass of root (Equation 21). This value provides an indication of the depth of soil which the tree is able to explore for available water.

$$D_R = \min \begin{cases} D_{soil} \\ {(W_R \times 1000)}/{SPH_d} \times f_{RD} \end{cases} \text{.......Equation 21}$$

Where D_{soil} is soil depth (m), W_R is stand root mass (t/Ha), SPH_d is the stand density (stems/Ha) on day *d* and f_{RD} is a parameter.

Calculation of soil water modifiers and leaf water potential

Relative soil water content is calculated in the present version by considering the wettest part of the soil to which the roots have access (Equation 22). For each time step, the available soil water is assessed for each 10 cm deep portion of soil within the rooting depth.

$$SWC_{rel} = {SWC_{max\,d}}/{(SWC_{max} \times 0.1)} \text{.......Equation 22}$$

Where $SWC_{max\,d}$ is the maximum available soil water (mm) in the wettest portion of the soil on day *d* and SWC_{max} is the maximum available soil water for the soil (mm/m).

Pre-dawn leaf water potential is calculated following the method described in Battaglia et al. (2004) based on SWC_{rel}, the soil textural class and the exponents of the soil water relation equation, with values from (Campbell and Norman 1998). The soil water modifier, limited to values between 0 and 1, is then calculated relative to pre-dawn leaf water potential (Equation 23).

$$f_{SW} = {(1 - \Psi_{PD})}/{\Psi_{PD\,\min}} \text{.....Equation 23}$$

Where Ψ_{PD} is pre-dawn leaf water potential on day *d* and $\Psi_{PD\,\min}$ is a parameter.

Allocation ratios

The foliage to stem allocation ratio is calculated slightly more simply than in the earlier 3PG version (Equation 24), and limited to remain between the minimum and maximum values of pFS_2 and pFS_{20}.

$$pFS = {((pFS_{20} - pFS_2) \times (\varnothing_{base} - 2))}/{(20 - 2)} + pFS_2 \text{.......Equation 24}$$

Where $\varnothing_{base}$ is the diameter of the stem at the tree base (cm) and pFS_2 and pFS_{20} are parameters.

Following mortality, the biomass of any component (foliage, stems or roots) is calculated as (Equation 25):

$$W_{*} = W_{*} - \left(W_{*} \times {\Delta_{SPH}}/{SPH} \right) \text{.......Equation 25}$$

Where $W_{\ast}$ is the mass of the biomass component (t/Ha), Δ_{SPH} is the loss of trees and SPH is the current stand density (stems/Ha) on day *d*.

Tree height

The volume of the average tree stem is calculated from a known individual stem mass (kg) (of the average tree in the stand) and wood density (kg m^{-3}) (Equation 26). Subsequently, tree height (for the average tree) is calculated assuming a conical stem, with a known base diameter (Equation 27), limited to values determined by parameters.

$$V_{stem} = {}^{m_{stem}}\!/_{\rho_{wood}} \text{……Equation 26}$$

Where m_{stem} is the mass (kg) of the average tree in the stand and ρ_{wood} is the assumed average wood density of the tree (kg m^{-3}).

$$h_{tree} \begin{cases} & > \varnothing_{\mathrm{base}} \times \mathrm{pHD}_{\mathrm{min}} \\ = & (V_{stem} \times 3) \Big/ \left(\pi \times \left({}^{\varnothing_{\mathrm{base}}}\!/_{2}\right)^{2}\right) \\ & < \varnothing_{\mathrm{base}} \times \mathrm{pHD}_{\mathrm{max}} \end{cases} \text{……Equation 27}$$

Where $\varnothing_{\mathrm{base}}$ is the diameter at the base of the stem (cm), V_{stem} is the volume of the stem (m^3) and $\mathrm{pHD}_{\mathrm{min}}$ and $\mathrm{pHD}_{\mathrm{max}}$ are parameters.

Results: Model predictive veracity and performance

Modelling wood property variation is a complex task. Not only is the process itself difficult to model even with access to the best possible data, but in any modelling context, as here, it is subject to a 'cascade' of errors. That is, when using the CaBala runs, the modelled wood property data is subject to the accuracy of the inputs. Furthermore, regardless of the stand-level modelling approach used, the accuracy of the inputs around site descriptions, regime information and weather data will all have an enormous impact on output predictions. Therefore, the results shown here need to be considered relative to these uncontrollable errors. Outputs are shown for 18 scenarios, at 16 sites, using both CaBala inputs and the IGM (Table 3). Sites and regimes developed using the two approaches were set up to be as similar as possible, although this was sometimes difficult given the difference in the level of complexity. All runs were undertaken using exactly the same set of *e*-Cambium parameters. Cabala runs all used an identical set of Cabala parameters (see Appendix 4). Where sites were known to have a duplex soil or hard-pans (e.g. Nangeela or Byjuke), only the upper layer is specified in Table 3, and the depth is depth to the second layer, which is effectively considered impenetrable here.

Table 3: Sites/treatments used for parameter development and testing. Soil depth in the case of duplex soil is taken to be depth to clay.

Site/scenario	Region	Site silviculture	Dominant soil type
Balmoral	**New Zealand S Island**	**Planted 1997 at 833 SPH**	**Silt loam**
Blackwarry (combined)	**Gippsland (Strezelecki ranges)**	**Planted 1995 at 1111 stems/Ha Thinned 2010 to 595 stems/Ha**	**Sandy clay**
Byjuke	**Green triangle**	**Planted 1975 at 1600 stems/Ha Thinned 1985 to 720 stems/Ha Thinned 1989 to 550 stems/Ha Thinned 1996 to 250 stems/Ha**	**Sand**
Caroline HQ	**Green triangle**	**Planted 1958 at 1736 stems/Ha Thinned 1970 to 1070 stems/Ha Thinned 1981 to 750 stems/Ha Thinned 1988 to 450 stems/Ha Thinned 1994 to 250 stems/Ha**	**Loamy sand**
Emerson's	**Green triangle**	**Planted 1976 at 1736 stems/Ha Thinned 1983 to 600 stems/Ha Thinned 1996 to 340 stems/Ha**	**Clay loam**
Flynn Creek thinned	**Gippsland**	**Planted 1995 at 1111 stems/Ha Thinned 2008 to 200 stems/Ha**	**Flynn sand**
Flynn Creek unthinned	**Gippsland**	**Planted 1995 at 1111 stems/Ha Not thinned although some mortality (to 900 SPH taken into account based on inventory data)**	**Flynn sand**
Kentbruck	**Green triangle**	**Planted 1970 at 2000 stems/Ha Thinned 1985 to 750 stems/Ha Thinned 1993 to 388 stems/Ha Thinned 1999 to 250 stems/Ha**	**Loamy sand**
Kongorong	**Green triangle**	**Planted 1974 at 2000 stems/Ha Thinned 1980 to 630 stems/Ha**	**Clay loam**

Site/scenario	Region	Site silviculture	Dominant soil type
		Thinned 1988 to 443 stems/Ha Thinned 2000 to 273 stems/Ha	
Long's	Green triangle	Planted 1965 at 1379 stems/Ha Thinned 1977 to 590 stems/Ha Thinned 1983 to 495 stems/Ha Thinned 1992 to 250 stems/Ha	Loamy sand
McGilllivray's	Green triangle	Planted 1970 at 1600 stems/Ha Thinned 1982 to 830 stems/Ha Thinned 1988 to 440 stems/Ha Thinned 1995 to 270 stems/Ha	Sand
Mt Gambier airport treatment E1	Green triangle	Planted 1995 at 2268 stems/Ha Thinned 2000 to 1111 stems/Ha Thinned 2007 to 555 stems/Ha	Sand
Mt Gambier airport treatment E2A	Green triangle	Planted 1995 at 2268 stems/Ha Thinned 2001 to 555 stems/Ha	Sand
Mt Gambier airport treatment E3	Green triangle	Planted 1995 at 555 stems/Ha	Sand
Myora	Green triangle	Planted 1969 at 1905 stems/Ha Thinned 1981 to 750 stems/Ha Thinned 1987 to 450 stems/Ha Thinned 1994 to 220 stems/Ha	Loamy sand
Nangeela	Green triangle	Planted 1977 at 1401 stems/Ha Thinned 1988 to 807 stems/Ha Thinned 1999 to 375 stems/Ha	Sand
Ohurakura	New Zealand N Island	Planted 1993 at 625 SPH	Sand
Porter's road	Green triangle	Planted 1979 at 1736 stems/Ha Thinned 1997 to 642 stems/Ha Thinned 2002 to 362 stems/Ha	Clay loam
VRK142 (Control)	Green triangle	Planted 1972 at 1667 stems/Ha Thinned 1984 to 1000 stems/Ha Thinned 1991 to 560 stems/Ha	Sand

Predictions of underbark stem growth

The *e*-Cambium model was primarily intended as a tool to predict variation in wood property parameters like wood density. However, it also predicts under-bark radial growth by tracking the accumulation of new wood cells, and an accurate prediction of growth is obviously an important component of an accurate representation of product recovery (sawn board numbers) independent of wood property values. The deviation of predicted under-bark stem diameter, as compared to actual under-bark DBH (calculated from the positions of annual rings allocated to SilviScan data from 3 – 12 trees at various sites) is shown in Figure 8 (based on Cabala inputs) and Figure 9 (based on in-house runs using the IGM). The veracity of these predictions is a useful first indicator of how well the model(s) are capturing growth and development at the simulated sites. In most cases based on Cabala simulations, modelled final diameter was within 5 cm of the final diameter calculated from ring position.

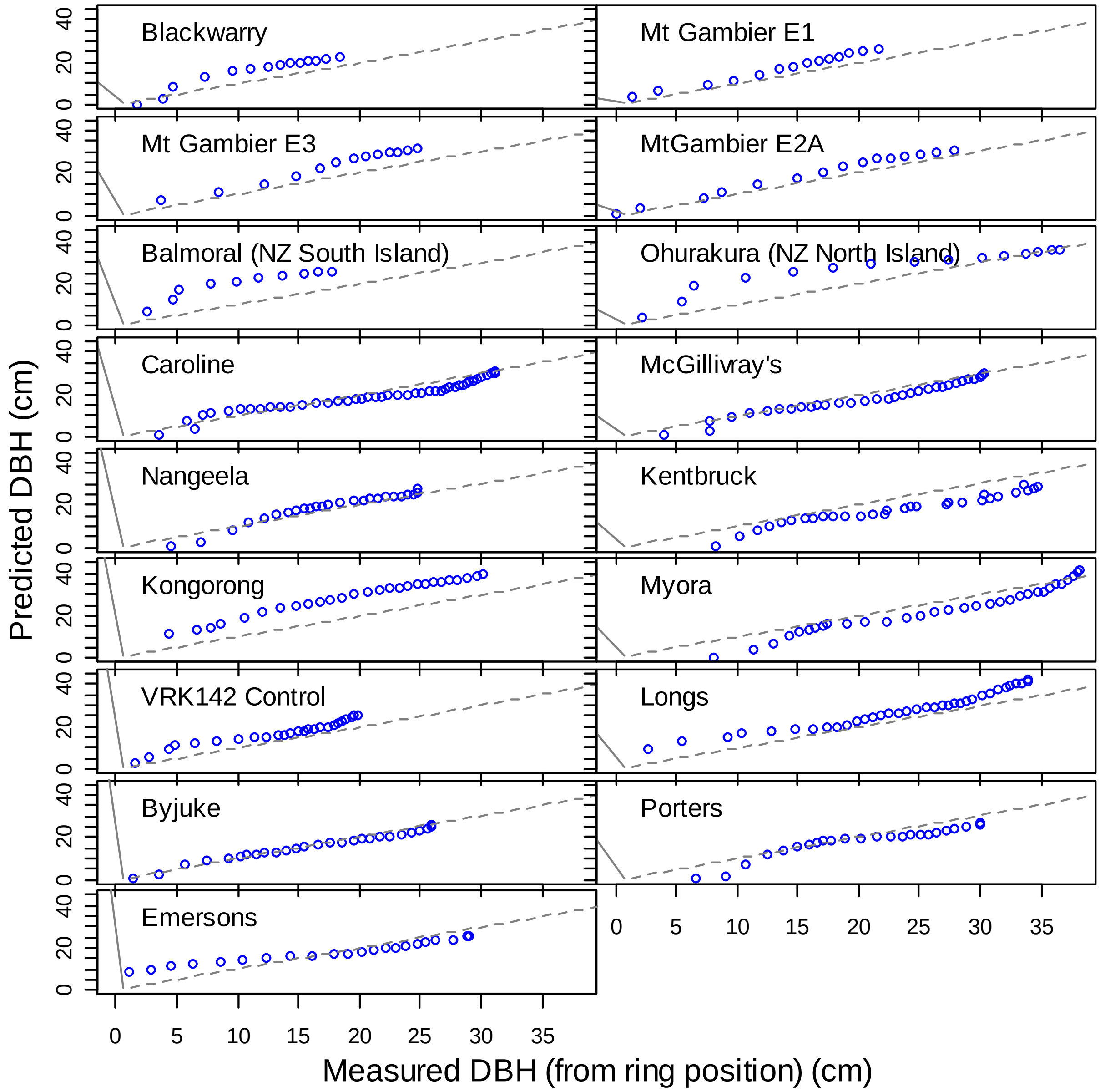


Figure 8: Predicted vs measured mean DBH (derived from ring position assessed on 3 – 12 trees from each site) from simulations using CaBala data. One-to-one line is shown in grey.

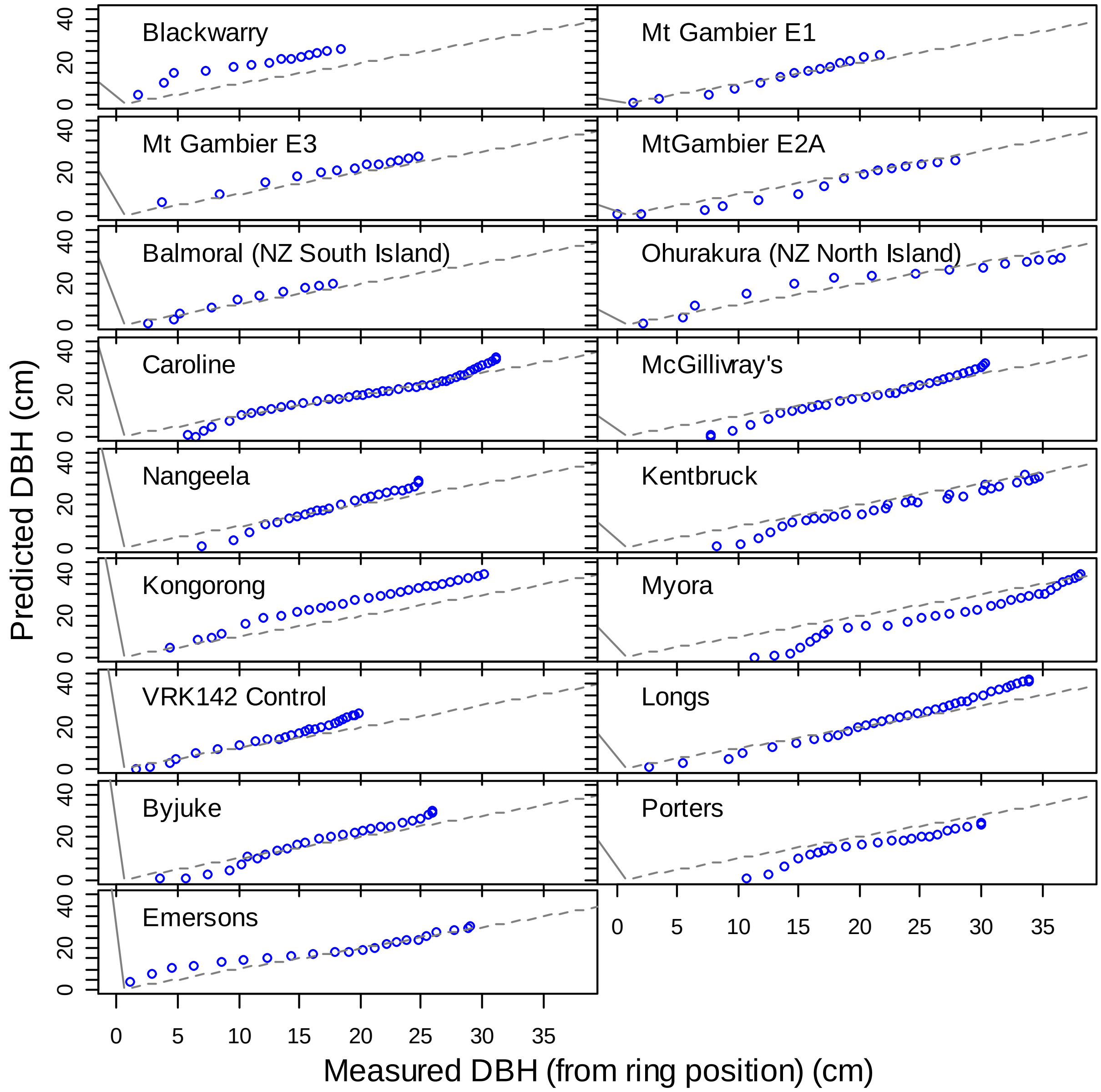


Figure 9: Predicted vs measured mean DBH (derived from ring position assessed on 3 – 12 trees from each site) from simulations using the internal stand growth model. One-to-one line is shown in grey.

It is notable in interpreting these data that the final diameter calculated from ring widths was often lower than the over-bark DBH values measured on a larger sample of trees from the FWPRDC Resource for Profit study at the time of sampling (Table 4). These differences were, in some cases, very large (e.g. at Caroline, where the difference was greater than 16 cm). The DBH values are averages of 30 trees measured at the site, where the SilviScan values are based on a single radius taken from 10 trees at breast height.

Table 4: Differences in final stem DBH based on ring positions in cores and measurements taken at the site at the time of sampling.

Scenario	Under-bark DBH measured from cores (cm)	Measured over-bark DBH at time of sampling (cm)	Difference (cm)
Balmoral	**17.7**	**18.7**	**1.0**
Byjuke	**30.5**	**32.4**	**1.9**
Caroline	**33.0**	**49.2**	**16.2**

Scenario	Under-bark DBH measured from cores (cm)	Measured over-bark DBH at time of sampling (cm)	Difference (cm)
Emerson's	37.6	38.7	1.1
Kenbruck	39.8	39.5	0.3
Kongorong	34.9	40.6	5.7
Long's	40.5	46.7	6.3
McGillivray's	44.7	42.3	2.4
Mt Gambier E1	25.7	31.2	5.5
Mt Gambier E2A	30.9	35.4	4.5
Mt Gambier E3	27.6	34.9	7.3
Myora	45.4	50.2	4.9
Nangeela	32.5	32.1	0.4
Ohurakura	36.6	39.2	2.6
Porter's	34.7	35.0	0.3
Strzelecki	25.9	27.9	2.0
VRK142 control	22.1	30.0	7.9

Potentially, in some cases, the sub-samples used for SilviScan represented smaller trees than the average for the stands. Alternatively, it is possible that severe eccentricity led to major errors in diameter estimates from SilviScan samples, or that samples never even reach the pith in very big trees. Whatever the cause, it illustrates the variability inherent in this kind of data, and the difficulty of testing model accuracy. As the models are attempting to capture variation at the "site" level, and yet wood property (and in this case, ring-by-ring-based DBH estimate) comparisons are being made on a small sub-set of trees, it becomes complex to properly assess model performance.

Model estimates of DBH and height correlated with over-bark DBH and height measured on standing trees at, or close to, the time of core extraction are shown in Table 5. It was evident that, overall, the model was capturing most of the variation ($R^2 > 0.7$), with slopes reasonably close to 1.

Table 5: Summary statistics of linear models of the relationship between average DBH and total height from e-Cambium predictions (using IGM and Cabala inputs) and actual values measured on standing trees from the 15 study sites.

	Tree height	Tree DBH
Cambium IGM	$R^2 = 0.82$ ($p < 0.0001$) Slope =1.10	$R^2 = 0.8$ ($p < 0.0001$) Slope =0.97
Cambium from CaBala	$R^2 = 0.73$ ($p < 0.0001$) Slope =0.82	$R^2 = 0.72$ ($p < 0.0001$) Slope =1.11

Overall prediction of "whole-core" and "partial-core" wood density, MFA and MOE

One of the most important tests for the model was whether it would accurately rank sites/scenarios in terms of expected mean wood density and MOE. Results were very encouraging.

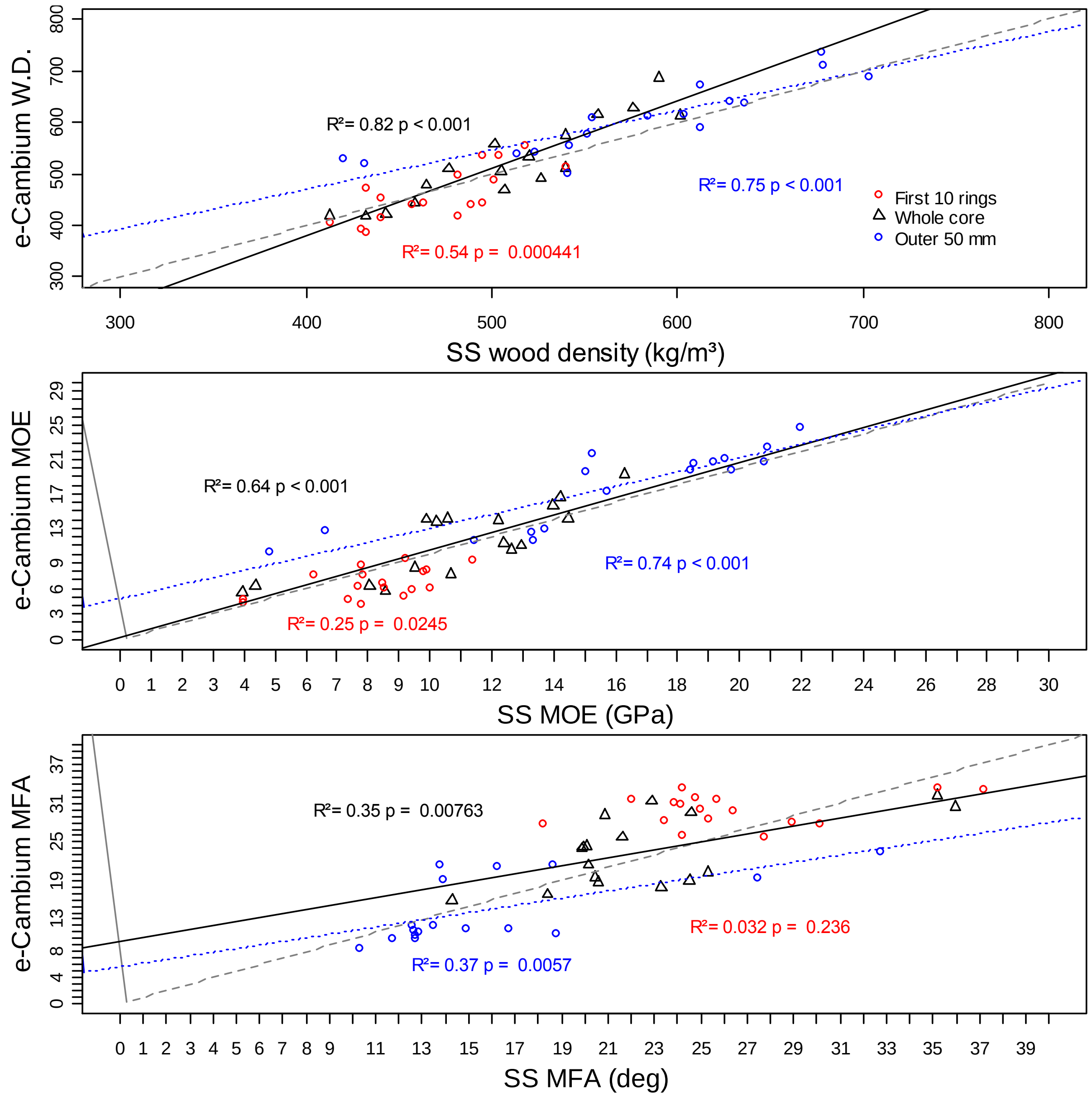


Figure 10: Predictions of mean wood density, MOE and MFA using inputs from existing CaBala simulations. The fitted line to the mean core data is shown in black (solid). The fitted line to the outer wood data is shown in blue (dotted). One-to-one line is shown in grey. (SS indicates SilviScan-generated data)

Using 17 scenarios from 15 sites (see Table 3; the Flynn scenarios were not used in this exercise), *e*-Cambium predicted about 80% of the variation in whole-core mean wood density based on a CaBala inputs. The prediction was slightly weaker for wood density in the outer 50 mm (R^2 = 0.75) and more so in the juvenile core (inner 10 rings) (R^2 = 0.54) (Figure 10). The average core wood density was slightly under-predicted at low density sites, and vice versa at high density sites. Outerwood density was somewhat over-predicted at the very low density sites. MOE predictions were close to the one-to-line line, however, because of an under-prediction of MFA at high-MFA sites (in particular, the two New Zealand sites at which measured MFA was remarkable, on average exceeding 35°). The average density of the outer 50 mm of the core was over-predicted at the low density sites (particularly the two New Zealand sites), and juvenile core MFA was poorly predicted, overall.

Using the internal stand growth model on the same sites yielded weaker predictions (Figure 11). The model predictions tended to under-estimate wood density at higher density sites more than was the case with Cabala-based simulations. Note that by removing the spurious prediction at the New Zealand Ohurakura site (marked in Figure 11), the prediction of outer-wood wood density was improved to $R^2 = 0.6$.

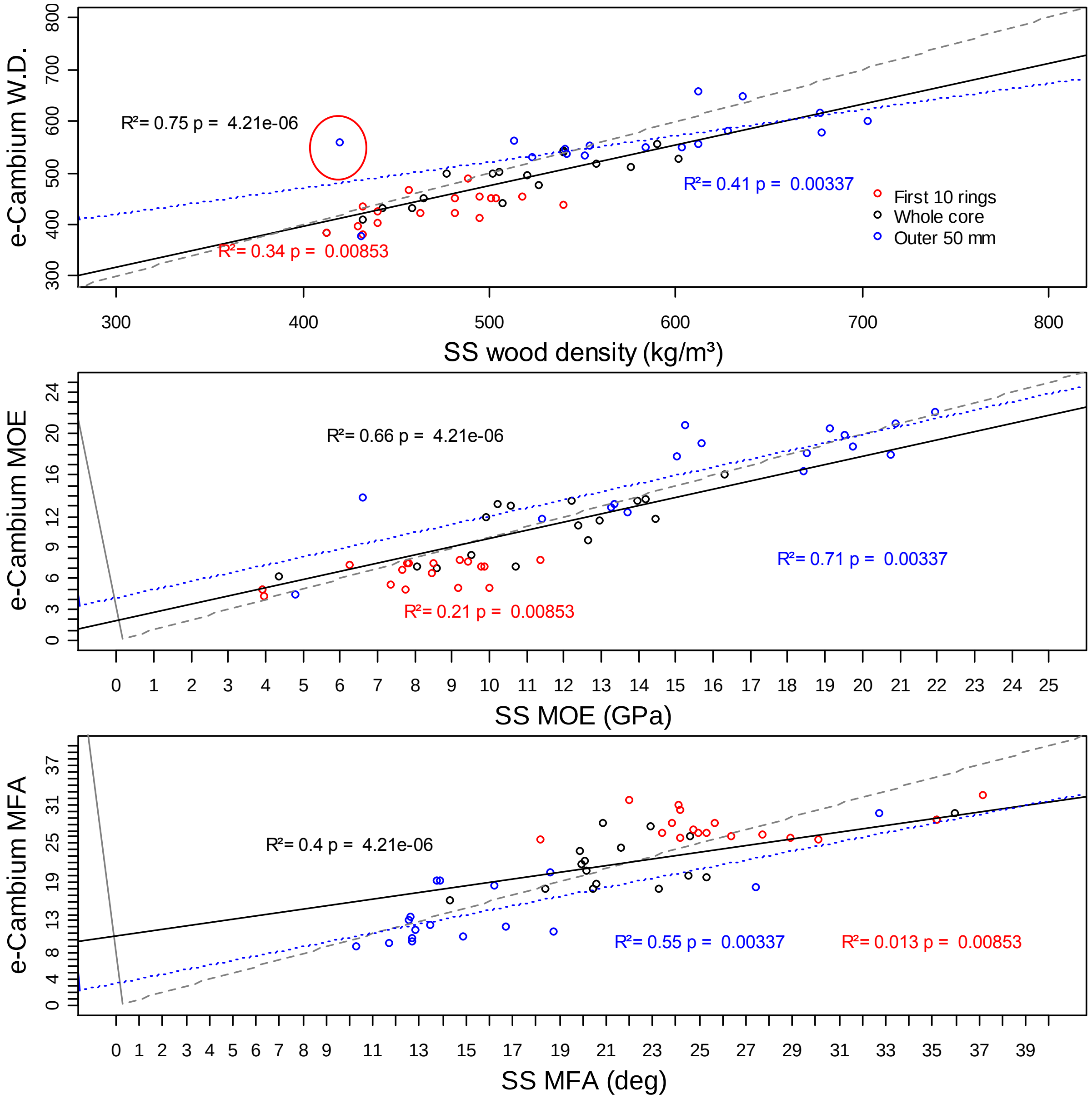


Figure 11: Predictions of mean wood density, MOE and MFA using the internal stand growth model. The fitted line to the mean core data is shown in black (solid). The fitted line to the outer wood data is shown in blue (dotted). One-to-one line is shown in grey. (SS indicates SilviScan-generated data)

As pointed out earlier, these predictions represent simulations based on approximations of silvicultural events in many cases, as well as of site descriptions. More accurate regime information would be expected to improve the prediction. Even small changes in regime led to large effects on mean wood density. If a thinning was delayed by two or three years, for example, outerwood density was predicted to be lower than reality.

Predictions of pith-to-bark variation in wood properties

Wood density

In general, the predicted ring average wood densities were within ± 30 % of the actual ring averages, with some departures (e.g. Byjuke 1981 – 1984) as high as 66% of the measured average mean wood density (Figure 12 and Figure 13). Periodic departures of the modelled data from the measured can be primarily explained by the averaging effect of multiple samples, as well as the inherent "smoothing" which occurs in SilviScan samples, each of which, in *P. radiata*, would typically comprise 50 – 70 cell files tangentially. Another determinant of prediction error is uncertainty associated with (a) site characterisation (b) accurate regime characterisation and (c) input weather data accuracy. At Byjuke, for example, thinning events were estimated from changes in ring width, which was often only clearly discernible in some samples, and only establishment and final stand densities were known with certainty.

The model outputs, based on CaBala simulations, tended to slightly overestimate the outerwood density in lower density sites (e.g. Balmoral, Ohurakura and Mt Gambier E3). Nevertheless, there were cases (e.g. Caroline HQ late in the juvenile core, Nangeela and Byjuke) when wood densities were overestimated in multiple consecutive rings.

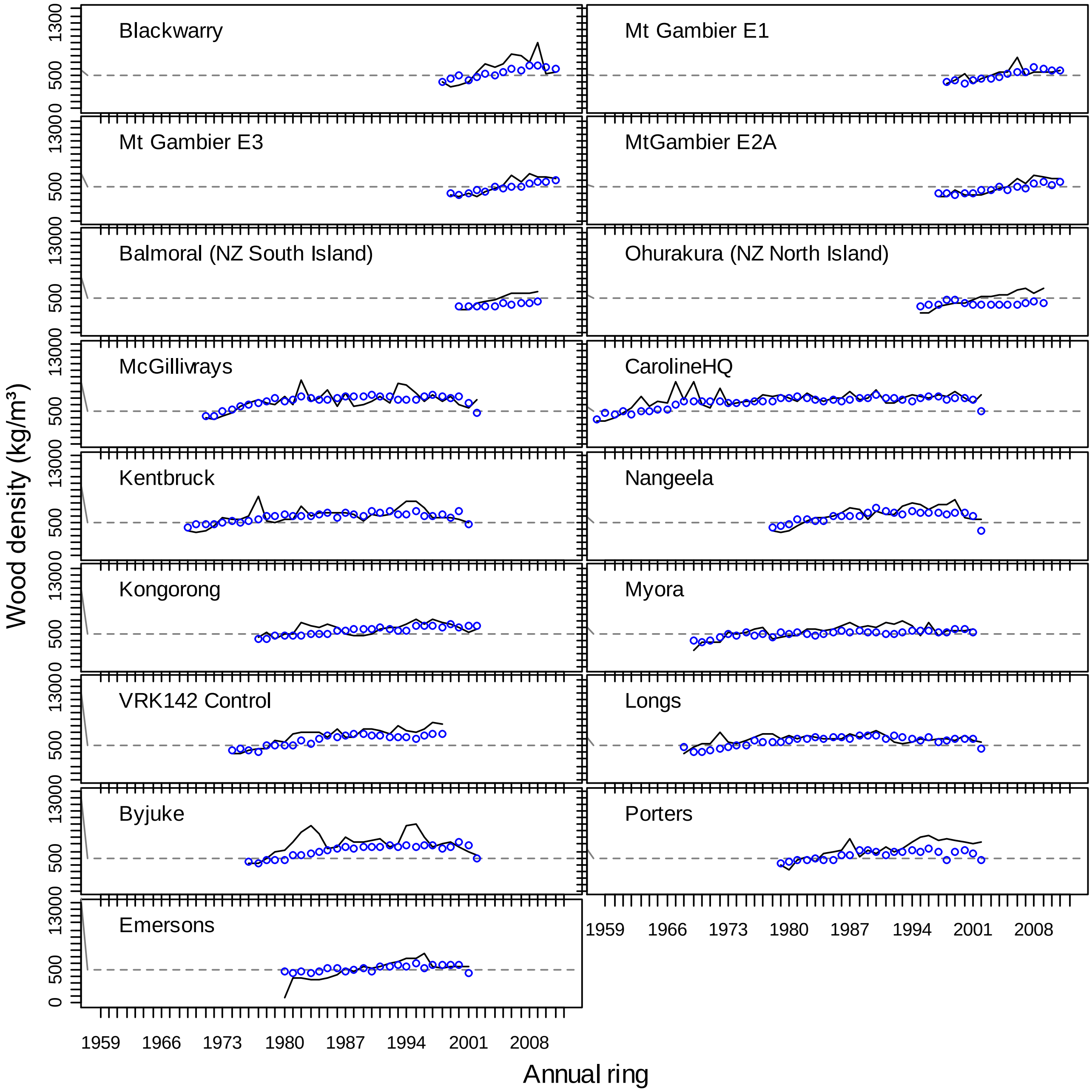


Figure 12: Predicted (black line) and measured (blue points) annual average wood density for 17 scenarios run from Cabala simulations.

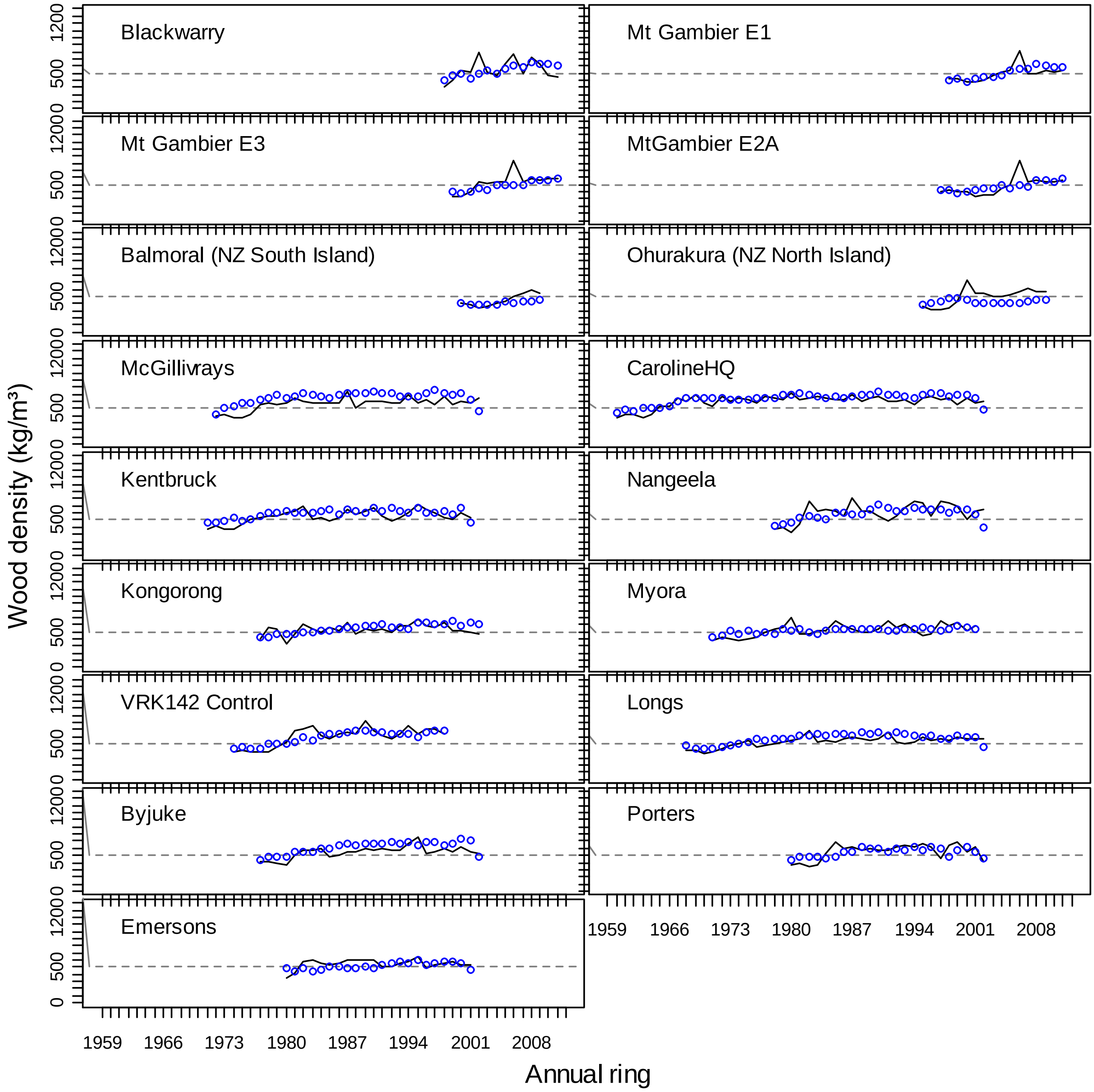


Figure 13: Predicted (black line) and measured (blue points) annual average wood density for 17 scenarios run from the IGM.

MOE

The model severely over-predicted MOE over time at the two New Zealand sites, even though density predictions at those sites were reasonable (Figure 14 and Figure 15). This was largely due to under-predictions of MFA in later rings. This effect was more pronounced in runs using Cabala inputs compared to those that used the IGM.

