Resources

Evaluating and modelling radiata pine wood quality in the Murray valley region

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by

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Executive summary

A survey of the wood property variability across the *Pinus radiata* resource grown in the Victoria and New South Wales Murray Valley Basin was undertaken, based mainly on a set of outerwood-50-mm cores taken from 30 trees per site from 53 sites covering a range of latitudes and elevations (and by association, precipitation), as well as varied soil types

- In parallel with the resource characterization study, a major upgrade was undertaken of the eCambium wood properties modelling tool, version 1 of which was developed in FWPA project PNC 196-1011. Version 2, improved upon version 1 in a number of respects, most particularly in terms of simulation speed. An initial release was made available mid-way after stage 1 (June 2015), with the final release (Version 2.1) to coincide with this final report.
- Further depth of understanding was gained from obtaining (a) detailed information about pith-to-bark variability in tracheid properties, wood density, microfibril angle (MFA) and wood stiffness from SilviScan analysis of cores from 3 trees per site at a subset of 26 sites and (b) from conducting a highly detailed sawmill study, involving the destructive sampling of 9-13 trees from 12 of the 53 sites.
- The research provided a good overview of wood quality, particularly in terms of wood density and modulus of elasticity (MOE: a measure of stiffness), varies across the NSW and northern Victoria radiata pine resource. The basic (oven-dry) density of outerwood cores ranged from as low as about 370 kg m^{-3} to as high as about 520 kg m^{-3}. A major finding was the confirmation of the important effect of previous improved-pasture sites on outerwood density (OWD) and MFA: these sites were invariably those with the lowest stiffness wood. In general, thinned stands had slightly higher OWD than unthinned stands, if there was any difference, but unthinned stands generally had higher outerwood stiffness, as measured by acoustic wave velocities (AWV). The effect on OWD may be attributable to the sampling method than an actual treatment effect. It was not possible to generalize any effects on OWD as a function of annual or seasonal temperature.
- A major objective of the study was to use publically-available, "off-the-shelf" data as far as possible for eCambium simulations. A primary goal was to test the utility of the tool when operated with parameters and input variables highly tuned at the site level, but based on the best available information readily available to growers. In this context, as part of the eCambium model development and testing, the use of the (at-the-time) new TERN interpolated soils surface was pioneered. Part of this process involved detailed soil properties (physical and chemical) from 24 sites. Samples showed that ex-improved pasture sites still had low carbon to nitrogen (C:N) ratios, and there was a poor correlation between C, N and P estimates from the TERN surfaces and the actual forest sites. Weather data, as previously, was derived from SILO interpolated surfaces.
- The eCambium tool was able to significantly predict more than 50% of the variability in actual OWD and about 60% of variation in breast height tree diameter. These predictions used a constant fertility rating across all sites as estimating fertility is difficult from the available data. Preliminary optimization showed that better R^2 values can be obtained, but care needs to be taken when fitting on only outerwood data, to avoid spurious pith-to-bark behaviour. Nevertheless, the model exhibited

stability and indications from a broad dataset of radiata OWD data, are that the tool can be very generally applied to the *P. radiata* resource in south Eastern Australia, significantly predicting actual OWD even for validation (non-fitted) sites.

- The sawmill study, undertaken on logs sourced from 12 sites, provided a comprehensive understanding of final product quality from a set of highly varied sites. One general finding indicated that an increase of 0.1 km per second of acoustic wave velocity equates to approx. $10 per cubic metre of lumber produced. When expressed as $ / m3, eCambium predicted about 60% of the variance in the actual site-average value, if one of the 12 sites was ignored as an outlier. This high-elevation site had been identified in an earlier stage as behaving differently to predicted.
- The eCambium predictions of variation in actual OWD were slightly weaker for the smaller sawmill study dataset than they were overall, but highly significant nonetheless. The model predictions of board grade distributions were found to be very sensitive to assumed thresholds, and with some adjustments, 67% of predictions of grade distributions were found to be statistically the same as actually observed in the mill study.
- The RESI tool, which has hitherto not been used in Australia as a resource characterization tool, was tested as part of the sawmill study on 12 sites, and was found to provide good predictions of solid wood performance. Site-average RESI measurements were able to explain close to 90% of the variance in site-average buttlog acoustic velocity and did a better job on predicting log MOE.
- The eCambium tool can be considered useful as a scoping tool, or for the purpose of broad-scale resource characterization. In particular, it can provide a means of identifying possible “red flag” sites which can be visited in a stratified resource characterization approach. It showed promise in quantifying effects of thinning on outerwood properties and as such can be considered a useful means of exploring the effects of alternative silvicultural regimes. The assumption of constant fertility rating is at present a major shortcoming and this needs improvement. But the stability of the modelling tool, when based on easily obtainable, highly standardized data, and a single largely non-optimised parameter set, is gratifying.

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Introduction

This report addresses the activities and analyses of the FWPA Project PNC325-1314 ("Evaluating and modelling radiata pine wood quality in the Murray valley region") as per the following milestone schedule (Table 1).

Table 1: Project milestone schedule

Milestone No:	Achievement Date	Milestone Description
1	30-Jun-14	Signing of Contract
2	31-Mar-15	Sites selected and NDE sampling and analyses completed
3	15-Jul-15	eCambium predictions made and validated for 30 sites
4	15-Dec-15	Destructive sampling and mill study
5	31-Mar-16	Data analysis completed and eCambium predictions assessed against actual mill data. Model redesigned for commercial deployment
6	31-May-16	Draft final report completed. Industry presentations and workshop given, including training as required by PSC
7	15-Aug-16	Complete Final Report and AFFR
		TOTAL

The purposes of the analysis and field work described in this report were twofold:

1. To produce a regional assessment of wood property variation from *P. radiata* sites that (a) are close to harvest and (b) represent as wide a range of productivities/expected resource variation as reasonable. These data would allow some degree of benchmarking of the resource in comparison with other resource evaluation projects undertaken over the past decade (Cown et al., 2006b; McKinley et al., 2003a).
2. To obtain a representative data set describing site average and variance data of tree size and basic wood properties that can be used as a basis for evaluating the performance of the eCambium hybrid wood properties modelling tool at the site-average level, and facilitating further development where appropriate.

As such, this report addresses the first point and contributes to achieving the second. The second point will be addressed in detail in under Milestone 3.

Background

Since the first establishment of *Pinus radiata* in the Southern Hemisphere, there have been substantial improvements in the management of commercial log production from this important timber species (Lewis et al., 1993) . However, greater volumes achieved by improvements in breeding and silviculture have frequently resulted in commercially harvestable volumes at younger ages (Apiolaza et al., 2013; O'Hehir and Nambiar, 2010). These gains have led, in many cases, to the production of logs with a less valuable distribution of products (Apiolaza et al., 2013) and radiata pine plantations grown over shorter and shorter rotations are increasingly experiencing quality issues related to lower stiffness, strength and poor dimensional stability (Baltunis et al., 2007; Kennedy, 1995; Li et al., 2012). Consequently, there is now a shift in the management and breeding of radiata pine towards wood quality improvement in addition to volume and form (Gapare et al., 2010).

Extensive investment to identify wood trait heritability has produced impressive genetic gains (Wu et al., 2008), and improving the quality and reducing the amount of juvenile wood through breeding has been a major focus of the FWPA-funded Juvenile Wood Initiative (Baltunis et al., 2007). A tremendous advance in the last decade has been the ability to select for important wood quality traits from very young trees, rather than those at rotation age (Chauhan et al., 2013; Wu et al., 2007). Also over the last decade, FWPA has funded a series of important *P. radiata* resource quality assessment studies in Australia to develop a better understanding of the effects of site and silviculture on timber quality. McKinley et al (2003b) compared wood quality across 44 sites in the Green Triangle region, with significant effects noted (although the specific drivers of variation were not explored). In Tasmania, based on a study that considered 26 sites across the state, Cown et al (2006a) found important site-related wood quality variation in the *P. radiata* resource. In Western Australia Blakemore et al. (2010) found that the resource was relatively uniform and of high quality in relation to basic wood density and stiffness. A similar study was also completed in New Zealand (Cown et al., 2005a). Following from these and other projects conducted to understand the link between growing conditions, product quality and processing, the forest industry is now increasingly eager to assimilate results and use the knowledge to increase productivity.

Improvement of properties like wood stiffness can have a big impact on revenue and profitability, by resulting in products being up-graded to more valuable grade classes. In New Zealand, for example, a 25 -50% increase in corewood stiffness, could result in 50% of corewood being up-graded from industrial quality to uses like framing, potentially leading to gains to growers of ~NZ$250 million per year (Alzamora et al., 2012). Unfortunately, however, assessing these gains is not easy, and the highly variable quality of logs is poorly reflected by log physical dimensions and appearance, upon which current log grading rules for structural timber are based (Dickson et al., 2004). This situation means that both growers and processors incur significant losses in value and require tools that can assist in categorizing logs based on a better understanding of wood quality (Dickson et al., 2004). But the source of the variation 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 (Li et al., 2012), before even taking into account varying product prices and regional contexts. Forest management approaches should be flexible to allow for adjustments to meet wood quality requirements of future market conditions (Moore, 2012). But the question remains: how do they do this effectively?

Forest managers, in addition to selecting improved genetic material can have important effects on wood quality by adjusting forest management and silvicultural regimes. 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., 2002b; McGrath et al., 2003; Nyakuengama et al., 2003; Nyakuengama et al., 2002). Similar relationships between growth and silviculture have been seen in European species (Lundgren, 2004), where later-age applications of fertiliser increased ring width and annual average MFA, and decreased annual density. Watt et al. (2011) found, in an experimental stand of 24-year old P. radiata, that the influence of stocking on wood density and stiffness was primarily expressed through a highly significant interaction between age and stocking, while wood stiffness has been found to increase with increased stocking (although this effect was largely attributed to reductions in diameter growth) (Lasserre et al., 2009).. The application of weed control has also been found to have an effect on wood stiffness (Xue et al., 2013).

In addition to genetic selection and the application of appropriate silviculture, site type and climatic variation are both of major importance in determining wood properties, as has been shown by a number of studies on radiata pine in Australia and New Zealand. In New Zealand, wood density varied with latitude, increasing to the north, attributable to temperature and soil nitrogen effects (Cown et al., 2005a). Broad spatial models of outerwood density variation throughout New Zealand were recently developed from these and other research data (Palmer et al., 2013). Effects of other factors, like drought, are also important (Ivković et al., 2013; Nanayakkara et al., 2014) but often complex to analyse and understand (Drew et al., 2013; Eilmann et al., 2011; Ivković et al., 2013).

It is also important to interpret observed patterns of growth and development in growing trees in the context of continually variable growing conditions. There exists, for example, a strong relationship between tree slenderness (height / diameter) and wood stiffness in radiata pine (Watt et al., 2006a). Stem slenderness together with average site temperature were considered to be the major determinants of stem stiffness variation across a wide range of stands. The effect of latewood proportion on stiffness across a range of sites (Watt et al., 2006c), together with the link to temperature and rainfall variation, is indicative of the need to understand site and management interactions on average stem properties in terms of sub-annual growth patterns and wood property variation. Waghorn et al (2007) examined effects of stocking density and genotype on radiata pine standing tree stiffness, with stiffness explained largely by height to diameter ratio and green crown depth. Significant genetic effects were noted.