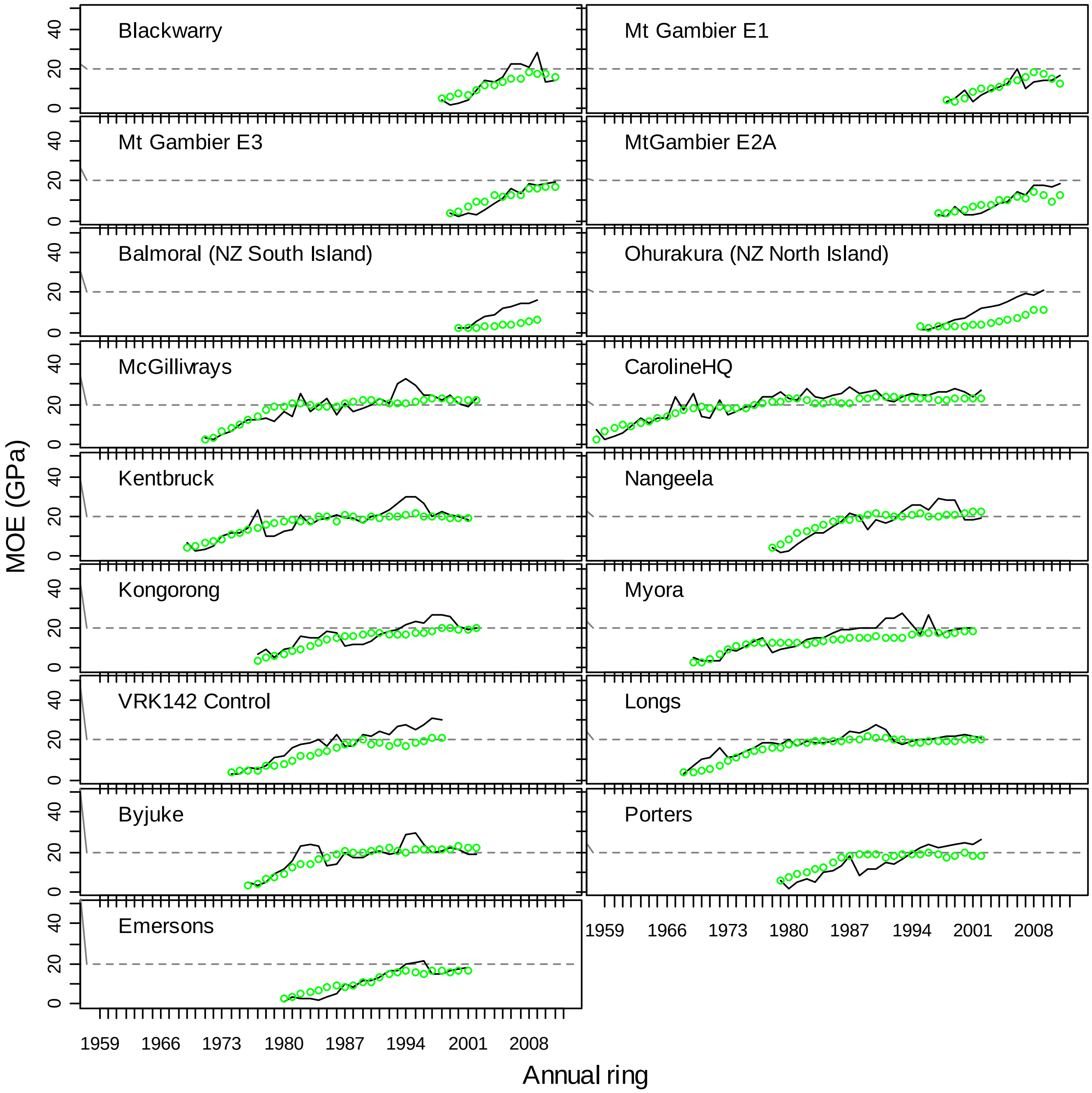


Figure 14: Predicted (black line) and measured (green points) annual average MOE for 17 scenarios run from Cabala simulations.

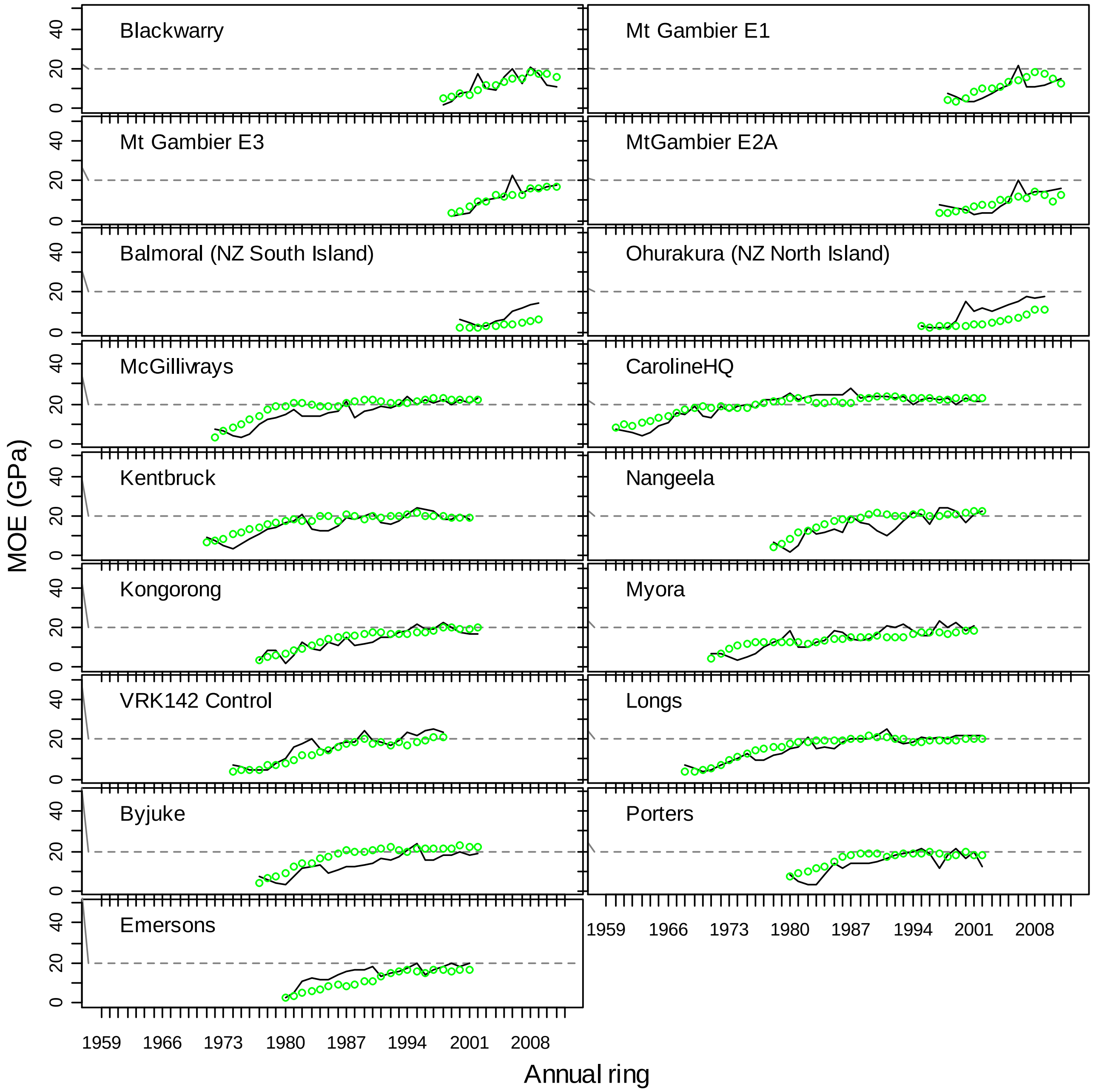


Figure 15: Predicted (black line) and measured (green points) annual average MOE for 17 scenarios run from the IGM.

Model performance at Flynn Creek

In addition to the sites at Blackwarry and Mt Gambier airport, dendrometers were also installed at a site in Gippsland at Flynn Creek. SilviScan samples were taken in May 2013 (see Appendix 1& 2 for more information). Only 10 cm long cores were able to be taken , so rings closest to the pith were missed, particularly from larger trees. The site was set-up (see Table 3) and run using parameters as developed previously. The predictions of wood density and MFA variation based on the IGM were good in the unthinned treatment, but in the last ring (2007) prior to the 2008 thinning in the thinned treatment, wood density was over-predicted. Subsequent wood density was under-predicted (Figure 16). The ranges of wood density and MFA expected within rings were reasonably well simulated, but ring widths following thinning were over-predicted (Figure 16 b & d).

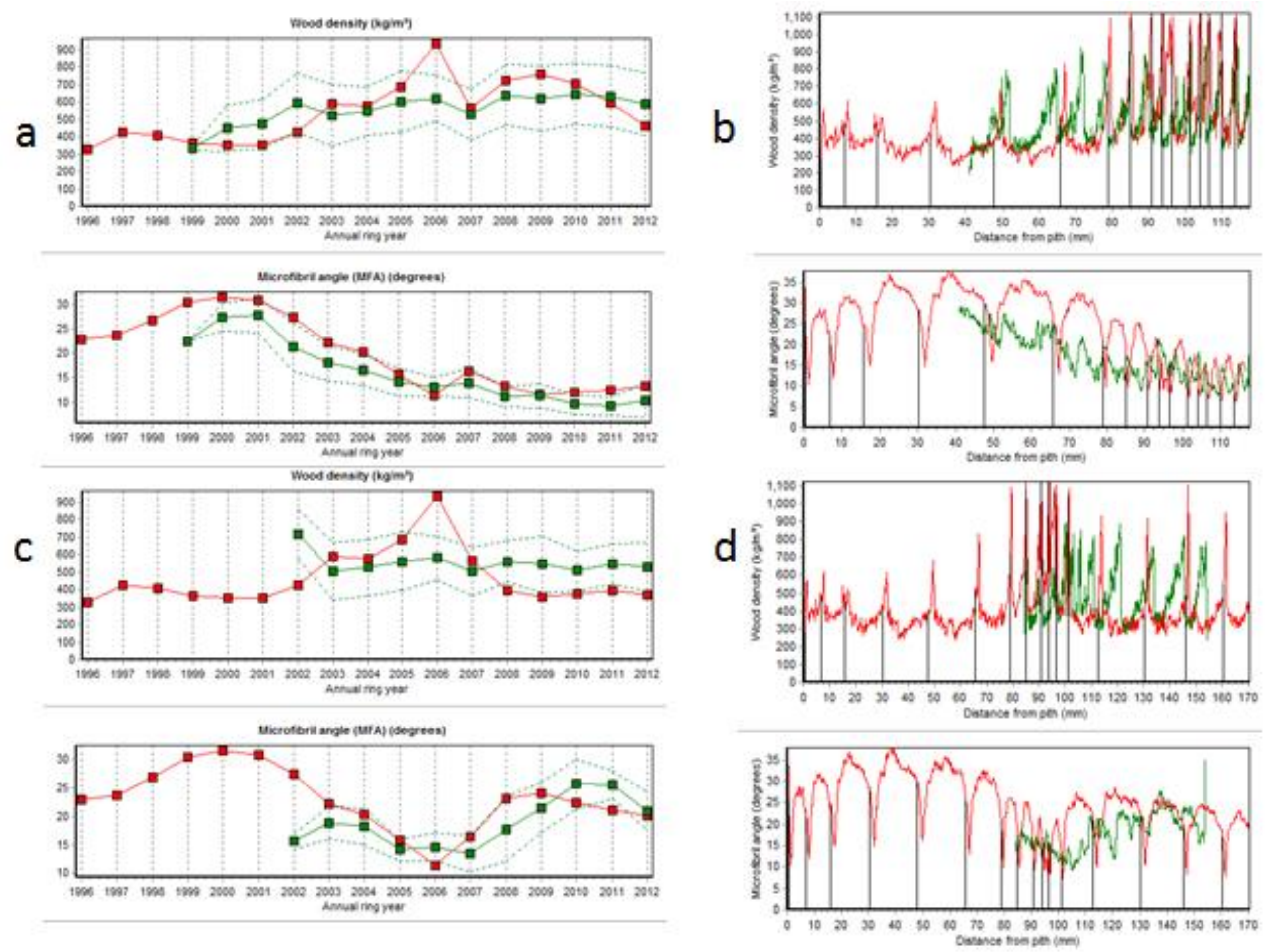


Figure 16: Actual (green) and predicted (red) predicted annual ring average wood density and MFA from the unthinned (a) and thinned (c) treatments at Flynn, based on the IGM. Also shown are modelled pith-to-bark trajectories from the unthinned (b) and thinned (d) treatments (shown in red), with an example of actual measured data, from a single core in each case, shown in green.

Simulations of wood density and MFA variation at Flynn based on CaBala simulations over-predicted wood density by approximately 150 kg m^{-3} in 2004 – 2007 in both treatments (Figure 17). The thinned simulation based on Cabala inputs over-predicted growth response following thinning.

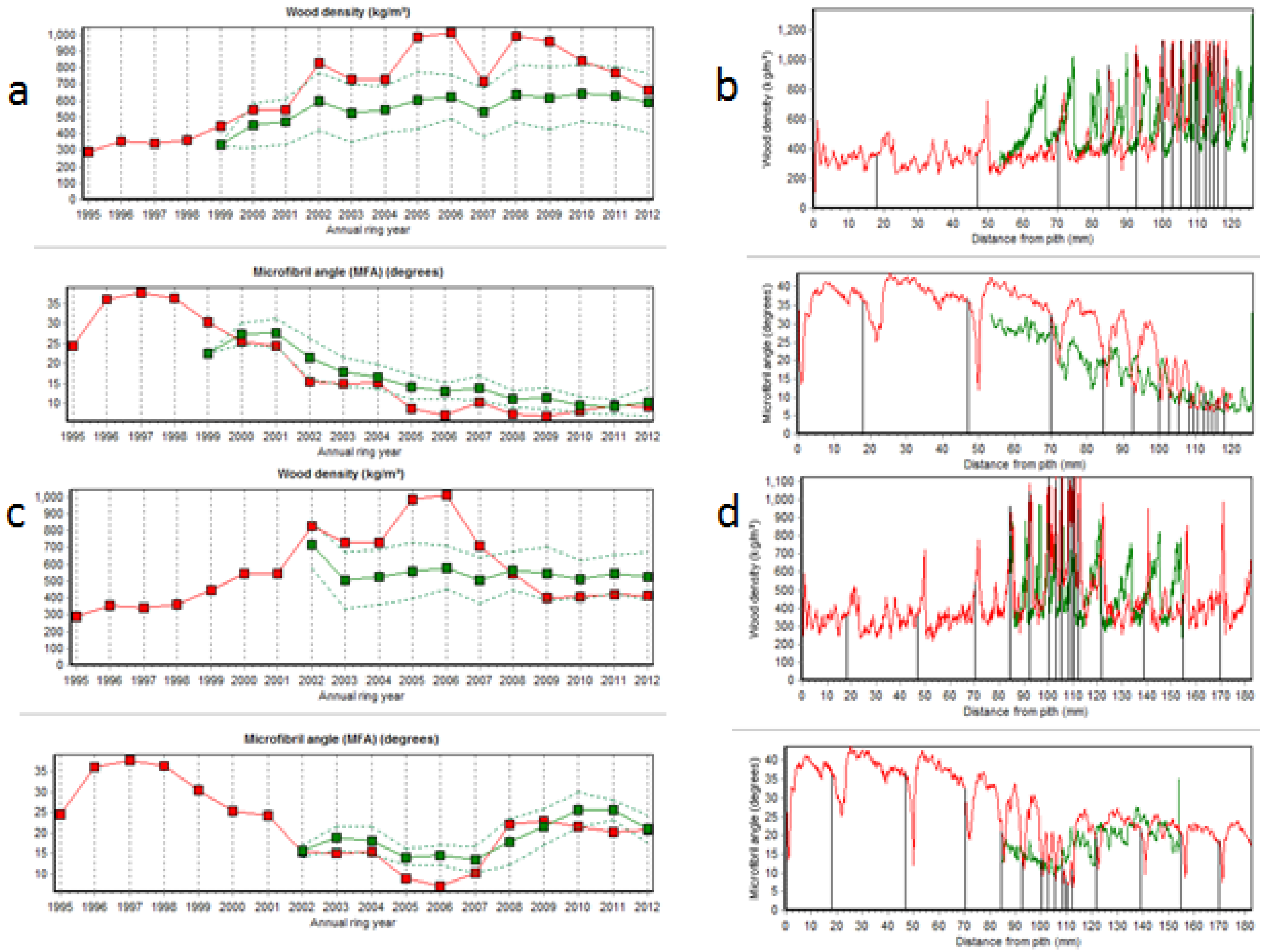


Figure 17: Actual (green) and predicted (red) predicted annual ring average wood density and MFA from the unthinned (a) and thinned (c) treatments at Flynn, based on the Cabala inputs. Also shown are modelled pith-to-bark trajectories from the unthinned (b) and thinned (d) treatments (shown in red), with an example of actual measured data, from a single core in each case, shown in green.

Short term wood property variation and responses

A stringent test for a model like *e*-Cambium is that it is accurate at a range of spatial and temporal scales. The veracity of predictions at the site level may not hold at the finer scale of daily variation, for example. For this reason, the model predictions were tested against re-scaled wood property variation (see Appendix 1) over the period that dendrometers were installed on trees at the Blackwarry, Mt Gambier airport and Flynn Creek sites (see Appendix 1 & 2). The model provided a reasonable simulation of the magnitude and timing of variation in wood density over very short time scales (Figure 18, using Cabala inputs and Figure 19, using the IGM). Interestingly, the IGM-based runs estimated the timing and slope of latewood development slightly better than the CaBala based simulations. It is important to note, however, that the re-scaling approach itself can be associated with some significant error, and the timing of formation of particular portions of the wood may vary from those shown. In fact, for this reason, data from the unthinned treatment at Flynn are not shown because of severe difficulties re-scaling two of the three monitored trees which, over the monitored period, grew very slowly.

Based on the CaBala inputs, the modelled wood density increase in latewood tended to be too abrupt in some cases, occurring too early at Mt Gambier and too late at Flynn Creek (Figure 18). The model predicted variation at the Blackwarry site more accurately. Based on IGM inputs, the latewood transition was more realistic at all sites.

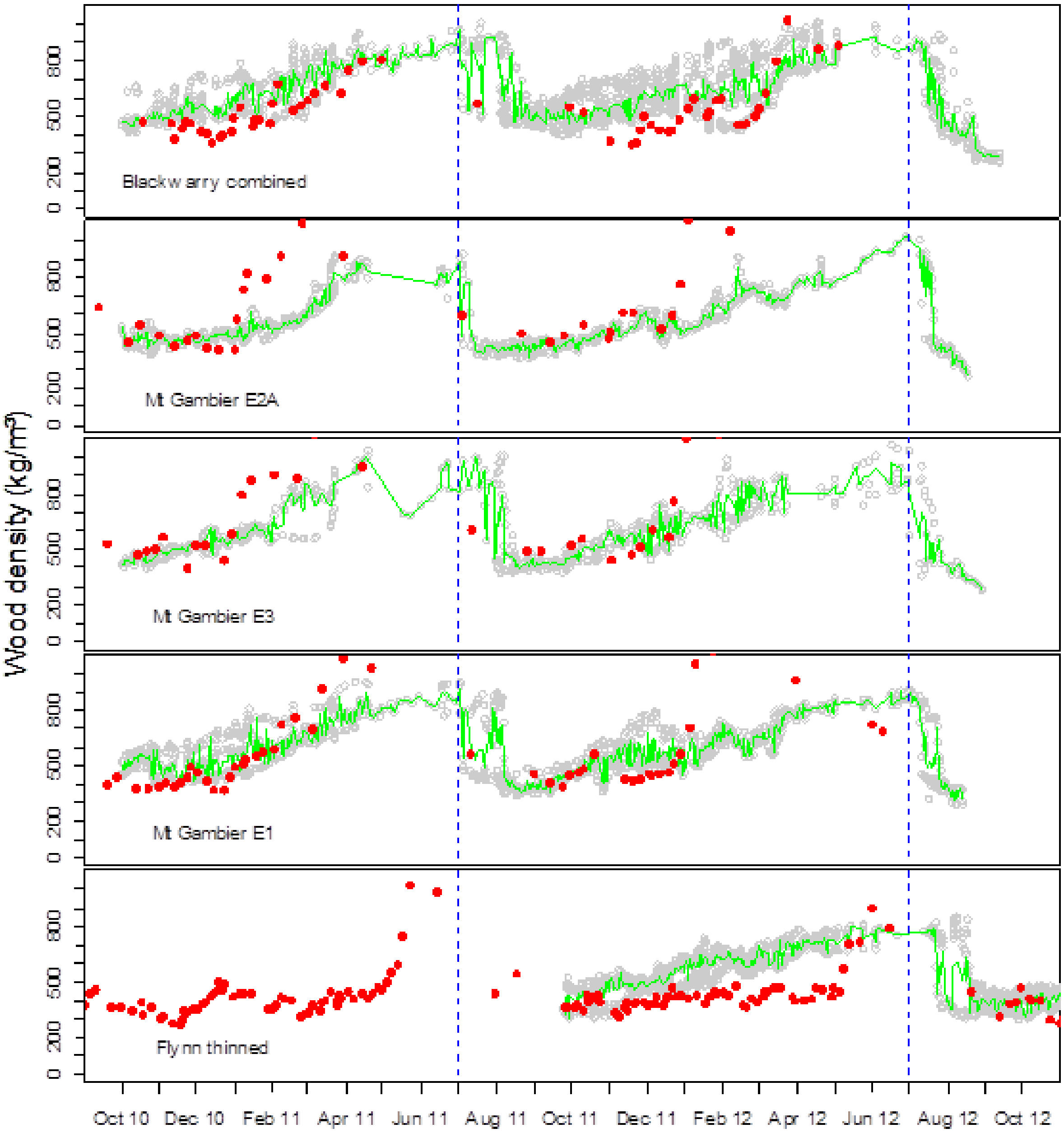


Figure 18: Re-scaled measured wood density from the Blackwarry site (all trees pooled) (grey points with average shown in green), the three considered treatments at Mt Gambier and the thinned treatment at Flynn Creek. Modelled wood density (red points) values are based on simulations using Cabala inputs.

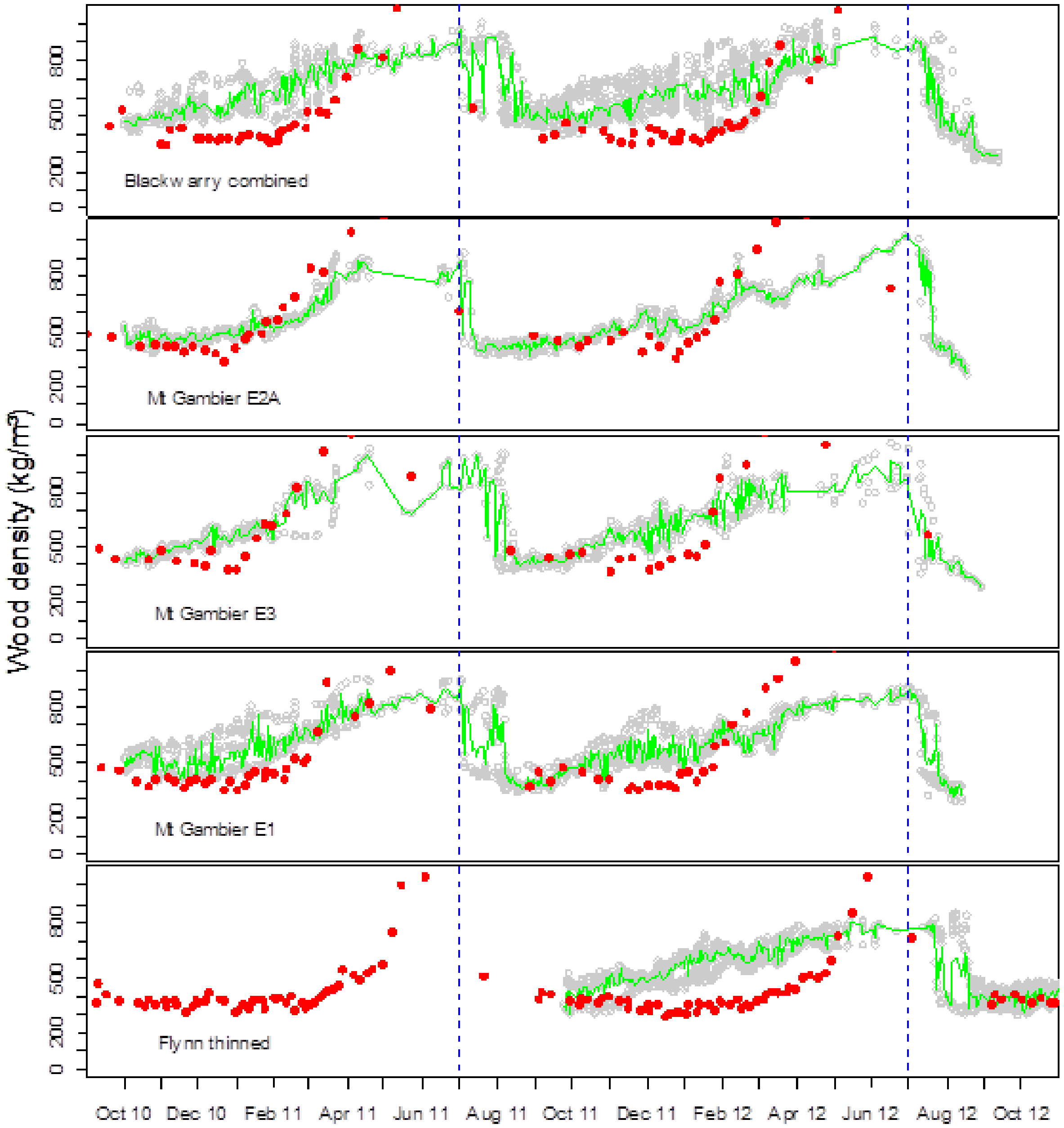


Figure 19: Re-scaled measured wood density from the Blackwarry site (all trees pooled) (grey points with average shown in green), the three considered treatments at Mt Gambier and the thinned treatment at Flynn Creek. Modelled wood density (red points) values are based on simulations using IGM inputs.

Prediction of board stiffness grades

Previous studies (FWPRDC Resource for Profit Report) demonstrated that breast height SilviScan data is a good predictor of sawn board stiffness across 10 sites studied in the Green Triangle. The sawn board and SilviScan data from the individual trees in that study were used to identify the appropriate stiffness thresholds (See Appendix 1), such that the predictions of radial trends arising from *e*-Cambium could be related to those estimated from SilviScan data. In this way some indication of the model's performance as a predictor of sawn board properties can be obtained by comparison directly with actual SilviScan data, avoiding the need (at this early stage) for more expensive sawmill validation studies.

The model predictions of the best board stiffness grade that could be expected from a site was broadly consistent with the predictions based on SilviScan breast height cores. In several cases, the model (whether based on a Cabala or IGM run, or both) also managed predict with reasonable accuracy the proportion of boards that could be expected within particular board grades (e.g. Byjuke, Long's, McGillivray's, Porter's Rd, Mt Gambier airport, Nangeela and Ohurakura). At other sites (e.g. Caroline HQ and Myora) it over-predicted the proportion of high stiffness boards, caused mainly by over-prediction of wood density, or under-prediciton of MFA (at Myora) prior to the final thinning. In both cases, inaccurate thinning information may have contributed to this weaker prediction.

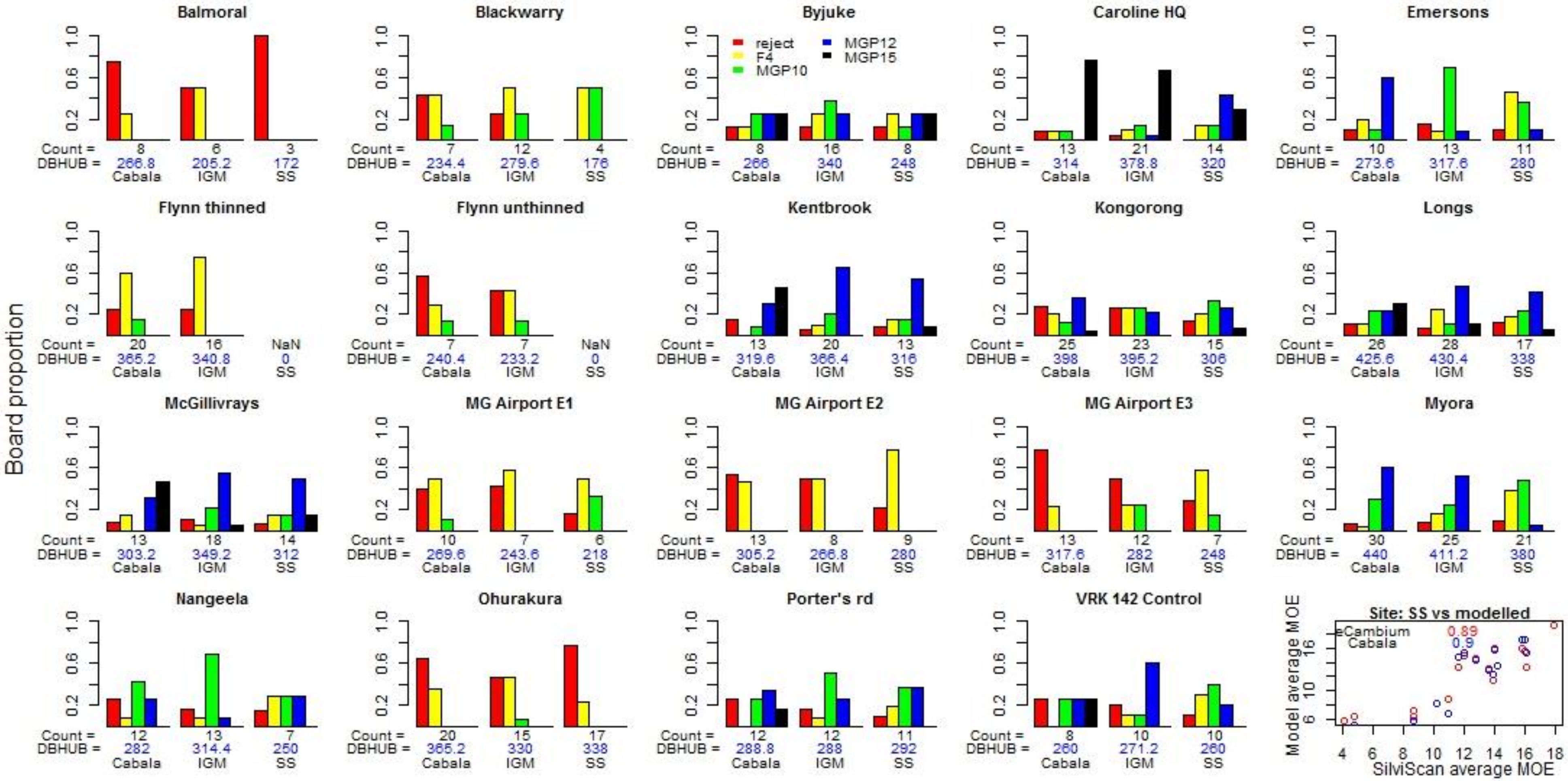


Figure 20: Comparison of proportions of boards of particular stiffness grades based on Cabala and IGM model runs with calculations from actual SilviScan data. As the SilviScan data from the site at Flynn did not extend to the pith, this data could not be used in this comparison. The total board count and average diameter of each log end is included under each x-axis to facilitate comparison, as variation in predicted vs measured diameters are a major driver for differences. The scatter plot compares the average board MOE for each site predicted by the model against that expected based on actual SilviScan data..

Using Cambium to explore scenarios

One of the primary benefits of the process-based approach to modelling forest growth or wood properties, as compared to an empirical model which relies on known conditions and an expected “similar” future, is that it allows a grower to explore scenarios that may lie outside of normal or current usage. Four examples are described below.

Growing a site “on”

The *e*-Cambium model provides the potential to allow a grower to explore what might be the final result of leaving a current site to grow for an extended period into the future. This is shown in the example below, where the E2A treatment at Mt Gambier airport was allowed to grow for 20 years beyond the age of sampling (note, the simulations were shifted backwards by 20 years to 1975). The model prediction suggested that, under the silviculture imposed on that site, potentially about half the board out-turn could be of MGP 12 or better.

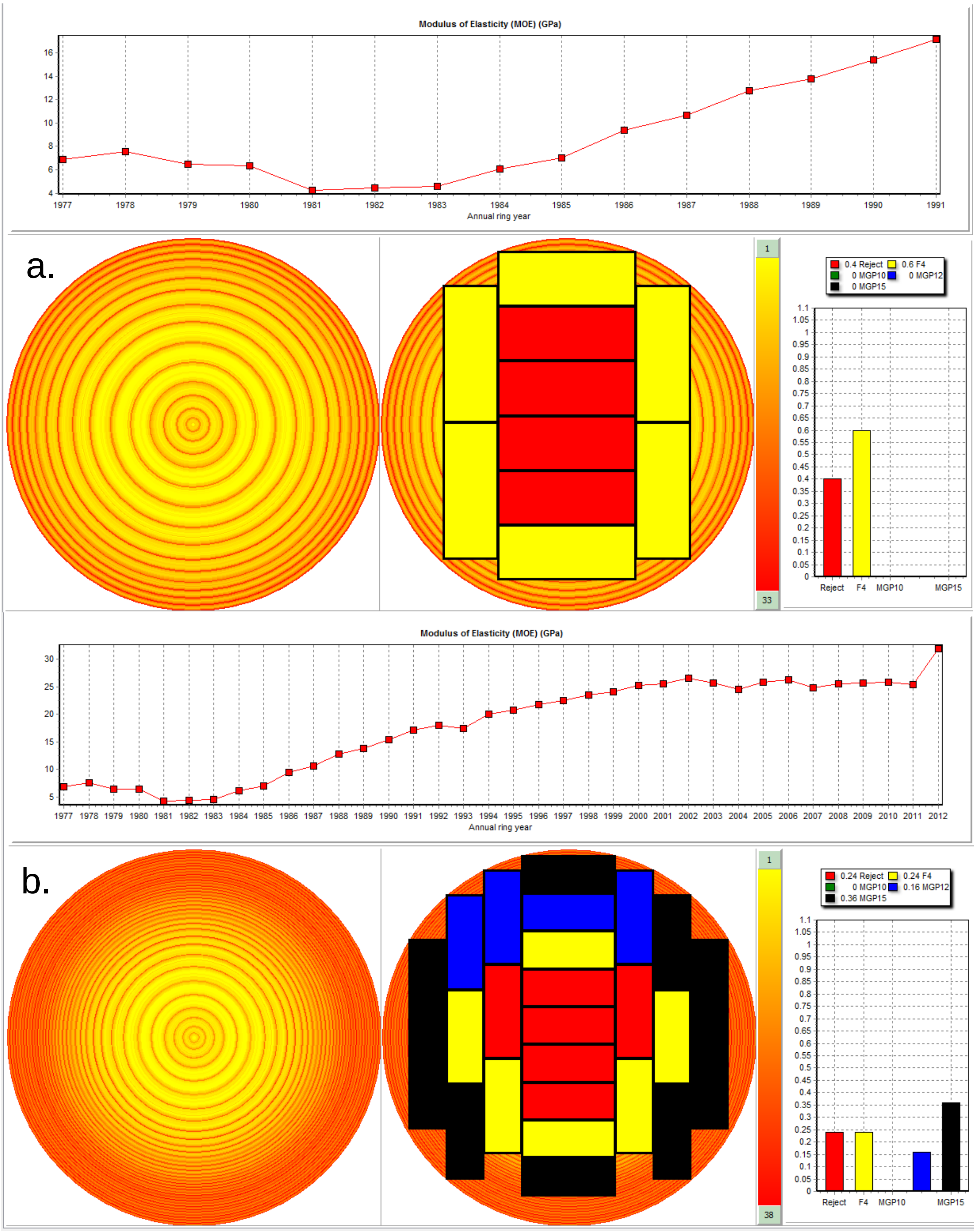


Figure 21: Model run at Mt Gambier from 1975 to 1992 (a) and then "grown on" until 2012 (b) to provide an indication of what might be expected in terms of board quantity and quality

Trying alternative management regimes

Another opportunity afforded by the process-based approach is to explore the effects of management interventions for which there is no precedent. Even if the model result will not always be a perfect reflection of reality, it provides a tool that can shape thinking and ideas. To illustrate this, some examples are shown for the site at Caroline (which was used for model parameterisation). The model predicted, for example, that using four conservative thinnings (Figure 22 a) might lead to the same size trees as one heavy thinning (Figure 22 d) but that the quality of the boards could be expected to be quite different.

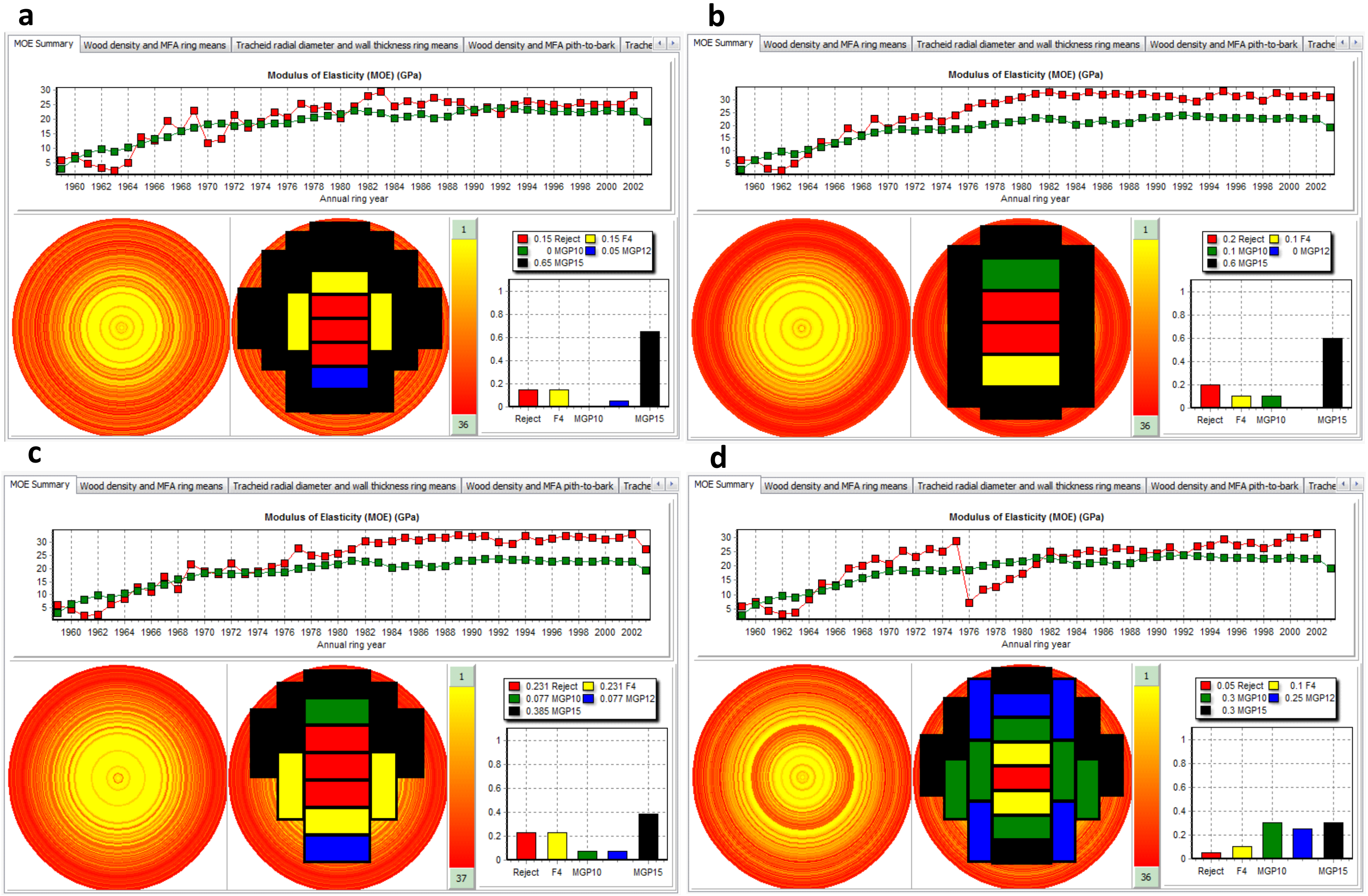


Figure 22: Effects of different scenarios on potential board out-turn at the Caroline site. In (a), the site was managed as described in Table 3. In (b), the site was established as in Table 3, but not thinned. In (c) the site was established at 555 stems/Ha and not thinned. In (d) the site was established as in Table 3 and then thinned only once after 18 years to 250 stems/Ha. The model does not account for the effect of branch defects. Low initial stocking such as (c) will tend to produce large knots and therefore reduce sawn board stiffness further.