Overall, it is obvious from the literature that genetic, site and silvicultural effects on wood properties are extremely difficult to generalise (Downes and Drew, 2008). Following from the body of research undertaken on *P. radiata* in Australia and abroad, and given the complexity involved, the focus in understanding wood quality variation is increasingly on the nexus between genetics, management, site and the value of products (Downes and Drew, 2008; Ivković et al., 2013). Under constantly changing climatic and management conditions, capturing the interactive effects of site, genotype, management and climatic interactions on growth and development, is beyond the scope of empirical approaches. The patterns of growth and development in growing trees, in the context of continually variable growing conditions, is fundamentally the cause of wood variability. Wood quality variation and its association with growth rate is determined largely by patterns of growth within each annual ring and the net effect of sub-annual variation in wood properties (Downes and Drew, 2008; Downes et al., 2008). The complex patterns vary as a function of the local environment of each tree and thus lend themselves to prediction by integrated algorithms that model the interactions of the underlying biology of the tree. In order to model these interactions, it is necessary to develop models that utilise knowledge of tree biology (often called process-based models), designed as single tools, or suites of tools (Landsberg and Sands, 2010).

Process-based models of forest 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; Landsberg and Sands, 2010). 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 there may be little if any precedent (e.g. increasing average temperatures, changing rainfall patterns 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 range of process-based models, designed to simulate cambial activity and ultimately wood property variation, have been described by various authors (Deckmyn et al., 2006; Deleuze and Houllier, 1998; Drew et al., 2010; Fritts et al., 1999; Hölttä et al., 2010; Kramer, 2002; Meicenheimer and Larson, 1983; Vaganov et al., 2006; Wilson, 1964; Wilson and Howard, 1968). Other models that have been developed to link crown activity to wood property variation are also promising (Fernández et al., 2011). Recently, work has been completed in the development of a prototype model ("eCambium") of wood formation in softwoods, with a particular focus on radiata pine (Drew and Downes, 2013b). This new model has shown promise, explaining 80% of the variation in wood density of samples taken from 16 sites in Australia and New Zealand. The model is the first of its kind to incorporate a module simulating MFA variation (an important predictor of wood stiffness), the underpinning biology of which is still very poorly understood (Barnett and Bonham, 2004; Donaldson, 2008; Donaldson and Xu, 2005).

This report addresses the validation and ongoing development of the eCambium software tool within the context of a resource evaluation of a wood variability across the Murray Valley Basin. This commercially important estate is primarily grown by Hancock's Victoria Plantations (HVP) and Forest Corporation New South Wales (FCNSW), and feeds a diverse range of processes including sawn timber (Hyne & Sons, Tumbarumba), veneer (CHH, Myrtelford), kraft pulp (Visy, Tumut) and mechanical pulp (Norske Skog, Albury).

Stage 1: Non-destructive resource evaluation

Empirical / statistical approaches to predicting measured wood properties (MS2)

Site Selection and initial screening

A list of potential sites was generated by HVP and FCNSW with final selections made to obtain the maximum reasonable spread of site types and productivities across the breadth of the resource (Figure 1) in close to harvest stands. The age distribution of the selected stands was minimized to avoid artificially enhancing the predictions made by the eCambium model. Over the period 25th August – 3rd September 2014, field sampling was undertaken at 27 sites across the HVP resource in NE Victoria. From 7th – 13th October 2014, field sampling was undertaken at 26 sites across the FCNSW resource.

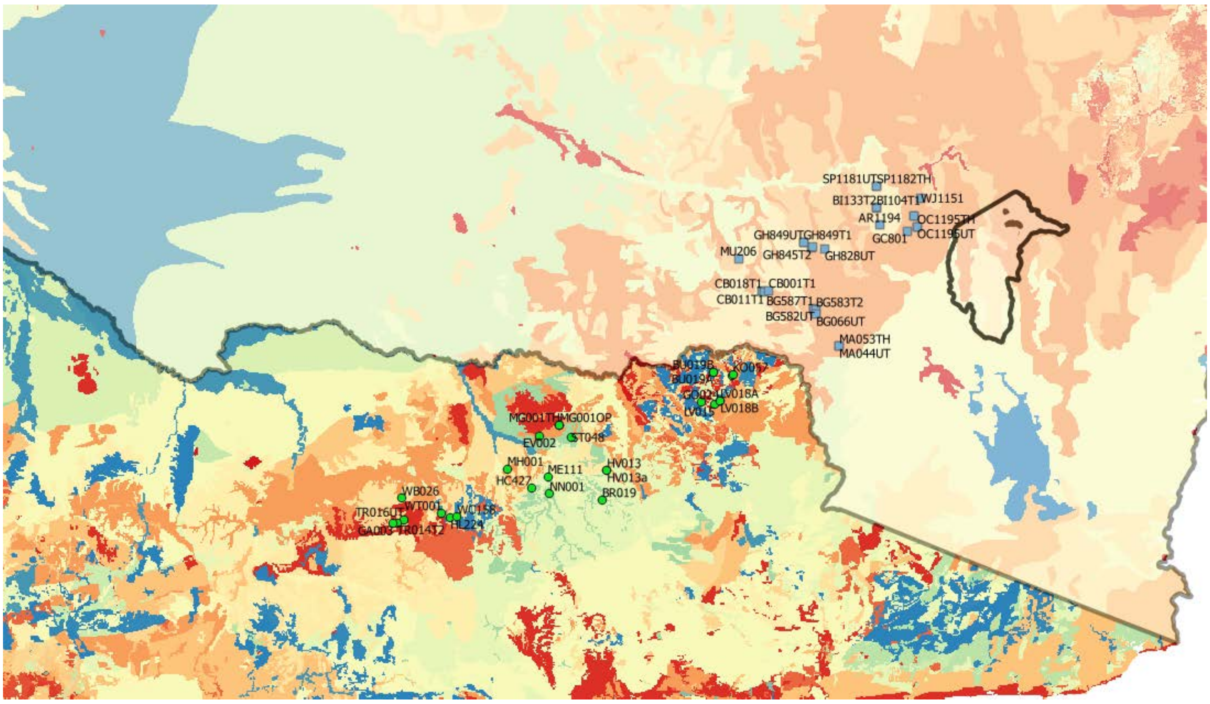

Figure 1. Image of sampled site locations in NSW and Victoria taken from the QGIS software.

At each site 30 co-dominant trees were sampled. Because eCambium models the "mean tree" of the stand, only co-dominant trees, representing the "typical" resource tree of the stand (i.e. those trees representing typical saw log trees) were selected. In this way, the effect of small trees (destined to be pulp logs) or exceptionally large trees on the results was minimized, which would bias the results within a sawing study. Trees selected by this method are likely to best represent the saw-log part of the resource, which is that component of the resource ultimately targeted in eCambium simulations.

From each site, the following data were obtained from the selected co-dominant trees:

- Tree height, bark thickness and average branch diameter (up to 4 m) (from a subset of 6 trees per site)
- Overbark diameter at breast height (1.3 m) (DBHOB), Acoustic wave velocity (AWV - ST300) and outerwood density [1] (OWD) (30 trees per site)

Daily weather data for each site's location was downloaded from the Queensland Government's SILO database (https://www.longpaddock.qld.gov.au/silo/). Soil descriptive data was obtained from the industry partners' databases (where available) and from the CSIRO Australian Soil Resources Information System (ASRIS). Silvicultural regime information was provided by the owner of each site.

Data analysis

An initial assessment using simple correlations examined covariance amongst site level means of the different variables. Variability among sites was explored using multiple regression and

[1] Outerwood density was measured on individual cores using the outer 50mm of ~13mm diameter increment cores

principal component analysis (PCA) to assess which environmental factors were most strongly contributing to OWD and AWV variation.

Site Index (SI) was calculated using Equation 1:

$$SI = H\left[\frac{1-e^{-0.073t_i}}{1-e^{-0.073t}}\right]^{1.013}$$ ………………Equation 1

Where SI is site index at age t_i (20 years) and H is height at the age t.

Although the coefficients do not reflect the particular case for *P. radiata* in the Murray Valley, the site index calculation should provide a reasonable means of assessing tree height at a common age as a basis for comparing sites. It is notable that the derived SI value may represent a systematic under-estimate as compared with operational values as the final height values used in the equation were not of dominant trees.

The Unscrambler[2] software was used to explore partial least squares (PLS) regression (Næs et al., 2002) as a means of establishing the maximum amount of variance that can be explained in wood properties as a function of site-related variation. Statistical parameters including the coefficient of determination (R^2), root mean square error of the cross validation (RMSECV) and the number of principal components required (rank) were obtained for the prediction of OWD and AWV. These were used to inform a more standard multiple regression approach, and the results compared with the regression approach identified in the Tasmanian resource evaluation study (Cown et al., 2006b).

The overall effect of previous stand use and elevation on OWD and AWV were assessed using analysis of variance (ANOVA). Sites were allocated into one of four elevation classes, between 250 m AMSL and 1100 m AMSL, for this analysis. The effects of thinning on OWD, AWV, DBH and height at common sites were tested using ANOVA and Tukey's HSD. It should be noted that in some cases, the effects of thinning on DBH must be assessed cautiously, as selections during thinnings may have adjusted the remaining population by selecting smaller, or in some cases, possibly larger trees.

Results

Regional and data summaries

Site summary data was collated as shown in Table 2. Sites covered a wide range of elevation (235 – 1100 m AMSL), rainfall (474 – 1318 mm per annum) and average temperature (16-23 °C). Note that these values are the averages over the actual rotation of each individual stand, not full long-term historical averages. Also, the data were extracted from interpolated climate surfaces (SILO), not from records at the actual sites[3].

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[2] http://www.camo.com/rt/Products/Unscrambler/unscrambler.html

[3] Debate over the BOM's treatment of past-temperature records may have minor impact on the use of eCambium. Eg. http://www.theaustralian.com.au/national-affairs/opinion/heat-is-on-over-weather-bureau-homogenising-temperature-records/story-e6frgd0x-1227033714144: "Marohasy says the unhomogenised/raw mean annual minimum temperature trend for Rutherglen for the 100-¬year period from January 1913 through to December last year shows a slight cooling trend of 0.35C per 100 years. After homogenisation there is a warming trend of 1.73C per 100 years. Marohasy says this warming trend essentially was achieved by progressively dropping down the temperatures from 1973 back through to 1913. For the year of 1913 the difference between the raw temperature and the ACORN-Sat temperature is 1.8C."