The impact of changing future climates or adjusted species range[1]

Research has been undertaken in the past to explore the risks to commercial forests under varied climates.

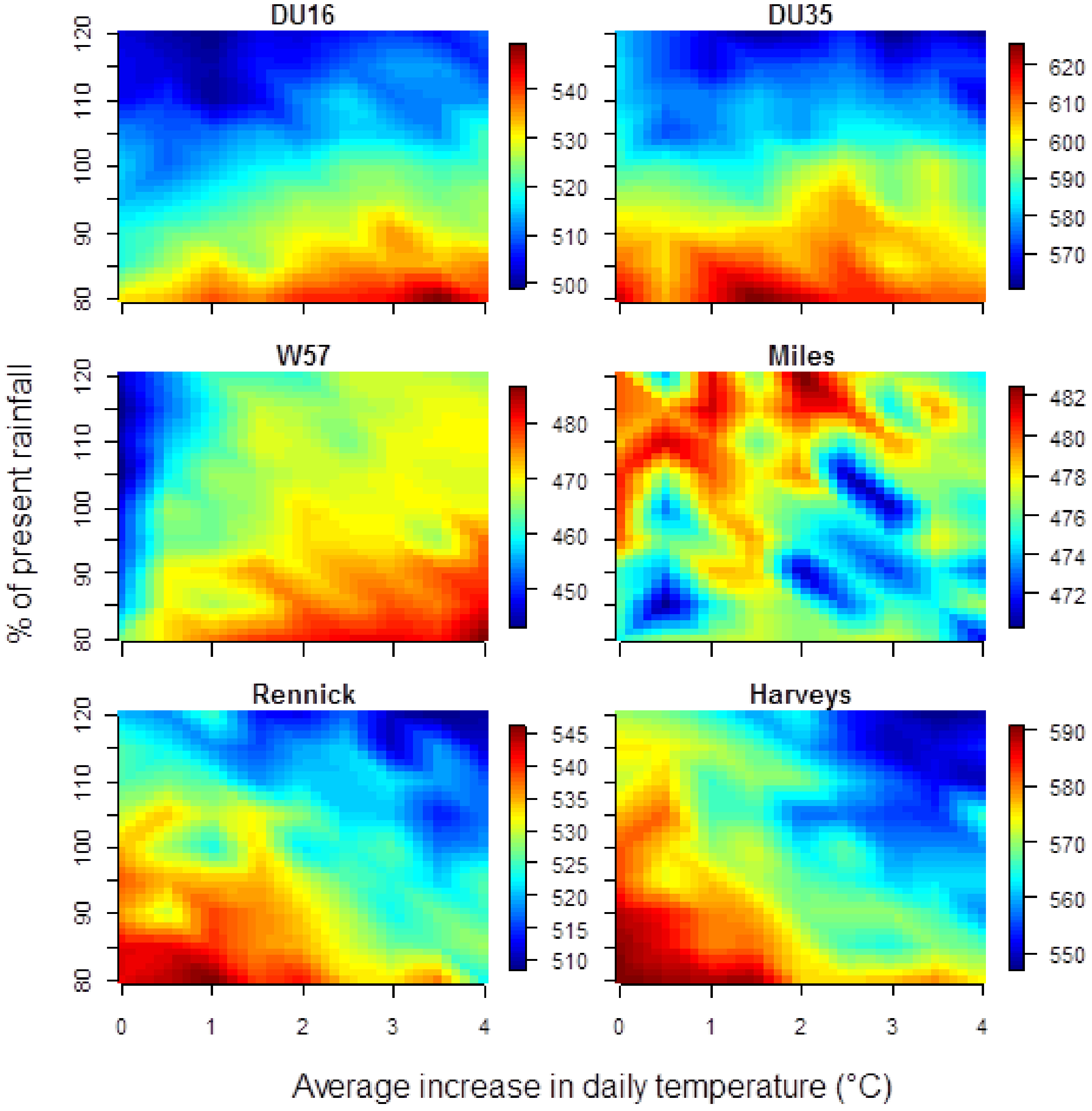


Figure 23: Simulated mean core wood density (kg m^{-3}) at 6 sites (all with identical silviculture) under hotter (x-axis) and drier or wetter (y-axis) conditions. Warmer colours show greater wood density.

This kind of work has not considered how wood properties might vary, however, under those different conditions. In Figure 23 variation in mean core wood density is shown when predicted under a hotter climate (between 0°C and 4°C hotter than present) with more, or the same, or less rain as presently received (in % of present rainfall). The simulation did not take into account increasing atmospheric [CO_2]. The simulation was run at three sites in Tasmania (DU16, DU35 and W57) and three sites in the Green Triangle (Miles, Rennick and Harvey's).

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[1] The data and outputs described in this section are based on simulations and analyses undertaken using CaBala and eCambium in an aligned FWPA project, PNC 228-1011: "Adaptation strategies to manage risk in Australia's plantations". More information on these simulations can be found in reports issued as part of that project.

In all cases, with the exception of Miles (where differences, overall, were predicted to be small), drier conditions were predicted to lead to higher wood density. The effect of temperature was quite different at the Tasmanian sites compared to Rennick and Harvey's. This preliminary study illustrates an obvious use of the e-Cambium tool. This same analysis could conceivably be used not only to test effects of future conditions, but to explore how wood properties might vary, all other things equal, on a hotter and drier, or hotter and wetter site.

Using modelled data in concert with wood sampling

Many growers *of P. radiata* conduct some sort of periodic, or occasional, wood quality assessment. In many cases, this involves taking wood samples for analysis using systems like SilviScan, or simply average basic density calculated on small core samples from the outer wood. There is also scope to use technologies like NIR, calibrated for properties like wood density, or to use standing tree acoustic velocity as an indicator of log stiffness. But these kinds of assessments are expensive, and unlikely to be conducted widely on the forest estate (at least while there is still limited return on such an investment). Similarly, some empirical models for predicting wood density and stiffness are used by some growers. But these also rely on a site-specific calibration associated with particular environmental conditions and standard management approaches. In that context, *e*-Cambium could potentially be used as a tool to generate predictions for cases that lie "between" sample points, thus providing a means of better estimating variation across the estate. Similarly, it could act in a complementary fashion to existing models of wood stiffness.

Industry workshops

A series of three industry workshops were held in July and August 2013. The first was on 25 July (Hobart), the second on 31 July in Melbourne and the last on 1 August in Mt Gambier. The model was presented to a wide variety of industry members in each case, who were able to comment on aspects of the software and the model that were useful, and which could be improved.

In Hobart, the workshop was attended by representatives from Norske Skog, Forestry Tasmania, Timberlands and Timberlink. In Melbourne, Hancocks Victoria Plantations (HVP) research and operational staff were present. In Mt Gambier, the workshop was attended by staff from ForestrySA, HVP, Timberlands and Green Triangle Forest Products (GTFP). Workshop attendees were able to see the model demonstrated, and then use the model themselves in an interactive way. Each person was provided with a copy of the installable software, and with demonstration datasets. Users were encouraged to bring real data as much as possible to test the model outputs.

A number of points were raised by workshop attendees that could be included in an operational version of e-Cambium in the future

- it would be useful to summarise data on a per-hectare basis, particularly looking at total volume and volume of wood "of particular quality or properties".
- the model would need to run more spatially, ideally linking directly with existing GIS soil and climate surfaces.
- Combining runs from multiple positions within the tree to develop pseudo-3D visualisation of wood variation in a whole tree with boards represented with length was considered a valuable future development.
- A scaled visualisation of the log-end would assist comparison of effects between runs.

- There was interest from both Forestry Tasmania and HVP in developing the model for use with *Eucalyptus*. This is considered very feasible despite the additional complexity of eucalypt anatomy.

Discussion

George E.P. Box, the well-known British mathematician and Professor of Statistics at the University of Wisconsin, once said “All models are wrong, but some models are useful”. The *e*-Cambium model, like any model, is a logical framework that describes a particular understanding of the processes of tree growth and wood formation. To a large extent, process-based models, like *e*-Cambium, are as useful for helping us understand what we *don’t* know about wood formation as they are for helping us understand what we do know, or for providing predictions. This has certainly been the case in the development process of *e*-Cambium, during the development it became clear that there is still much we do not understand about tree growth in general and xylem development in particular.
The complexity and subtlety of wood property variation from site to site, under varied conditions, was hard to capture and explain using a generic set of parameters and descriptors. Despite this two important aspects of model performance need to be noted:

- all predictions, for 36 scenarios (18 scenarios, run twice, based on Cabala and then on IGM inputs) used exactly the same parameter set. If a process-based framework requires extensive site-by-site parameterisation, it loses one of its main advantages.
- the results from the 3-PG-based internal stand growth model (IGM) were better than expected, and it is hoped that further development of this relatively simple modelling framework will enable *e-Cambium* to be a simple to use but powerful prediction tool.

Of critical importance to model operation is the accuracy of the four key data types that are used to drive the stand growth aspect of the model. When a modelled regime is wrong compared to the actual regime being used for comparison, or if the soil information is incorrect, predictions of growth or wood properties will reflect this. The problem becomes amplified in a hierarchical approach such as is used in *e*-Cambium. If the tree height, or the NPP or the level of drought experienced by the tree, is incorrectly estimated, estimates of wood development processes will follow suit, and lead to inaccurate predictions of properties like wood density. For example, over-estimated tree height will mean that even relatively accurately estimated amounts of allocated NPP must be divided between too many developing cells, leading to unrealistic levels of “carbohydrate starvation” and poor predictions. Partly for this reason, it was evident in some runs that the models sometimes predicted a too severe narrowing of ring width, which in turn meant mean annual density predictions that were too high. Interestingly, this was often more pronounced when using CaBala based runs than runs based on the IGM.

Two aspects of the e-Cambium model have been identified where further research work would lead to valuable improvements in model performance.

1. Sharp latewood peaks
    a. The model still has a tendency to over-estimate peak latewood wall thickness and wood density at some sites. This effect is associated with strong flows of carbohydrate as the cambial zone reduces to a minimum size, and suggests that the carbohydrate balance and timing of cambial slow-down should be reviewed.
    b. The weak latewood observed at sites like those in New Zealand were difficult to predict for this reason
2. Microfibril angle
    a. Although model predictions of MFA were reasonable, the mechanisms by which the microfibrils are adjusted are still not clear. A better understanding of the

mechanisms controlling MFA is not elementary and requires focussed, detailed research.

Conclusions

Overall, the *e*-Cambium model represents a unique technology in forest management, providing a useful link between the grower and the processor. Following the calibration and validation work undertaken in the study reported here, the model showed great potential as an accurate tool for assessing and predicting the effects of varied environmental conditions and forest management practices both on tree growth and wood properties. If its predictions are shown to be precise and accurate at a commercially-useful level over a broader resource range, then its development to an operationally-ready tool would provide a sound basis for better managing forests and wood flows.

Recommendations

The version of the e-Cambium model described in this report, and released to FWPA levy payers, is intended to be industry tested. The model is designed primarily as a scenario exploration tool, by which the effects of different sites, regime or weather conditions on both tree growth and wood properties can be tested. It is expected to be a useful companion to existing resource evaluation tools. It is recommended that the software be used, in consultation with CSIRO where necessary, across a broad range of sites, and tested under varied management regimes, to explore its validity and accuracy. Information about soils (basic for the IGM and more detailed for CaBala) and weather data must be accurate, as well as regime information, for any assessments to be reasonable. Provided a set of regimes can be accurately described, we recommend particularly trialling the model in situations where actual data from sawn boards is available.

General references

Abe, H. and T. Nakai. 1999. Effect of the water status within a tree on tracheid morphogenesis in *Cryptomeria japonica*. Trees. 14:124 - 129.

Almeida, A.C., J.J. Landsberg, P.J. Sands, M.S. Ambrogi, S. Fonseca, S.M. Barddal and F.L. Bertolucci. 2004. Needs and opportunities for using a process-based productivity model as a practical tool in *Eucalyptus* plantations. Forest Ecology and Management. 193:167-177.

Anfodillo, T., A. Deslauriers, R. Menardi, L. Tedoldi, G. Petit and S. Rossi. 2012. Widening of xylem conduits in a conifer tree depends on the longer time of cell expansion downwards along the stem. Journal of Experimental Botany. 63:837-845.

BARNETT, J.R. 1973. Seasonal Variation in the Ultrastructure of the Cambium in New Zealand Grown Pinus radiata D. Don. Annals of Botany. 37:1005-1011.

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

Battaglia, M., P. Sands, D. White and D. Mummery. 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management. 193:251–282.

Campbell, G.S. and J.M. Norman. 1998. An Introduction to Environmental
Biophysics. New York.

Chan, J. 2011. Microtubule and cellulose microfibril orientation during plant cell and organ growth. Journal of Microscopy:no-no.

Cocozza, C., A. Giovannelli, B. Lasserre, C. Cantini, F. Lombardi and R. Tognetti. 2012. A novel mathematical procedure to interpret the stem radius variation in olive trees. Agricultural and Forest Meteorology. 161:80-93.

Cosgrove, D.J. 2001. Wall Structure and Wall Loosening. A Look Backwards and Forwards. Plant Physiology. 125:131 - 134.

Deckmyn, G., S.P. Evans and T.J. Randle. 2006. Refined pipe theory for mechanistic modelling of wood development. Tree Physiology. 26:703 - 717.

Deleuze, C. and F. Houllier. 1998. A simple process-based xylem growth model for describing wood microdensitometric profiles. Journal of Theoretical Biology. 193:99 - 113.

Deslauriers, A., T. Anfodillo, S. Rossi and V. Carraro. 2007a. Using simple causal modeling to understand how water and temperature affect daily stem radial variation in trees. Tree Physiology. 27:1125-1136.

Deslauriers, A., H. Morin, C. Urbinati and M. Carrer. 2003. Daily weather response of balsam fir (Abies balsamea (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Québec (Canada). Trees. 17:477-484.

Deslauriers, A., S. Rossi and T. Anfodillo. 2007b. Dendrometer and intra-annual tree growth: what kind of information can be inferred? Dendrochronologia. 25:113-124.

Donaldson, L. 1992. Lignin distribution during latewood formation in Pinus radiata D. Don. Cell. 2:9-10.

Donaldson, L. 2008. Microfibril angle: measurement, variation and relationships - a review. IAWA Journal. 29:345 - 386.

Donaldson, L. and P. Xu. 2005. Microfibril orientation across the secondary cell wall of Radiata pine tracheids. Trees - Structure and Function. 19:644-653.

Downes, G., C. Beadle, W. Gensler, D. Mummery and D. Worledge. 1999a. Diurnal variation and radial growth of stems in young plantation eucalypts. *In* Tree-Ring Analysis: Biological, Methodological and Environmental Aspects. New York, CABI Publishing, p 103.

Downes, G., C. Beadle and D. Worledge. 1999b. Daily stem growth patterns in irrigated Eucalyptus globulus and E. nitens in relation to climate. Trees. 14:102-111.

Downes, G., R. Wimmer and R. Evans. 2004a. Interpreting sub-annual wood property variation in terms of stem growth. Wood fibre cell walls: methods to study their formation, structure and properties, Swedish university of Agr. sciences, Dept. of Wood Science:267-283.

Downes, G.M., C. Beadle, W. Gensler, D. Mummery and D. Worledge. 1999c. Diurnal variation and radial growth of stems in young plantation eucalypts. *In* Tree Ring Analysis. Biological, methodological and environmental aspects Eds. R. Wimmer and R.E. Vetter. CAB International, New York, pp 83 - 104.

Downes, G.M., D. Drew, M. Battaglia and D. Schulze. 2009. Measuring and modelling stem growth and wood formation: an overview. Dendrochronologia. 27:147-157.

Downes, G.M., R. Evans, L. Schimleck and H. Fritts. 2000. The commercial cambium: understanding the origin of wood property variation. Savidge, R, A,, Barnett, J, R,, Napier, R ed (s). Cell and molecular biology of wood formation. Experimental Biology Reviews... BIOS Scientific Publishers Ltd.: Oxford, UK:325-335.

Downes, G.M., J.G. Nyakuengama, R. Evans, R. Northway, P. Blakemore, R.L. Dickson and M. Lausberg. 2002a. Relationship between wood density, microfibril angle and stiffness in thinned and fertilized Pinus radiata (D.Don). IAWA Journal. 23:235-266.

Downes, G.M., R. Wimmer and R. Evans. 2002b. Understanding wood formation: gains to commercial forestry through tree-ring research. Dendrochronologia. 20:37-51.

Downes, G.M., R. Wimmer and R. Evans. 2004b. Interpreting sub-annual wood property variation in terms of stem growth. *In* Wood Fibre Cell Walls: Methods to Study their Formation, Structure and Properties Eds. U. Schmitt, P. Ander, J.R. Barnett, A.M.C. Emons, G. Jeronimidis, P. Saranpaä and S. Tschegg. Swedish University of Agr. Sciences, Dep. of Wood Science pp 267 - 283.

Drew, D.M. and G.M. Downes. 2009. The use of precision dendrometers in research on daily stem size and wood property variation: a review. Dendrochronologia. 27:159-172.

Drew, D.M., G.M. Downes and M. Battaglia. 2010. CAMBIUM, a process-based model of daily xylem development in *Eucalyptus*. Journal of Theoretical Biology. 264:395-406.

Drew, D.M., G.M. Downes and R. Evans. 2011a. Short-term growth responses and associated wood density fluctuations in variously irrigated Eucalyptus globulus. Trees. 25:153-161.

Drew, D.M., G.M. Downes, A.P. O'Grady, J. Read and D. Worledge. 2009. High resolution temporal variation in wood properties in irrigated and non-irrigated Eucalyptus globulus. Annals of forest science. 66:406-406.

Drew, D.M., A.E. Richards, G.M. Downes, G.D. Cook and P. Baker. 2011b. The development of seasonal tree water deficit in Callitris intratropica. Tree physiology. 31:953-964.

Evans, R. 1994. Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata*. Holzforschung. 48:168-172.

Evans, R. 1997. Rapid scanning of microfibril angle in increment cores by x-ray diffractometry. *In* IAWA/IUFRO International workshop on the significance of microfibril angle to wood quality Ed. B.G. Butterfield, Westport, New Zealand, pp 116-139.

Evans, R., G.M. Downes, D. Menz and S. Stringer. 1995. Rapid measurement of variation in tracheid transverse dimensions in a radiata pine tree. Appita Journal. 48:134 - 138.

Fritts, H., A. Shashkin, D. Hemming, S. Leavitt, W. Wright and G. Downes. 2005. TREERING 2000-Advances in process-based modelling of the softwood cambium. *In* IUFRO workshop on connection between forest resources and wood quality: modelling approaches and simulation software, Waiheke Island, New Zealand, pp 20-27.

Fritts, H.C. 1976. Tree rings and climate. London, New York, San Francisco.: Academic Press.

Fritts, H.C., A. Shashkin and G.M. Downes. 1999a. A simulation model of conifer ring growth and cell structure. Tree-ring analysis: biological, methodological and environmental aspects.. CABI publishing: Wallingford, UK:3-32.

Fritts, H.C., A. Shashkin and G.M. Downes. 1999b. TreeRing 3: A simulation model of conifer ring growth and cell structure. *In* Tree Ring Analysis: Biological, Methodological and Environmental Aspects Eds. R. Wimmer and R.E. Vetter. CAB International, Oxford, pp 3 - 32.

Hölttä, T., H. Mäkinen, P. Nöjd, A. Mäkelä and E. Nikinmaa. 2010. A physiological model of softwood cambial growth. Tree Physiology. 30:1235-1252.

Kramer, E.M. 2002. A mathematical model of pattern formation in the vascular cambium of trees. Journal of Theoretical Biology. 216:147 - 158.

Kutschera, U. 2004. The biophysical basis of cell elongation and organ maturation in coleoptiles of rye seedlings: implications for shoot development. Plant Biology. 6:158 - 164.

Landsberg, J.J. and P.F. Wareing. 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.

Larson, P.R. 1994. The vascular cambium: development and structure. Springer-Verlag.

Meicenheimer, R.D. and P. Larson. 1983. Empirical models for xylogenesis in *Populus deltoides*. Annals of Botany. 51:491 - 502.

Nyakuengama, J.G., G.M. Downes and J. Ng. 2003. Changes caused by mid-rotation fertilizer application to the fibre anatomy of *Pinus radiata*. IAWA Journal. 24:397 - 409.

Nyakuengama, J.G., D. G.M. and J. Ng. 2002. Growth and density responses to later-age fertilizer application in *Pinus radiata* D. Don. IAWA Journal. 23:431-448.

Ridoutt, B.G. and R. Sands. 1993. Within-tree variation in cambial anatomy and xylem cell differentiation in *Eucalyptus globulus*. Trees. 8:18 - 22.

Ridoutt, B.G. and R. Sands. 1994. Quantification of the processes of secondary xylem fibre development in *Eucalyptus globulus* at two height levels. IAWA Journal. 15:417 - 424.

Rossi, S., A. Deslauriers, T. Anfodillo and V. Carraro. 2007. Evidence of threshold temperatures for xylogenesis in conifers at high altitudes. Oecologia. 152:1-12.

Rossi, S., A. Deslauriers, T. Anfodillo, H. Morin, A. Saracino, R. Motta and M. Borghetti. 2006. Conifers in cold environments synchronize maximum growth rate of tree-ring formation with day length. New Phytologist. 170:301-310.

Sands, P.J. 2004. 3PGPJS vsn 2.4 – a user-friendly interface to 3-PG, the Landsberg and Waring model of forest productivity. Cooperative Research Centre for Sustainable Production Forestry, Hobart.

Vaganov, E.A., M.K. Hughes and A.V. Shashkin. 2006. Growth dynamics of conifer tree rings: an image of past and future environments Springer-Verlag, New York. 354 p.

Watt, M.S., G.M. Downes, T. Jones, M. Ottenschlaeger, A.C. Leckie, S.J. Smaill, M.O. Kimberley and R. Brownlie. 2009. Effect of stem guying on the incidence of resin pockets. Forest Ecology and Management. 258:1913-1917.

Watt, M.S., J.R. Moore, J.-P. FaÇOn, G.M. Downes, P.W. Clinton, G. Coker, M.R. Davis, R. Simcock, R.L. Parfitt and J. Dando. 2006. Modelling environmental variation in Young's modulus for Pinus radiata and implications for determination of critical buckling height. Annals of botany. 98:765-775.

Wilson, B.F. 1964. A model of cell production by the cambium of conifers. *In* The formation of wood in forest trees Ed. M.H. Zimmerman. Academic Press, New York, pp 19 -36.

Wilson, B.F. and R.A. Howard. 1968. A computer model for cambial activity. Forest Science. 14:77 -90.

Wimmer, R. 1995. Intra-annual cellular characteristics and their implications for modeling softwood density. Wood and fiber science. 27:413-420.

Wimmer, R., G. Downes and R. Evans. 2002a. Temporal variation of microfibril angle in Eucalyptus nitens grown in different irrigation regimes. Tree physiology. 22:449-457.

Wimmer, R., G.M. Downes and R. Evans. 2002b. High-resolution analysis of radial growth and wood density in Eucalyptus nitens, grown under different irrigation regimes. Annals of forest science. 59:519-524.

Zweifel, R., L. Zimmermann and D.M. Newbery. 2005. Modeling tree water deficit from microclimate: an approach to quantifying drought stress. Tree Physiology. 25:147-156.

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Appendix 1: Monitoring radiata pine stem growth across six sites with contrasting productivities: a description of methods.

Introduction

Previous research has demonstrated in many ways and in many species the effect of growth and environment on consequent wood properties. Previous work on temperate eucalypts in Tasmania showed how growth patterns over the year vary between species and regimes of water availability (Downes et al. 1999a; Downes et al. 1999b; Drew et al. 2009) and also proposed methods of data analysis to allow environmental effects on growth to be better explained in terms of the changes in the factors limiting growth over the season (Downes et al. 2004a). In particular the use of dendrometers to allow wood data generated by instruments such as SilviScan, to be rescaled onto a time axis, allows the effect of growth and environment on fine-scale wood property variation to be examined (Drew and Downes 2009; Drew et al. 2011a; Wimmer et al. 2002a; Wimmer et al. 2002b).

The application of high-resolution dendrometer measurements to softwoods has been more widely applied in boreal forests (Deslauriers et al. 2003; Deslauriers et al. 2007b) and allows insight into factors driving growth rates at different times of the year. (Cocozza et al. 2012; Deslauriers et al. 2007a; Rossi et al. 2007; Rossi et al. 2006).

The difficulty in trying to understand these effects is to identify how these relationships can be integrated, and preferably quantified, into a system of understanding that allows consistent conclusions to be drawn about the effects of a given environmental or management event on the growth and wood quality produced within a planted forest(Wimmer et al. 2002a; Wimmer et al. 2002b). Local environment may affect wood formation directly (e.g. temperature affecting metabolic activity, mechanical effects of wind sway, changing water status) or indirectly, mediated through effects on growth rate (Downes et al. 2009; Downes et al. 2002b; Drew and Downes 2009; Watt et al. 2006). To this end, if some generic means of predicting wood properties as a function of environment and management is achievable, it will require a process-based approach that relates this continuously varying and interacting factors (Downes et al. 2000).

Monitoring stem growth at high temporal and spatial resolution using automated dendrometers provides a means of exploring these relationships and informing the construction of such a process-based model. Dendrometers allow us to ask questions about when growth starts and stops, and the conditions that existed during those times. We can explore variation between trees, within and across sites, in terms of when maximum growth occurs and what maximum rates are achieved. They inform us about the effect of water stress on growth and how the tree responds to the release-from-stress events. All of these issues provide benchmarks for determining what is a realistic response from a model to such events. But just as importantly dendrometers provide a means of relating temporal (growth, environment) to spatial (wood property variation) measurements (Downes et al. 2004a; Wimmer et al. 2002b), and facilitating the interpretation of the cause of changes in wood over time. When we look at wood variation over the lifetime of a tree we can often (but not always) identify annual growth rings as sequences of low and high density wood. Fortunately radiata pine is a species that typically forms clear annual growth rings. However within these annual rings, because growth rate is not constant, or even consistently varying, over the year we are limited in our ability to relate intra-annual changes in wood properties (Wimmer 1995) measured as a function of distance, with environmental events measured as a function of time.

To that end this project utilised dendrometer measurements made at 6 contrasting sites (2 in New Zealand, 2 in East Gippsland in Victoria and 2 in the Green Triangle, South Austalia) over two annual growth cycles to provide insights into tree growth and wood variation at these sites and provide a means of assessing the performance of a process-based prediction of growth and wood variation.

These data can be used to explore a wide range of issues such as those listed below.

1. Relationships between sites (and the various climate regime x soils they represent) in terms of
    a. When growth started and ended at each site / treatment in each year
    b. Identification of environmental factors which affected variation
    c. Identify peak growth rates in terms of time of year and environmental conditions in which it occurs
    d. Explore summer slowdown events
        i. presence / severity / drivers
    e. Explore TWD severity and duration
        i. Explore shrinkage/recovery and increment (SRI (Downes et al. 1999b)) relationships with tree water deficit (TWD (Drew et al. 2011b))
        ii. Can TWD be modeled as a function of a soil water balance model?
2. Examine cambial structure from sections with dendrometer data in terms of relationship with growth rate
3. Demonstrate whether rescaling SilviScan data to daily steps or vice-versa provides a basis for improving our understanding of tree growth responses
    a. illustrate where such rescaling works well
    b. illustrate where rescaling doesn't work well and try to identify reasons why
    c. For cases of good rescaling calculate SRI and explore the
        i. No. days taken for each portion of wood (e.g. 100 um sections) to form
        ii. Whether increment rate or duration drives cell size or wall thickness
        iii. Does the
4. Provide suitable real data at high resolution against which to assess the performance of *E-Cambium*.

The objective of this appendix is to provide the background information describing the dendrometer installations at the six sites used in this study, indicating the nature of the data, background processing requirements involved in preparing the data for analysis and to describe issues encountered in operating the equipment. This will include site descriptions used in generating the Cabala growth predictions.

Site descriptions

Automated dendrometer data was obtained from multiple trees from 6 contrasting sites (Table 1) within which various silvicultural treatments were applied.

Table A1.1: General descriptions for the six sites used in this study for dendrometer based monitoring of growth.

Site	Lat	Long	Period of monitoring	Owner
Ohurakura	39.22°S	176.73°E	2008–2010	Rayonier
Balmoral	42.83°S	172.80°E	2008–2010	Rayonier
Blackwarry	-38.40	146.67	2010–2012	HVP
Flynn Creek	-38.26	146.68	2011–2013	HVP
MG airport	-37.74	140.78	2010–2012	ForestrySA
Reedy Creek	-37.28	140.18	2011–2012	ForestrySA

Automated dendrometer data from two existing sites in New Zealand were available at the commencement of this study. These data arose from a study jointly funded by the NZ Wood Quality Initiative (WQI) and Ensis (joint venture between CSIRO and Scion) directed at understanding the physiological basis for the occurrence of resin defects in radiata pine(Watt et al. 2009). Ohurakura is located on the North Island of New Zealand on a deep pumice soil with low water holding capacity, although water available to plants was very high. It is at a relatively high elevation and subject to frequent rain events and misting (low cloud) conditions. The Balmoral Forest site was a clonal study located north of Christchurch on the Canterbury plains and subject to low rainfall. It experiences half of the wind run that Ohurakura experiences. These sites were instrumented in April 2007 (Balmoral) and February 2008 (Ohurakura).

Two Hancocks Victoria Plantations (HVP) sites were instrumented in the East Gippsland region and two ForestrySA (FSA) sites in the Green Triangle region of South Australia. A high elevation site at Blackwarry (HVP), located in the Strzelecki ranges in East Gippsland, was instrumented in Oct 2010 along with an FSA site near Mt Gambier airport. In Oct 2011 sites at Flynn (HVP) and Reedy Creek (FSA) were instrumented. Instrumentation was removed from Ohurakura and Balmoral in December 2010, from Blackwarry and MG airport in October 2012 and from Flynn in July 2013. The Reedy Creek installation was destroyed by fire on January 20, 2013.

Instrumentation types

Different types of instrumentation were used at different sites but produced similar types of data.

2007 systems

The systems installed at the NZ sites were supplied by the Agricultural Electronics Corporation (Tucson, Arizona). These were a new generation of instruments that utilised Linear Variable Displacement Transducers (LVDT's) to monitor stem growth. Various technical issues were experienced with the equipment in the form of electrical artefact that required considerable loss or manual correcting of the data. However reasonable data was collected over the final two years of monitoring from a sufficient numbers of trees for use in this study.

2010 systems

The dendrometer sensors for these systems were custom-built by Bestech Pty. Ltd. (http://www.bestech.com.au/) using LVDTs. They experienced several design flaws which were resolved throughout the study; flaws which particularly affected the higher elevation, wetter Blackwarry site resulting in loss of useful data on many trees. Sensors were connected to a Campbell data logger via a multiplexor arrangement to provide a conditioned power supply.

2011 systems

These systems were deployed in response to a request from the Project Steering Committee to expand the site types represented. A different type of dendrometer was used based on a radial potentiometer. These sensors required a simpler (5V) power supply, which was readily available as a stabilised output from the Campbell Scientific dataloggers we used . However at the Reedy Creek site, a collaboration was established with a Swiss supplier (www.DecentLab.com). This system employed a wireless data logger which reduced the on-site cabling (and therefore reduced the risk of damage from herbivore browsing) which automatically uploaded data to a database which could be accessed via the internet.

Dendrometer measurements were programmed to be collected every 15 minutes (except at Reedy Creek where measurements were at approximately 10 minute intervals).

Treatment comparisons

On most sites dendrometers were used to compare treatment effects as follows:

- Ohurakura and Balmoral were part of a WQI study to examine the effect of wind on the occurrence of resin defects. Consequently 50% of the trees measured were guyed to minimise wind- mediated movements. Four dendrometers were mounted on trees within each of these treatments at each site. Only the data from unguyed trees was used in this study.
- Blackwarry compared the effects of weed control and fertilisation. Within each treatment an additional dendrometer was mounted at 7.5m on one tree giving 15 dendrometers in total.
    - D2R: Ripped, weed control + N,P,K at establishment, DA P100/N90 in 2000
    - A3R: Ripped, No weed control or fertilisation
    - B3R: Ripped, weed control at establishment and triple super P100 in 2000
- Flynn compared two stocking levels (both established at 1111 SPH, with the second treatment thinned to 200 SPH) with 3 dendrometers in each mounted at 1.3m above ground
- Mt Gambier Airport (FSA) compared the effects of thinning where treatments were established at different stockings then brought to the same stocking in 2009. Four trees per treatment were instrumented. Within each treatment an additional dendrometer was mounted at 7.5m on one tree giving 15 dendrometers in total.
    - E1 Initial Stocking 2222 stems/ha (2.5 X 1.8); T1, thin to 1111 Stems/ha @ PDH=12m; T2, thin to 555 Stems/ha @ PDH=22m
    - E2A Initial Stocking 1111 stems/ha (2.5 X 3.6) T1, thin to 555 Stems/ha @ PDH=12m
    - E3 Initial Stocking 555 stems/ha (5.0 X 3.6) No thinning
- Reedy Creek (FSA) two stocking levels (568 & 1333 sph) with 4 dendrometers in each mounted at ~3 m above ground to avoid deer browsing. Four of these dendrometers were mounted on trees within a permanent sample plot (Plot no. PSP600).

At each site data was collected regularly via monthly visits (Ohurakura and Balmoral) or by modem link (Blackwarry, Flynn and MG airport). At Reedy Creek data was automatically uploaded to the web database periodically.

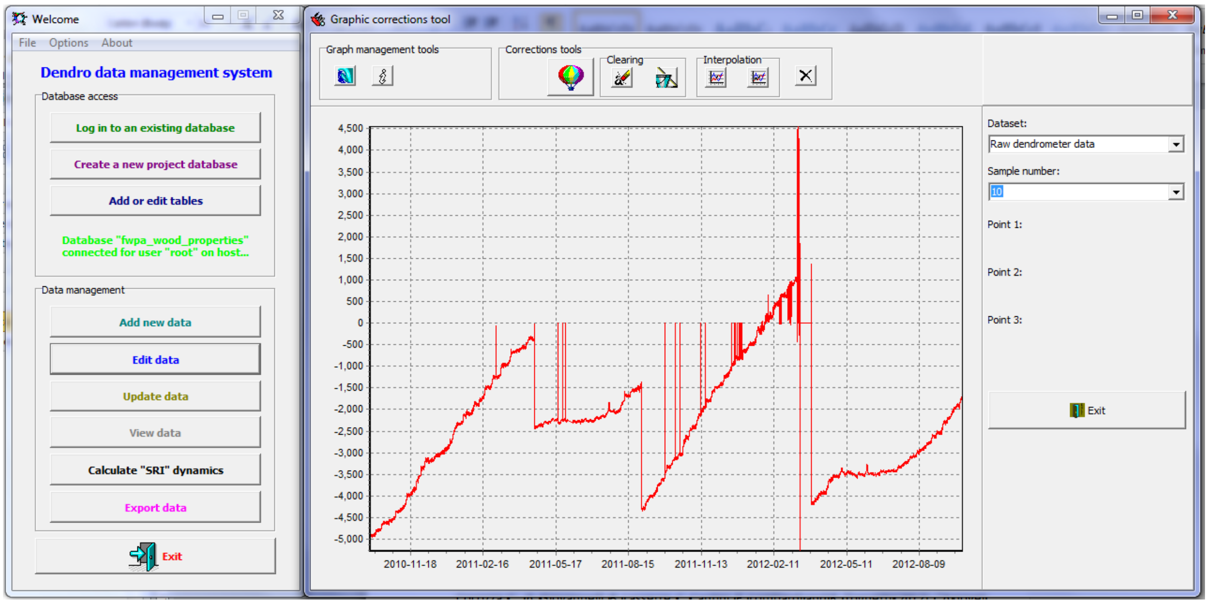
Data checking and storage

All data was stored in a MySQL database on a secure server. High-resolution dendrometer data needs to be checked regularly throughout the monitoring period to ensure the system is functioning correctly and errors identified and remedied. The nature of the data quality problems encountered in this study were as follows:

1. Cable damage
   This was particularly a problem at Blackwarry where cables were chewed by wombats and possibly deer. At MG airport some damage by rabbits was experienced. In this case the stream of dendrometer data ceases and the numbers generated indicate typical patterns of electrical noise.
2. System component damage / failure.
   At Blackwarry problems were encountered with the signal conditioner – multiplexor. This took some time to diagnose and replace. Troublesome instruments and systems were replaced but significant data loss on 7 trees was sufficient to render the long-term growth patterns un-useable. Two of the radial potentiometer-based dendrometers used at Flynn showed data quality deterioration (with one failing completely) due to internal corrosion.
3. Power failure.
   The ability of the solar panel to recharge batteries resulted in several power failure episodes at Blackwarry, Flynn and MG airport. Once identified these were not always able to be rectified quickly. The availability of sufficiently exposed locations for solar panels, especially over winter, was a problem at Flynn and Blackwarry. At MG airport the solar panel was dislodged several times resulting in sub-optimal (or zero)charging. At Reedy Creek solar panel damage was sustained due to an impact with a speeding kangaroo. The protection to the panel and logger was upgraded.
4. Dendrometer design flaws
   The Bestech dendrometer system experienced some design flaws in two main areas. The LVDT component was housed within a custom built housing and a brass bushing used to allow the LVDT sensing rod to emerge and contact the tree stem. The fit on this bushing was intentionally tight to provide weather-proofing capability, but on occasion impeded the movement of the sensing rod. In addition the internal springs used in the initial, delivered sensor were not rust resistant and corroded rapidly. Both these flaws were fixed by BesTech but resulted in some loss of data at Blackwarry and Mount Gambier.

5. Loss of connectivity to the mobile phone network
   This was primarily an issue at Reedy Creek. The DecentLab system relied on constant access to the network with minimal onboard data storage on the data logger. The system also had no local connectivity to allow data download on site. Both these aspects have been modified in newer DecentLab systems. However data loss is evident at random points within the data stream where connection to the mobile phone network was unavailable.

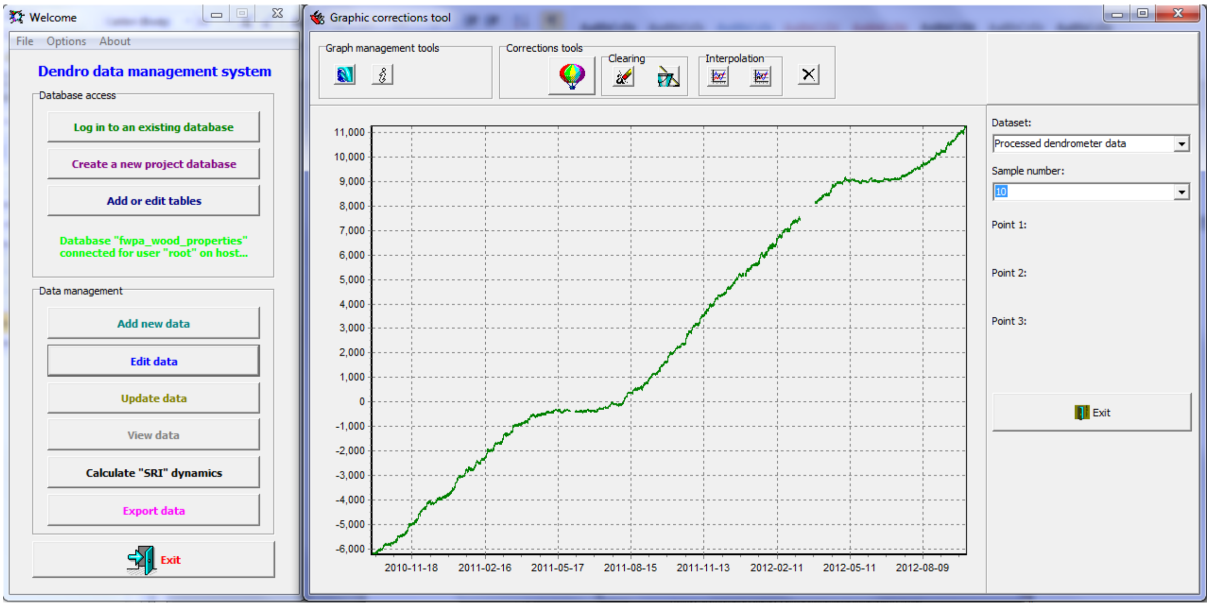
Consequently dendrometer data needed to be checked for integrity and continuity. For this, custom-built software was employed (DendroTools). This program allows the user to manage and query the database, record experimental information about the dendrometers (i.e changed and faulty sensors), view the raw data, copy it and correct any errors or discontinuities. These errors occur in the form of missing data or non-biological artefacts. Other discontinuities arise when dendrometers need to be repositioned to accommodate stem growth. Figure 1a illustrates the data from sensor 10 at Blackwarry. Three repositioning events are indicated by large drops in the data. These are usual and expected during this kind of study, resulting from the physical moving of the sensor away from the tree stem to bring the sensor back into range as the tree grows. They are easily corrected, and the software allowed this to be done routinely. Electrical artefacts in the data are also illustrated, that can result when the sensing circuit is broken or disrupted for various reasons. The intermittent nature indicates issues experienced in the BesTech system with electrical noise that were progressively overcome throughout the life of the study. These events were manually processed to generate the continuous growth time series (Figure 1b).


Database "fwpa_wood_properties" connected for user "root" on host...

Dataset: Raw dendrometer data

Sample number: 10

Figure A1.1a: DendroTools graphical user interface illustrating the raw data from sensor 10 at Blackwarry


Database "fwpa_wood_properties" connected for user "root" on host...

Dataset: Processed dendrometer data

Sample number: 10

Figure A1.1b: DendroTools graphical user interface illustrating the same data from sensor 10 at Blackwarry shown in Figure 1a after processing.

The time series for each dendrometer consists of repeated daily cycles of expansion and shrinkage (Figure 2). As transpiration commences after sunrise the loss of water from needles generates a tension in the xylem which results in a contraction of the stem, and extraction of water from storage tissues. Sometime in the afternoon / evening as transpiration slows and ceases, root water uptake catches up with loss and the stem recharges (expands). On most days, when drought is not too severe, the measured dendrometer position returns to at least the position prior to the commencement of shrinkage, and the cambium can be considered to be at zero “water deficit” (Drew et al. 2011b). The longer – hotter days combined with the shorter nights in summer result in larger cycles (Figure 2 bottom left) compared to those during winter (bottom right). Thus dendrometer data allows the daily increment gained to be analysed in terms of growth hours per day and rate of growth per hour. It is also evident that under hot-dry conditions, root water uptake might not be sufficient to account for the water lost during the day. In this case shrinkage events extending over days to weeks can occur where no net growth is observed. Shrinkage events can also be observed during winter but are probably more attributable to temperature effects on the rate of growth (cell division and expansion).

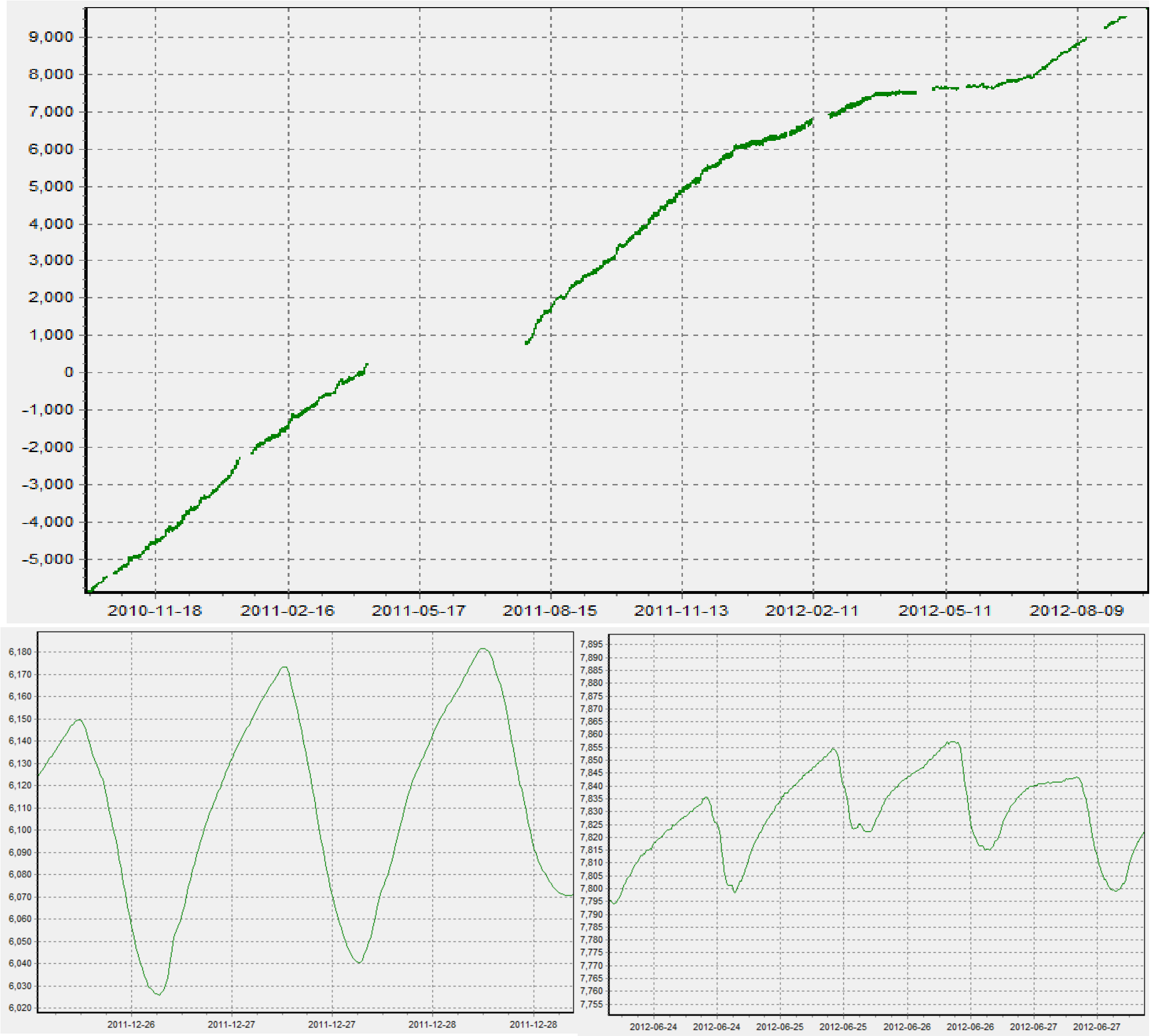


Figure A1.2: The upper plot illustrates the full data time series of growth after processing. Several months of data are missing over the winter period of 2011 when the BesTech dendrometer was being repaired. The bottom left plot shows the typical diurnal growth pattern during summer which is 2 to 4 times the magnitude of that observed during winter. This is driven by the effect of drier, warmer and longer days experienced during summer on tree water status and affects the rate of growth I terms of hours per day and growth rate per hour.

Data analysis

Within the context of this study, processed dendrometer data was used to obtain a variety of insights into the effect of site and environment on tree growth and wood properties.

When growth started and ended at each site / treatment in each year

Attempts were made to develop an automated approach to identify when tree growth started each year. However the variation between trees and sites, combined with the irregularity of growth on some sites made this process more suited to a manual decision. As in Figure 3, each individual dendrometer was checked and the timing of the onset and cessation of growth in each annual cycle was determined. The different sites yielded contrasting growth rates and patterns over the year. In particular Reedy Creek exhibited relatively constant growth over the year with only some indication of a plateau (potentially a form of environmental, rather than true physiological dormancy) in March/April.

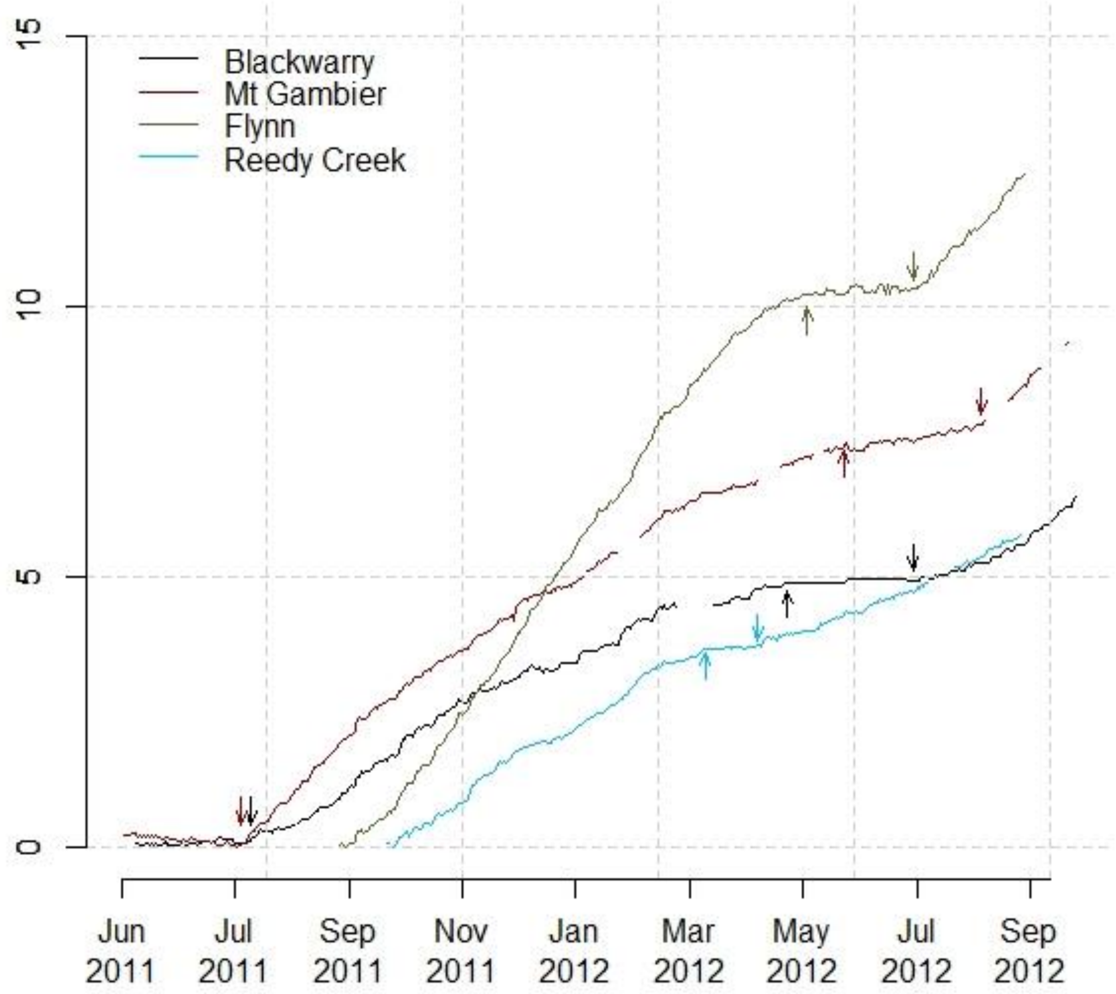


Figure A1.3: One dendrometer profile from each of the four Australian sites illustrates the variance in growth pattern between the sites across a single growing season. Arrows indicate the start and cessation of growth in each tree's growth.

Timing of peak growth rates in terms and environmental conditions when it occurs

By definition, the fastest growth rates are times of maximum rates of wood formation. To be able to identify these peaks and their effect on wood properties provides an important means of checking the performance of the *e*-Cambium model. The physiological processes modelled, need to be able to generate similar variation in timing as well as rates of growth. In Figure 4 this timing varied markedly between trees and sites both in terms of timing and magnitude. The trees used are those shown in Figure 3. The growth of the Reedy Creek tree is evident peaking in February. In contrast the peak growth rate at Mt Gambier was August / September.

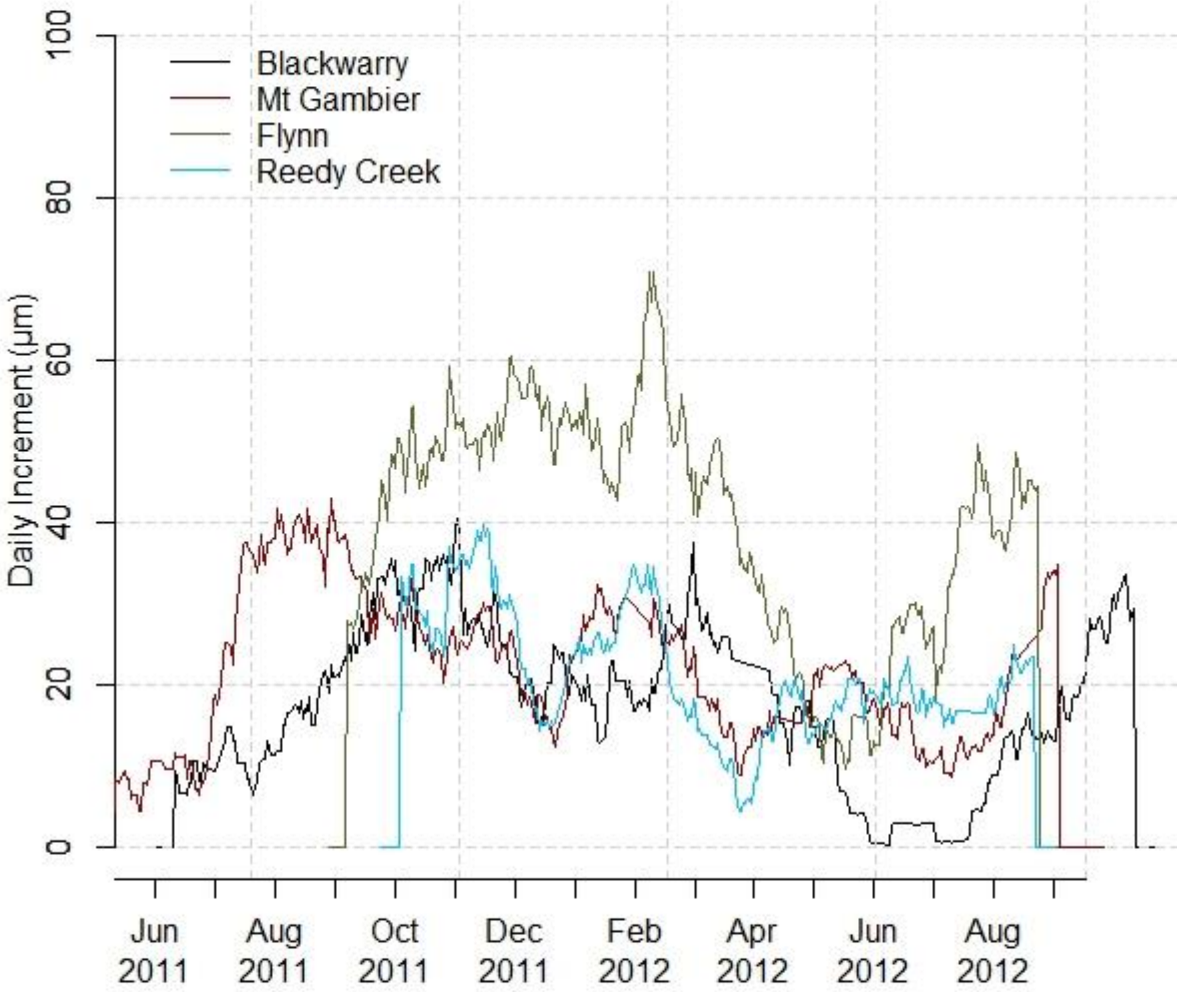


Figure A1.4: The daily increment of the four trees shown in figure 3 illustrates the differences that exist between sites in terms of the timing of peak growth. The data has been smoothed using a 21 day running mean.

Explore summer slowdown events in relation to the effect of water stress, daylength and environmental conditions.

The predominant change in wood properties across the annual cycle is the change from early wood (wood formed during spring) to late wood (formed during mid to late summer or autumn). This is characterised by a change in the size of cells and thickness of cell walls and consequently wood density. The dominant paradigm for the past 4 decades in the scientific community as to the cause of this shift has been attributed to the hormonal changes associated with foliage (needle) production of the growth hormone, auxin (Larson 1994). While this view seems consistent with slower growing northern hemisphere trees, radiata pine typically exhibits a multiple flushing growth habit capable of producing multiple whorls per year and consequent multiple periods of needle production and elongation within an annual cycle. Thus in fast growing trees where cycles of growth over a long growing season are stimulated by cycles of drought and rainfall, the concept of earlywood and latewood is less clear. This is evident in Figure 4 where the patterns of daily increment, even when smoothed, show considerable variance over time. Thus patterns of wood variability can probably be better understood in terms of cycles of increasing / decreasing growth mediated by changes in water availability. Although phenology probably does still have an over-riding effect, environmental drivers are just as important, and these effects are not independent; environment will influence phenology.

The severity and duration of tree water deficit (TWD)

When the growth trend within an individual dendrometer profile is removed, the data provides a detailed insight into the effects of water stress on trees. Each day, as a consequence of water loss via transpiration, balanced by root water uptake, trees can generate a degree of water deficit even when soil water content is adequate. During summer when days are longer and drier, these deficits increase (Figure 5). When combined with inadequate rainfall, tree diameters can shrink significantly and result in major effects on local wood properties produced around that time. In Figure 5a&b the growth trajectory is shown with shrinkage events (black line) and with these events removed (red line). Subtracting the red line from the black line (Figure 5c) the shrinkage effect is evident. In summer this is typically a result of drought stress. However, such events can also appear in winter, even under conditions in which water stress would be less likely.

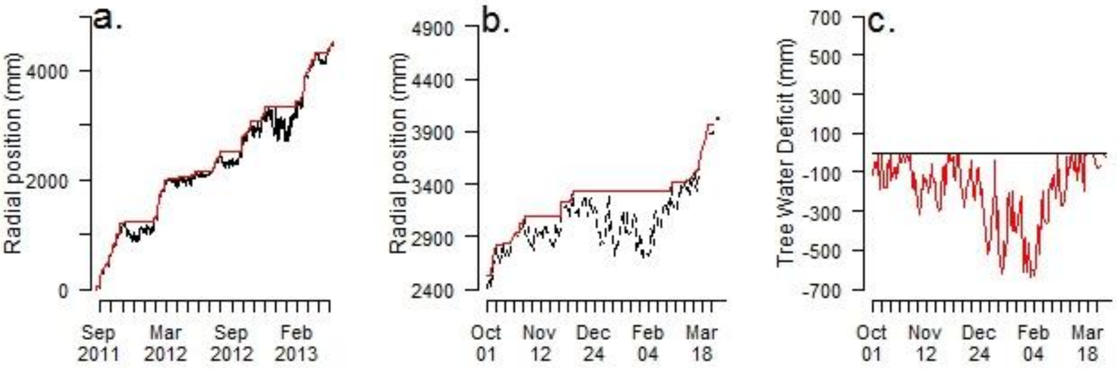


Figure A1.5: (a) the radial growth pattern together with (black) and without (red) shrinkage events. (b) a portion of the data in (a) shows stem shrinkage can occur over prolonged time periods. (c) The shrinkage of the stem can be assessed more clearly by removing the growth component.

Rescaling SilviScan data to daily steps or vice-versa to help understand the effect of tree growth responses

Dendrometers measure growth (millimetres) over time (days). SilviScan measures wood variation as a consequence of growth (millimetres). Environmental variation is measured over time (days). Consequently the dendrometer data provides a means of rescaling either the SilviScan data onto a time basis (Figure 6a), to show the wood property variation as a function of time, or the environmental data onto a spatial basis (Figure 6b) to show the environment variation as it relates to each portion of the growth ring. This provides a means of assessing the timing of events in the *e-Cambium* model .

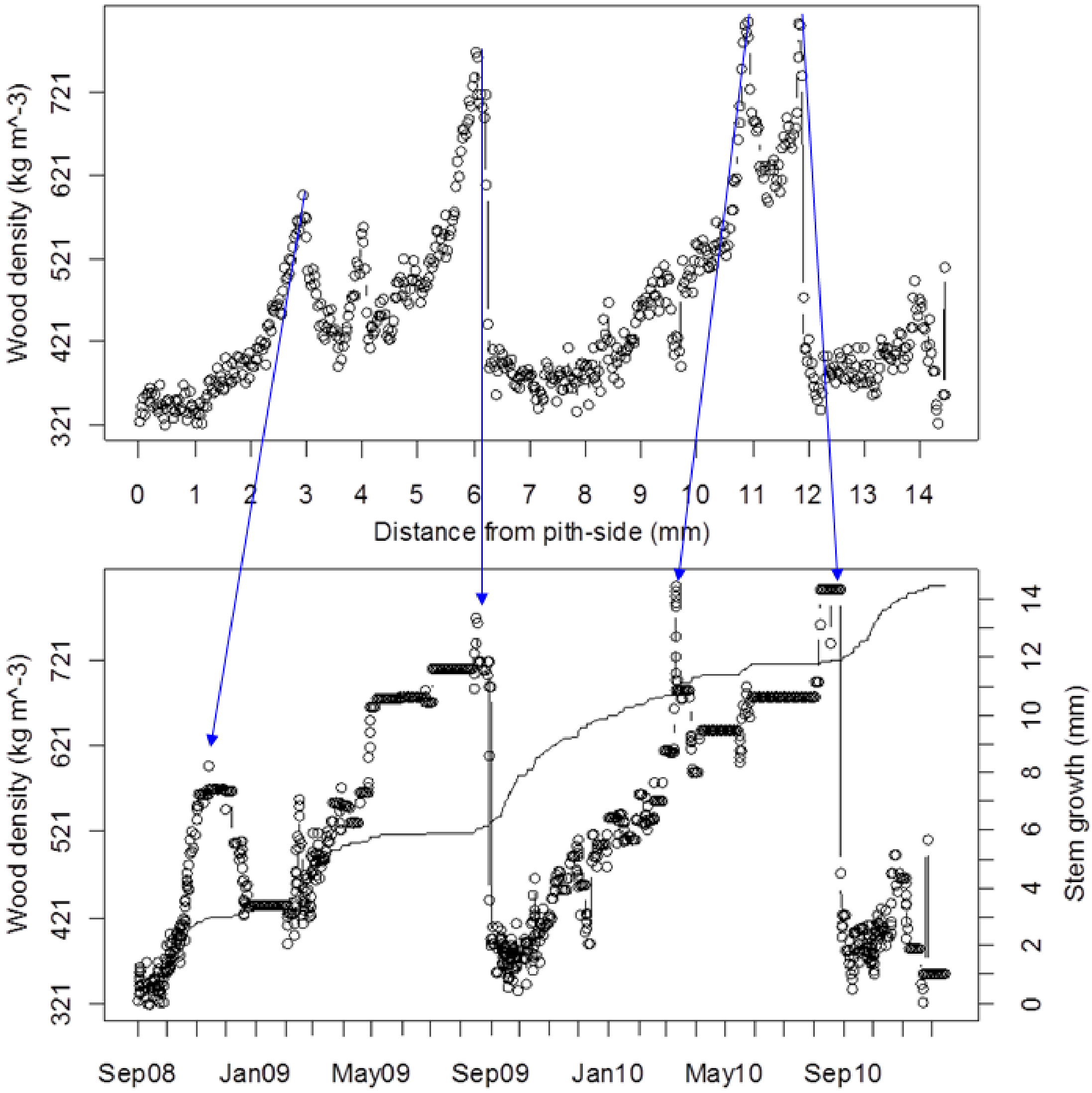


Figure A1.6: Silviscan density data taken at 25 µm intervals from the pith side (top), and re-scaled, using dendrometer growth data from a typical tree at Balmoral, New Zealand (bottom). Note that some 25 µm segments take longer to form (i.e., when growth is slower), resulting in the "horizontal" periods in the re-scaled data.

The rescaling process (Figure 7) makes a number of assumptions about the data.

1. That the final reading of the dendrometer data is consistent with the time that the sample was taken.

   If the dendrometers were removed a significant period of time before the wood sample was taken, then the matching of the start of the period of stem radius covered by the dendrometer data may be difficult to align with confidence.
2. That in preparing the wood sample, that the end of the profile relates to the time of sampling

   In taking an increment core and preparing a SilviScan sample, sometimes a portion of the outer wood can be lost/damaged during the coring process. This means the "time-anchor" of the dendrometer data to the end of the profile of wood data is lost. Clear annual growth rings can help the alignment process.
3. That the ratio of phloem to wood production is constant across the year

   The cambium produces both wood and phloem (bark) and the dendrometer measurements confound these. In approximate terms bark production accounts for 6-10% of the radial growth in these trees. While it is not unreasonable to assume that the ratio of production through out the year is approximately constant, this has not been proven. For example bark production may precede xylem (wood) production at the start of the season, in which case the increase in diameter recorded by the dendrometer may not be wood.

During the rescaling process the two data series can be adjusted relative to each other to identify the best position and bark adjustment proportion (Figure 7). The

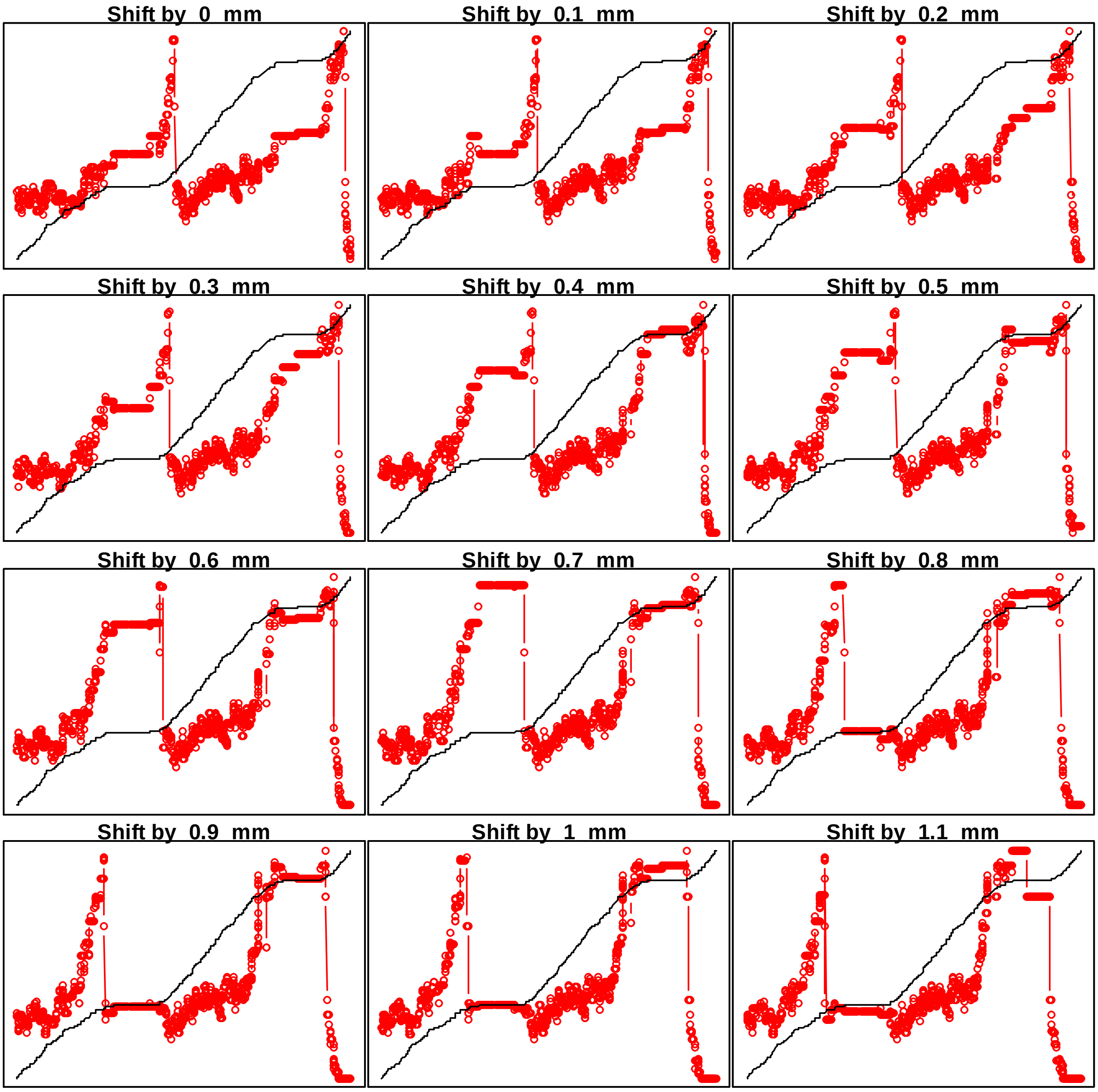


Figure A1.7: (a) Assuming the possibility of damage to the bark-side of the core, SilviScan data end-points were shifted by 0.1 mm at each step of a checking routine to see at which point the wood property data (red points) best aligned with dendrometer data (black line). Note: The x-axis in these figures is time, not distance-from-pith, so that the plotted dendrometer data remains constant, but the wood formed on a particular date changes. In this example, the best match was at about 0.7 mm, and was found to be the case with a bark growth rate of only 1%.

No. days taken for each 100 um to form

By rescaling the SilviScan data in this way we can start to associate external influences more directly with links to changes in wood properties. Given the time it takes for a single xylem cell to form (2 – 10 weeks) at different times of the year, this alignment at a daily time step should not be over interpreted. However co-incidence of changes in the series can be used to provide cause- effect inferences. The transition then allows us to look at the amount of time a given portion of the radius takes to form. For example when the tree is rapidly growing in spring, a given increment may be formed in less than a day. However under summer conditions of drought, there may be no growth, and even shrinkage, indicating that cell development of this increment occurred over periods of days to weeks.

Changing limiting factors over the annual cycle

Cell division and subsequent growth and cell differentiation is determined by the most limiting factor at the time (Fritts 1976), be that temperature, nutrients, carbohydrate or water. These factors vary over the growing season. For example a significant rainfall event during a dry period would suddenly release the limitation of water availability, and the next most limiting factor is what limits wood production. The hierarchy of limiting factors changes over time and would vary among sites and treatments. The rescaling of the wood data onto a time axis allows the relationship between environmental and growth variables to be explored in terms of consequent effects on wood variability. The data generated in this project was partially examined in this light, but more time would be required to explore this fully.

Whether increment rate or duration drives cell size or wall thickness

Previous methods for processing dendrometer data have described ways of resolving the diurnal dendrometer data into measurable quantities in terms of the magnitude, timing and duration of changes in stem radius(Downes et al. 2004a). Because tree diameters vary as a consequence of water loss / uptake, this affects both the hours per day stems spend growing and the rate at which they grow. Longer days, shorter warmer nights reduce these hours even when soil water is sufficient. These result in markedly different physiological drivers of stem growth over an annual cycle. Resolving wood property profiles onto a daily axis allows some assessment of these drivers.

Generating comparison data

The *e-Cambium* model works on a daily time step. As such it makes predictions of wood properties on a daily time step. Having a means to rescale SilviScan data to a similar scale facilitates the assessment of the model's performance. The between-tree variability within a site or treatment can be considerable and the model's purpose (at this stage of development) is to provide a site or treatment average profile. Rescaling to a time axis facilitates the production of a site average combining multiple trees, and thus generating a measure of acceptable variance in model predictions.

Summary

The above descriptions indicate the value and purpose of the dendrometer studies to constructing and validating the *e-Cambium* model. We have described the sites studied, the way tree and site data has been collected, processed and stored. In addition we have endeavoured to indicate the value of the data to model development and some of the uses to which the data has been put within the constraints of the project needs and resources.

Appendix 2: Dendrometer-based comparison of growth across sites and assessment of growth season duration and timing of peak growth.

Overview

In appendix 1 we described the sites and dendrometer equipment installed to monitor tree growth at high spatial and temporal resolution at six contrasting sites. We also described some ways the dendrometer data can be processed to better visualise and quantify the variation in growth rate and growth patterns. The primary purpose here is to identify key features from the data which the model needs to emulate. Specifically, the onset and cessation of growth within each annual period and the timing of peak growth rates is targeted. The detailed monitoring of growth and growth responses at the study sites has informed the way in which various physiological mechanisms have been modelled in the *e-Cambium* software to better simulate the predicted growth patterns and the consequent wood properties produced.

Site effects

Tree growth was monitored at six sites covering a relatively broad range of environmental conditions, soil types and silviculture (Table A1.1). These generated a corresponding variety of growth rates (annual increment) and patterns. Within this context, growth pattern is considered as the distribution of daily growth increments over an annual cycle (Downes et al. 2009). It is well known that the properties of wood formed at different times of the year can vary markedly, as embodied in the concepts of early and latewood. It is less clear to what extent these are caused by or linked to growth rate. A tree (affected by site, silviculture) can produce a given annual increment by a more even, steady daily rate of production, or by interspersing faster and slower rates of production. Based on our current level of understanding we would expect different strategies for producing a given annual increment to result in different annual average wood properties.

Across the six sites monitored (Figure A2.1) a variety of contrasting annual increments and growth patterns were observed. The treatments applied within each site varied, but serve to illustrate the effects that silviculture can cause. The highly thinned treatment at Flynn Creek in Gippsland (200 sph from 1111 sph) resulted in markedly greater growth than the unthinned (1111 sph). These plots beg the question of the difference between treatments in terms of growth patterns. If we normalise the growth magnitudes, do the treatments result in proportionally similar amounts of growth across the annual cycle?

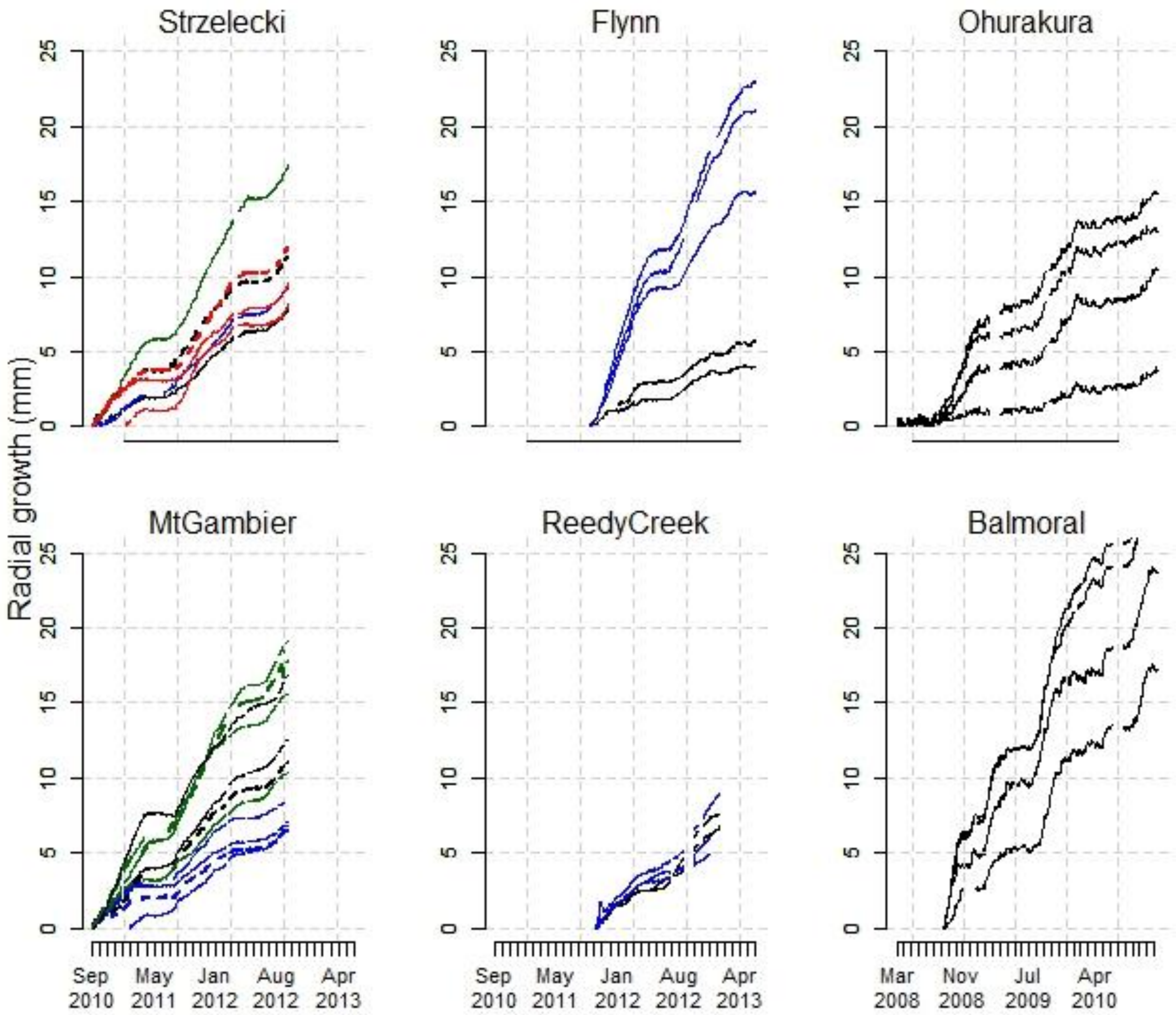


Figure A2.1: Daily growth data is shown for each of the six monitored sites. Dashed lines (Blackwarry and Mt Gambier only) represent measurements at 7.5 m. Different colours indicate different treatments as described in Table A1.1. All plots cover a 3 year range.

Within each site the growth patterns among trees was very similar (Figure A2.2), but between sites there were marked differences. There were also marked differences between treatments in the proportional amount of wood produced at different times of the year. For example the unthinned trees at Flynn stopped growing in summer earlier than the unthinned stand. This is not surprising, but in terms of model development, it is useful to clarify /quantify tree performance differences of this kind. Thinning a stand should allow soil water availability to be maintained longer into the summer and thus allow growth to continue later into summer. The variance between trees within a treatment with respect to the onset and cessation of growth each year was also considerable. Each profile was visually assessed and these variables estimated (Table A2.1).

Table A2.1: Manually estimated start and end dates of the growing seasons for which data exists for each site.