Variability in OWD was large, despite the narrow age range sampled. The sites with the highest OWD were at Carabost in NSW (516 kg m^{-3}) and Havilah in Victoria (514 – 522 kg m^{-3}). The Carabost stand was thinned once, and the Havilah stand unthinned. The two sites at Splitters in NSW (369 – 380 kg m^{-3}) and Moyhu in Victoria (388 kg m^{-3}) had the lowest OWD, although it is notable that Moyhu was the second youngest stand in the study, planted in 1991. The next lowest OWD in Victoria was at Gardiners, of 420 kg m^{-3}.

The same sites emerged as being extreme in the case of AWV, with CB011 (Carabost compartment 11) having the highest values measured in the NSW sites (4.6 km s^{-1}) and one of the two cases considered at Havilah being the highest in Victoria (5.0 km s^{-1}). The sites at Splitters had the lowest AWV measured in the NSW resource (3.4 – 3.5 km s^{-1}) and Stanley (which was the youngest material sampled; planted in 1997) was the lowest measured in Victoria (4.2 km s^{-1}).

It is important to note that extreme sites were targeted in this study as a means of testing and developing the eCambium tool, and the very low AWV or OWD measured at some sites does not reflect the broader resource, even in the same region. Consequently, some of the sites selected are likely to be atypical with respect to the broader resource. Differences in silviculture may have contributed to differences between these extreme sites.

Effects of environmental variables on wood properties

Annual averages and seasonal averages for weather data were calculated, and the correlation between these and the measured site-average tree attributes determined (Table 3). Only correlations significant at $p < 0.01$ are shown.

Table 2: Site information and associated summary of actual rotation weather.

Site Number	Site Code	Site Name	Prev. Land Use	Silv. Trt	Region	Elev.	Site Index	Annual Rainfall	Annual Max. Temp	Annual Min. Temp	Annual Min. RH	Annual Evap.	Annual Radiation	DBHOB	Tree Ht	Tree Sld	AWV	Bark Th.	Branch Dia	OW Density
						m		(mm)	oC	oC	%	mm	MJ/m2	mm	m		km/sec	mm	mm	kg/m^3
1	HV013	Havilah	ex-native	UT	Ovens	790	19.2	1305	18.6	6.8	50.4	1035	5886	293.6	22.6	80.7	4.7	18.0	27.2	514
2	HV013a	Havilah	ex-native	UT	Ovens	792	24.8	1291	18.7	6.7	50.0	1046	5900	317.9	29.3	90.6	5.0	17.4	14.7	522
3	BR019	Bright	ex-native	T1	Ovens	549	26.8	1318	18.7	6.9	50.4	999	5795	301.8	29.8	98.1	4.9	19.0	21.0	484
4	ST048	Stanley	ex-native	T1	Ovens	765	26.3	1082	17.9	6.7	51.2	1043	5851	313.2	24.4	78.0	4.2	14.2	22.3	432
5	MG001UT	Magpie	ex-native	UT	Ovens	723	24.9	916	19.3	7.0	49.9	1139	5975	274.7	27.3	103.7	4.8	15.1	19.4	459
6	MG001OP	Magpie	ex-native	T3	Ovens	705	25.7	916	19.3	7.0	49.9	1139	5975	370.2	28.3	78.2	4.7	23.5	24.4	468
7	MG001TH	Magpie	ex-native	T2	Ovens	682	26.0	916	19.3	7.0	49.9	1139	5975	428.8	28.6	68.7	4.4	23.6	21.6	457
8	ME111	Merriang	ex-native	T2	Ovens	331	29.7	1148	19.0	6.9	50.4	1056	5884	372.7	32.6	87.6	4.5	23.9	21.0	469
9	NN001	Nug Nug	ex-pasture	UT	Ovens	258	26.5	1023	21.1	7.9	47.5	1138	5921	398.7	30.6	79.0	4.4	21.4	31.1	465
10	HC427	Hurdle Creel	ex-native	T1	Ovens	358	27.1	1180	18.8	7.0	50.7	1033	5868	359.0	30.5	91.0	4.7	21.4	20.4	485
11	MH001	Moyhu	ex-pasture	T1	Ovens	253	24.0	771	21.7	7.9	46.5	1241	5940	319.3	25.5	76.9	4.5	21.3	30.3	388
12	WT001	Wrightleys	ex-native	T1	Benalla	702	26.6	898	19.8	7.5	49.1	1117	5801	381.4	29.6	77.1	4.6	24.3	25.4	447
13	HL224	Hollands	ex-native	T1	Benalla	459	30.9	474	22.6	9.1	44.4	1549	6303	383.3	36.9	92.7	4.8	24.7	22.3	491
14	WC158	Whiskey Cree	ex-native	T1	Benalla	746	32.2	959	19.0	7.2	50.3	1055	5778	443.3	37.1	74.1	4.6	32.0	28.4	444
15	EV002	Everton	ex-pasture	UT	Ovens	421	18.2	797	20.6	7.3	48.0	1213	6023	319.3	20.6	64.3	4.3	26.9	27.0	430
16	JN058	Johnsons	ex-pasture	T2	Shelley	545	26.7	966	19.7	7.1	48.1	1159	6022	363.9	30.1	87.7	4.7	22.3	20.3	488
17	KO057	Koetong	ex-pasture	T2	Shelley	476	28.4	966	19.7	7.1	48.1	1159	6022	373.1	31.9	91.2	4.7	18.3	21.3	444
18	LV015	Lucyvale	ex-native	T2	Shelley	812	32.6	1245	15.9	6.0	53.7	942	5911	425.0	37.1	83.1	4.7	31.9	23.6	479
19	LV018b	Lucyvale	ex-native	UT	Shelley	689	24.0	1150	17.6	6.5	51.3	1033	5959	338.3	27.4	86.1	4.9	24.1	26.7	465
20	LV018a	Lucyvale	ex-native	T1	Shelley	685	27.2	1150	17.6	6.5	51.3	1033	5959	419.0	31.0	77.1	4.5	29.1	26.4	488
21	GO024	Goulds	ex-pasture	UT	Shelley	749	34.4	1124	18.3	7.0	50.6	1076	5959	408.5	38.3	93.4	4.7	26.0	30.3	445
22	BU019a	Burrowye	ex-native	UT	Shelley	585	22.6	842	21.6	8.3	46.2	1298	6055	339.9	25.2	77.4	4.9	22.0	24.0	485
23	BU019b	Burrowye	ex-native	T2	Shelley	598	24.0	842	21.6	8.3	46.2	1298	6055	262.8	26.7	97.5	5.0	22.9	23.4	463
24	TR016UT	Toorour	ex-native	UT	Benalla	584	29.1	975	19.0	7.1	50.2	1100	5755	383.0	33.2	83.8	4.7	25.6	25.6	446
25	TR014TH	Toorour	ex-native	TH	Benalla	693	25.8	1032	17.1	6.4	52.8	1016	5713	388.4	29.4	72.8	4.7	34.6	33.4	497
26	GA003	Gardiners	ex-pasture	T3	Benalla	661	29.7	1016	17.1	6.5	52.9	1015	5693	527.0	33.1	65.7	4.2	28.0	42.4	422
27	WB026	Warrenbayn	ex-native	T2	Benalla	543	30.9	1025	18.8	7.0	49.9	1173	5853	509.2	39.2	75.9	4.9	36.7	25.7	474
28	AR1194	Argalong	ex-pasture	T1	Buccluegh	687	26.9	1076	19.3	6.9	48.0	1143	6177	380.4	30.4	85.5	4.2	24.0	19.5	459
29	GC801	Gass creek	ex-native	UT	Buccluegh	1041	28.0	1213	16.1	5.1	51.2	999	6064	415.5	31.6	74.4	4.4	30.8	25.8	498
30	OC1195TH	Oak Creek	ex-native	TH	Buccluegh	1097	26.5	1215	15.9	5.0	51.5	993	6059	421.2	29.8	77.7	4.3	29.7	21.7	450
31	OC1195UT	Oak Creek	ex-native	UT	Buccluegh	1100	24.8	1215	15.9	5.0	51.5	993	6059	375.9	28.0	70.9	4.3	34.7	21.2	451
32	OC1012UT	Oak Creek	ex-native	UT	Buccluegh	1049	32.2	1129	17.4	5.8	49.9	1073	6115	354.3	37.5	107.1	4.6	25.7	14.7	454
33	OC1012TH	Oak Creek	ex-native	TH	Buccluegh	1022	30.3	1129	17.4	5.8	49.9	1073	6115	547.8	35.3	61.9	4.0	37.7	10.0	446
34	WJ1151	Wee Jasper	ex-native	T2	Buccluegh	919	30.2	1083	18.1	6.3	49.4	1110	6148	445.7	34.8	82.2	4.2	26.7	29.4	463
35	SP1181UT	Splitters	ex-pasture	UT	Buccluegh	502	22.4	907	20.3	7.8	47.7	1203	6231	324.7	25.3	87.5	3.4	20.5	40.0	369
36	SP1182TH	Splitters	ex-pasture	TH	Buccluegh	512	21.3	907	20.3	7.8	47.7	1203	6231	346.3	24.1	69.6	3.5	22.7	40.0	380
37	BI104T1	Billo	ex-native	T1	Buccluegh	836	25.1	1109	17.8	6.1	49.8	1091	6152	356.5	29.0	79.6	4.5	27.8	25.0	505
38	BI133T2	Billo	ex-native	T2	Buccluegh	792	24.3	1109	17.8	6.1	49.9	1092	6151	413.2	27.8	67.8	4.3	33.8	28.3	493
39	MA044UT	Maragle	ex-native	UT	Maragle	833	24.7	896	18.2	5.4	48.0	1053	6038	325.6	28.8	92.8	4.5	20.3	25.0	465
40	MA053TH	Maragle	ex-native	TH	Maragle	945	26.5	890	18.3	5.5	48.0	1049	6037	347.9	29.9	82.5	4.5	24.5	35.0	479
41	BG582UT	Bago	ex-native	UT	Bago	804	29.9	1079	17.6	5.5	49.3	1056	6087	371.4	34.8	93.2	4.3	21.5	36.7	448
42	BG587T1	Bago	ex-native	T1	Bago	849	25.0	1085	17.6	5.5	49.4	1053	6084	375.3	28.6	72.8	4.5	31.7	38.3	465
43	BG583T2	Bago	ex-native	T2	Bago	846	27.4	1079	17.6	5.5	49.3	1056	6087	474.9	31.9	66.6	4.3	34.0	38.3	457
44	BG066UT	Bago	ex-native	UT	Bago	1006	22.3	1080	17.6	5.5	49.3	1053	6085	372.3	25.7	72.1	4.2	23.2	42.0	436
45	GH849UT	Green Hills	ex-pasture	UT	GreenHils	450	20.9	1078	18.3	6.2	49.0	1133	6170	324.0	23.5	80.7	4.1	26.0	30.0	443
46	GH849T1	Green Hills	ex-pasture	T1	GreenHils	450	23.6	1078	18.3	6.2	49.0	1133	6170	369.2	26.7	72.5	4.1	28.7	31.7	439
47	GH845T2	Green Hills	ex-pasture	T2	GreenHils	718	24.0	1018	19.3	6.6	47.9	1174	6190	379.7	27.4	66.4	4.2	24.5	31.7	450
48	GH845T1	Green Hills	ex-pasture	T1	GreenHils	608	23.3	1018	19.3	6.6	47.9	1174	6190	372.2	26.6	64.2	4.3	30.0	40.0	442
49	GH828UT	Green Hills	ex-pasture	UT	GreenHils	479	25.0	1013	19.5	6.7	47.6	1179	6195	373.7	29.1	71.3	4.1	31.8	46.7	412
50	CB001T1	Carabost	ex-native	T1	Carabost	643	23.0	959	19.2	6.6	47.8	1183	6157	397.8	25.9	67.0	4.3	26.1	24.0	460
51	MU206	Murraguldri	ex-native	UT	Murraguldri	437	19.5	698	21.5	8.1	45.4	1424	6288	320.9	23.5	75.4	4.5	25.0	25.0	458
52	CB011T1	Carabost	ex-native	T1	Carabost	537	21.5	969	19.2	6.6	48.0	1182	6156	296.1	24.6	80.7	4.6	28.8	21.7	516
53	CB018T1	Carabost	ex-native	T1	Carabost	551	23.8	968	19.2	6.5	48.0	1185	6161	322.9	27.7	87.5	4.6	21.3	20.0	495

Table 3: Correlations among variables describing weather and tree attributes. Only those significant at p < 0.01 are shown (n = 53).