		Growing Season									
		2008-2009		2009-2010		2010-2011		2011-2012		2012-2013	
Ohurakura	Start			28-Aug	(18.7)	18-Sep	(24.1)				
	End	24-Jan	(17.8)	04-Feb	(2.4)						
	duration			160							
Balmoral	Start			13-Aug	(0.5)	31-Aug	(4.7)				
	End	25-Apr	(10.6)	31-May	(3.9)						
	duration			291							
Blackwarry	Start							12-Jul	(13.7)	10-Jul	(8.6)
	End					09-Apr	(20.9)	21-Apr	(12.4)		
	duration							284			
Flynn	Start									27-Jul	(25.9)
	End							04-May	(31.7)	24-Apr	(13.9)
	duration									271	
Mt Gambier	Start							13-Jul	(17.6)	04-Jul	(15.7)
	End					10-Apr	(21.8)	03-Apr	(18.9)		
	duration							265			
Reedy Creek	Start									14-May	(25.9)
	End							31-Mar	(11.2)		
	duration										

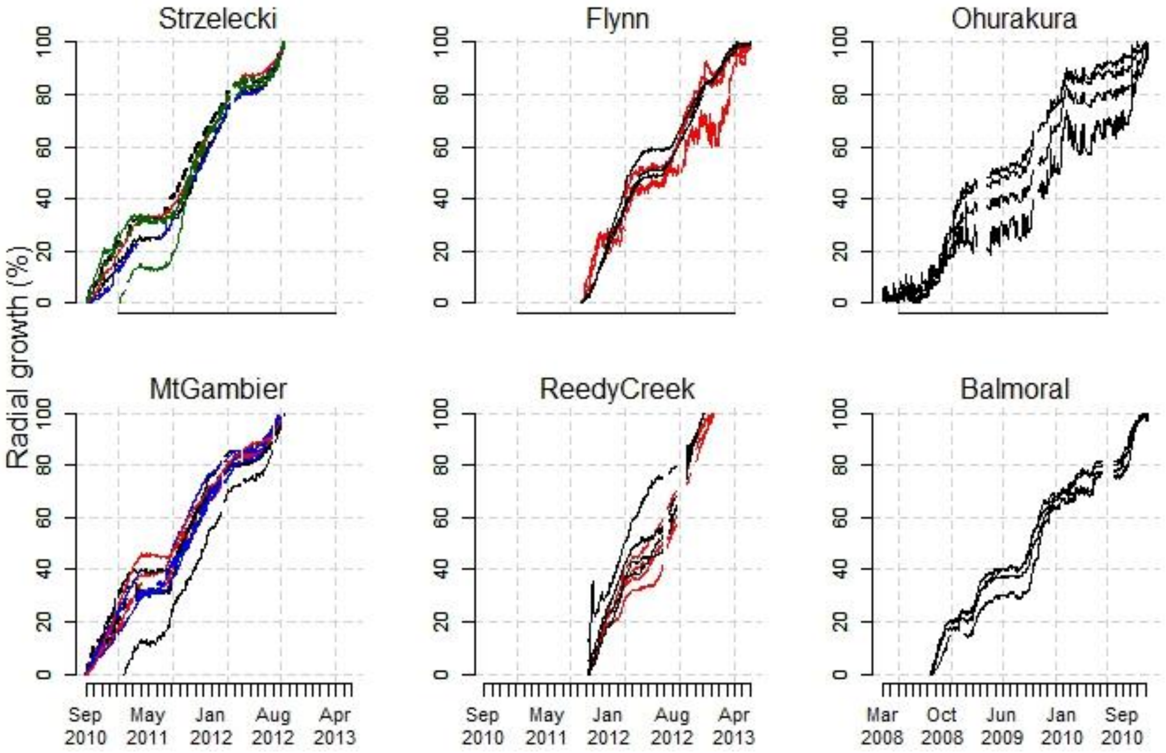


Figure A2.2: Daily growth data is shown for each of the six monitored sites where each dendrometer series is normalised to a constant magnitude. Dashed lines (Blackwarry and Mt Gambier only) represent measurements at 7.5 m. Different colours indicate different treatments as described in Table A1.1.

A major factor in previous models of softwood formation was the concept of “winter” dormancy. For example the TreeRing model (Fritts et al. 2005; Fritts et al. 1999a) requires an average temperature of 15^{o}C to be exceeded over 15 consecutive days following winter, before the model restarts its cambial growth. The assumption of dormancy in radiata pine is called into question by the data shown here. For example, the Reedy Creek data showed virtually linear growth (Figure A2.2), with the indication of a brief plateau for only a few weeks in March / April. Growth during winter was relatively high, indicating that winter temperature is not limiting at this site. All of the Australian sites showed a plateau in late autumn-early winter, with growth generally resuming in early July. For those sites where growth was monitored over multiple years, there were marked differences in the extent and duration of the “dormant” period (Table A2.1). Many of the trees exhibited no complete growth cessation. Unfortunately the destruction of the Reedy Creek site by fire in Jan 2013 prevented a second year of data collection.

The commencement of growth across all sites between May and July suggests that the growth plateau, evident across all sites, was not related primarily to temperature. The degree to which the growth resumption is related to bark or wood production is unclear.
Many of the sites also exhibited a reduction in growth during summer but less pronounced than annual “dormancy” (Figure A2.3). At some sites (e.g. the Blackwarry site in the Strzelecki ranges) this was minimal, more evident at Mt Gambier, but in the unthinned treatment at Flynn, it was very pronounced. This is most likely driven by diurnal water deficits of the trees, impacted by the effect of shorter nights following longer warmer days, and the reduced ability of the roots to recharge the water lost throughout the day.

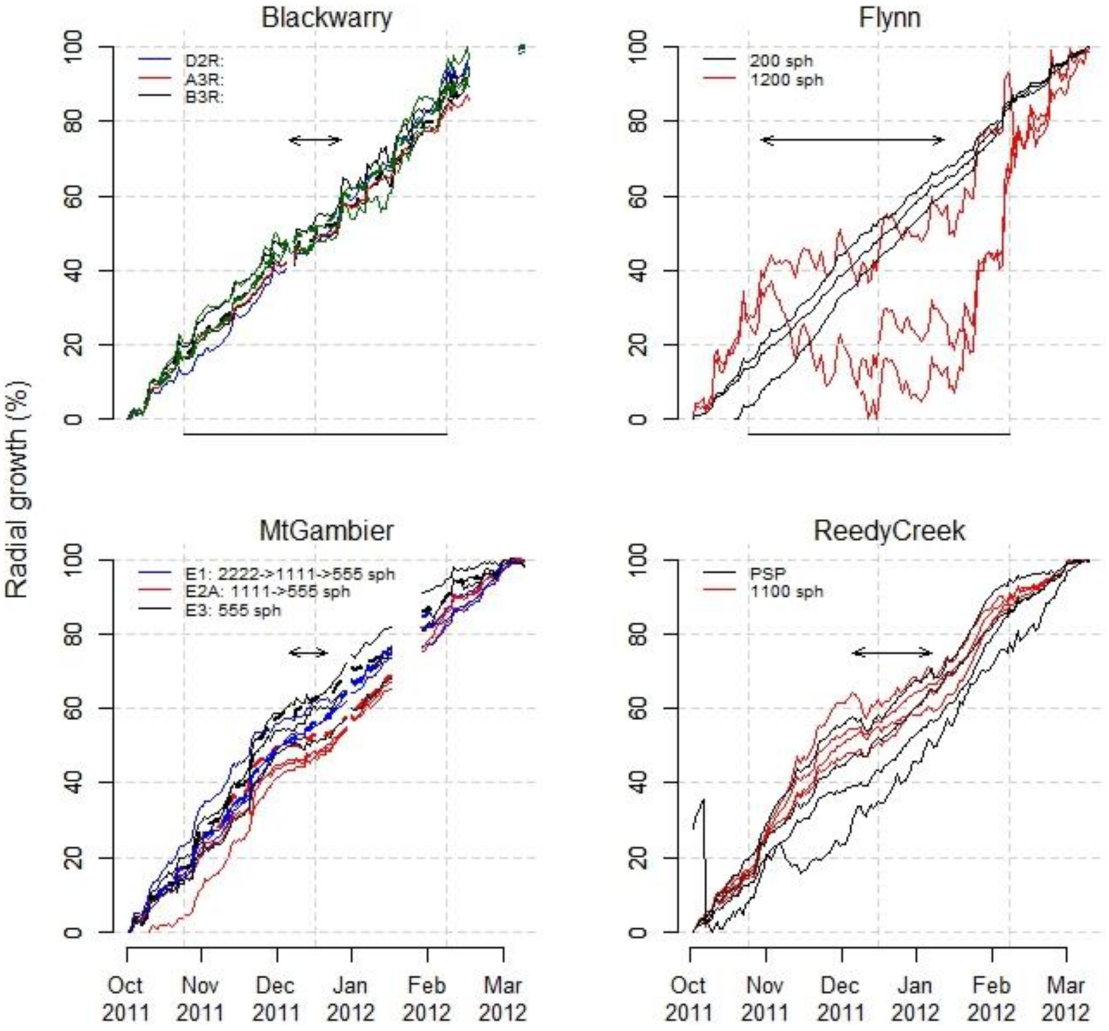


Figure A.2.3: Growth over the summer 2011 – 2012 growing season expressed as a percentage. The effect of thinning on maintaining growth over summer at Flynn is evident. Arrows indicate period over which growth is affected.

Timing and rates of peak growth

Peak growth rates varied considerably between trees and between sites over the monitored period. In Figure A.2.4 the daily increment (smoothed using a 21 day running mean), the arrows indicate the maximum increment for each dendrometer time series. At Flynn the peak growth rate in the unthinned treatment occurred earlier in the spring compared to the heavily thinned treatment. At Mt Gambier the relatively constant high daily increment over the spring period is evident. Unusually at Reedy Creek, peak growth rates are generally in late February early March while also having high rates in late spring. At Blackwarry the peaks tended to be in mid-Spring.

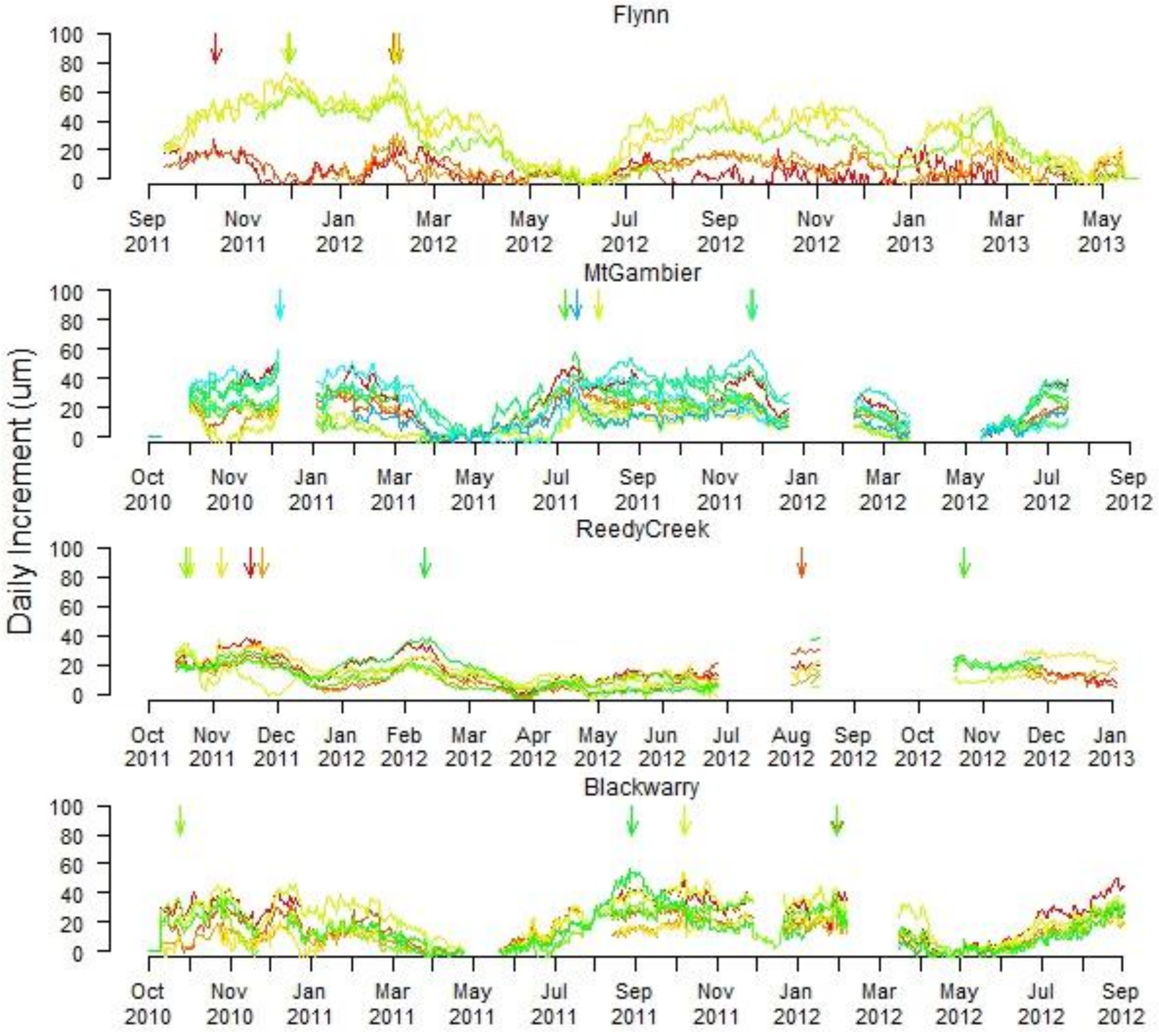


Figure A2.4: Each trees daily growth increment (um) is plotted and the max. increment position indicated by an arrow.

In Appendix 1, the calculation of tree water deficit (TWD)(Drew et al. 2011b; Zweifel et al. 2005) was illustrated (Figure A.1.5) to allow the study of the effects of rainfall / drought on radial stem growth. The daily growth data generated by dendrometers allows shrinkage events to be a calculated, and the association with weather events assessed. Each dendrometer time series was processed to calculate TWD (Figure A.2.5) and the timing of the maximum deficit marked with an arrow.

Presented in this way the term "Tree Water Deficit" may be inappropriate as generally the largest deficits occurred over the slower-growth periods, typically late autumn to early winter.

Trees are still transpiring, and a net TWD might develop in these periods. However it is possible that some other mechanism during these cooler periods is involved in these shrinkage events other than water stress. In essence TWD is simply cumulated stem shrinkage relative to the previous largest radial measurement. So the large deficits at Blackwarry that occurred over winter seem unlikely to be related to water stress, when the summer shrinkages are so much less. Closer examination showed that at this site (Figure A.2.6) the large deficits seem to be related to some persistent reductions in stem diameter during winter that are as yet unaccounted for. This is accentuated by variability in stem radius at the end of growth. However the data from Flynn (Figure A.2.5) does seem to be indicative of high water stress experienced particularly in the unthinned trees. To use stem shrinkage as a measure of TWD may only be warranted over the drier seasons.

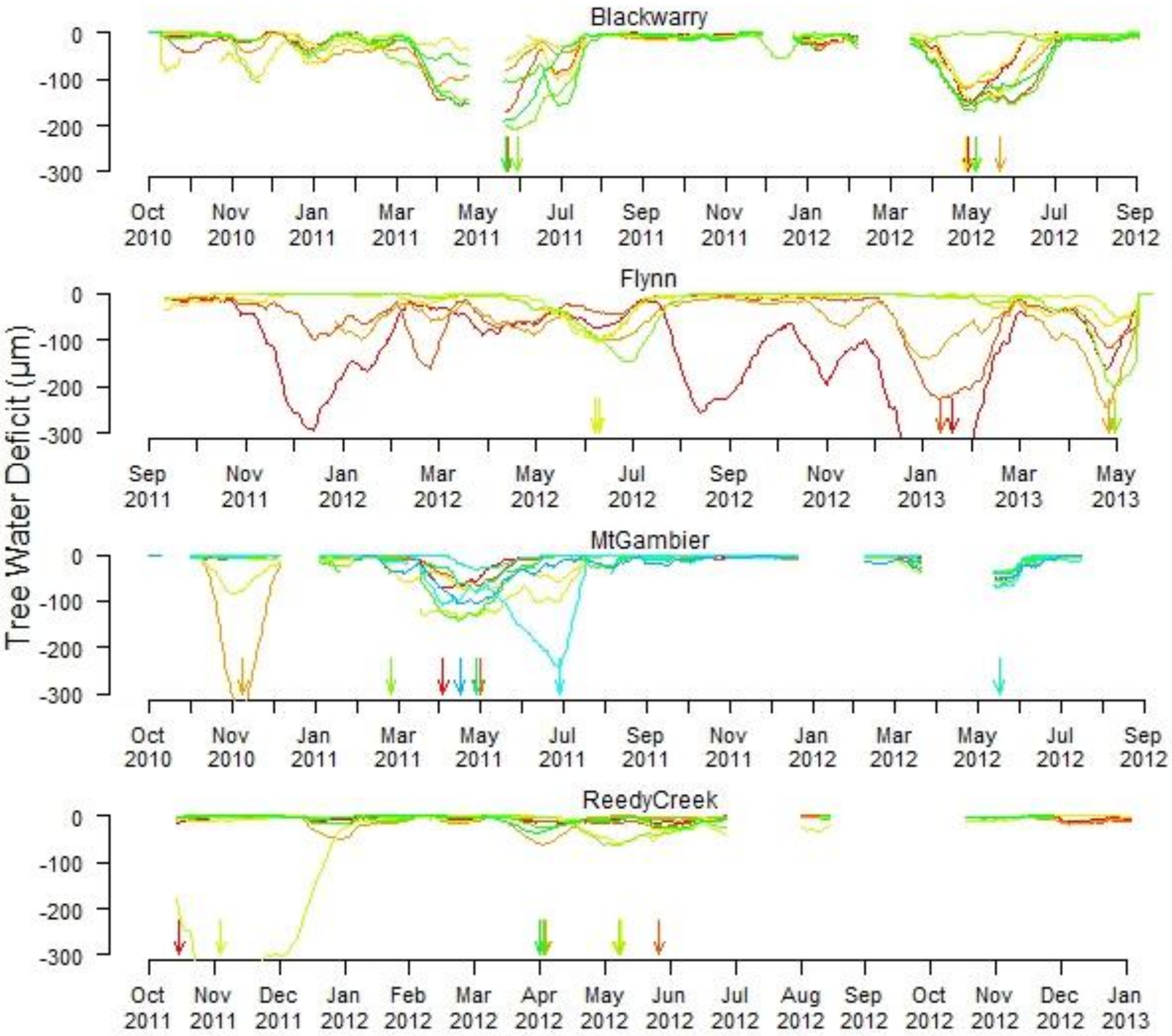


Figure A2.5: Each tree's daily tree water deficit (um) is plotted and the largest deficit in each series indicated (down arrow).

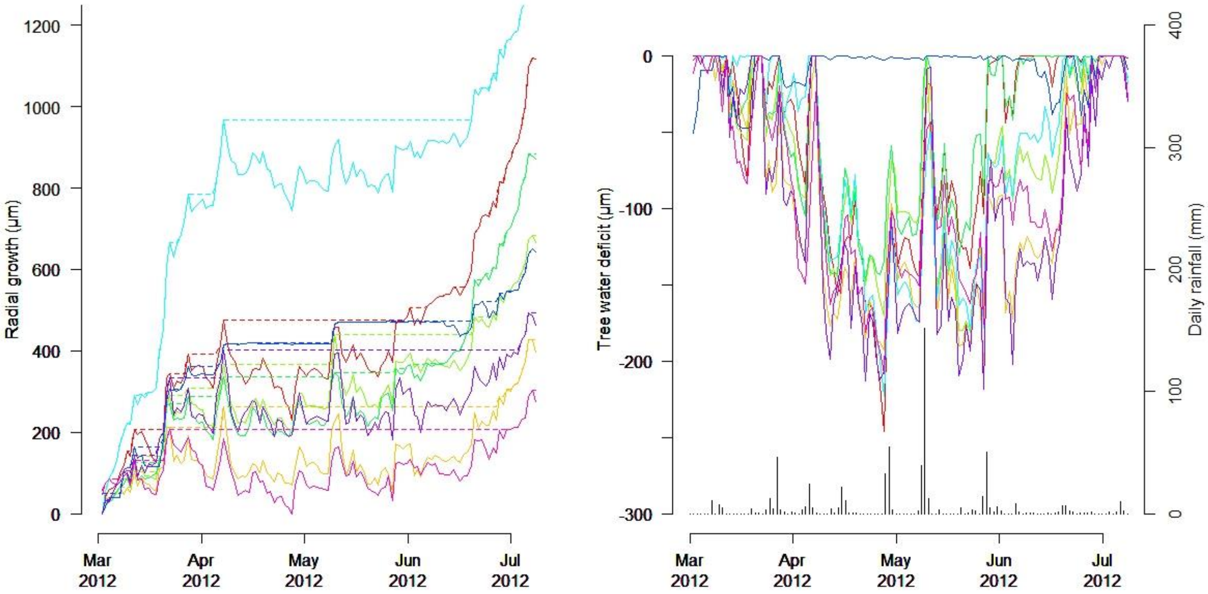


Figure A2.6: Stem shrinkage events at Blackwarry and over winter suggest a cause unrelated to water deficit. Rainfall over the period was regular while evaporative demand would have been low.

Summary

The dendrometer data was useful in identifying growth onset and cessation among different trees and across the various sites and treatments. The extent of variation among sites was larger than expected, and the ability for the trees to maintain often rapid growth throughout winter was surprising. This suggests P. radiata does not exhibit "true" dormancy as defined for many other tree species. This supports the observations of Barnett (1973)and make some sense in the study of latewood lignification by Donaldson (1992).

The data warrants much greater examination than was possible in this study. Quantification of the effect of environmental and seasonal variance on the rates of growth and the diurnal patterns of shrinkage, recovery and increment would provide additional insight into the response of radiata pine.

Appendix 3: *e*-Cambium model user guide

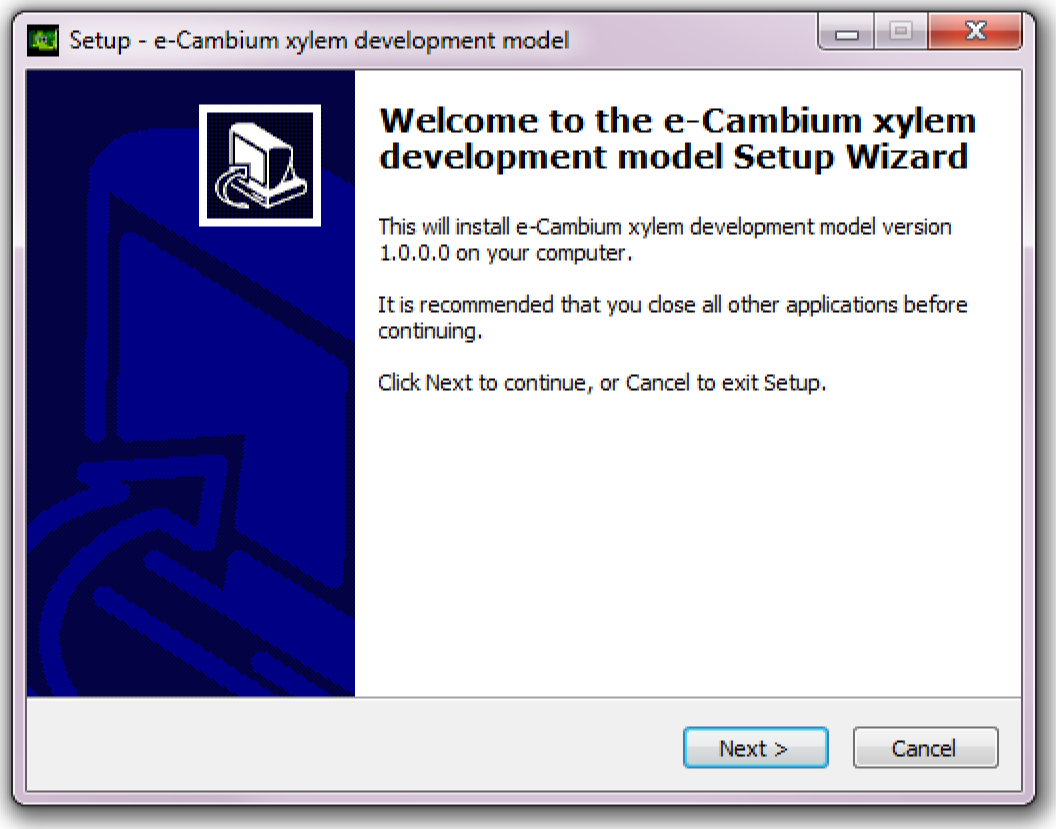
Introduction

e-Cambium is a process-based model that predicts stem diameter growth as well as pith-to-bark variation in tracheid radial diameter and wall thickness, wood density, microfibril angle, and a derived indication of board stiffness. It is available as installable software, which is described in this manual.

It is designed primarily as a tool to predict how changes in conditions or forest management approaches might affect not only stem growth, but also wood properties (particularly wood density). The version described in this manual is a prototype, and is still undergoing testing, and further development.

Installing e-Cambium on your computer

The software is designed to run on Microsoft Windows, and has been tested on MS Windows XP and Windows 7. Install the software by double-clicking on the installation file ("e-Cambium setup.exe"), and following the instructions in the Wizard. It is necessary to accept a set of terms and conditions, and a password is also required. Once installed, the software will use about 5.5 MB of disk space on your computer. The user can create a desktop icon or fast-button. Once installed, the software can easily be removed by clicking on the uninstall option under the Windows Start menu or in the control panel.



Welcome to the e-Cambium xylem development model Setup Wizard

This will install e-Cambium xylem development model version 1.0.0.0 on your computer.

It is recommended that you close all other applications before continuing.

Click Next to continue, or Cancel to exit Setup.

Figure A3.1: The set-up wizard will guide the user through the installation.

How the model works

e-Cambium incorporates a stand growth model (which predicts stand-level information on net primary productivity, stand water use, etc.) and a wood formation model. The wood formation model requires inputs of daily stand-level information:

(a) Carbohydrate available to the stem
(b) Maximum (pre-dawn) leaf water potential
(c) Tree height

Two options to provide this data are available in the present version. First, the user can select pre-run scenarios from a CaBala data file (*.mbc). Second, users can develop their sites, regimes and weather datasets in the e-Cambium software interface and run the internal stand growth model (IGM) to produce their own e-Cambium scenario.

The e-Cambium software is set to read from "projects". Each project is a stand-alone data file which contains the data and information for creating a set of "scenarios" on which a model run can be undertaken. Each "scenario" represents a particular combination of site and regime information, along with known weather data and a parameter set. For a detailed description of the model itself, refer to Drew and Downes (In Prep)[2].

To create a new project

e-Cambium simulations are project-based. That is, a user can create a project that consists of multiple scenarios, which may include different sites, or multiple regimes applied to a single site, etc. The make-up of the scenario will depend on what the objective is of the modelling exercise.

To create a new project click on "Create a new project" on the main window. There is, strictly speaking, no limit to the size of a project, although data files may begin to get unstable in large (> 2 GB) projects. To minimise this effect, it is possible to compress/repair the data file (click File|Compact/repair e-Cambium data file). The data file will temporarily disconnect while the compacting and repair process is underway. For large files this may take several minutes. Do not close e-Cambium while this happens as the data file may become corrupted.

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[2] Drew, D.M. and Downes, G.M. (In Prep). The e-E-CAMBIUM process-based model for wood property prediction in *Pinus radiata.* FWPA report XXX-XXX. Note: This FWPA report is not yet complete. A draft can be made available on request.

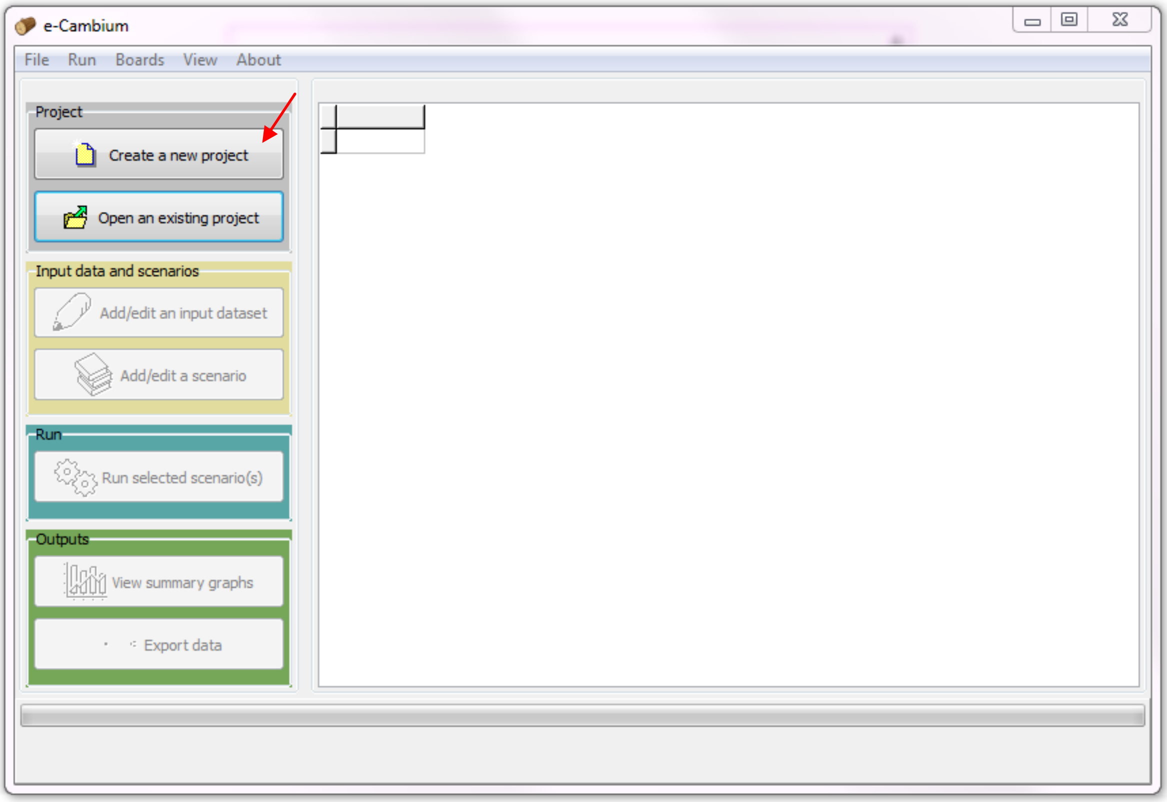


Figure A3.2: Click on "Create a new project" to create a new e-Cambium data file

Once "Create a new project" is clicked, a standard windows dialog will appear. Specify a name for the project (the filename will have the extension ".e-Cambium" as default, and click "Save". If for some reason the new project cannot be seen in the save or open dialog window, check that the *.e-Cambium extension was indeed added to the file name. If not, it can be added manually using Windows explorer or another file management program.

If the project is successfully created, a line will now become visible in the table which displays the scenarios in the project. As no scenarios will yet have been created, it will be empty. All other buttons and functionality will be enabled.

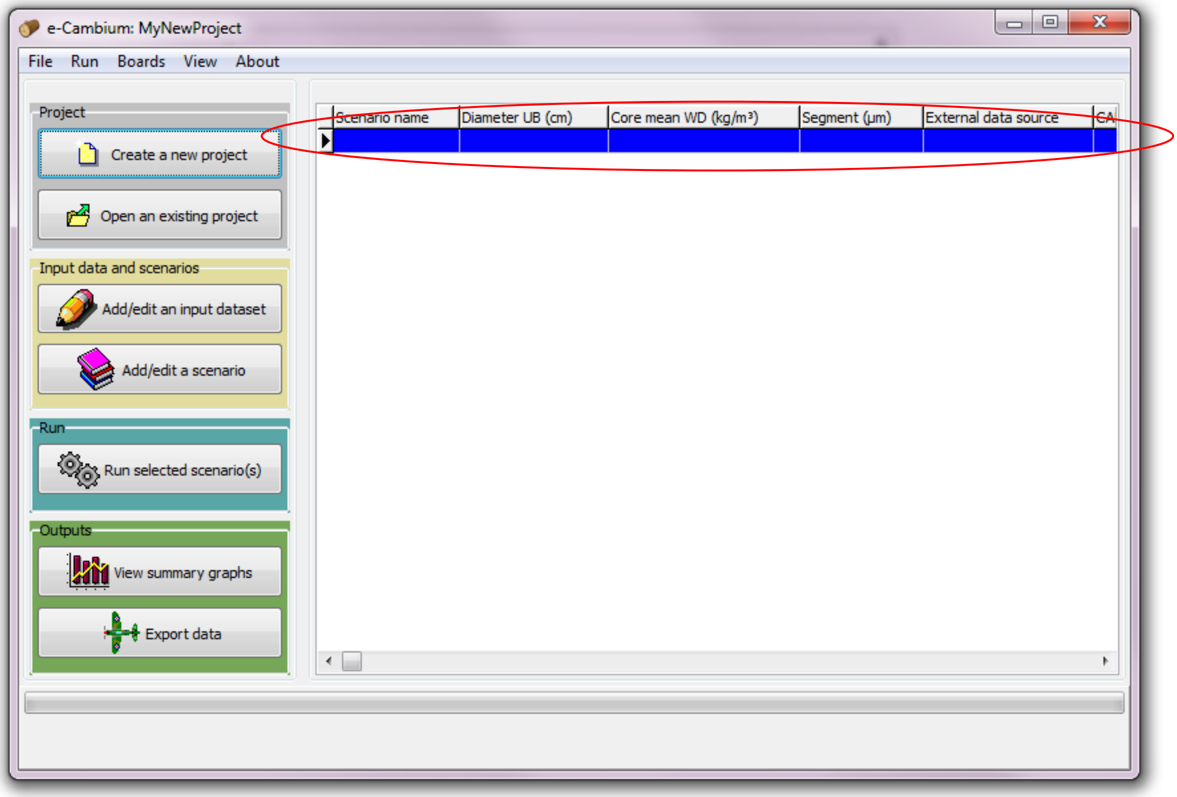
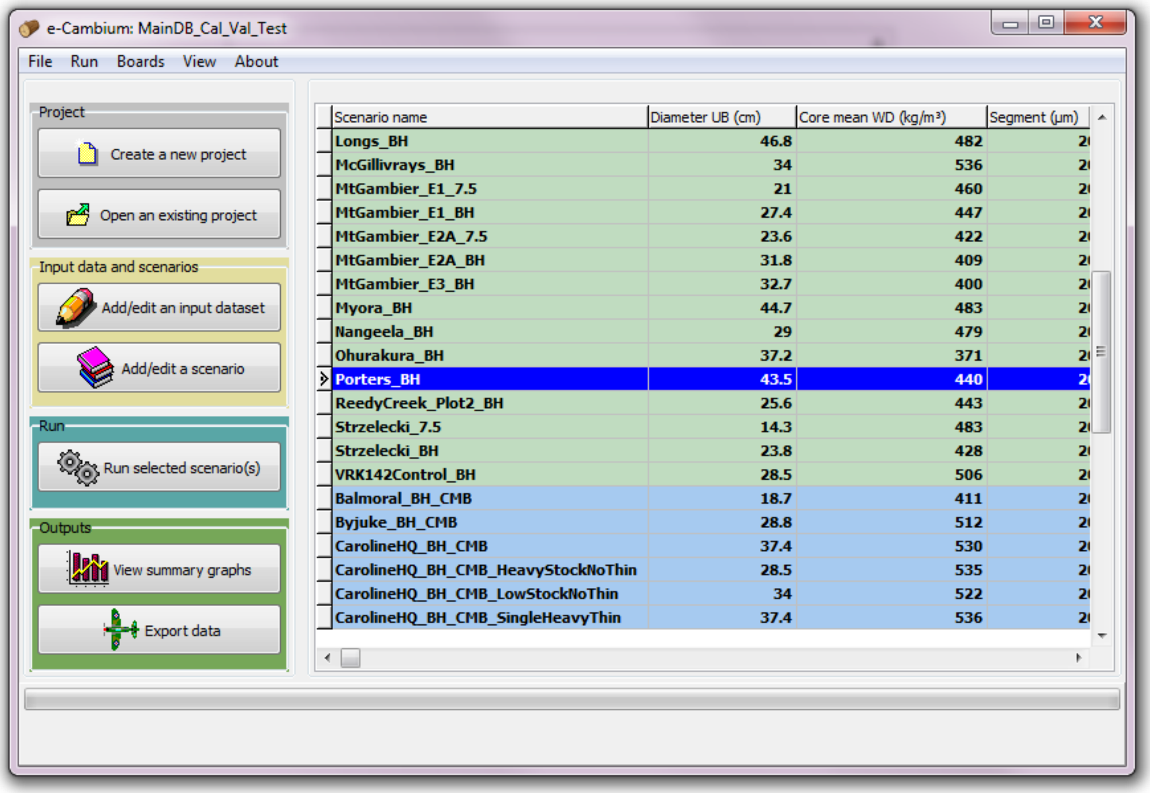


Figure A3.3: The empty first line indicating that the current open project has no scenarios

To open an existing project

If you have already created a project, you can open it by clicking on “Open an existing project”. A standard windows dialog will display. Navigate to the folder where the file of interest is saved. All *.cambium files will be visible in the current directory. If your data file is not visible, check it does indeed have a *.cambium extension. If it doesn’t, it will be necessary to edit the file name manually. Select the file of interest and click “Open”.

If the project opens successfully, all scenarios in the project will be displayed in the table. Scenarios that link to an existing CaBala database have a green background. Native ee-Cambium scenarios (using the ee-Cambium internal stand growth model, or IGM) are blue. Scenarios that have successfully been run will display a variety of predicted values and other information. Otherwise, the data columns will be blank. It is possible to write only wood properties data to disk, or both wood properties data and daily growth and development data (see Running the model). If both data types have been written to disk for a scenario, it is shown in bold font. Otherwise, if only wood properties data is available, the scenario information is not emboldened. By default, the software will order the scenarios in ascending order of scenario type followed by scenario name. The table can be sorted (in ascending order) on other fields by clicking on the applicable column heading.



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
Longs_BH	46.8	482	2
McGillivrays_BH	34	536	2
MtGambier_E1_7.5	21	460	2
MtGambier_E1_BH	27.4	447	2
MtGambier_E2A_7.5	23.6	422	2
MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

Figure A3.4: Listed scenarios in an open project.

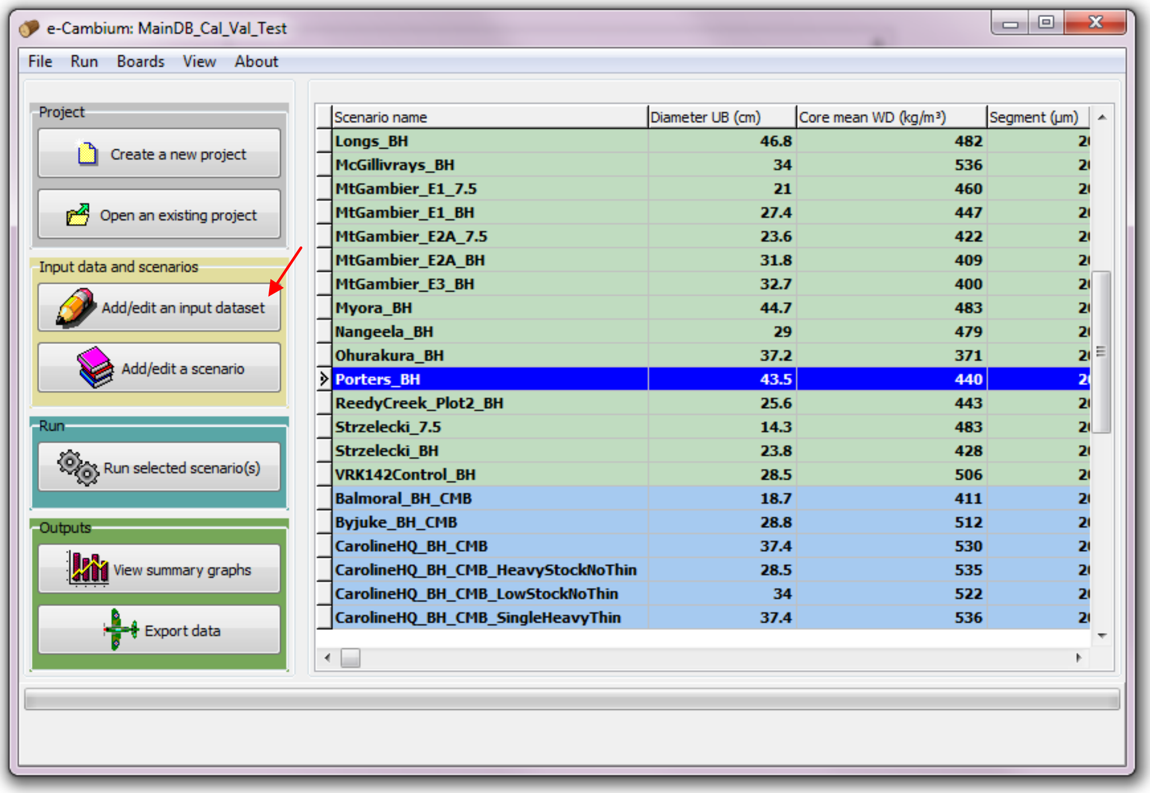
Warning: sometimes, when the computer is already busy with other write operations, opening medium to large e-Cambium data files can be quite slow. It is highly recommended to avoid closing the program before a file opens, as it can become severely corrupted.

To add or edit input data

Once a project is open, it is possible to add or edit the data and information that is needed for a successful simulation. For both the CaBala and IGM-based simulations there are four categories of data required:

- Model parameters,
- Site information,
- Regime information and
- Weather data.

To change these items for a Cabala run, it is necessary to use the Cabala software. To add/edit these data for an IGM run, click on “Add/edit an input dataset” on the main window. A new window will open up with the four data categories listed as individual tabs along the top (see below).



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
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MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

Figure A3.5: To create a new parameter set (always required), site, regime or weather dataset click on "Add/edit an input dataset

Model parameters.

The software provides the option of automatically creating a default parameter dataset for both the xylem development component and the IGM. If a Cabala simulation is being used as the basis for a xylem development simulation the latter parameter set is not used. The data are in the form of a list of parameters which are used by the model in generating the predictions of tree growth and wood formation. Varying these parameters changes the way the model operates and in general these parameters should relate to real physiological analogues, providing indications of limitations to processes in a given tree species or genotype.

A major part of model development is getting these parameters optimised. In general, for a given species, these parameters should remain relatively constant. However there might be scope for further refining the parameter values for genotypic variation within a species. Consequently several parameter sets might be created in testing the model. The two parameter sets given below are a suggested radiata pine set for the xylem development model (Table 1) and the IGM (Table 2), which were developed by testing the model across a wide variety of sites. Nevertheless, these parameter sets should still only be considered useful starting points for adjustments undertaken by the user.

Table A3.1: e-Cambium parameters with suggested ranges

Parameter description and units	Estimate parameter value ranges
The critical concentration of carbohydrates for the cessation of secondary thickening (g/ml)	0.05 - 0.15

Parameter description and units	**Estimate parameter value ranges**
The proportion of cell length after a cell division	0.88 – 0.93
The target ratio of enlarging to cambial cells (# EZ cells/# CZ cells)	0.2 – 0.35
Maximum wall extensibility (µm/MPa/d)	8 – 12
The maximum angle of microfibrils in the S_2 wall layer (degrees)	60 – 66
The maximum length of a mature tracheid (µm)	2000
The maximum diameter of a mature tracheid (µm)	50 – 55
The maximum ratio of wall area to cell cross sectional area (μm^2 / μm^2)	0.65 – 0.85
The maximum rate of wall thickening (μm^3/d)	10000 - 12000
Factor determining MFA responsiveness to carbohydrate allocation across the differentiating zones	0.35 – 0.45
The minimum time required between successive cell divisions (cell cycle) (d)	5 - 7
Minimum radial diameter for periclinal division (µm)	16 – 18
The minimum osmotic potential achievable by differentiating cells in the cambial zone (MPa)	-4 - -4.5
The lower air temperature at which metabolic activity in the developing xylem is inhibited (deg C))	0 - 2
The target turgor for growing cells (MPa)	1 - 1.3
Ratio of tracheid length/radial growth (µm/µm)	9 – 12
Scaling factor to adjust from lumen volume to the “effective” volume for osmotic adjustment	0.045 – 0.055
Density of the cell wall (g/cm^3)	1.5
The cell wall yield threshold (MPa)	0.2 – 0.4
Distance from crown apex at which juvenile production completely ceases (m)	8 – 10
The minimum rate of carbohydrate extraction per cell (%)	0.15 – 0.35

Table A3.2: Internal growth model parameters

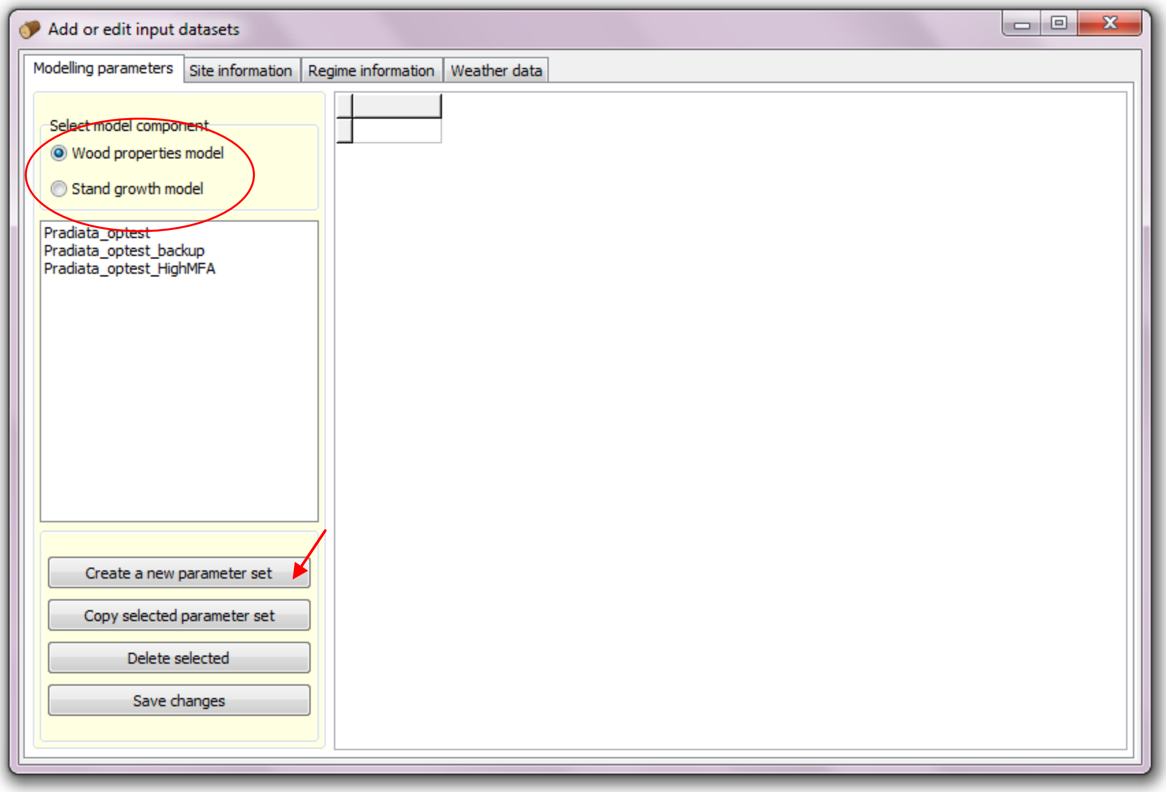
Parameter description	**Estimated parameter value ranges**
Canopy quantum efficiency	0.045 – 0.052
Canopy boundary layer conductance, assumed constant	0.2
Determines response of canopy conductance to	0.045 – 0.055

Parameter description	Estimated parameter value ranges
VPD	
Value of fN when FR = 0	0.55 – 0.65
Age at full canopy cover (Y)	7 – 8
Litterfall rate at t = 0 (1/day)	0.00003
Maximum daily litterfall rate	0.0025 – 0.004
Root turnover rate per day	0.0004 - 0.0006
Radiation extinction coefficient	0.5
LAI required for maximum canopy conductance	5
LAI at maximum canopy rainfall interception	5 – 7
Value of m when FR = 0	0
Maximum stand age used in age modifier	250
Maximum canopy conductance (gc, m/s)	0.008 – 0.12
The maximum height/base diameter ratio (m/cm)	0.6 – 0.8
Rainfall interception in a canopy with LAI for maximum interception (mm)	0.8 – 1.2
The minimum height/base diameter ratio (m/cm)	0.5
Fraction mean single-tree stem biomass lost per dead tree	0.2
Power of relative age in function for fAge	3.8 – 4.2
Foliage:stem partitioning ratios for stems with base diameter 2 cm	0.7 - 0.9
Foliage:stem partitioning ratios for stems with base diameter 20 cm	0.4 – 0.7
Minimum root biomass partitioning	0.2 – 0.4
Maximum root biomass partitioning	0.5 – 0.8
Minimum achievable pre-dawn leaf water potential (MPa)	-3 - -2
intercept of net v. solar radiation relationship (W/m2)	-90
slope of net v. solar radiation relationship	0.8
Relative age to give fAge = 0.5	0.5
The rate of root vertical growth per unit root mass (m/kg)	0.5 – 1
Specific leaf area at age 0 (m^2/kg)	5 - 6
Specific leaf area for mature leaves (m^2/kg)	5 - 6
Age at which litterfall rate has median value (d)	800 – 1200
Power in self-thinning law	1.5
Critical max temp, optimum and minimum temperatures for tree growth and physiological activity (deg C)	40, 20 & 0

Parameter description	**Estimated parameter value ranges**
Stand age (years) for SLA = (SLA0 + SLA1)/2	1.5 – 3
Max tree stem mass (kg) likely in mature stands of 1000 trees/ha	160 – 200
Assimilate use efficiency (Ratio NPP/GPP)	0.45 – 0.50

To create a new default parameter set, select either “Wood properties model” or “Stand growth model” and then click “Create a new parameter set”. Specify a new, unique name for the parameter set in the pop-up edit box (e.g. “radiata_default”). If an existing name is specified, the user will be prompted to replace the dataset by that name with the new parameter set (the original set will be deleted).

By toggling the radio-buttons, the parameter sets for the two model types (i.e. xylem model and the IGM) will display in the adjacent table. The parameter values can then be edited. To ensure values are saved, after editing a value, click on another cell, to move the cursor, to “cement” the altered value, and then click “Save changes”. To refresh, click again on the name of the parameter set in the list box. It is also possible to copy an existing parameter set: first select the parameter set in the list box, then click on “Copy a selected parameter set”. The user will be prompted for a name for the new, copied parameter set, before it is created and added to the list box. To delete a parameter set, select it from the list box and then click on “Delete selected”.



Pradiata_optest
Pradiata_optest_backup
Pradiata_optest_HighMFA

Figure A3.6: The main window for editing input data for the IGM and e-Cambium model, with the two parameters types and the “Create a new parameter set” (which creates a default parameter set) indicated.

Site information

The Site information is entered into the form headed by the “Site information” tab next to the “Modelling parameters” tab. Prior to entering site and regime information, a standard set of data needs to be known (Table 3)

Table A3.3: List of essential site and regime information required by the e-Cambium IGM, with an example

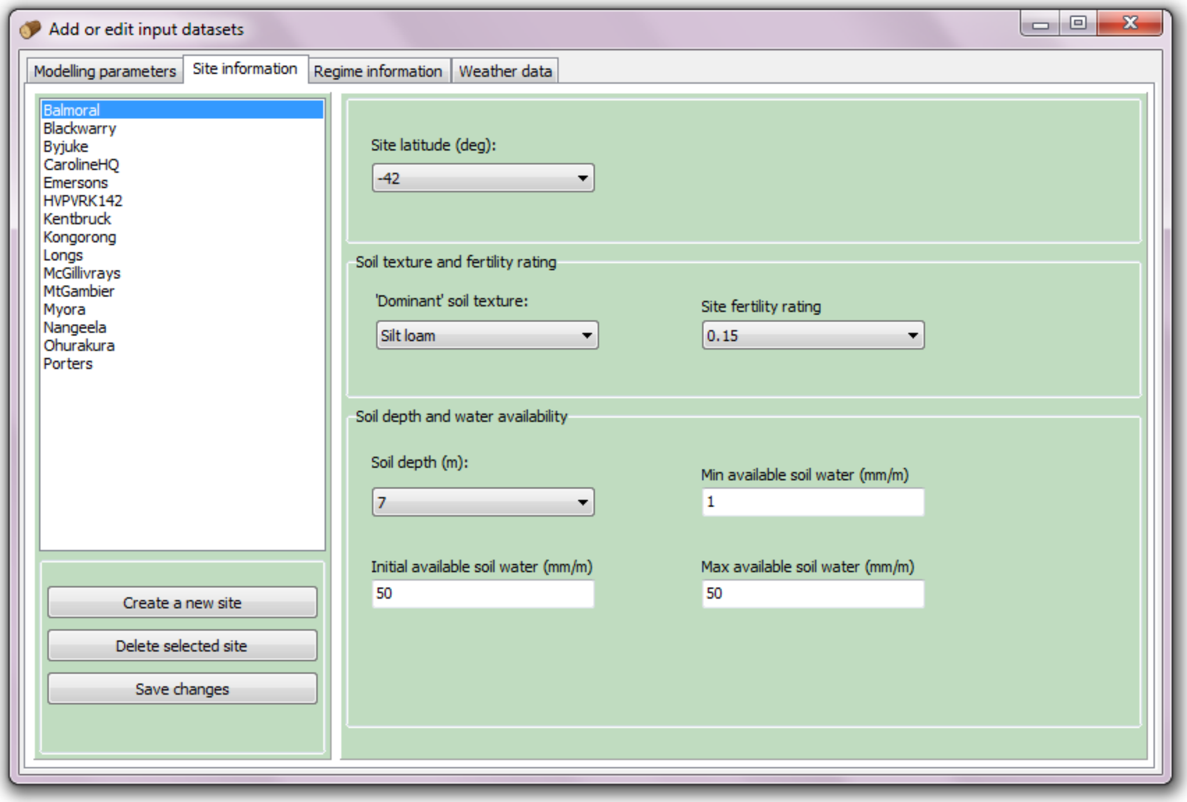
	Descriptor	Units	Example
Site Information	Name		Test_site
	Latitude	Degrees	37.28
	Longitude	Degrees	140.18
	Soil Texture		Sand
	Site Fertility rating		0.4
	Soil depth (m)	m	4
	Min available soil water	mm/m	10
	Initial Soil water	mm/m	200
	Max Available Soil water	mm/m	200
Regime Information	Planting date		1 July 1969
	Harvest date		23 September 2009
	Initial Stocking	SPH	1111
	Thinning date		1 July 1979
	residual stocking	SPH	550
	Fertiliser date		2 July 1969
	Fertility increase		0.15
	Pruning date		12 June 1973
	% crown removed		0.25

To create a new site, **first** fill in all the data fields on the form, and then click “Create a new site”. The IGM is based on the 3PG model and site descriptors are similar. Note that this information is intentionally simplistic, designed to make site characterisation as easy as possible. If desired, far more detailed site descriptions are possible using Cabala.

- Dominant soil texture
  - 11 soil types are given that provide a range of textural classes, ranging from soils with virutally no clay (sand) to soils that are predominantly clay.
- Site fertility rating
  - This is a 0-1 scale with 0 being completely infertile and 1 being highly fertile (forest sites with FR = 1 would be exceptionally rare). For good model performance at most forest sites, the normal range for FR should be between 0.1 and 0.6. Higher FR tends to lead to higher leaf area.
- Soil depth (m)
  - An estimate of soil depth is required to limit and control root exploration by the model.
- Minimum available soil water (mm/m)
  - This value provides a lower limit, beyond which any water in the soil is inaccessible to the plant.
- Initial available soil water (mm/m)
  - This is the starting value for the model and as such will be most important for initial growth response.
- Maximum available soil water (mm/m)

   - This is analogous to field capacity and will vary according to the soil type and physical and chemical properties.

Specify a new, unique name for the site in the edit box. Ensure all fields have numbers: a blank is not an acceptable character. Once the "Create a new site" button is clicked, the new site is automatically saved. The "Save changes" button is used when subsequently editing information on an existing site. The form will not allow a user to specify an initial water value below the minimum or above the maximum for the site.



Balmoral
Blackwarry
Byjuke
CarolineHQ
Emersons
HVPVRK142
Kentbruck
Kongorong
Longs
McGillivrays
MtGambier
Myora
Nangeela
Ohurakura
Porters

Site latitude (deg): -42

'Dominant' soil texture: Silt loam

Site fertility rating 0. 15

Soil depth (m): 7

Min available soil water (mm/m) 1

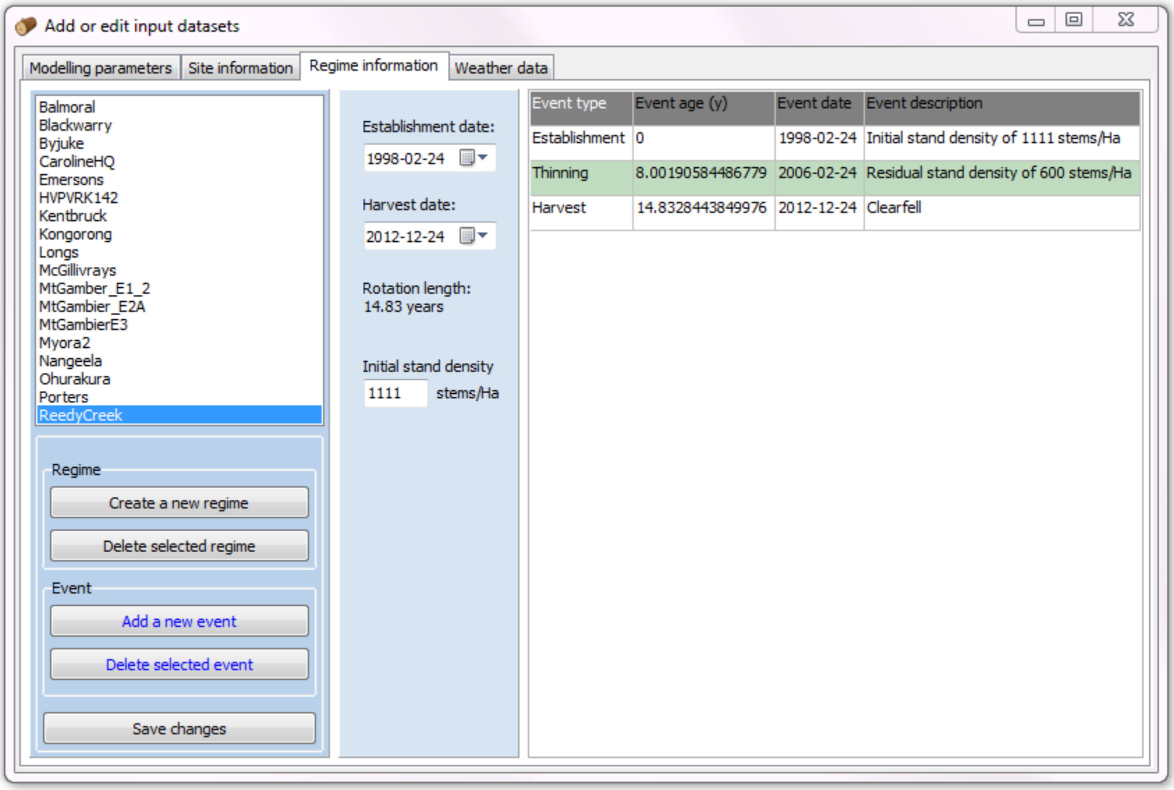
Initial available soil water (mm/m) 50

Max available soil water (mm/m) 50

Figure A3.7: The main window for editing site information for the IGM.

Regime information

To create a new regime, first select the plantation establishment and harvest dates (minimum 365 days difference between them), and the initial stand density, then click on "Create a new regime". Dates prior to 1900 are not permitted. Specify a new, unique name for the regime in the edit box. Only after a regime has been created, can new regime events be added.



Balmoral
Blackwarry
Byjuke
CarolineHQ
Emersons
HVPVRK142
Kentbruck
Kongorong
Longs
McGillivrays
MtGamber_E1_2
MtGambier_E2A
MtGambierE3
Myora2
Nangeela
Ohurakura
Porters
ReedyCreek

Establishment date: 1998-02-24

Harvest date: 2012-12-24

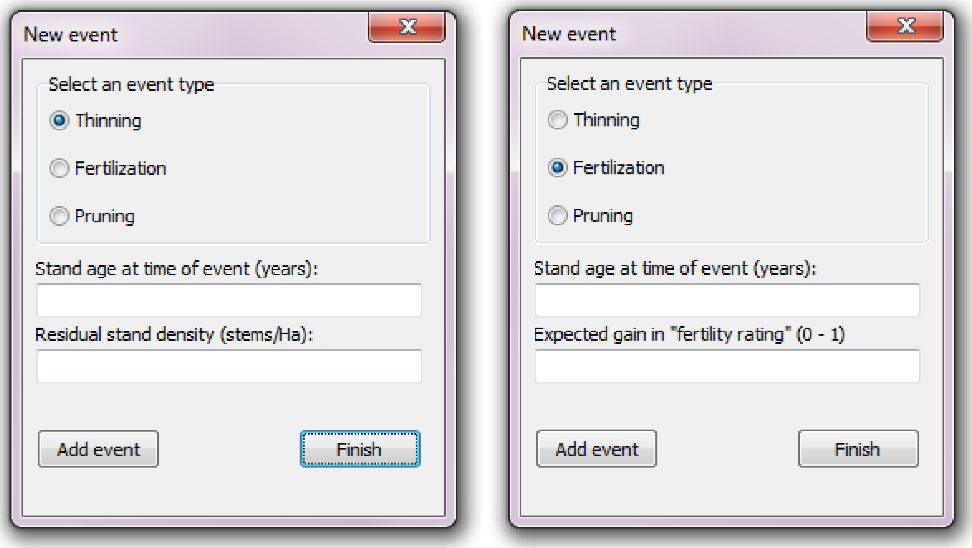
Rotation length: 14.83 years

Initial stand density 1111 stems/Ha

Event type	Event age (y)	Event date	Event description
Establishment	0	1998-02-24	Initial stand density of 1111 stems/Ha
Thinning	8.00190584486779	2006-02-24	Residual stand density of 600 stems/Ha
Harvest	14.8328443849976	2012-12-24	Clearfell

Figure A3.8: The main window for editing regime information for the IGM. Planting and harvesting events are shown in white; other events are indicated in colour.

To add a new event, select a regime in the list box, then click on “Add a new event”. An event dialog box will become visible (see below). At present, only thinning, fertilisation and pruning events are available to model. Specify the age of the event (in years) and the “event value”. In the case of a thinning, this would be the residual stand density (stems/Ha). For thinning, specify an estimated “effect on fertility rating”. This refers to the expected gain that is anticipated in the site fertility rating as a relative value from 0 – 1. E.g., fertilization might lead to a 0.1 gain on an existing FR of 0.4 leading to a new FR of 0.5. For pruning, specify a pruning intensity (from 0 – 1, where 0 is no pruning and 1 would remove the whole crown). Then click “Add event”. Clicking “Finish” will close the window. Finally click on the “Save changes” button (on the above window) to save the event in the selected regime.


New event

Select an event type

● Thinning

○ Fertilization

○ Pruning

Stand age at time of event (years):

Residual stand density (stems/Ha):

New event

Select an event type

○ Thinning

● Fertilization

○ Pruning

Stand age at time of event (years):

Expected gain in "fertility rating" (0 - 1)

Figure A3.9: The regime event window, showing selections of "thinning" or "fertilization".

If the user specifies one thinning with a residual SPH higher than a prior thinning, the event will still be added, but will be ignored in the model. Similarly, if cumulative fertility gains add up to greater than 1, or pruning events to a "negative" crown size, the events will be permitted, but will be ignored by the model. If the user attempts to change the establishment of harvesting dates to prior or following an event, the change will not be allowed. The particular event must first be deleted.

Weather data

Presently, only SILO data in standard text format can be imported by clicking on the "Import new SILO data" button. A sample header of this data file is shown below. If the data is not in this format, the import will not be successful.

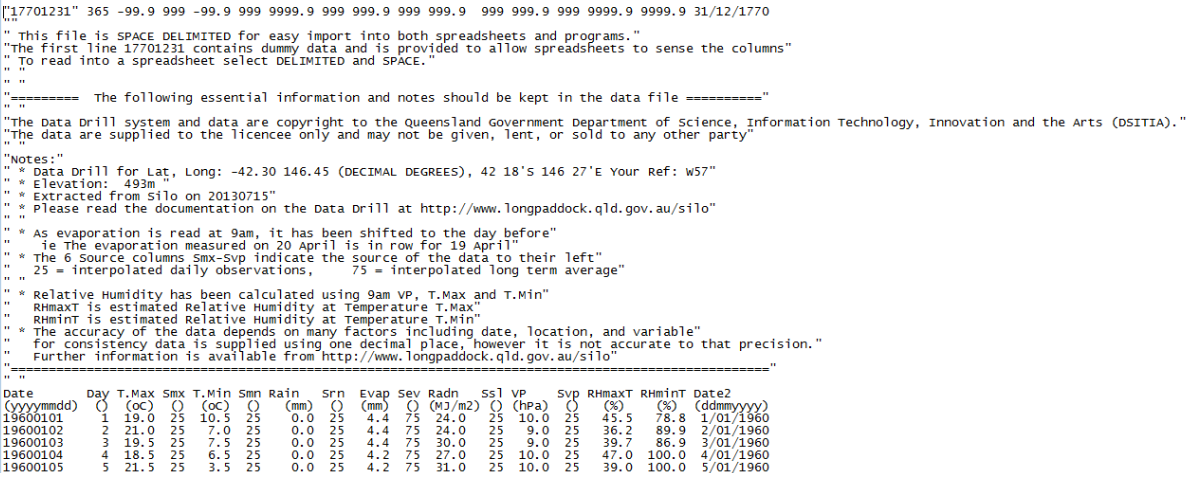

```
"17701231" 365 -99.9 999 -99.9 999 9999.9 999 999.9 999 999.9  999 999.9 999 9999.9 9999.9 31/12/1770
""
" This file is SPACE DELIMITED for easy import into both spreadsheets and programs."
"The first line 17701231 contains dummy data and is provided to allow spreadsheets to sense the columns"
" To read into a spreadsheet select DELIMITED and SPACE."
" "
" "
"=========  The following essential information and notes should be kept in the data file =========="
" "
"The Data Drill system and data are copyright to the Queensland Government Department of Science, Information Technology, Innovation and the Arts (DSITIA)."
"The data are supplied to the licencee only and may not be given, lent, or sold to any other party"
" "
"Notes:"
" * Data Drill for Lat, Long: -42.30 146.45 (DECIMAL DEGREES), 42 18'S 146 27'E Your Ref: W57"
" * Elevation:  493m "
" * Extracted from Silo on 20130715"
" * Please read the documentation on the Data Drill at http://www.longpaddock.qld.gov.au/silo"
" "
" * As evaporation is read at 9am, it has been shifted to the day before"
"    ie The evaporation measured on 20 April is in row for 19 April"
" * The 6 Source columns Smx-Svp indicate the source of the data to their left"
"   25 = interpolated daily observations,     75 = interpolated long term average"
" "
" * Relative Humidity has been calculated using 9am VP, T.Max and T.Min"
"   RHmaxT is estimated Relative Humidity at Temperature T.Max"
"   RHminT is estimated Relative Humidity at Temperature T.Min"
" * The accuracy of the data depends on many factors including date, location, and variable"
"   for consistency data is supplied using one decimal place, however it is not accurate to that precision."
"   Further information is available from http://www.longpaddock.qld.gov.au/silo"
"=============================================================================================="
" "
Date       Day T.Max Smx T.Min Smn Rain   Srn  Evap Sev Radn   Ssl VP    Svp RHmaxT RHminT Date2
(yyyymmdd)  ()  (oC)  ()  (oC)  ()   (mm)  ()  (mm)  ()  (MJ/m2) () (hPa)  ()   (%)    (%)  (ddmmyyyy)
19600101    1  19.0  25  10.5  25    0.0  25   4.4  75   24.0   25  10.0  25   45.5   78.8  1/01/1960
19600102    2  21.0  25   7.0  25    0.0  25   4.4  75   24.0   25   9.0  25   36.2   89.9  2/01/1960
19600103    3  19.5  25   7.5  25    0.0  25   4.4  75   30.0   25   9.0  25   39.7   86.9  3/01/1960
19600104    4  18.5  25   6.5  25    0.0  25   4.2  75   27.0   25  10.0  25   47.0  100.0  4/01/1960
19600105    5  21.5  25   3.5  25    0.0  25   4.2  75   31.0   25  10.0  25   39.0  100.0  5/01/1960
```

Figure A3.10: Example of the header of standard SILO output required for successful e-Cambium data import.

Upon clicking on "Import new SILO data", a standard Windows "Open" dialog will become visible. Specify the *.txt file, and click "Open". A second window will request a name for the dataset. Type a meaningful name for the weather dataset and click OK. A box showing import progress will display. Once the import has started, it cannot be stopped, and for large SILO datasets this import may take several minutes.

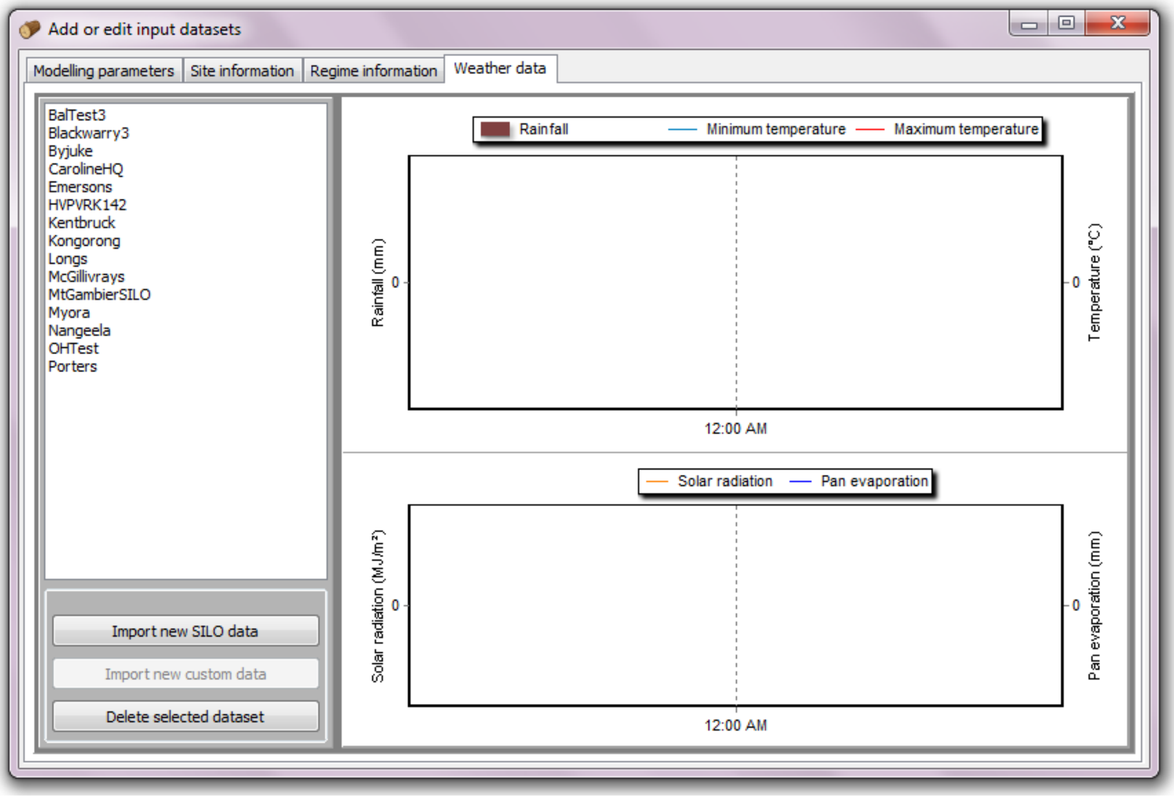


Figure A3.11: The main window for importing and viewing weather data for the IGM.

If the import is successful, the new weather dataset name will be added to the list box. By clicking on the name of the dataset of interest, daily minimum and maximum temperature, rainfall, solar radiation and pan evaporation data will be displayed in the adjacent graphs, for checking (see below). To zoom in on data, click with the left mouse button and drag down-and-to-the-right.

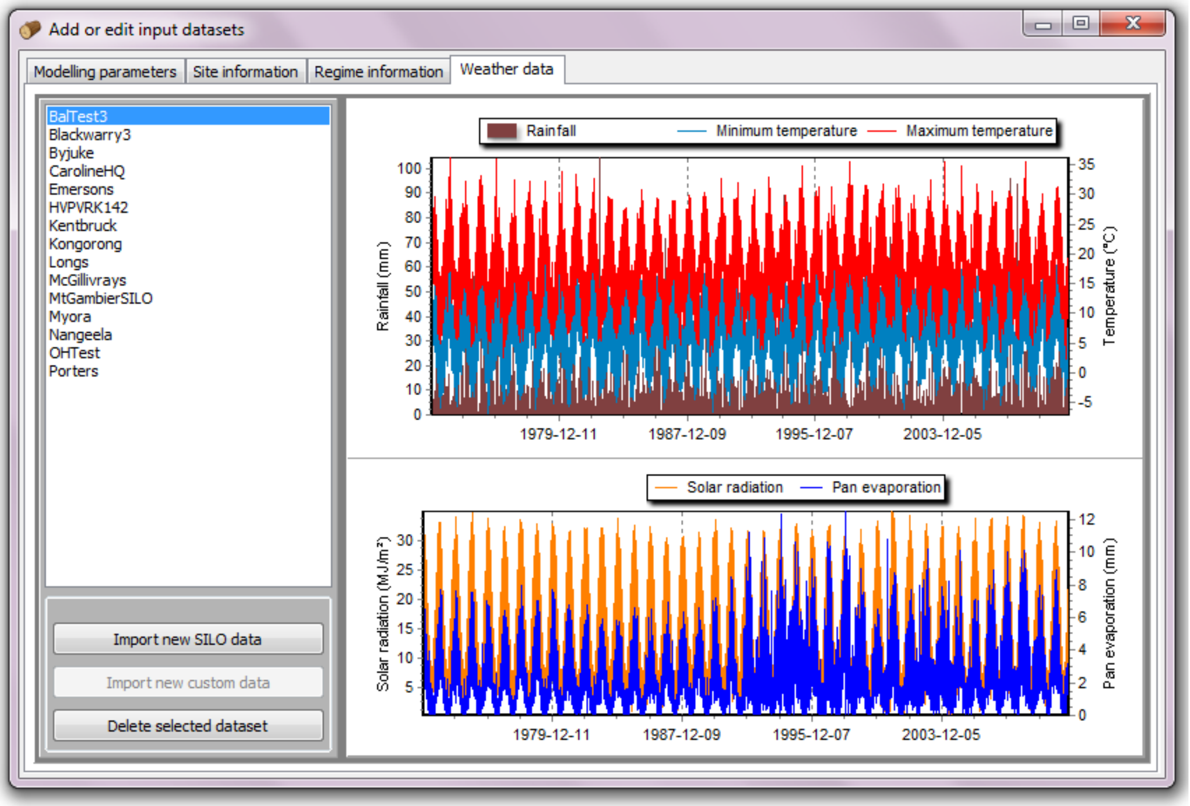
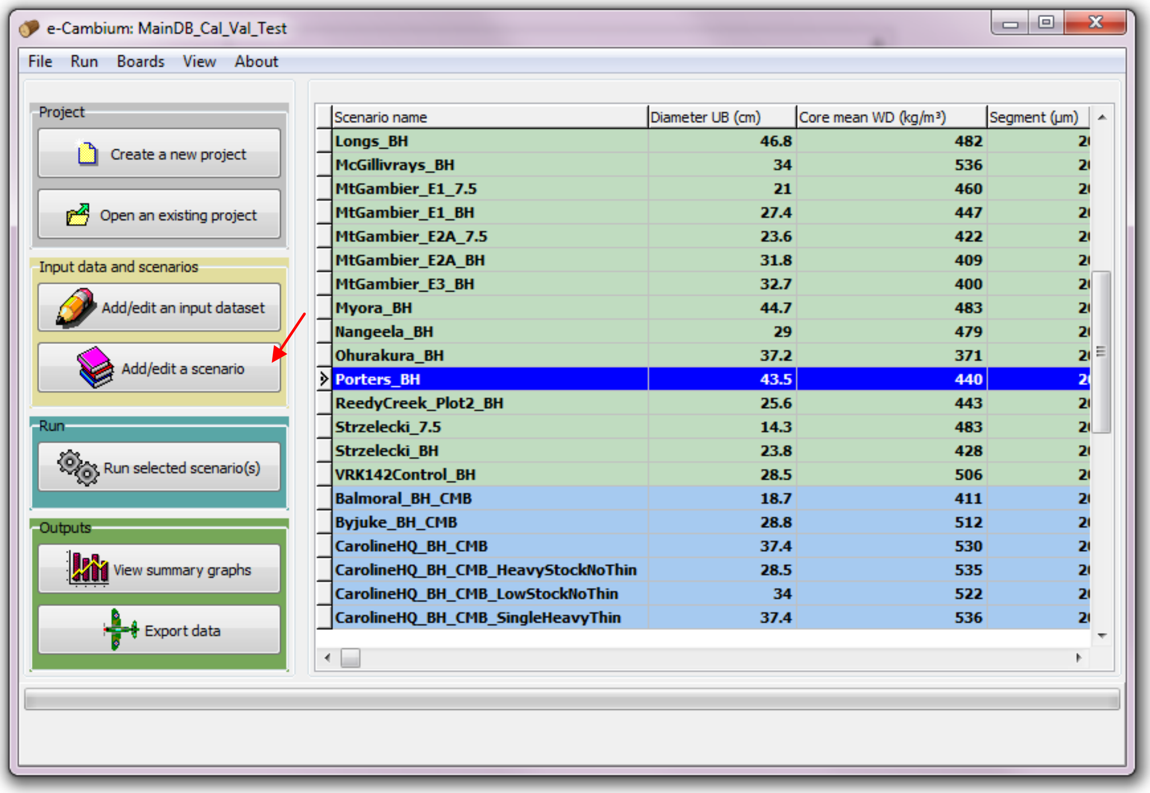


Figure A3.12 The main window for importing and viewing weather data for the IGM with imported data for the selected dataset shown.

This completes the sequence for generating the components required to build a scenario to run. Close the open panel by clicking in the top right hand corner to return to the main user interface. Created sites, scenarios, weather datasets and parameters will now be available to add to a new scenario..