		Annual				Winter				Spring			Summer			Autumn			Tree attributes					
N=53 r(.01)=0.354	Site Index	Max T	Min T	Min RH	Qa	Rnf	Max T	Min T	Qa	Max T	Min T	Qa	Max T	Min T	Min RH	Max T	Min RH	Qa	DBH	Tree Ht	Tree Sld	AWV	Bark Th	Br Dia
DBHOB	0.60	-0.40	-	0.38	-	-	-0.36	-	-	-0.40	-	-	-0.42	-0.36	-	-0.40	0.42	-	1.00					
Tree Ht	0.96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.37	-	0.64	1.00				
Tree Sld	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.49	-	1.00			
AWV	-	-	-	-	-0.46	-	-	-	-0.56	-	-	-0.52	-	-	-	-	-	-0.47	-	-	0.50	1.00		
Bark Th	-	-0.43	-0.39	-	-	-	-0.41	-0.39	-	-0.40	-0.40	-	-0.44	-	0.39	-0.42	-	-	0.67	-	-0.57	-	1.00	
Br Dia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.40	-0.48	-	1.00
OWD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.66	-	-0.49

DBHOB was correlated negatively with annual and seasonal temperature (Table 3). Standing tree AWV (ST300) values were correlated negatively with average incoming solar radiation[4]. Interestingly no single weather variable was significantly correlated with OWD. However, AWV and OWD were correlated positively and OWD negatively correlated with branch diameter. As a further check, correlations were calculated between variables and the average weather values over the last 5 years of growth only. Correlations reflected those shown here based on data calculated over the full rotation.

Of the 15 sites that were recorded as previously being under pasture (see Table 2), 13 (87%) had mean OWD below the average for the study as a whole (460 kg m^{-3}) and 12 (80%) had mean AWV below the study average (4.5 km s^{-1}). Both OWD and AWV were significantly (p = 0.0005 & p = 0.0100 respectively) lower at ex-pasture compared to other sites. Neither DBH nor tree height, however, were significantly different at ex-pasture compared to other sites. There was no evidence of a significant effect of elevation on either OWD (p = 0.198) or AWV (p = 0.288), nor was there evidence of an interaction between previous land use (i.e. ex-pasture or forest) and elevation (p > 0.173).

There was no apparent overall effect of late thinning or final stand density on OWD. In the case of many sites (e.g. Billo 133, Carabost 018 and Toorour 014), thinning took place on or after 2010. On the other hand, all sites with very high AWV (4.9 km s^{-1} and above) were unthinned, with the exception of the much older stand at Warrenbayne (WB026).

Effects of differing thinning on the same sites

In a number of cases, differing thinning regimes were considered at the same site. Comparisons are only made here where planting dates, stocking, and the timing of thinning were similar (Table 4). At sites like Maragle 044 and 053, the establishment dates and densities were markedly different and therefore the effect of thinning alone would not be clear in this simple analysis.

[4] High ST300 values indicate relatively stiffer wood which is associated with lower solar radiation values.

Table 4: Effects of thinnings on OWD, AWV, DBH and tree height. NS denotes effects not significant at $\alpha = 0.05$. UT denotes unthinned, T1, T2 and T3 denote one, two or three thinnings, respectively.

Sites	Regimes	Effects on OWD	Effects on AWV	Effects on tree DBH	Effects on tree Height
Bago 582 and 583	**UT, T2**	**NS**	**NS**	**T2 > UT ($p < 0.0001$)**	**UT > T2 ($p = 0.031$)**
Burrowye 019	**UT, T2**	**T2 > UT ($p = 0.01$)**	**NS**	**T2 > UT ($p < 0.0001$)**	**NS**
Green Hills 845	**T1, T2**	**NS**	**NS**	**NS**	**NS**
Green Hills 849	**UT, T1**	**NS**	**NS**	**T1 > UT ($p = 0.008$)**	**T1 > UT ($p = 0.024$)**
Lucyvale 015 & 018	**UT, T1*,T2**	**T1 > UT ($p = 0.033$)**	**UT > T1 ($p < 0.0001$) UT > T2 ($p = 0.014$)**	**T1 > UT ($p < 0.0001$) T2 > UT ($p < 0.0001$)**	**T2 > T1 ($p = 0.010$) T2 > UT ($p < 0.0001$)**
Magpie 001	**UT, T2, T3**	**NS**	**UT > T3 > T2 ($p \leq 0.012$)**	**T2 > T3 > UT ($p < 0.0001$)**	**NS**
Oaks Creek 1012	**UT, T2**	**NS**	**UT > T2 ($p < 0.0001$)**	**T2 > UT ($p < 0.0001$)**	**UT > T2 ($p = 0.002$)**
Oaks Creek 1195	**UT, T2**	**NS**	**NS**	**T2 > UT ($p = 0.0016$)**	**NS**
Splitters 1181 & 1182	**UT, T1**	**NS**	**NS**	**NS**	**NS**
Toorour 014 & 016	**UT, T2**	**T2 > UT ($p < 0.0001$)**	**NS**	**NS**	**UT > T2 ($p = 0.040$)**

*T1 one year earlier at LV015 compared to LV018

In general, in cases where there was an effect of thinning on OWD, it was the thinned stands that had the higher OWD, rather than the unthinned (UT) stands. There was no indication in these data, however, that the timing of the thinning (i.e. how recent it was) had any effect on whether or not a difference was found. For example, both Burrowye 019 and Oaks Creek 1195 had a second thinning in 2011, but in the latter case, no difference was found in OWD.

In cases where AWV differed significantly between thinning treatments, UT trees had greater AWV than those which had been thinned. There was no indication that sites where thinning had significantly changed AWV were the same sites where OWD had been increased or decreased (e.g. the Magpie sites).

As would be expected, in cases where a DBH effect was found, thinning always increased DBH compared to unthinned stands. There was no evidence that a second or third thinning increased DBH over a first thinning. In three out of the five cases where a difference in height was found, trees in UT stands were taller.

Multiple regression

In the FWPA-funded Tasmanian resource evaluation (Cown et al., 2006b), a regression relationship between tree age, average maximum temperature and site index was identified that explained 74% of the variance in OWD (Equation 2). That study included a broader range of age classes than the current study, and given the age-related effect on wood density, would consequently be expected to account for a greater proportion of the variance.

OWD = 120.81943 − 0.2079214(S I) +18.295311(AveMaxTemp) + 0.44411859(Age)…………..Equation 2

This relationship was assessed using the current data set (Table 5) and calculating a site index value based on Equation 1 reflecting mean dominant height at age 20. The resultant regression explained only 10% of the variance. Only stand age had a close to significant effect.

Table 5: Summary of the application of the Tasmanian OWD model to the Murray Valley data

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	478.2	76.9	6.217	1.08e-07	***
Site Index	-0.182	1.27	-0.143	0.89	
Annual Max. Temp (oC)	-4.24	2.95	-1.436	0.16	
Stand Age (yrs)	2.34	1.184	1.979	0.053	.

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05'.' 0.1

Alternative regression models were explored using stepwise regression approaches for both OWD and AWV. In general, regression analyses were more effective at explaining AWV than OWD, as might be expected from the correlation matrix presented in Table 3.

<u>Multiple regression to predict Outerwood density</u>

The regression model summarised in Table 6 explained 38% of the variance in OWD.

Table 6: Overall regression model predictors

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	1006.3	243.2	4.138	0.0002	***
Site Index	-11.18	4.24	-2.640	0.011	*
Branch Diameter	-1.63	0.509	-3.204	0.0025	**
DBHOB	0.147	0.085	-1.720	0.092	.
Annual Rainfall	0.071	0.0485	1.458	0.152	
Annual Temperature	-15.92	8.310	-1.915	0.062	.
Annual Evaporation	0.212	0.136	1.555	0.127	
Annual Radiation	-0.091	0.043	-2.126	0.039	*
Tree Height	9.60	3.523	2.726	0.009	**

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05'.' 0.1

- Residual standard error: 24.8 on 44 degrees of freedom
- Multiple R-squared: 0.4723, Adjusted R-squared: 0.3764
- F-statistic: 4.923 on 8 and 44 DF, p-value: 0.0002195

Simplifying the above (equation 3), still explained 33.0% with a residual standard error of 25.9 kg/m3

OWD = 396.6 - 1.93 * Branch Diameter + 0.174 * Spring Rainfall + 2.43 * Age Equation 3

Given the combination of silvicultural treatments in the sites (i.e. where thinning treatments have been included as separate "sites" at adjacent locations), regressions were fitted to subsets of the site list categorised as unthinned (19 sites) and single thinning (T1) (21 sites). Regressions fitted within these categories performed better. Equation 3a (UT sites) explained 55% of the variance in OWD with a standard error (SE) of 23.4 $kg.m^{-3}$.

UT_OWD = 392 – 2.36*Branch Diameter + 0.63*Autumn Rainfall + 4.64*Max. Autumn Temp. + 2.45*Age Equation 3a

Equation 3b (T1 sites) explained 77% of the variance in OWD with a SE of 17.1 $kg.m^{-3}$. While demonstrating the ability to explain variance in OWD, this relationship has a large number of independent variables (relative to the number of sites), of which "Age" accounts for 20% of the variance.

T1_OWD = 1187 - 2.26*Branch Diameter - 0.476*DBHOB - 0.066*Annual Rainfall - 21.55*Ave. Temp. -0.07*Annual Radiation + 10.1*Age Equation 3b

Multiple regression to predict standing-tree acoustic velocity

Standing tree AWV was better explained by site level variables, with an R^2 of 67% (Table 7).