To create or edit a scenario

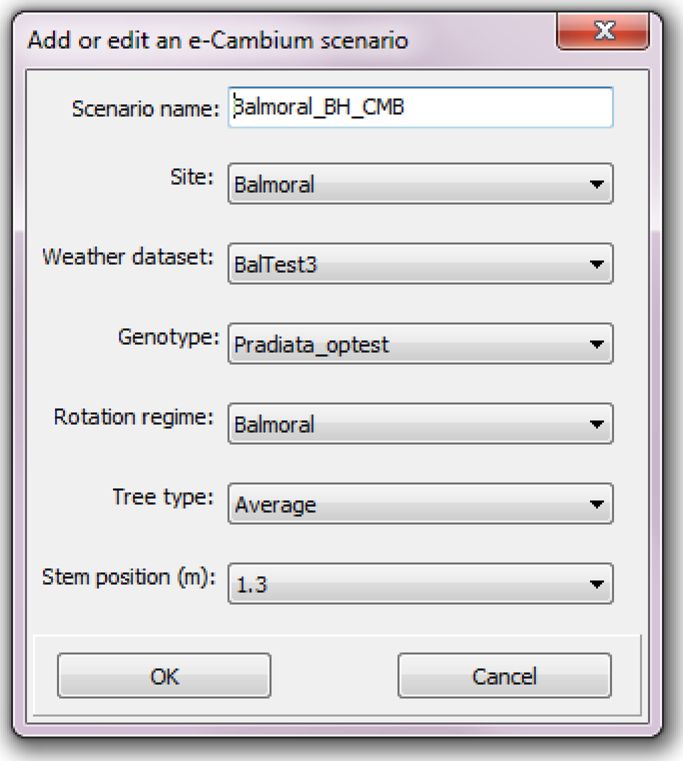
Once at least one dataset has been created for each of the four data categories, or if the user has access to at least one completed CaBala run (on a daily step) and an e-Cambium parameter set exists, it is possible to create a scenario. A scenario is just a particular combination of the four data categories. Building a new scenario can be done by clicking on "Add/edit a scenario".



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
Longs_BH	46.8	482	2
McGillivrays_BH	34	536	2
MtGambier_E1_7.5	21	460	2
MtGambier_E1_BH	27.4	447	2
MtGambier_E2A_7.5	23.6	422	2
MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

Figure A3.13: The e-Cambium GUI with the "Add/edit a scenario" button indicated

If a scenario is selected on the adjacent grid listing scenarios, the appropriate edit dialog will automatically display with values already updated on the drop-down lists. However, if no scenario is selected from the list in the adjecent grid, a dialog will become visible allowing the user to specify the type of scenario to add. **To deselect any scenario/s already selected, simply click somewhere on the main e-Cambium window** (aside from the table of scenarios). If the user selects "Create a new e-Cambium scenario", then the following dialog will appear:



Scenario name: Balmoral_BH_CMB

Site: Balmoral

Weather dataset: BalTest3

Genotype: Pradiata_optest

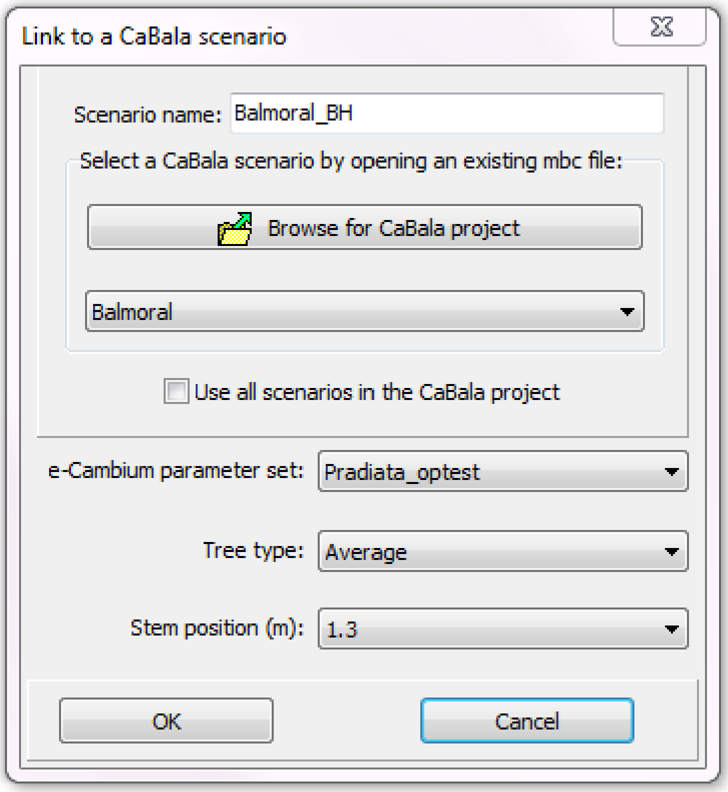
Rotation regime: Balmoral

Tree type: Average

Stem position (m): 1.3

Figure A3.14: The e-Cambium scenario building dialog for scenarios using the IGM. In this example, all input datasets have already been specified, as well as a name for the scenario

First the user must specify a new name for the scenario. Provided some data exists for all categories each drop-down menu will be populated with the available datasets. A value must be selected for each one. Finally, if a selection has been made for all data input categories, click on "OK". If the scenario is successfully created it will be added to the list in the grid on the main form. If the name is the same as an existing scenario, or an existing scenario has been altered, the user will be warned that all simulated data will be lost by clicking on "OK". If, after selecting "Add/edit a scenario" the user selects to "Link to an existing CaBala scenario", the following dialog displays:



Scenario name: Balmoral_BH

Select a CaBala scenario by opening an existing mbc file:

Balmoral

☐ Use all scenarios in the CaBala project

e-Cambium parameter set: Pradiata_optest

Tree type: Average

Stem position (m): 1.3

Figure A3.15: The e-Cambium scenario building dialog for scenarios using Cabala inputs.

An existing CaBala project is selected by clicking on "Browse for CaBala project" and selecting the desired *.mbc file. Most Cabala files should be able to be used (there may be problems with very old files). Thereafter, it is possible to link to all scenarios in the selected CaBala project by clicking on "Use all scenarios in the Cabala project". In that case, no name is required for the e-Cambium scenario that will link to the CaBala scenario, and e-Cambium will automatically generate a set of scenario names based on the scenario names in the parent Cabala data file. It is also necessary to specify what e-Cambium parameter set to use and at what stem position to model.

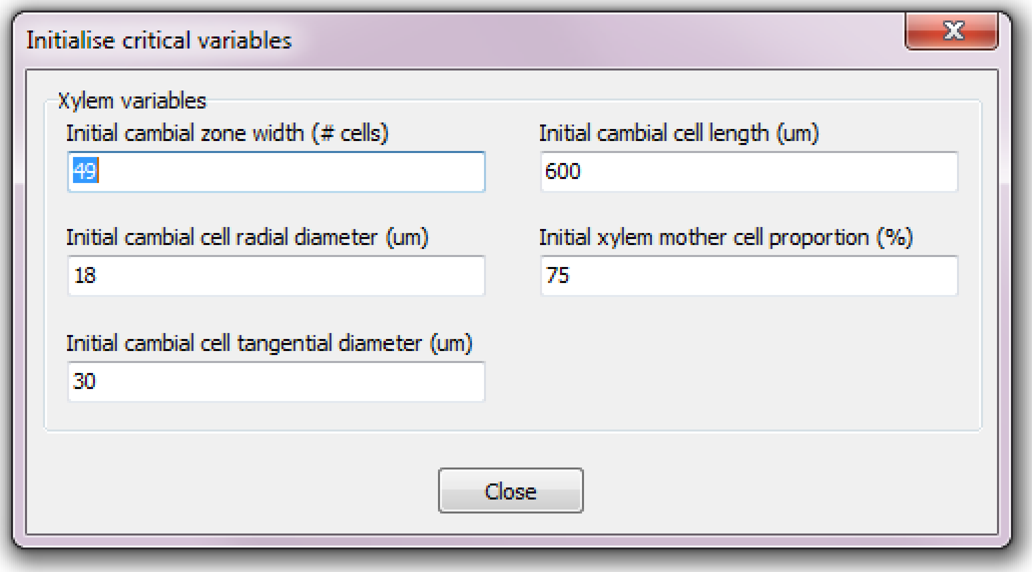
If linking to only one CaBala scenario is desired, select the scenario from the drop-down list which will propulate if a CaBala project has been successfully opened. In this case, it is necessary to specify a name for the scenario. Once this is done, click on "OK". If the name already exists, the user will be prompted to check if the existing scenario should be replaced. Otherwise, the new scenario will be created and will be listed on the scenarios grid on the main form. In both scenario types, the only tree-type option that currently exists is for an average tree. Future model versions are anticipated to make it possible to modify input data to provide estimates of wood properties that could be expected from suppressed or dominant trees.

Running the model

Before running the model, the values of a set of initial values can be specified by clicking on the main menu bar: Run|Initialise model run. Variables entered will be saved and stored for any future model runs. Other options that can or should be specified prior to running the model are:

- The segment width: the width of sequential "chunks" of wood within which averages of properties like wood density are averaged. Click on Run|Set segment length, and update the drop-down list in the window that becomes visible.

- The daily write option: Should data from each day of the model run be written to disk or only the segment averaged (see above) data? All daily data takes much longer to write, but includes a number of growth and physiological variables that are otherwise not stored when the run completes (see section on growth and physiological data below). Click on Run|Write daily data to disk.
- Whether or not the cell plate position should be randomised. This adds a certain stochasticity to the runs and is useful if multiple runs from the same scenario are intended to be used to calculate an average. Click on Run|Cell plate position randomised.



Xylem variables

Initial cambial zone width (# cells): 49

Initial cambial cell length (um): 600

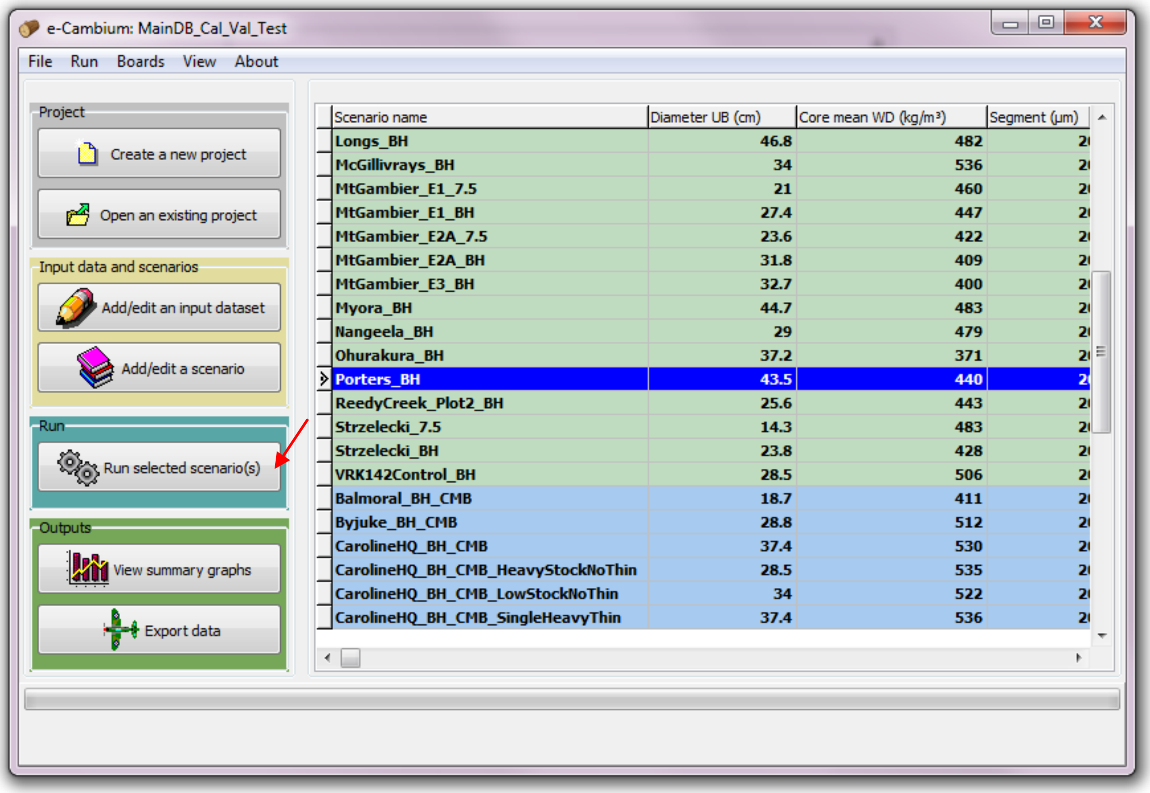
Initial cambial cell radial diameter (um): 18

Initial xylem mother cell proportion (%): 75

Initial cambial cell tangential diameter (um): 30

Figure A3.16: Xylem model variables initialisation window

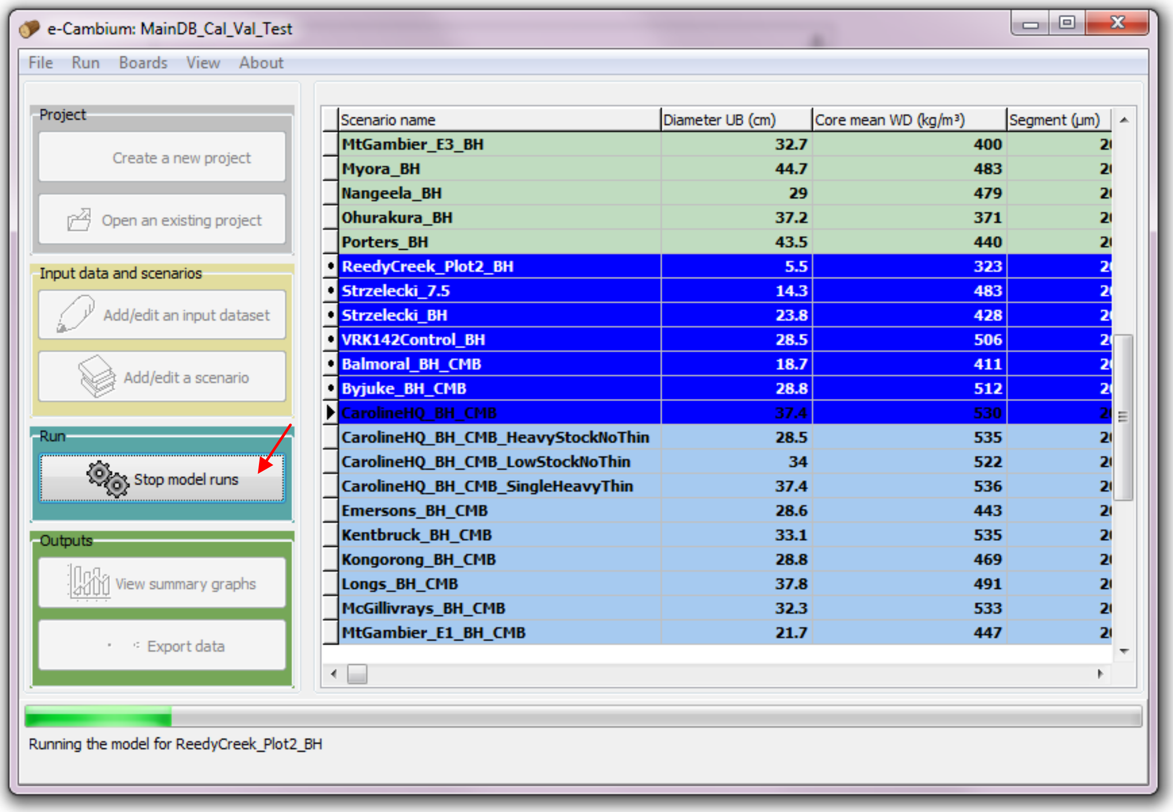
If at least one scenario exists, it is possible to run the model. This is achieved by selecting one or more scenarios using the left mouse button in conjunction with the “CTRL” key, or using “SHIFT” and the up/down arrows on the keyboard. A selected scenario is indicated by the row being highlighted in blue, and with an open arrow head (the last of the selection) or a round dot (all other selections). Note: A solid arrow head indicates only cursor position, and not that a selection has been made for a model run.



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
Longs_BH	46.8	482	2
McGillivrays_BH	34	536	2
MtGambier_E1_7.5	21	460	2
MtGambier_E1_BH	27.4	447	2
MtGambier_E2A_7.5	23.6	422	2
MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

Figure A3.17: Click on "Run selected scenarios" to initiate one or a set of model runs.

Once at least one scenario is selected, click on "Run selected scenarios". A progress bar will activate showing progress for each successive scenario run. In each case, information will display about progress (whether the software is reading data, running the model or writing data to disk). At the end of each run, the software writes outputs to the project file for later retrieval. A limited number of warnings or errors are also reported: these can be seen by selecting View|View warnings. During the run process, buttons and functionality are disabled. It is possible, however, to stop a run by clicking on "Stop model runs". <u>This is only available while the model is running, not while data is being written to the data file.</u>



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	5.5	323	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2
Emersons_BH_CMB	28.6	443	2
Kentbruck_BH_CMB	33.1	535	2
Kongorong_BH_CMB	28.8	469	2
Longs_BH_CMB	37.8	491	2
McGillivrays_BH_CMB	32.3	533	2
MtGambier_E1_BH_CMB	21.7	447	2

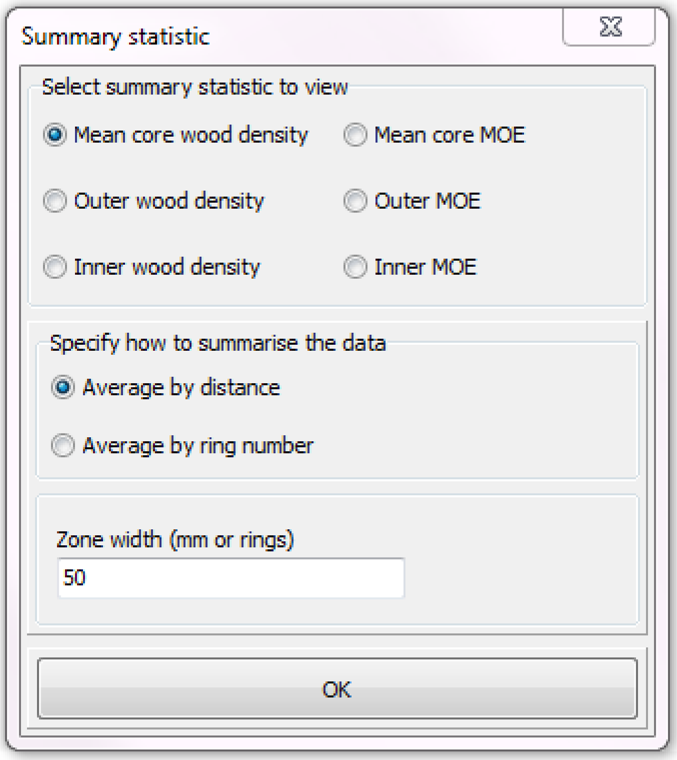
Running the model for ReedyCreek_Plot2_BH

Figure A3.18: Click on "Stop model runs" will exit the current loop.

Viewing summary graphs and data

Changing the summary information in the main table

It is possible to view an average wood density or modulus of elasticity (MOE) estimate in the main table, if runs have been completed. This metric can be summarised for the whole "core" (in keeping with the concept of simulating what SilviScan measures), or for the inner or outer portions of the core, by ring number or distance (in mm). To change the display, click on the main menu bar: View|Change display statistics. A window will show in which the user can specify the data summary. If a greater width in mm or rings is specified than the size of the hypothetical core, then the whole core average is effectively calculated.



Summary statistic

Select summary statistic to view

● Mean core wood density ○ Mean core MOE

○ Outer wood density ○ Outer MOE

○ Inner wood density ○ Inner MOE

Specify how to summarise the data

● Average by distance

○ Average by ring number

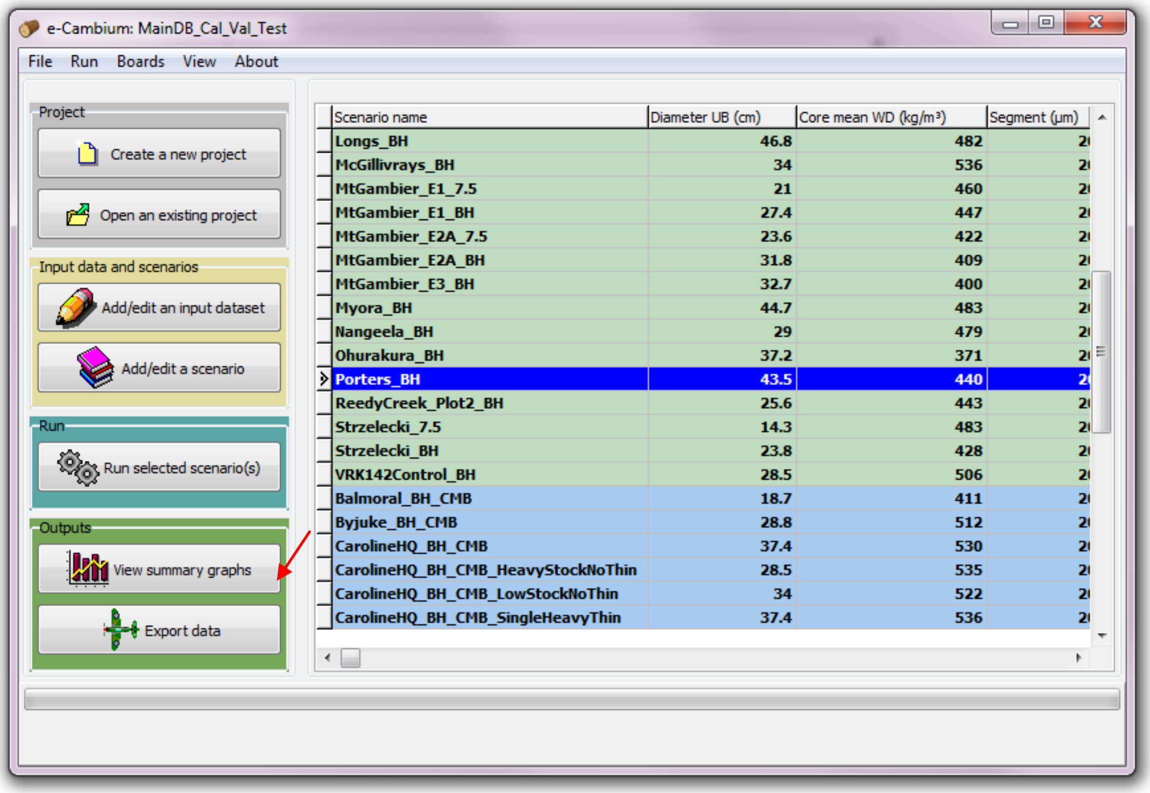
Zone width (mm or rings)

50

Figure A3.19: Window to change summary statistics shown in main table

Graphics

To view summary graphics of model predictions (assuming at least one run has been completed), first select a completed scenario (one at a time) by double-clicking or by clicking on “View summary graphs”.



Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
Longs_BH	46.8	482	2
McGillivrays_BH	34	536	2
MtGambier_E1_7.5	21	460	2
MtGambier_E1_BH	27.4	447	2
MtGambier_E2A_7.5	23.6	422	2
MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

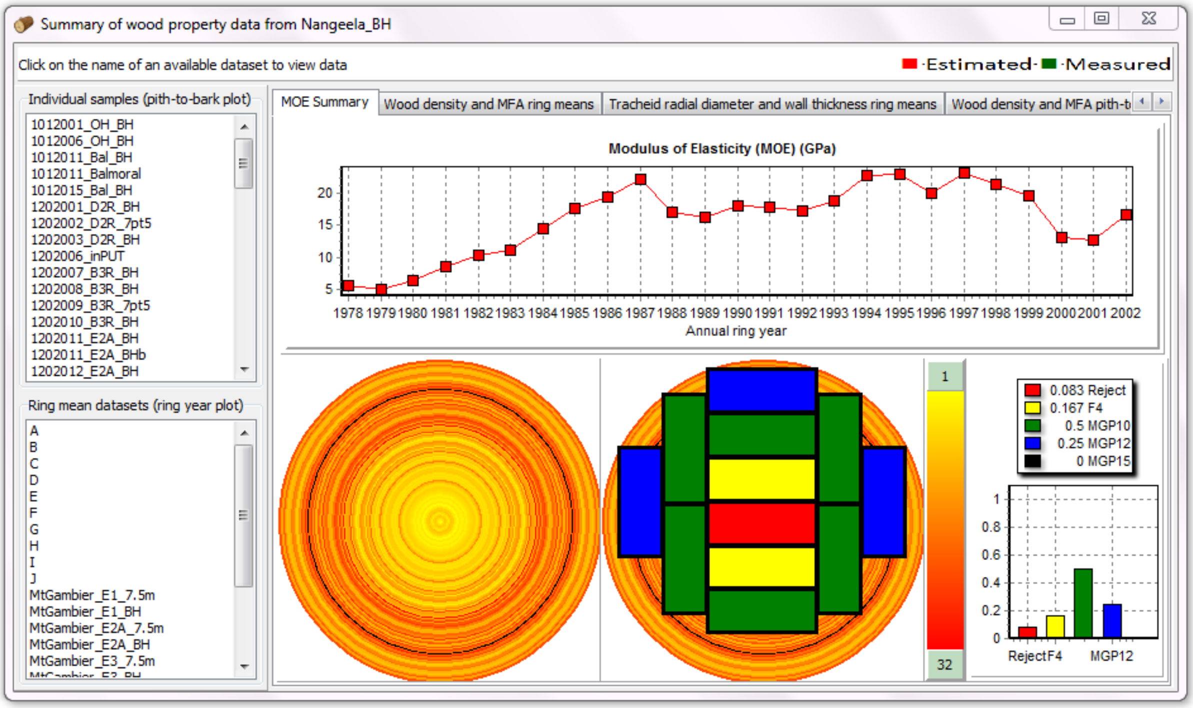
Figure A3.20: View graphical outputs from the selected scenario.

A dialog will become visible and the user can specify whether to view

- Wood properties data, or
- Daily growth and developmental data.

Viewing wood property summaries

By selecting the first option, the window shown below will display. By selecting the appropriate tab, the user can choose to view summaries of MOE, wood density, microfibril angle (MFA), tracheid radial diameter or tracheid wall thickness predictions, summaried by ring, or on a distance-from-pith basis.



Summary of wood property data from Nangeela_BH

Click on the name of an available dataset to view data

Figure A3.21: Graphical output of predicted ring average MOE and hypothetical potential board quality

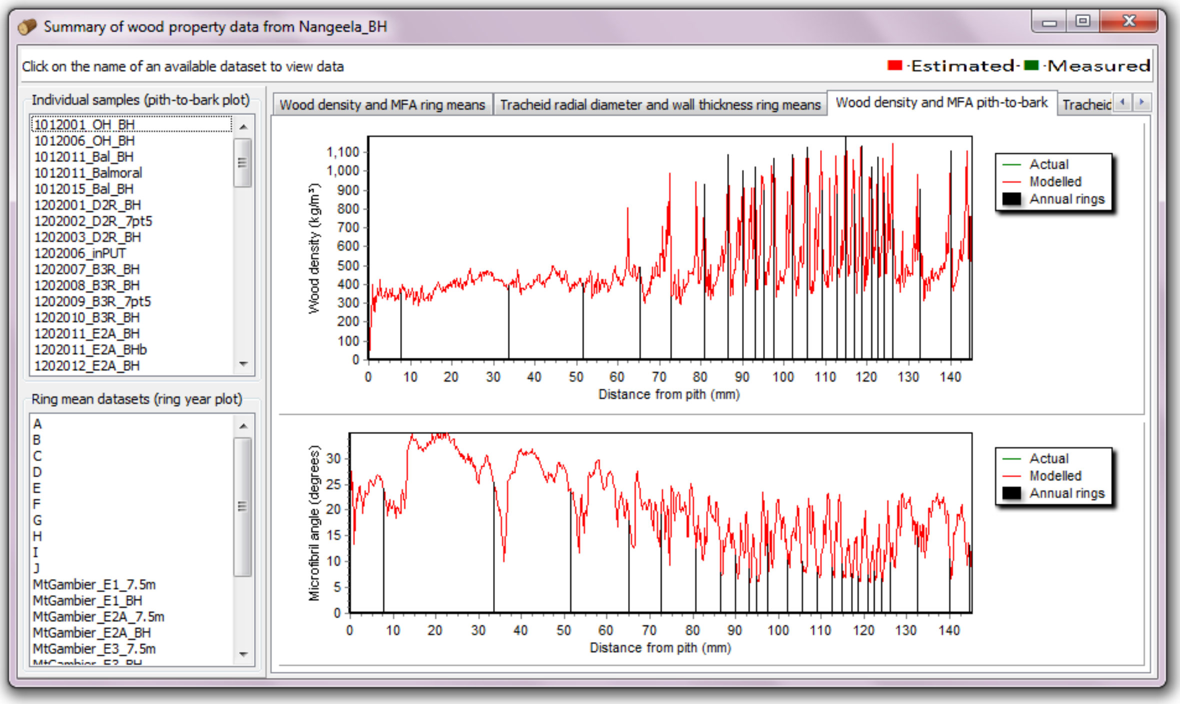


Figure A3.22: Graphical output of predicted pith-to-bark variation in wood density and microfibril angle.

The software also shows a simplified representation of expected board grade outputs (based solely on predicted MOE and not accounting for non-modelled defects such as knots, in effect reflecting a predicted clear wood board out-turn). Thresholds that determine these board grades can be set under the “Boards” menu. If measured wood property data (e.g.actual SilviScan measurements) have been uploaded (these data can be uploaded separately; See section below: Importing data), it is possible to view it in the same window, by clicking on the datasets listed in the boxes on the left of the window. In the upper box, datasets from systems like SilviScan, with the x-axis as distance from pith (mm) are shown. These are shown on the graphics in the last two tabs. In the lower box, datasets which are average wood properties for rings with known years are shown. These are shown in the first three tabs.

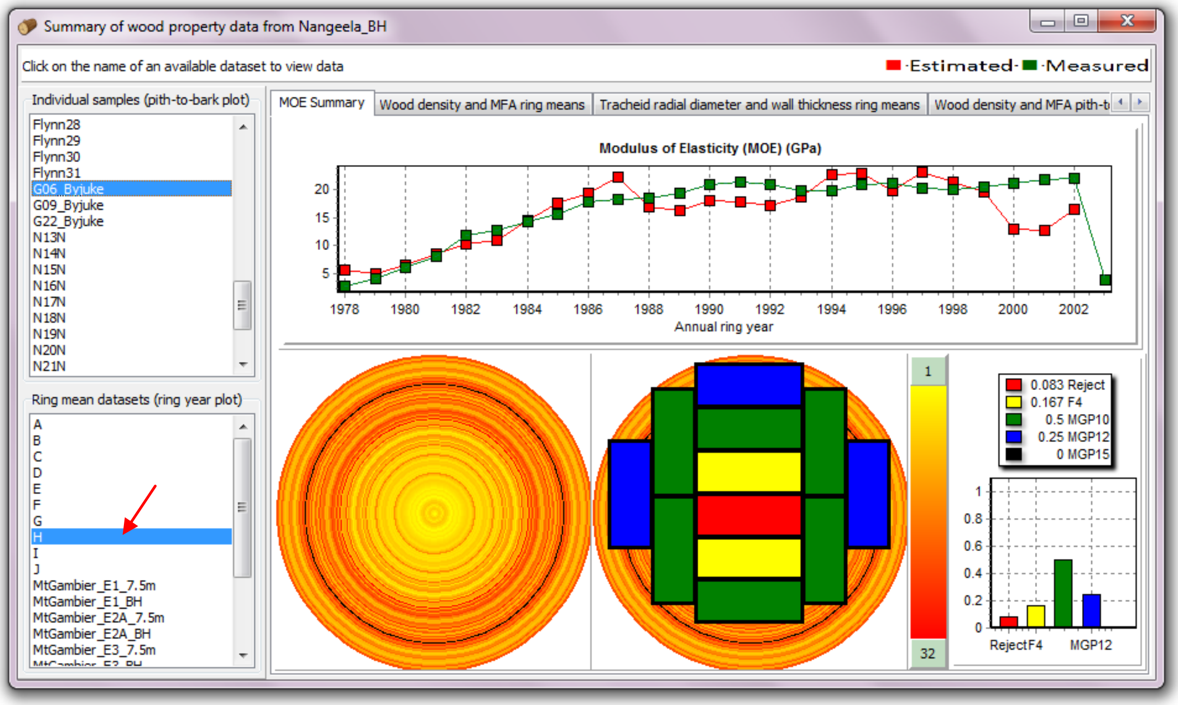
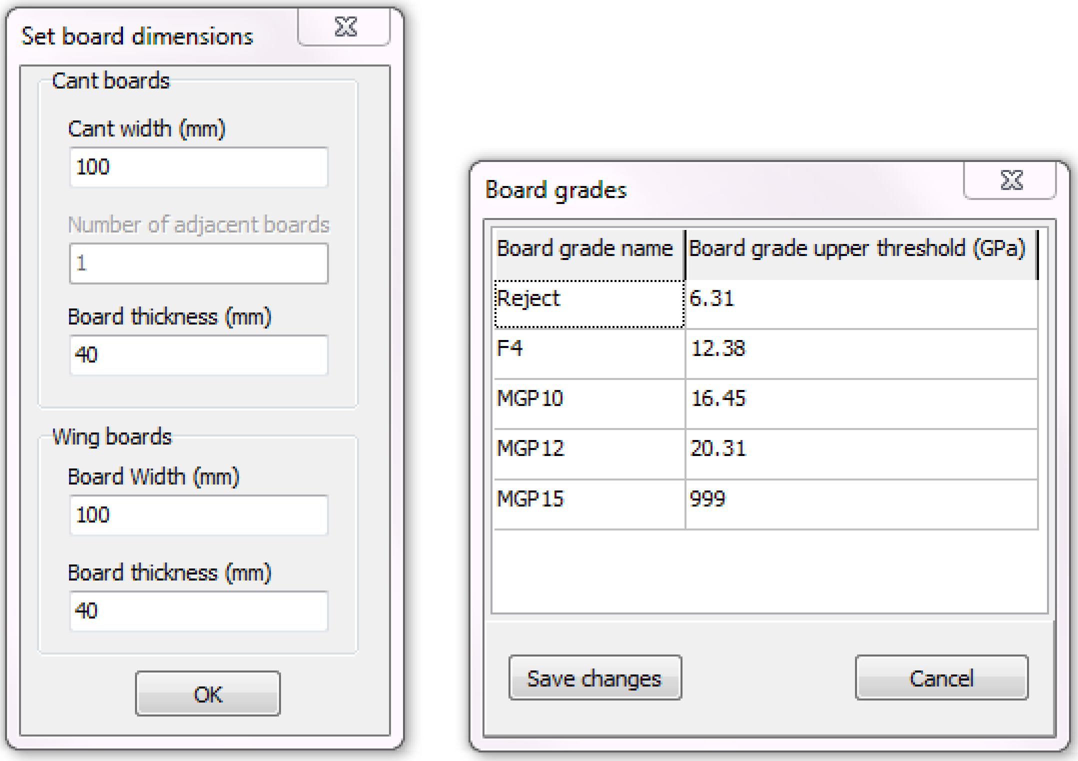


Figure A3.23: By clicking on available datasets in the left-most list boxes, it is possible to compare measured with predicted data. The two list boxes plot data on distance-based or ring averaged graphs respectively.

Changing the board visualisation

The dimensions of hypothetical boards can be adjusted by clicking on the main menu bar: Boards|Set board dimensions. The window shown below will display. Users can select the dimensions of boards cut from a cant or wing boards. It is also possible to specify the MOE thresholds used to define the putative MGP grades of the hypothetical boards, by clicking on the menu bar: Boards|Set board grade thresholds. The default values are based on an completed FWPA study in the Green Triangle region where SS data from 6 trees across 10 sites were related to the boards produced in a sawing study. Further information can be found in various FWPA reports. The window shown below will appear. The upper threshold (in GPa) must be specified for each of 5 specified MGP classes.



Set board dimensions

Cant boards

Cant width (mm): 100

Number of adjacent boards: 1

Board thickness (mm): 40

Wing boards

Board Width (mm): 100

Board thickness (mm): 40

Board grades

Board grade name	Board grade upper threshold (GPa)
Reject	6.31
F4	12.38
MGP10	16.45
MGP12	20.31
MGP15	999

Figure A3.24: Hypothetical board dimensions can be set, as well as the upper MOE thresholds assumed for different MGP grades.

Daily outputs

If daily output data was written during the run (see section: Running the model), indicated in the scenarios table by emboldened text, selecting to view “Growth and developmental data” will display the window shown below. The user can select from a range of tabs to view different data types. If measured growth data has been imported into the data file, these datasets will be shown in the list box to the left. Clicking on a dataset will plot the data on the stem diameter and tree height graphs. By pressing the delete key, the highlighted measured dataset can be deleted.

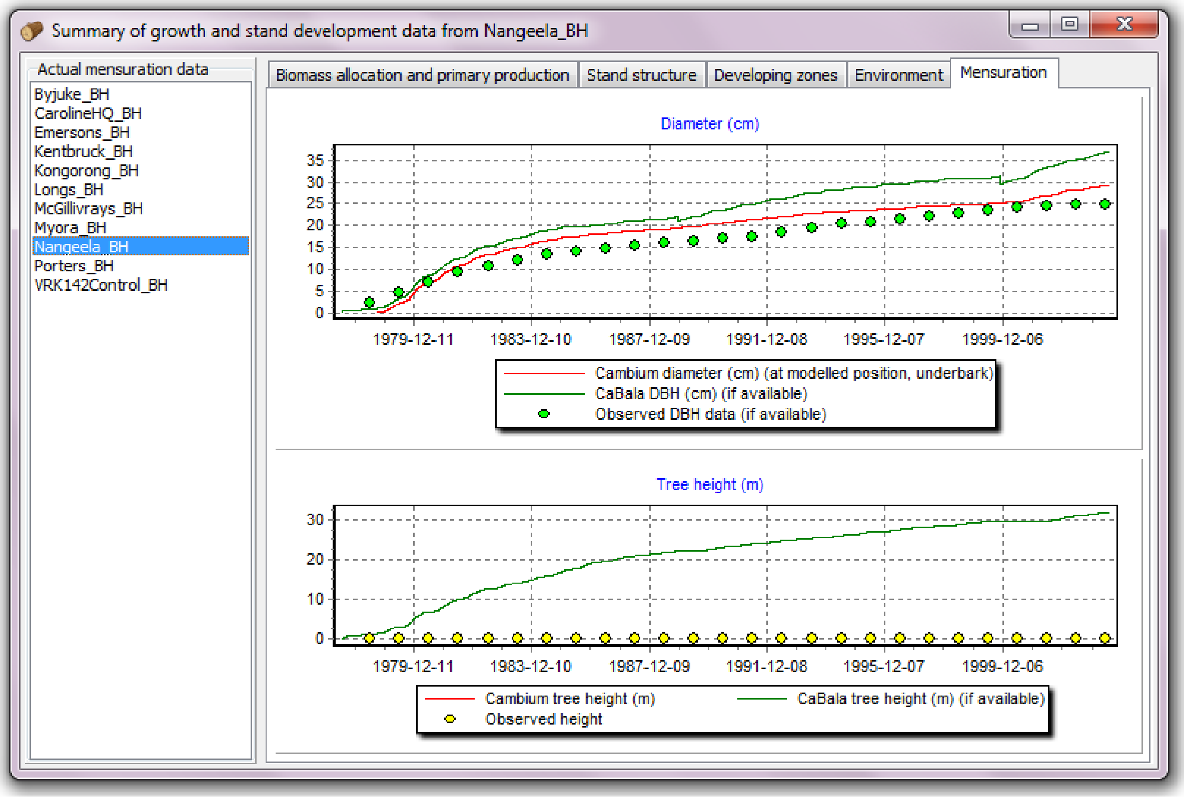


Figure A3.25: Daily outputs of simulated stem diameter (Cabala overbark DBH prediction and e-Cambium prediction of underbark diameter at 1.3 m), tree height from Cabala as well as measured underbark diameter from ring positions.