Table 7: Predictors for the overall model of AWV

Coefficients:	Estimate	Std.Error	t value	Pr(>|t|)
(Intercept)	17.35	2.245	7.730	<0.0001
Site Index	-0.198	0.085	-2.320	0.025
Branch Diameter (mm)	-0.010	0.0038	-2.691	0.010
DBHOB (mm)	-0.0032	0.00064	-4.939	<0.0001
Annual Rainfall (mm)	0.00066	0.00039	1.702	0.096
Annual Temperature (oC)	-0.21	0.067	-3.123	0.003
Annual Evaporation (mm)	0.0041	0.0012	3.518	0.001
Annual Radiation	-0.0023	0.00036	-6.198	<0.0001
Tree Height (m)	0.197	0.074	2.663	0.011
Age (yrs)	-0.038	0.025	-1.534	0.13

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05'.' 0.1

- Residual standard error: 0.1872 on 43 degrees of freedom
- Multiple R-squared: 0.7252, Adjusted R-squared: 0.6677
- F-statistic: 12.61 on 9 and 43 DF, p-value: 1.678e-09

A simpler model (Equation 4) still explained 59%, with each of the predictor variables having a highly significant effect, and a residual standard error of 0.208 ($p < 0.0001$)

AWV (ST300) = 12.06 - 0.11*SI - 0.0139*Branch Diameter - 0.003*DBHOB - 0.0011*Annual Radiation + 0.119*Tree Height Equation 4

As with OWD, relationships within the UT and T1 categories were examined. No improvement in variance explained within the UT set was found. Some improvements in the amount of variance explained by the model were observed within the T1 category, but not to the same degree as with OWD. In selecting variables for multiple regression, co-linearity among the independent variables is evident and often resulted in different variables being selected when subsets were used.

Principal components regression

Partial Least Squares regression (PLSR) is a statistical approach to relate variance among a large set of independent variables (i.e. site and related weather averages) to variance in a dependent variable (e.g. OWD and AWV). This approach is often used when more traditional multiple regression approaches are invalidated by a large degree of co-linearity among the independent variables (e.g. NIR spectroscopy). The variation among the larger independent data set is reduced to a smaller number of uncorrelated variables (principal components), and these used to predict variance in the dependent variable. The purpose here is to establish, in the available data set, the maximum amount of explained variance we might expect to explain using empirical approaches.

With respect to OWD, 44% of the variance was explained in the fitted model (Figure 3a), which reduces to only 20% in the cross-validation model (Figure 3b). The latter is the result of a calibration being fitted to all the data set leaving out a single site, and using that site to compare with predicted actual values. This is repeated sequentially until all sites have been excluded and the average variance explained determined. Model performance was better with AWV, with the fitted model explaining 74% of the variance (Figure 3b) and the cross-validation model explaining 53% (Figure 3b)

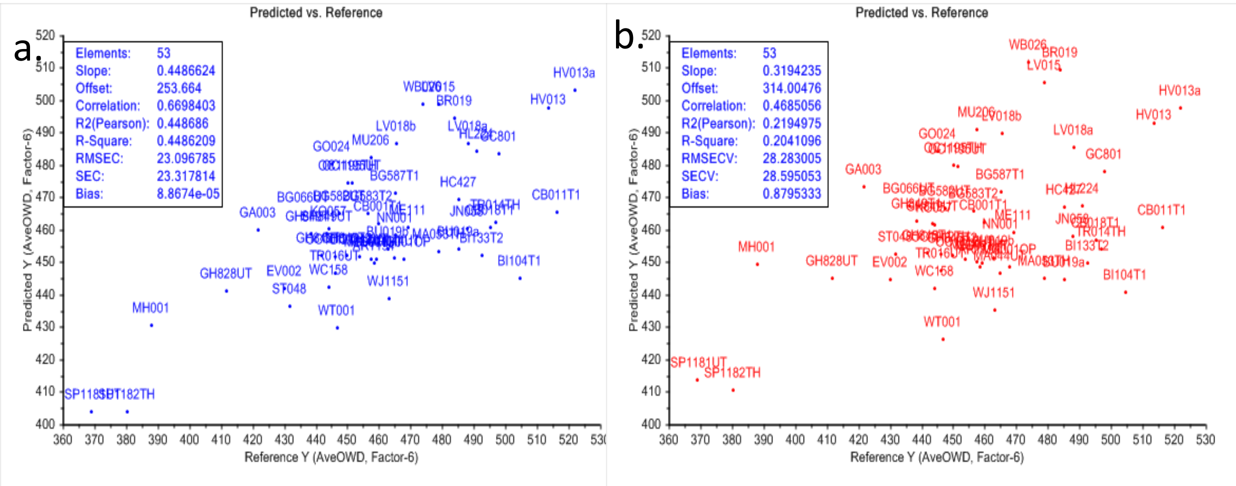

Figure 2. PLS regression showing fitted model using 4 factors to predict outer-wood density

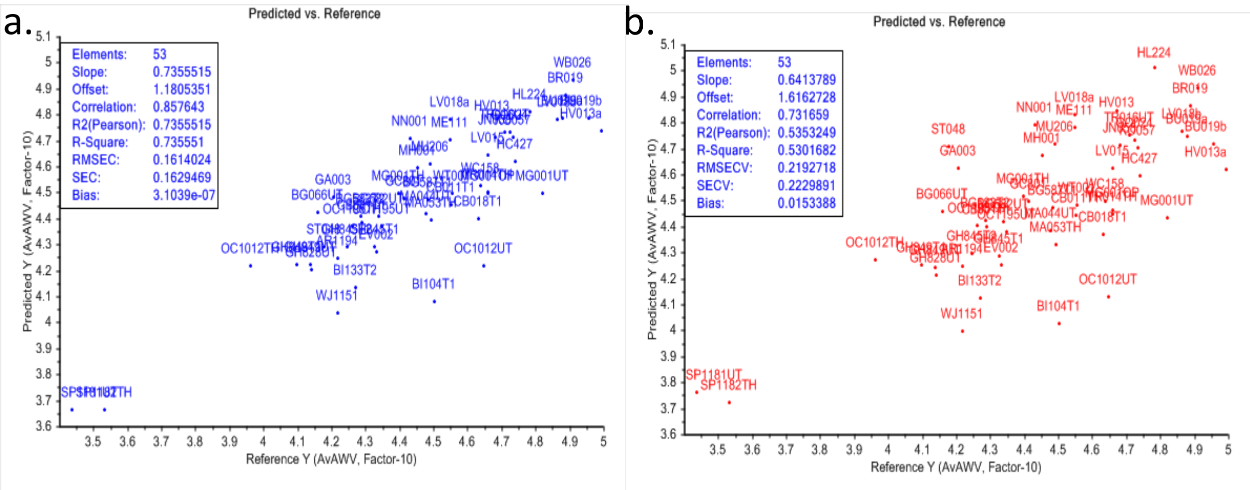

Figure 3. PLS regression showing fitted model using 10 factors to predict standing-tree acoustic velocity

Discussion

Predicting outerwood density via empirical regression analyses using site and weather variables as predictors did not explain as much variability has did other studies (e.g. the FWPA Tasmanian radiata pine resource evaluation (Cown et al., 2006b) or the NZWQI Benchmarking study (Cown et al., 2005b)). Relationships were stronger within silvicultural categories (e.g. UT or T1). Standing tree acoustic wave velocity was better explained by the available predictors. This study included a significant number of ex-pasture sites, and these were found to be an important driver of site-level wood property variance. Thinning treatments also had significant effects, predominantly on acoustic wave velocity. Plantation age also explained some variance in outerwood properties, despite the relatively mature age of the plantations sampled.

Age had a significant effect on OWD

The prediction of BH outerwood properties in mature age plantations is probably the hardest task for a model such as eCambium. The study demonstrated the wide range of site average properties that exists in the Murray Valley basin resource, with outerwood basic density varying from 368 to 520 kg.m^{-3} and AWV from 3.4 to 5.0 km.sec^{-1}. By limiting the age range to the end-of-rotation stands, the outer 50mm ideally represents wood in which the variability due to age has plateaued (Figure 4a), effects of thinning are minimal, and we are not "stacking the odds" by predicting across a wide age range where natural variation artificially improves the predicted vs. actual r-squared (Figure 4b).

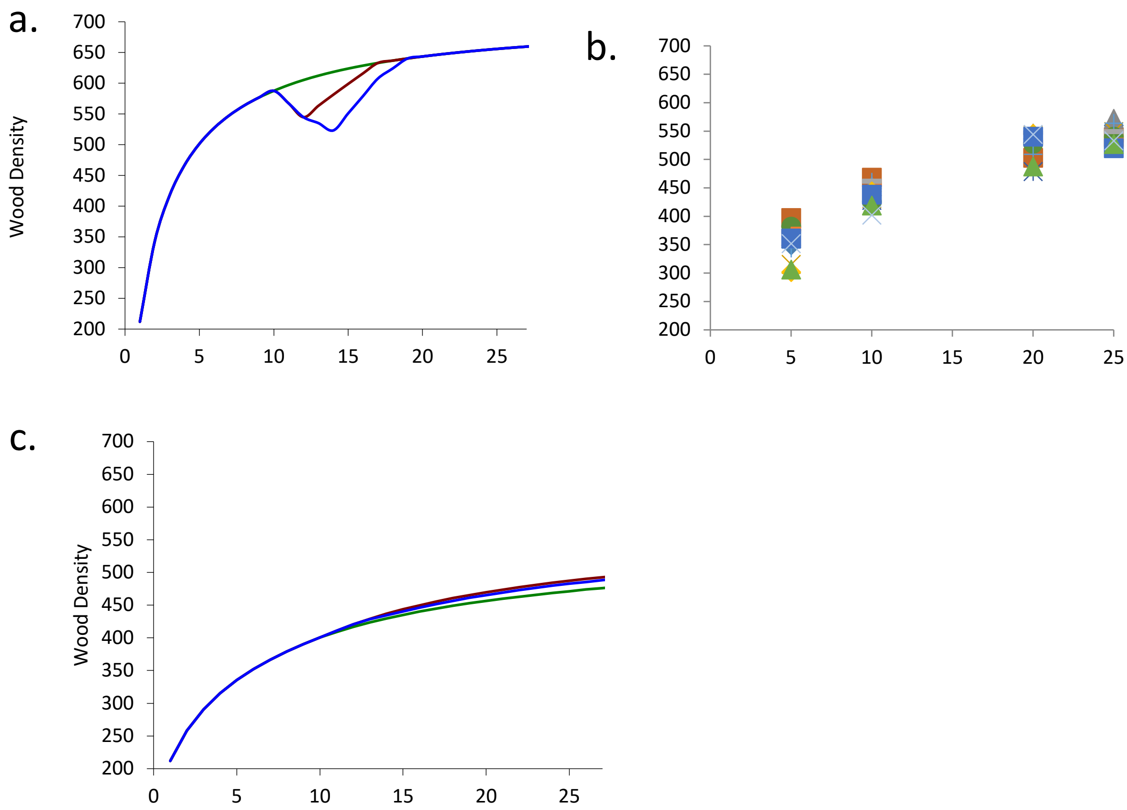

Figure 4: Hypothetical radial patterns of (a) annual wood density variation with the effects of thinning and fertilisation added. (b) hypothetical outerwood density trend if sites were sampled at different ages. (c) sum of the effects in (a) with the change in average core density if the entire radius was sampled at a given age.

The suite of figures presented in Figure 4 were obtained from a simulation model developed to help explain the effect of thinning and fertilisation on average wood properties in a previous FWPRDC study (Nyakuengama et al., 2001). The effects on ring width (volume) and annual density were simulated to levels consistent with patterns found in the actual data, to assess the likely effects on whole-core (i.e. full radius) and log average properties. Whereas Figure 4a shows the radial trend in annual ring density, Figure 4c shows the same data except that the radial whole-core average is shown as if the core was sampled at different stand ages. This study demonstrated the potential for mid-rotation thinning and fertilisation to actually increase core average density, even though the local effect within the radial trend was to reduce density. This is to the annual average density, while significantly reduced after thinning, being typically greater than the juvenile core density, and combined with the greater volume of wood (wider rings) *could* increase whole-radius core density. This scenario is consistent with some of the findings in this study, where thinning tended to increase OWD.

However, measuring, OWD by using the outer 50mm also introduces random variance. It is self-evident that if OWD is assessed using a constant radial length (50mm) then smaller diameter trees will be represented by a proportionally greater amount of younger wood. As both annual average wood density and MOE tend to increase radially, particularly over the first 8-15 years, sampling a greater proportion of the radius can tend to artificially reduce mean density. Figure 5 attempts to illustrate this effect using 2 contrasting radial profiles of wood density, over the same time period but differing only in terms of stocking. In Figure 5a, the outer 50mm contains approx. 9 annual rings. In contrast in Figure 5b an unthinned tree is illustrated and the outer 50mm contains approx. 15 annual rings and projects well into the juvenile core. In contrast the outer 5 years are well beyond the juvenile core in both profiles and it is evident that the annual rings in the more open-grown scenario contain a greater proportion of earlywood, bringing down the average density.

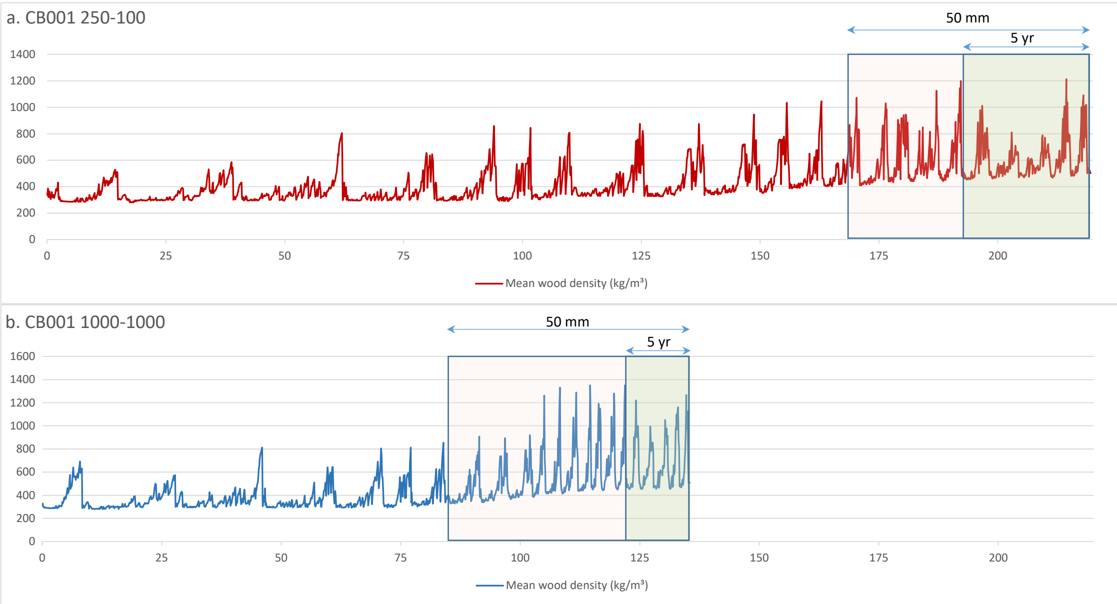

Figure 5. Two contrasting eCambium simulations of radial variation in wood density grown at the same site under identical weather conditions but varying only in initial and final stocking. (a) was established at an initial stocking of 250 sph and thinned to 100 ate age 8. (b) was planted at 1000 sph and unthinned throughout the 23 year rotation. Nb the effect of thinning in (a) is evident in after year 7, and the first year is only part of a ring. This reflects the time taken for the tree to reach 1.3m, the height at which the predictions were made.

Regression analysis did not explain as much variation in OWD as did the Tasmanian FWPA study

In 1976, Hal Fritts in his seminal book "Tree Rings and Climate" (Fritts, 1976) described tree growth and annual ring formation in terms of limiting factors. Tree growth will vary across sites, years and seasons dependent upon what is limiting growth at any given point in time. If growth is limited by drought during summer, for example, growth will be slowed or stopped. A rainfall event removing this limitation would allow growth to be resumed up to the rate allowed by the next limiting factor. This rate will vary; at some sites, nitrogen might be limiting to lesser or greater degrees. At other sites, available photosynthate may be limiting due to the amount of needle lost as a consequence of the previous drought. These qualitatively different conditions will also vary quantitatively to greater or lesser degrees.

Empirical modelling approaches (i.e. models based entirely on a statistical model fitted to past data) are thus limited in their ability to capture these physiologically-linked, and time-related variations. Consequently, regional regression relationships that hold in one region (e.g. the Tasmanian resource evaluation project, or the NZWQI benchmarking study) will have no or limited application in another. Thus it is not surprising the Tasmanian relationship did not perform well across the sites in the Murray valley. Even so, the fitted regression explained less variation than might have been expected, partly because of the narrower age range, with only 7 of the 53 sites falling outside the 25-30 year age class (Figure 6). Age accounted for only 26% of the variance in this study compared to 32% in the Tasmanian study, which included more slightly younger sites.

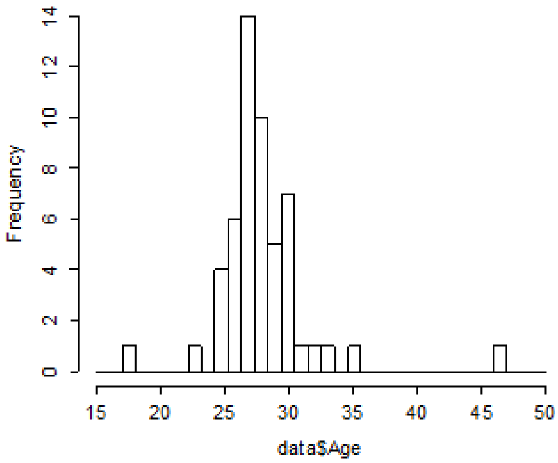

Figure 6. Age class distribution of the sampled sites in the Murray Valley basin.

More significantly, the Murray Valley study included a greater proportion of silvicultural comparisons (thinning effects) than other studies. Although these had relatively little effect on outer-wood density, regressions explaining variance in OWD performed better within UT and T1 categories than they did in the combined data set.

AWV better explained than OWD and by a wider range of variables.

Site average standing-tree AWV was well correlated (R^2 = 45%; $p < 0.0001$) with OWD, but more weakly than found in the Tasmanian study (R^2 = 81%) (Cown et al., 2006b), the NZWQI Benchmarking study (R^2 = 81%) (Cown et al., 2005b) and the Green triangle study (R^2 = 55%) (McKinley et al., 2003a). The Tasmanian study tended to have lower stiffness values in general than those reported here, a trend that is consistent with general temperature and latitude effects described elsewhere (Cown et al., 2006b). AWV was also better explained by site and weather variables in all empirical approaches. Simple correlation suggested that solar radiation (particularly in winter) was significantly related to outerwood stiffness, perhaps indicating a latitude effect, with more northern trees tending to have longer, warmer winter days, and hence perhaps a greater opportunity to produce higher density latewood.

The predictors used in the multiple regression analyses made intuitive sense with larger branch diameter and DBH reducing AWV (greater earlywood with its higher microfibril angle (MFA)), and taller trees increasing AWV (e.g. previous studies show that increasing site average slenderness (stocking) increases stiffness (Watt and Zoric, 2010)).

PLS regression for both OWD and AWV produced significant models. The commercial robustness of these models would require their testing against an independent data set. The relationship might be expected to hold for sites within the Murray Valley, but unlikely to be applicable within other regions.

Ex-pasture is an important driver of wood quality

In the late 1980's a significant effort was directed at understanding the effect of nitrogen availability on tree growth and form in young radiata stands (Downes and Turvey, 1992). This was driven by the observed effect of fast-growth on tree form, mediated by the establishment of plantations on ex-pasture sites. Carlyle et al. (1989) showed that the high levels of nitrate associated with ex-pasture was qualitatively different from the more ammonifying soils of ex-native forest, and related to the rapid growth flushes associated with spring growth, driving the increased sinuosity on ex-pasture sites (Turvey et al., 1993). An extensive breeding program, selected for resistant genotypes and largely minimised the problem, albeit with some suggestion (Downes and Turvey, 1992) that in doing so, trees were being selected for reduced height growth.

As has previously been reported for *P. radiata* (e.g. (Beets et al., 2001), it was evident in this study that previous improved pasture has a profound effect on wood density/stiffness in the first rotation, even after more than 20 years, and must be taken into consideration. Branch diameter seems to provide a good indicator of whether or not a site was a fertile ex-pasture site and can indicate possible low density/stiffness wood. It was interesting, in that context, that site index was a far poorer predictor of AWV or OWD than branch diameter. Site index is a highly integrating variable, taking into account temperature, drought, and other site factors as well as fertility.

In this resource, elevation did not represent an important direct source of OWD or AWV variation. Nor did it appear that this was obscured by the effect of ex-pasture fertility on lower elevation sites. Possibly, the relatively cold nights that would be expected even at the lower elevations in this region, reduces the apparent effect of elevation. It is noteworthy, for example, that some sites at relatively low elevations (~300 m ASL) had lower mean minimum temperatures than higher sites (~700 m ASL) over the last rotation (based on the interpolated weather data).

Thinning had significant effects on wood properties

As mentioned above, a previous FWPRDC study investigated the effects or later-age management in radiata pine (including a site from Carabost), the improved volume growth mediated by thinning and fertiliser application on wood properties, and consequent sawn board volumes and value (Nyakuengama et al., 2001). Effects of thinning and fertilisation applied in mid-rotation reduced density and stiffness, but at a time when wood was being produced outside the juvenile core. The greater volume of mature wood, was of sufficiently high stiffness to not reduce the value (Downes et al., 2002a). It was also noted that under some conditions, while thinning might cause a local, temporal reduction in density within a radius, the overall effect on average radial density could be unaffected or even slightly increased (e.g. Figure 4c above).