Importing data

Uploading data from external files

It is possible to import data into the e-Cambium data file from external comma-delimited (*.csv) files. This is found by clicking on the menu bar: File|Import data from external files. Data of four different types can be imported:

(1) Weather data, in a format other than the standard SILO format, with columns for:
    a. Date
    b. Total daily rainfall (mm)
    c. Minimum and maximum daily temperature (°C)
    d. Minimum and maximum daily relative humidity (%)
    e. Daily total solar radiation (MJ m^{-2}) and
    f. Pan evaporation (mm).

(2) Silviscan (or similar) wood property data with measurements on a distance (mm) basis with columns for:
    a. Distance from pith (mm)
    b. Wood density (kg m^{-3})
    c. Tracheid radial and tangential diameter (µm)
    d. Tracheid wall thickness (µm)
    e. MFA (degrees)
    f. MOE (GPa)
    g. Cell density (cells mm^{-2})

(3) Silviscan (or similar) wood property data where data is summarised by ring year with columns for
    a. Ring year (an integer value for year e.g. 1993)
    b. Mean wood density (kg m^{-3})
    c. Mean tracheid radial and tangential diameter (µm)
    d. Mean tracheid wall thickness (µm)
    e. Mean MFA (degrees)
    f. Mean MOE (GPa)
    g. And columns specifying standard devriation for the ring for all of the wood properties
(4) Stand growth data with columns for:
    a. Stem diameter (cm)
    b. Tree height (m)
    c. Crown length (m)
    d. Stem volume (m^3)

All data types require that a name for the dataset either be read from the input file, or specified as a constant value. Upon select an input comma-delimited file, columns in the file will be numbered. If some columns of the input file do not have text in the top line, no numbers will be allocated to those columns. It is still possible to complete an upload, but it may be more time-consuming to match columns to fields.

It is then possible to link each column in the target data table with the appropriate column in the input data file. If no column exists in the external file for a particular column in the data file, it is necessary to specify a constant value which will be substituted. Once all fields have been linked, or a constant value specified for fields which have no analogous field in the input data file, click on “Import”. For large files this may take several minutes. A progress bar will display. The process cannot be stopped without completely shutting down the program.

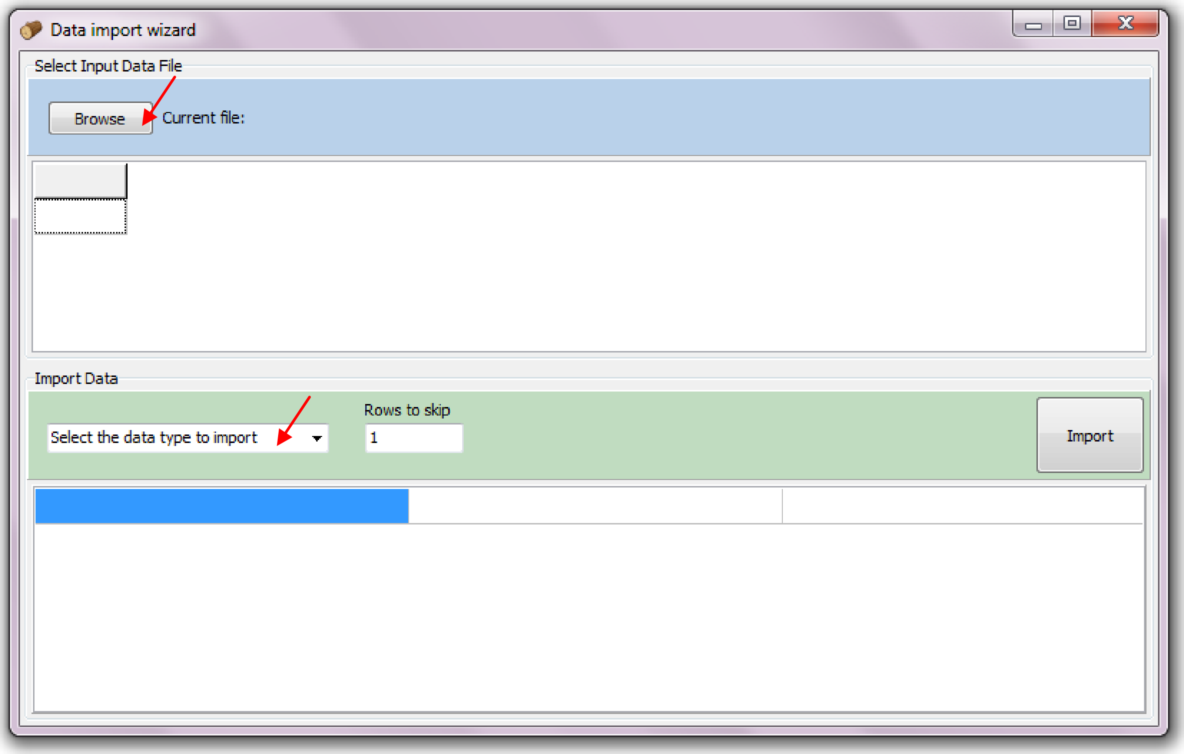
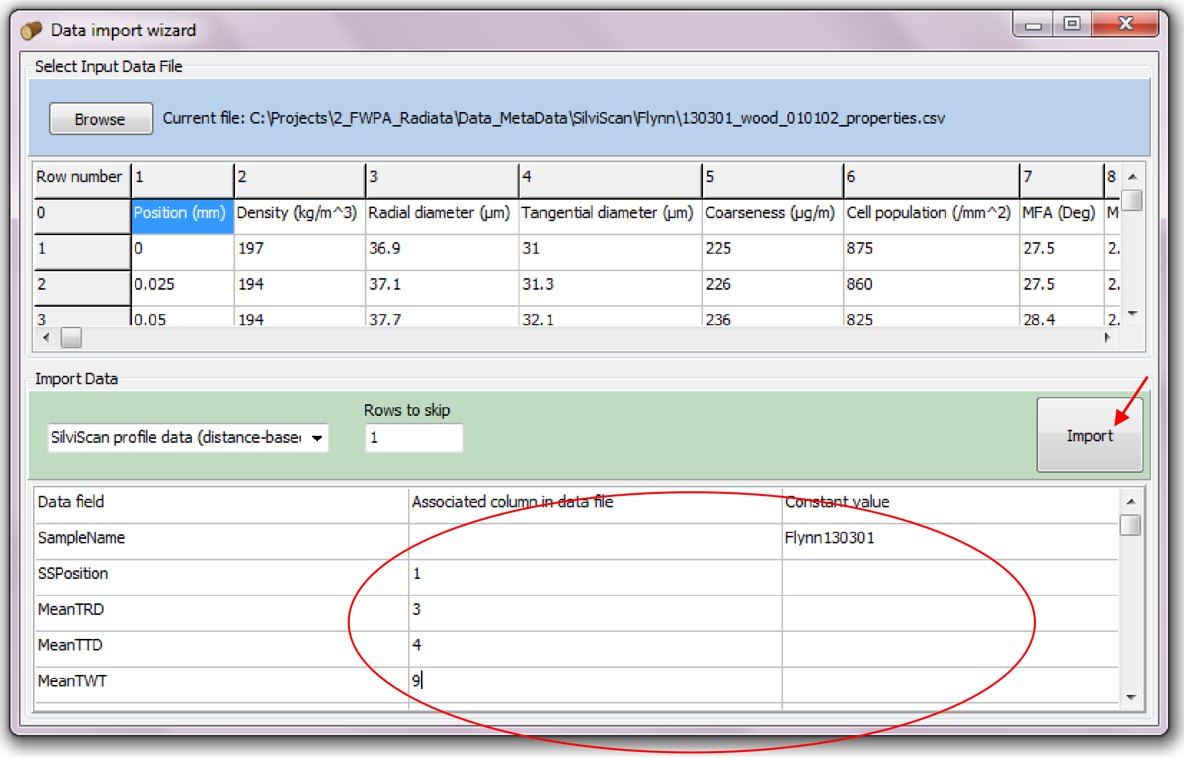


Figure A3.26: First select a csv file to import, followed by a data type table into which to import the data.



Current file: C:\Projects\2_FWPA_Radiata\Data_MetaData\SilviScan\Flynn\130301_wood_010102_properties.csv

Row number	1	2	3	4	5	6	7	8
0	Position (mm)	Density (kg/m^3)	Radial diameter (µm)	Tangential diameter (µm)	Coarseness (µg/m)	Cell population (/mm^2)	MFA (Deg)	M
1	0	197	36.9	31	225	875	27.5	2.
2	0.025	194	37.1	31.3	226	860	27.5	2.
3	0.05	194	37.7	32.1	236	825	28.4	2.

SilviScan profile data (distance-base

Rows to skip: 1

Data field	Associated column in data file	Constant value
SampleName		Flynn130301
SSPosition	1	
MeanTRD	3	
MeanTTD	4	
MeanTWT	9	

Figure A3.27: Specify which columns in the csv data file correspond to which field in the e-Cambium data table (e.g the SilviScan distance-from-pith is in column 1 of the csv file, and corresponds to the field “SSPosition” in the selected target data file). Note that in this example the SampleName field has been specified as “Flynn130301” and is not read from the csv file.

Importing data from another e-Cambium data file

It is also possible to import parameter sets, weather data, site descriptions and regime information from other e-Cambium files (*.cambium). This feature is found by clicking on the menu bar: File|Import data from another e-Cambium project. First select a file by clicking on “Browse”. Then, either select individual sites, regimes, parameter sets or weather datasets, or click on “Select All”. Once at least one dataset has been selected, click “Import”.

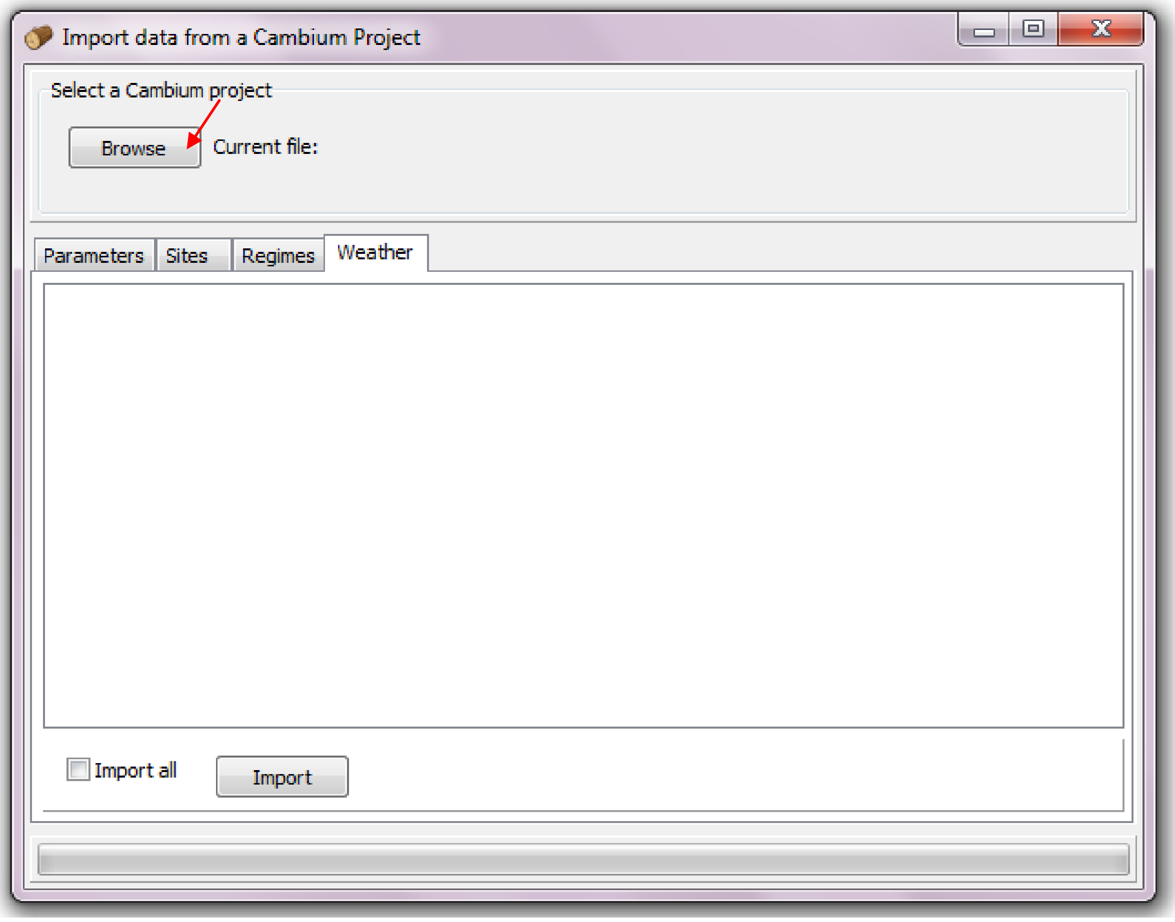
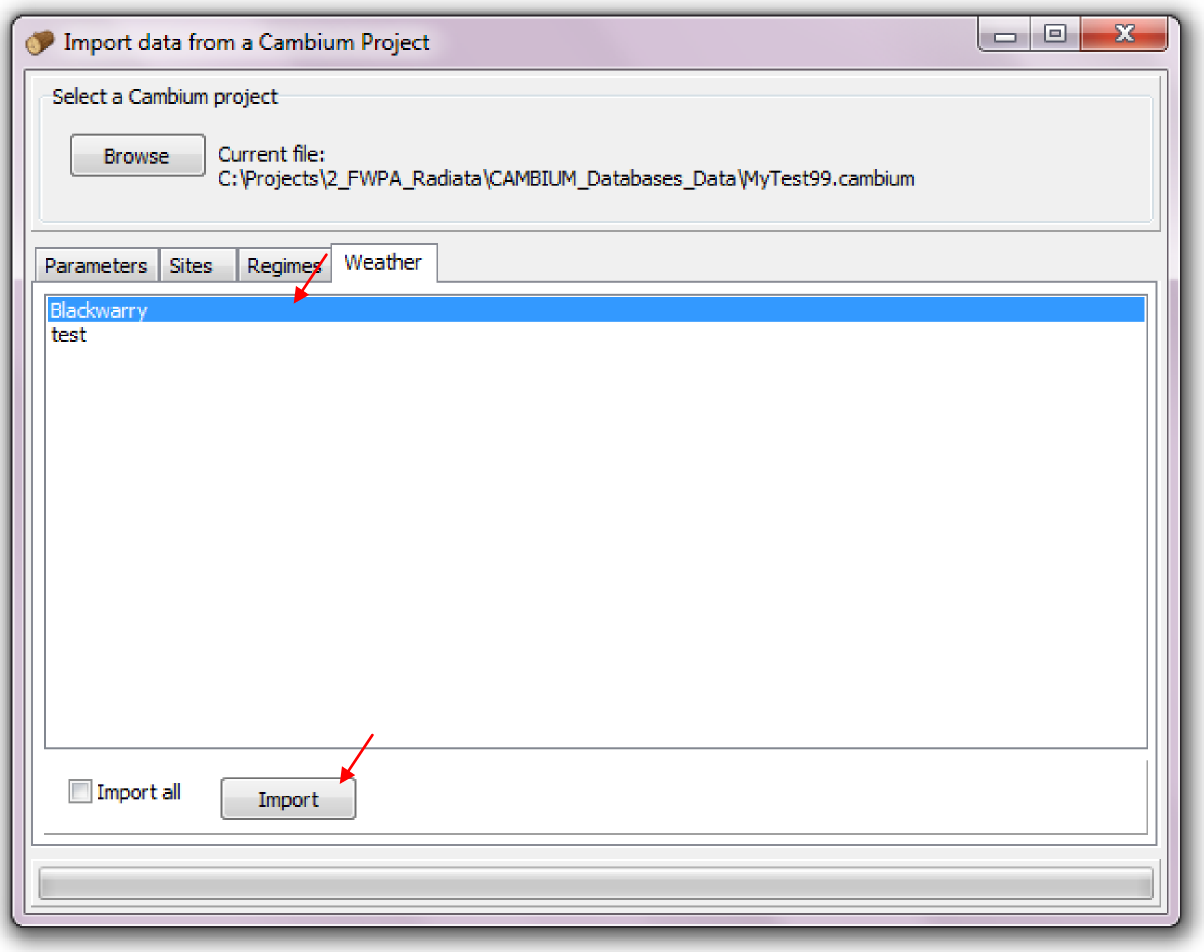


Figure A3.28: Select a e-Cambium data file from which the import data and information



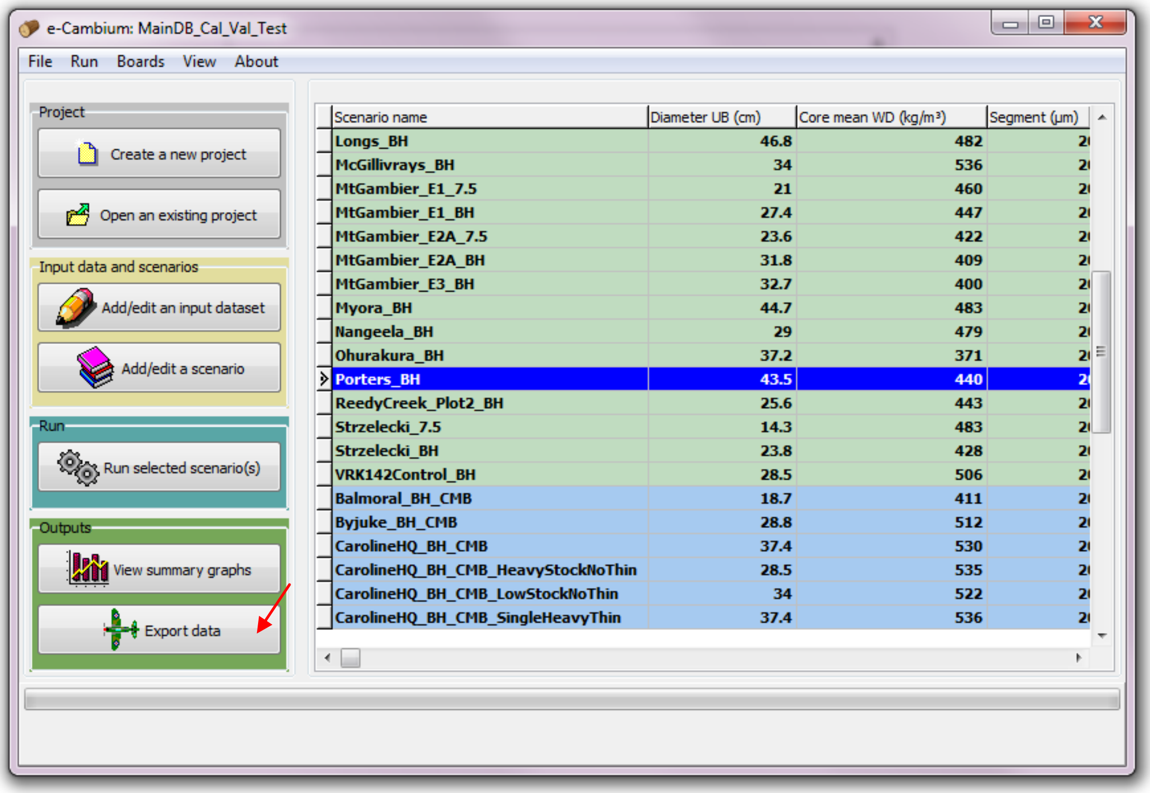
Current file:
C:\Projects\2_FWPA_Radiata\CAMBIUM_Databases_Data\MyTest99.cambium

☐ Import all

Figure A3.29: Select at least one dataset or click on “Import all” before clicking on “Import”

Exporting data to comma-delimited files

Data can be exported for individual scenarios out of the e-Cambium data file, and saved as comma-delimited (*.csv) files.



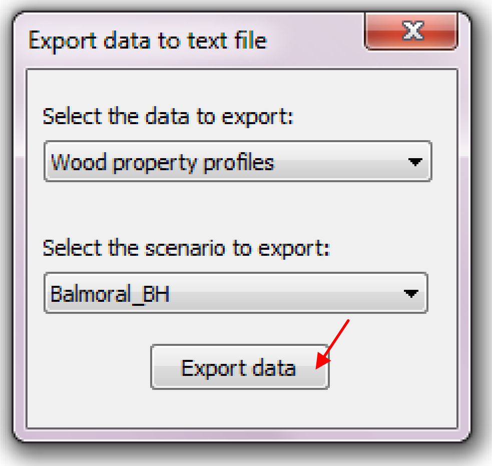
Scenario name	Diameter UB (cm)	Core mean WD (kg/m³)	Segment (µm)
Longs_BH	46.8	482	2
McGillivrays_BH	34	536	2
MtGambier_E1_7.5	21	460	2
MtGambier_E1_BH	27.4	447	2
MtGambier_E2A_7.5	23.6	422	2
MtGambier_E2A_BH	31.8	409	2
MtGambier_E3_BH	32.7	400	2
Myora_BH	44.7	483	2
Nangeela_BH	29	479	2
Ohurakura_BH	37.2	371	2
Porters_BH	43.5	440	2
ReedyCreek_Plot2_BH	25.6	443	2
Strzelecki_7.5	14.3	483	2
Strzelecki_BH	23.8	428	2
VRK142Control_BH	28.5	506	2
Balmoral_BH_CMB	18.7	411	2
Byjuke_BH_CMB	28.8	512	2
CarolineHQ_BH_CMB	37.4	530	2
CarolineHQ_BH_CMB_HeavyStockNoThin	28.5	535	2
CarolineHQ_BH_CMB_LowStockNoThin	34	522	2
CarolineHQ_BH_CMB_SingleHeavyThin	37.4	536	2

Figure A3.30: Click on "Export data" to save simulation datasets as CSV files

Select the type of data to export, and the scenario, and click on "Export data". Three categories of data can be exported:

- Wood property profile data, which outputs predicted pith-to-bark wood property data in a format similar to what would be available from a system like SilviScan. For each "segment" (which can be specified at run time, see Running the model). Ring number is also included.
- Daily growth and developmental data, which provides daily estimates of all of the variables displayed in the daily output data graphs (see Viewing summary graphs and data | Daily outputs). This is only possible if daily data was written to disk (see Running the model).
- Summary information about all existing scenarios. This is really a dump of the summary table displayed in the e-Cambium GUI and the export will ignore any particular selected scenario and export summary information about all scenarios.
- Board summary data, which provides estimates of board average wood density, MFA and MOE, and information about board positions and dimensions. Boards will be calculated according to the user defined properties currently set in the GUI (see Changing the board visualisation).

Once "Export data" is clicked, a dialog will display, and the user can specify a file name and location for the output *.csv file. The file can then be easily viewed in a spreadsheet program like Microsoft Excel, or similar.



Select the data to export: Wood property profiles

Select the scenario to export: Balmoral_BH

Figure A3.31: Select a data type and a scenario from which to export

Appendix 4: Values of Cabala parameters used in model runs

For Cabala runs, the parameter values estimated for *P. radiata* were used, summarised in the table below.

Variable name	Description	Values	Units
alpha0	Value of light use efficiency at base temperature (20oC)	0.05	mol(CO2) mol^{-1}(PAR)
alpha1	Temperature sensitivity of light use efficiency	0.016	°C^{-1}
aoptstar	Intracellular CO2 saturated rate of carbon assimilation	30	mmol (CO2)m^{-2} (leaf) s^{-1}
toptstar	Optimum temperature for photosynthesis	20	°C
k	Canopy light extinction coefficient	0.5	m^{2}(ground) m^{-2}(leaf)
theta	Shape of single-leaf light response curve	0.9	
thalflow	Determines sensitivity of assimilation to low diurnal temperatures	9	°C
thalfhigh	Determines sensitivity of assimilation to high diurnal temperatures	9	°C
gammastar	Photosynthetic CO2 compensation point	42	Pa
tau	Determines extent of seasonal acclimation of Topt	0	
Tpref	Parameter determining seasonal acclimation of Topt	20	°C
thstarLow	Determines acclimation of Aopt to low seasonal temperatures	999	°C
thstarHigh	Determines acclimation of Aopt to high seasonal temperatures	999	°C
upregulation	proportional up regulation of photosynthesis following partial defoliation	1.2	
kdav	Temperature rate constant for foliar respiration	0.03	°C^{-1}
rd0	Value of foliar respiration at temperature T=T0	1.2	mmol (CO2)m^{-2} (leaf) s^{-1}

Variable name	**Description**	**Values**	**Units**
kd0	Value of kdav at temperature T=T0	0.09	°C^{-1}
kd1	Temperature sensitivity of kdav	0.015	°C^{-1}
respC	Construction respiration ratio	0.25	
rocrsw	Specific coarseroot sapwood respiration (kg C/kg N/yr)	10	kg(C)kg^{-1}(N)yr^{-1}
robsw	Specific branch sapwood respiration (kg C/kg N/yr)	10	kg(C)kg^{-1}(N)yr^{-1}
rofr	Specific fineroot sapwood respiration (kg C/kg N/yr)	100	kg(C)kg^{-1}(N)yr^{-1}
rossw	Specific stem sapwood respiration (kg C/kg N/yr)	10	kg(C)kg^{-1}(N)yr^{-1}
Q10	Q10 for respiration	1.3	
g0L	Minimum stomatal conductance	0.01	mol(H20)m^{-2}(ground)s^{-1}
g1L	Determines VPD dependency of water use efficiency	3	mol(H20)m^{-2}(ground)s^{-1}
ga	Maximum tree canopy boundary layer conductance	4	mol(H20)m^{-2}(ground)s^{-1}
vpdcond1	Multiplier in VPD:gc relationship	1.1	
vpdcond2	Exponent in VPD:gc relationship	1	kPa^{-1}
pot1	Multiplier in soil water potential:gc relationship	1	
pot2	Exponent in soil water potential:gc relationship	-1	MPa^{-1}
timewaterstreseffect	Number of days todays water stress influences conductance	20	days
crownreflect	Fraction of radiation that is reflected by crown	0.3	
soilevapmax	Maximum daily soil evaporation rate; supply side	3	kg(H20)m^{-2}(ground)day^{-1}
gasoil	Maximum soil boundary layer conductance	4	mol(H20) m^{-2}(ground)s^{-1}
maxgcsoil	Maximum rate of soil conductance	0.05	mol(H20) m^{-2}(ground)s^{-1}
soilevapalbedo	Fraction of radiation that is reflected by soil	0.3	

Variable name	**Description**	**Values**	**Units**
laiint	Scalar between lai and interception	0.25	kg(H20)m^{-2}(leaf)m^{-2}(ground)
maxintercept	Maximum proportion of any rainfall event intercepted by closed canopy	0.75	
psimin	lowest predawn leaf water potential trees reduced to	-2.7	
psimax	predawn leaf water potential at field capacity	-0.3	
acond	predawn water potential at which embolism commences	-2	
bcond	predawn water potential at which embolism to 50% of sapwood conducting area	-5	
critwatpotgrow	predawn water potential at which new foliage intitiation ceases	-1	
aWlog	Fraction by which water-logging reduces photosynthetic rate	0.5	
critRASWwlog	Critical realtive available soil water for waterlogging	0.9	
Wfrwloggamma	Number of days of waterlogging before all fine roots killed	180	days
Wcrwloggamma	Number of days of waterlogging before all coarse roots killed	1095	days
pan1	Parmeter in influence of soil hardness on root water access	0.0047	
pan2	Parmeter in influence of soil hardness on root water access	0.0064	
pan3	Parmeter in influence of soil hardness on root water access	0.0028	
watcrit	amount of soil water before any canopy evap constraint	250	mm
salta	parameter in relationship between salt and stress sfc=(1-Salta)/(1+saltb*salt^2)+salta	0.3	

Variable name	Description	Values	Units
saltb	as above	0.0002	
S50	soil conductivity in 1:5 extract (mSm-1) that causes a 50% reduction in A or E	277	mSm^{-1}
trangepn	Temperature range between 0 and 100% Pn damage from low temp	5	°C
minhardtempf	Temperature at which 50% folia damage in unhardened material	-10	°C
maxhardtempf	Temperature at which 50% foliar damage in fullyhardened material	-15	°C
trangef	Temperature range between 0 and 100% foliar damage from low temp	5	°C
minhardtemppn	Temperature at which 50% pn damage in unhardened material	0	°C
maxhardtemppn	Temperature at which 50% pn damage in fully hardened material	-5	°C
ahardpn	Constant in definition of pn frost hardiness	-10	°C
bhardpn	Constant in definition of pn frost hardiness	1	
chardpn	Constant in definition of pn frost hardiness	0.02	
ahardf	Constant in definition of foliar frost hardiness	-26	°C
bhardf	Constant in definition of foliar frost hardiness	2	
chardf	Constant in definition of foliar frost hardiness	0.02	
pfrostpn	Exponent of frost impact factor defining long term pn impact	0.15	
pnrecovery	Number of days for full pn recovery from long term frost damage	14	days
opttemprecovery	Average daily temperature below which pn recovery reduced	15	°C
Nfxopt	Optimum foliage nitrogen concentration at top of canopy	0.011	$kg(N)kg^{-1}(DM)$

Variable name	Description	Values	Units
N0	Minimum foliar N for positive net Pn	0.005	kg(N)kg^{-1}(DM)
an	Attenuation of N through canopy with cumulative LAI	0.2	m^{2}(ground) m^{-2}(leaf)
Nb	Average branch nitrogen concentration	0.0025	g(N)g^{-1}(DM)
Nssw	Average stem sapwood nitrogen concentration	0.002	g(N)g^{-1}(DM)
Nshw	Average heartwood (root and stem) nitrogen concentration	0.0005	kg(N)kg^{-1}(DM)
Nbk	Average bark nitrogen concentration	0.0025	kg(N)kg^{-1}(DM)
Nfr	Average fine root nitrogen concentration	0.005	kg(N)kg^{-1}(DM)
Ncr	Average coarse root nitrogen concentration	0.002	kg(N)kg^{-1}(DM)
Nretrans	Fraction of nitrogen retranslocated from tissues on senescence	0.75	
maxNchangeperday	Maximum increase/decrease in foliar N conc. per day	0.00010958904	kg(N)kg^{-1}(DM)day^{-1}
nlowerlimit	Minimum foliar N at which retranslocation effective	0.005	kg(N)kg^{-1}(DM)
gammaf	Reciprocal of maximum foliage longevity	0.2	yr^{-1}
gammabk	Reciprocal of maximum bark longevity	0.01	yr^{-1}
gammafr	Reciprocal of maximum foliage longevity	1	yr^{-1}
gammacr	Reciprocal of maximum fine root longevity	0.01	yr^{-1}
density	Mean density of stem, branch and coarse root wood	0.425	kg(DM) m^{-3}
crratio	Ratio of coarse root biomass to aboveground biomass	0.25	kg(DM)kg^{-1}(DM)
Wfalloc1	Multiplier in relationship between SSA and L	1.5	
Wfalloc2	Exponent in relationship between SSA and Ht	0.725	
Wfalloc3	Exponent in relationship	0.4	

Variable name	Description	Values	Units
	between SSA and L		
Wbkalloc1	Multiplier in relationship between bark mass and stem mass	0.377	
Wbkalloc2	Exponent in relationship between bark mass and stem mass	-0.264	
barkratiomax	Maximum ratio bark/(bark+stem)	0.3	kg(bark)kg^{-1}(stemwood)
beta1	Multiplier in volume equation	0.211	
beta2	Exponent of ht in volume equation	1.238	
beta3	Exponent of ba in volume equation	0.867	
West1	Multiplier in stem ht to diam ratio equation	130	
West2	Exponent in stem ht to diam ratio equation	-0.21	
West3	Exponent stem ht to diam ratio equation	-0.1328	
sla0	Average branch angle from the horizontal	12	
sla1	Lower limit of specific leaf area	5	m^{2}kg^{-1}
tsla	Rate of change of specific leaf area with leaf nitrogen concentration	70	kg(DM)kg^{-1}(N)
branchangle	Average branch angle from the horizontal	60	degrees
branchtaper	Volume of branch as proportion of cylinder with same basal diameter and length	1.3	
crownratio	Crown length to width ration of free grown tree	1	
wSx1000	Size of largest possible individual tree(kg) at 1000 spha	600	kg
krn	Shape parameter in Wfr-Nuptake relationship	0.5	kg(N)kg^{-1}(DM)day^{-1}
maxtranspiration	Potential maximum rate of stand water use	6	kg(H20)m^{-2}(ground)day^{-1}
krw	Shape parameter in Wfr-Nuptake relationship	2	kg(H20)kg^{-1}(DM)day^{-1}
rootExtension	Potential maximum annual	50	cm yr^{-1}

Variable name	Description	Values	Units
Rate	vertical root growth		
BkdnFineRoots	Fraction of fine root litter that breaks down in one month	0.001826484	
BkdnCoarseRoots	Fraction of coarse litter that breaks down in one month	0.000456621	
BkdnFol	Fraction of foliage litter that breaks down in one month	0.0006849	
BkdnBranch	Fraction of branch litter that breaks down in one month	0.0002739726	
BkdnBark	Fraction of bark litter that breaks down in one month	0.0001369863	
BkdnStems	Fraction of stem litter that breaks down in one month	0.0001369863	
FOLCARB	Breakdown fraction of foliage to soluable carbohydrate	0.3	
FOLCELL	Breakdown fraction of foliage to cellulose	0.6	
FOLLIGNIN	Breakdown fraction of foliage to lignin	0.1	
WOODCARB	Breakdown fraction of wood to soluable carbohydrate	0.05	
WOODCELL	Breakdown fraction of wood to cellulose	0.45	
WOODLIGNIN	Breakdown fraction of wood to lignin	0.5	
FRCARB	Breakdown fraction of fine roots to soluable carbohydrate	0.3	
FRCELL	Breakdown fraction of fine roots to cellulose	0.6	
FRLIGNIN	Breakdown fraction of fine roots to lignin	0.1	
CRCARB	Breakdown fraction of coarse roots to soluable carbohydrate	0.01	
CRCELL	Breakdown fraction of coarse roots to cellulose	0.45	
CRLIGNIN	Breakdown fraction of coarse roots to lignin	0.5	
FCFOM	fraction of carbon in the	0.4	

Variable name	**Description**	**Values**	**Units**
	fresh organic matter		
RDECR1	Fractional decomposition per day of carbohydrate pool	0.8	
RDECR2	Fractional decomposition per day of cellulose pool	0.05	
RDECR3	Fractional decomposition per day of lignin pool	0.0095	
kdecomp	Rate parameter for lignin:N ratio impact on decompostion rate	0.01	
ligninNopt	lignin:N ratio below which no effect on decompostion rate	15	
optTdecomp	optimum temperature for litter decompostion	20	
ATMOSDEP	daily atmospheric deposition of nitrogen	0.006849315	
DMINR	non-limited rate of humus mineralisation	0.00015	
upperlimit	pH at which NH4 conversion to NO3 not pH limited	6	
lowerlimit	pH at which no NH4 conversion to NO3	3	
MicroEff	biological efficiency of carbon turnover by microbes	0.4	
EF_HUM	proportion of N release in litter incorporated into humus	0.8	
Ncmicrobes	N:C ratio of microbes	0.125	
HUMDCMPTOPT	optimum temperature for humus decomposition	35	
HUMDCMPTLOW	lower temperature limit for humus decompostion	5	
nleachlimit	% H20 layer in excess of field cap before leach of N	0.05	
CECFAC	fraction of ammonium in liquid phase	0.1	
pnFlag	Flag for CO2 model in which we have no (1) no up-regulation (2) partial up-regulation (3) unconstrained up-regulation	1	

Variable name	Description	Values	Units
ReductPn	Proportional reduction in CO2 and light-saturated Pn followinglong term doubling of Ca from the reference Ca	0.2	
RefCa	Reference atmospheric CO2	350	ppm
txHotDay	Threshold temperature for a hot day	35	°C
MinMonthPredawnDryDay	Threshold pre-dawn water potential for a hot day	-2.5	MPa
Nfixer	Nitrogen fixer	0	
varscalar	variation in productive capacity of non-selfed seedlings	0.3	
varscalarself	variation in productive capacity of selfed seedlings	0.5	
percentselfs	percentage of selfed seedlings in population	30	
performself	average performance of selfed seedlings to non-self seedlings	0.7	
seedvar	variation in initial seedling sizes	0.3	
bnormdistseed	seedlings normally distributed in height, otherwise uniform	-1	
monthcstarve	number of months of no production for tree to die - maximum is 60 months	24	
mindeltapsi	maximum difference between leaf and soil water potential	0.5	
turgorlosspoint	turgor loss point	-3	
lethalwaterpot	water potential at which tree dies of hydraulic failure	-4.5	
capacitanceperleaf	capacitance per unit leaf area	50	
kmaxintercept	maximum hydraulic conductivity	0.06	
kmaxslope	rate of change of hydraulic conductivity with predawn water potential	0.02	

Variable name	Description	Values	Units
windspeed	average wind speed	3	
laminarwidth	leaf laminar width	0.005	
lethaltemperature	lethal temperature for leaves	311	
edvj	(null)	198738	
eavj	(null)	45981	
delsj	(null)	643	
jmax25	maximal photosynthetic electron transfer rate	180	
vcmax25	maximal carboxylation rate	100	
eavc	(null)	120000	
delsc	(null)	0	
edvc	(null)	0	
dayresp	proportion of dark respiration observed in light	0.6	
tbelow	lower temp threshhold for respiration	0	
rtemp	temperate at which resp=rd0	20	
q10f	q10 of foliar daytime respiration	0.0575	
AJQ	quantum efficiency	0.324	
thetaf	curvature of quantum efficiency with light	0.9	
koea	temp response of ko	3600	
oi	oxygen partial pressure	205000	
kc25	Michaelis-Mentem coeff of Rubisco for CO2	404	
ko25	MM coefficint for Rubisco for) O2	248000	
kcea	temp response of kc	59400	
doublepropchangejmax	proportional reduction in vcmax at double referenceCa	0.05	
referenceCa	referenceCa	350	
doublepropchangevcmax	proportional reduction in vcmax at double referenceCa	0.1	
CoppiceReduceAoptstar	proportional reduction in Aoptstar for coppice	1	
StemStarchReservesMax	Maximum stem starch content as a proportion of stem biomass	0.038	

Variable name	**Description**	**Values**	**Units**
StarchMobilisationShapeFactor	shape of exponential function to describe starch accumulation or mobilization	10	
StarchMobilisationMaxRate	proportion of starch mobilisible per day max to supply new allocation	0.01	
CoppiceReductionTime	days after establishment for reduction to single stem - this is an input via the ecoppice cut event	30	
reduceCoppiceRootResp	coppice root NSC respiration rate as proporton of CR sapwood	0.1	
coppicebeta1	value of beta1 for coppice	0.6	
coppicebeta2	value of beta2 for coppice	0.968	
coppicebeta3	value of beta3 for coppice	0.825	
coppicewfalloc1	value of wfalloc1 for coppice	2.5	
coppicewfalloc3	value of wfalloc3 for coppice	0.3	
CoppiceReduceAlpha0	proportional reduction in Alpha0 for coppice	1	
CoppiceReduceJmax	proportional reduction in Jmax for coppice	1	
CoppiceReduceVcmax	proportional reduction in Vcmax for coppice	1	
CoppiceReduceAJQ	proportional reduction in AJQ for coppice	1	
RootStarchReservesMax	Maximum root starch content as a proportion of root biomass	0.038	
RootStarchReservesMin	Minimum root starch content as a proportion of root biomass	0.012	
RootStarchReserves	Starting root starch content as a proportion of root biomass	0.038	
CanopyStarchReserves	Starting canopy starch content as a proportion of canopy biomass	0.038	
StemStarchReservesMin	Minimum stem starch content as a proportion of stem biomass	0.012	
coppicewfalloc2	value of wfalloc2 for coppice	0.7	