Based on the analyses conducted in this study, it was not possible to draw general or consistent conclusions about the effects of thinning on OWD and AWV. It did appear, that thinning, when it has a significant effect on outerwood properties, could be advantageous in increasing diameter growth as well as OWD. There was no evidence that it would have a deleterious effect in either case. On the other hand, wood stiffness (as measured using the ST300) is affected by other factors, and (at least in the outer wood) may still be higher overall in unthinned stands.

Given the timing of the thinning events (late in the rotation) and the age of the stands sampled, it is not surprising that effects on outer wood properties were minimal. It is important, in assessing the effects of thinning, to also consider the pith-bark and ultimately whole-of-log mean wood density and log stiffness.

eCambium predictions of standing-tree wood properties

The eCambium forest growth and wood properties simulation tool (Version 1) was first developed in the FWPA project PNC 191-1011, using a *P. radiata* dataset predominantly from the Green Triangle (South Australia), as well as some sites from Gippsland (Victoria) and New Zealand. The first version of the model, which relied heavily on Cabala inputs (Battaglia et al., 2004), performed sufficiently well to warrant evaluation across a wider range of growing conditions and further develop the internal tree growth model (IGM) as an alternative to Cabala.

In this section, we evaluate eCambium performance in the prediction of OWD and MOE work in the Murray Valley region sites described above. Compared to the previous project, the internal growth model (IGM), adapted from 3PG, was further developed and tested. Important changes were also made to the wood properties prediction module as follows.

eCambium version 2 was released as part of the current project (V 2.0; June 2015) and incorporated a number of changes. The model still rests of four data input types:

1. Site: Information describing site location and soil characteristics
2. Silviculture: Data describing silvicultural history (in simplified terms)
3. Weather: Daily rainfall, temperature, incoming solar radiation and relative humidity data
4. Genotype: A parameter set (genotype) bounding model assumptions

Major improvements over the previous version are

- Speed: The software is dramatically faster, completing a run in a fraction of the time it took in version 1
- Stability: Simulations are more stable, providing reasonable results across a broader input data and parameter space
- Patterns: Patterns of fine-scale variability more realistically reflect actual SilviScan data.
- Parameters: The IGM and wood formation modules both use fewer parameters, simplifying setup.
- Generality: The new version has predicted variation significantly in resources in completely different regions (northern Tasmania, Murray Valley, Green Triangle) using the same parameter set.

The IGM has been further developed. Key changes have been the modification of approaches to the calculation of some relationship modifiers to reduce parameter numbers and calculation complexity. A number of additional changes have also been made to the software interface. The GUI of version 2.0 provides the following additional displays and options

- A summary of stand volume and tree height for each scenario on the main display table
- The option to show wood density as “air-dried” (to compare with SilviScan data) or “oven-dried”
- A new tool for scenario exploration that allows the user to toggle site, weather and silvicultural values “on the fly” and quickly assess possible growth and wood property implications.

The model operates in the context of a daily time step. All variables are re-calculated to take account of daily changes in weather and other variables at three scales

- Stand: Stand-level calculations of canopy development and rates of carbon sequestration, allocation and water use.
- Tree: Stand-level data is used to calculate attributes of a conceptual “average tree in the stand”.

- Stem position: Tree-level information is used to calculate a set of variables at the within-stem position where the user wants to simulate wood formation (e.g. breast height)

The first of these three broad steps can be performed using other modelling tools if available. At present, the eCambium software allows the user to link to scenarios run using the CaBala modelling system. However, the usual application would utilise the IGM. The model essentially performs calculations along a cascade of scales: stand level to tree level to a position in the stem and finally to a single file of conceptual developing cells. Data from this last step then needs to be up-scaled to provide higher-level estimates. Changing scales is a potential source of error which needs to be considered when testing model outputs.

The essential logic of a simulation loop is shown in Figure 7.

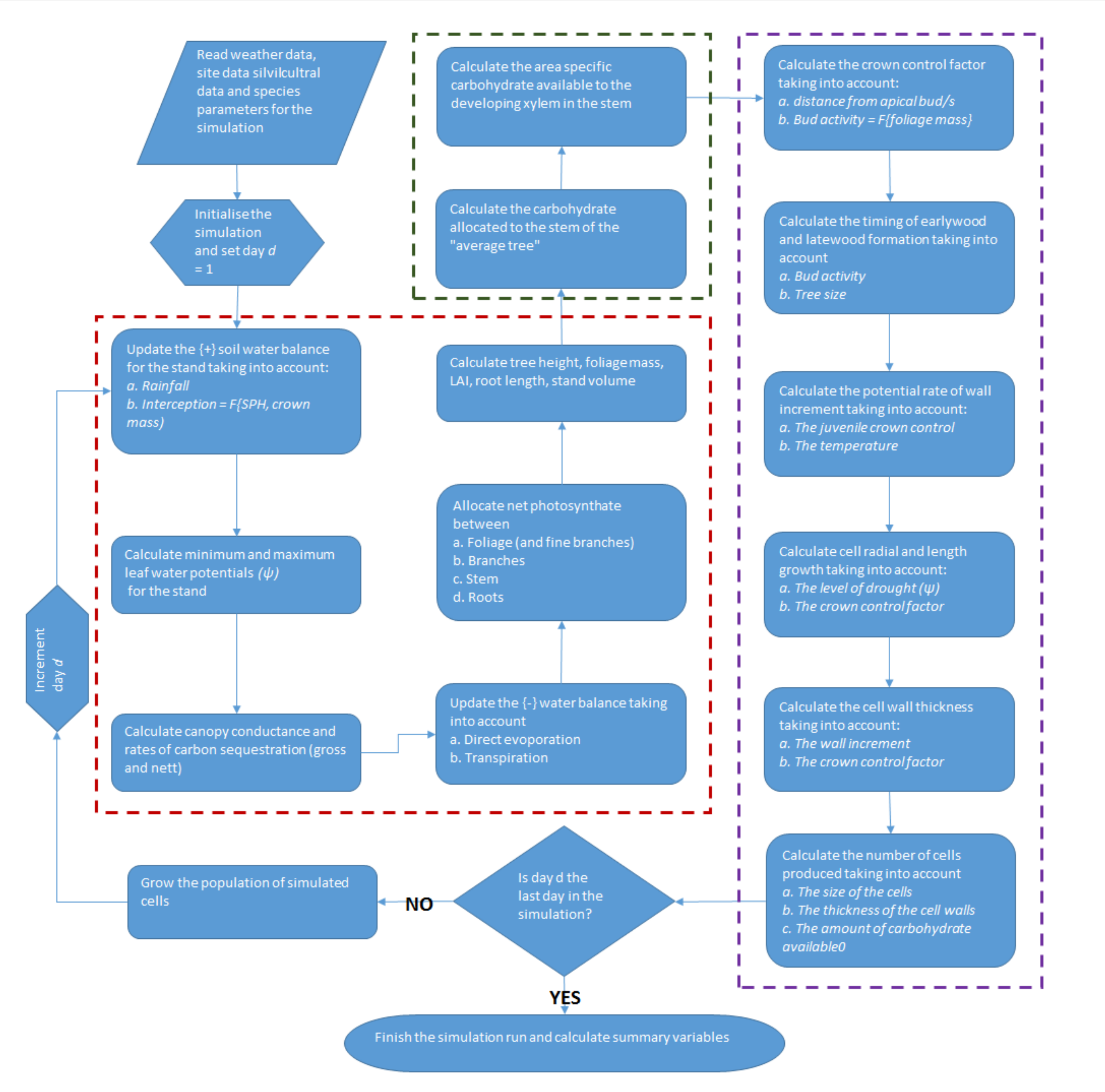

Figure 7. The logic of a simulation loop in eCambium v2. The steps within the red block are stand-level calculations (IGM), within the green block are "average tree" level calculations and the purple block are calculations performed at a position of the stem.

Software overview

The main window of the eCambium graphical user interface (GUI) provides a summary of all scenarios in a project (Figure 8). A more detailed user guide is included in Appendix 1. For each scenario, a summary is provided of predicted under-bark stem diameter (at the modelled position), tree height, stand volume, wood density and MOE (outer, inner or whole core). Scenarios fully simulated in the eCambium environment have blue backgrounds, while those linked to CaBala simulations have green backgrounds.

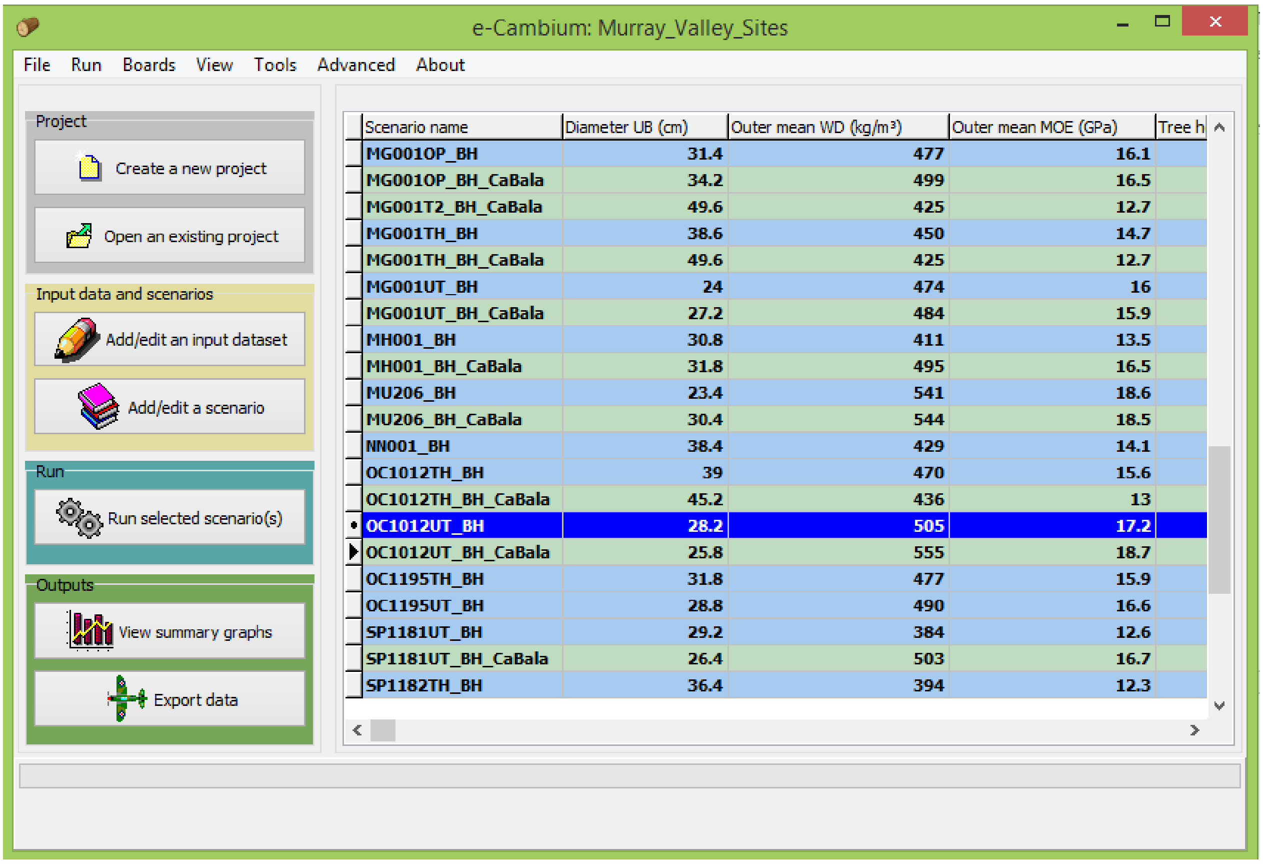

Figure 8: Main model window, showing function buttons and scenario summaries

The model produces a series of outputs describing tree growth at increasing levels of detail. Shown below are outputs predicted from an unthinned stand at Oaks Creek. Figure 9 shows the main graphical output of the software, with a trajectory of predicted annual mean MOE, representation of a log end at the modelled stem position (showing rings and also with hypothetical boards superimposed) and a proportion of the expected log grades if the modelled position was the small end.

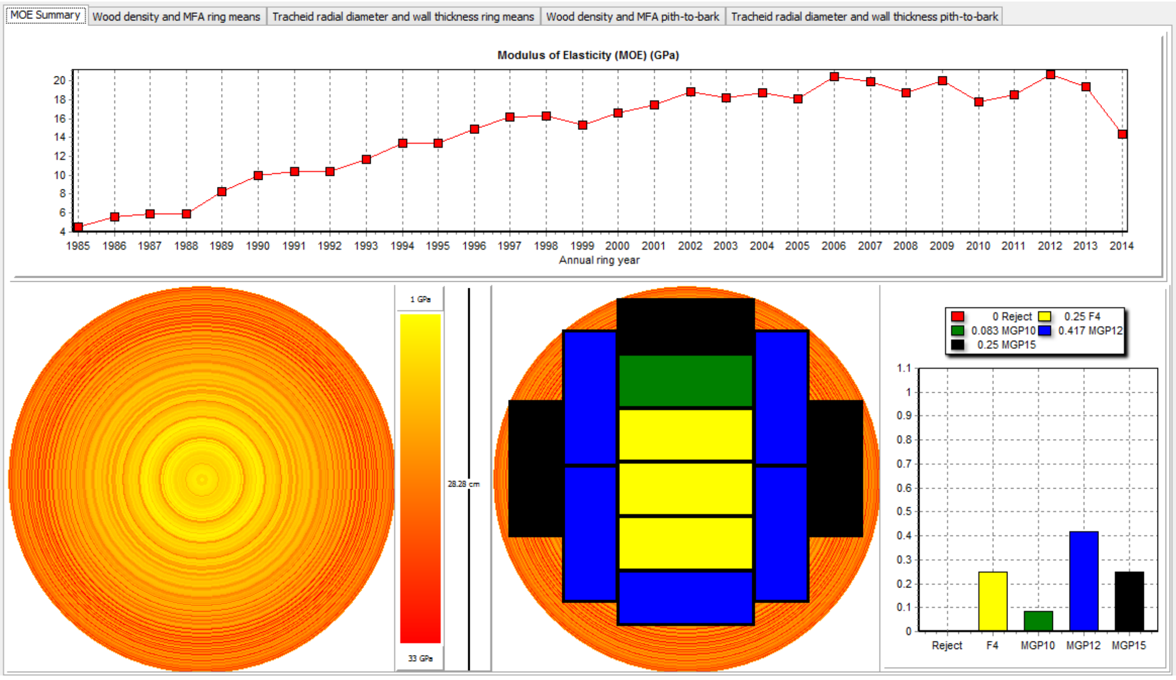

Figure 9. Main model output summary screen

The software also provides output graphs of ring mean wood density (Figure 10), MFA, tracheid radial diameter and tracheid wall thickness.

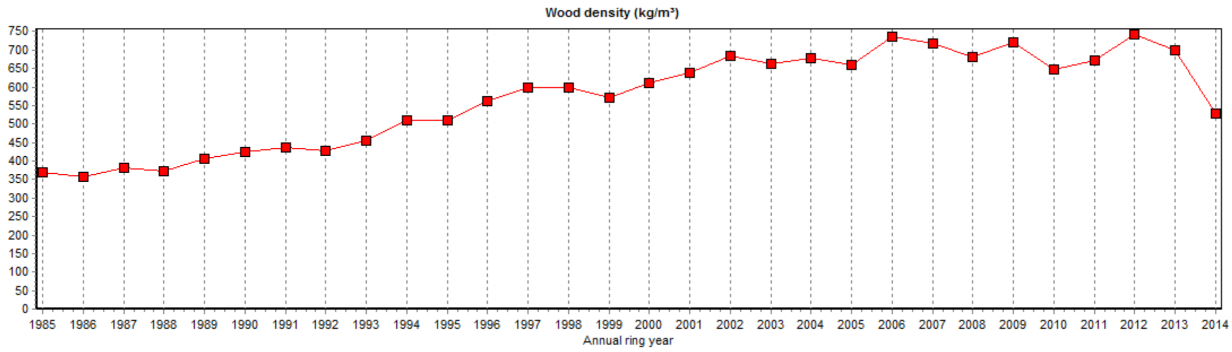

Figure 10: Model predictions of pith-to-bark variation in ring mean wood density

The user can drill down to higher levels of detail as required; graphs of pith-to-bark variation in wood properties can be viewed against the distance from the pith (rather than ring average data) (Figure 11).

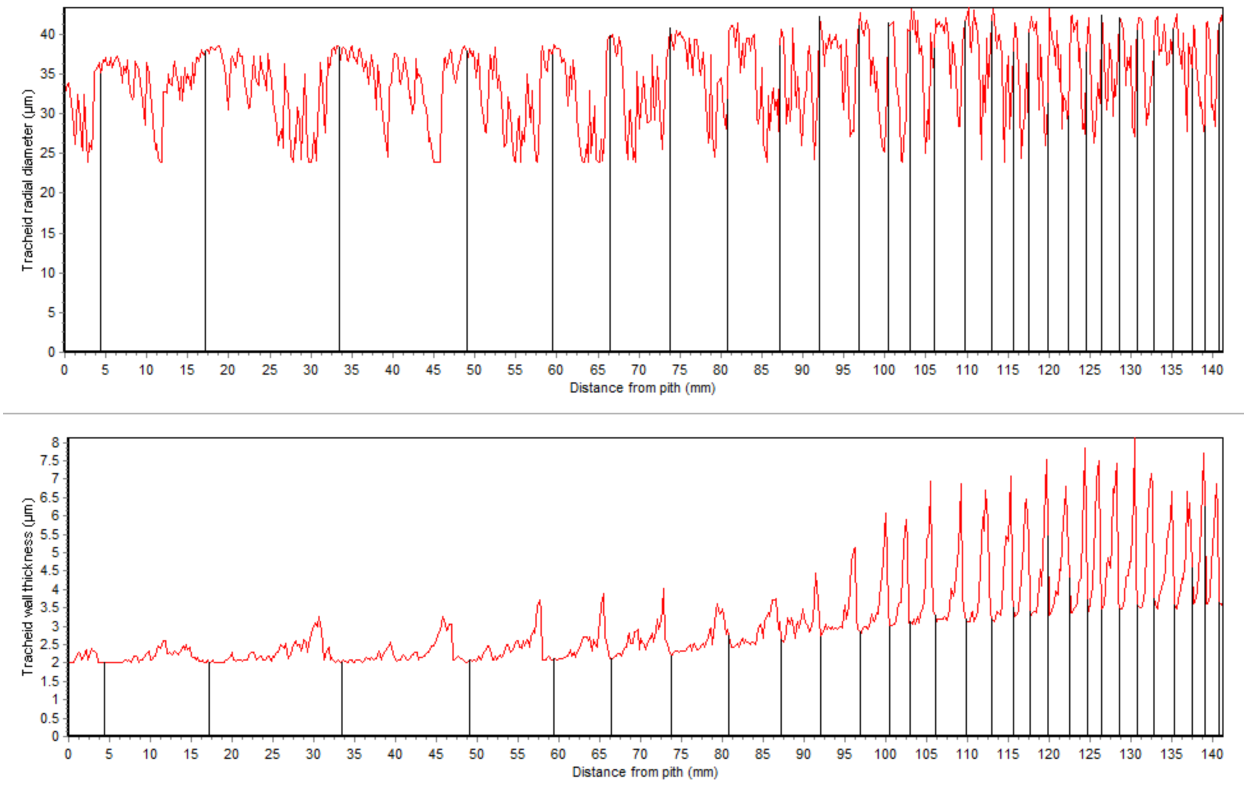

Figure 11. Model predictions of pith-to-bark variation in tracheid radial diameter and tracheid wall thickness

In addition to predictions of wood properties, the software also provides graphs of tree growth variables, such as DBH, height, stem biomass etc.

The software allows the user to simulate diameter growth and wood properties at any point up the stem (Figure 12).

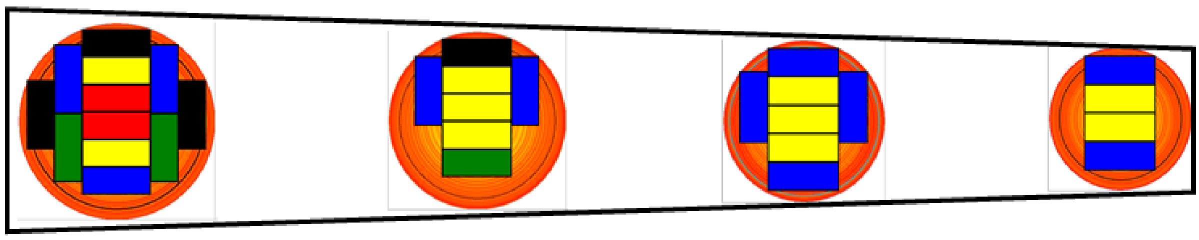

Figure 12. Representation of a log from breast height (1.3 m) to 7m with predicted boards at 1.3 m, 3m, 5m and 7m.

Model setup

The approach in the eCambium GUI, similar to that used in the CaBala system, is to combine parameter, site, silviculture and weather information into "scenarios". For example, in two scenarios, site, weather and parameters may be the same, but with differing regimes (e.g. planting density or timing of thinnings). This is basic to the modelling approach. Thus eCambium provides the user with the option to predict what is actually at a given site, but also what might have been if a different silvicultural regime had been employed.

A preliminary set of parameter ranges[5] was developed which performed stably across all simulation runs in the project dataset (Summarised in Appendix 4: Model parameter values and description).

Parameters

Parameters were estimated as far as possible from data in the literature (including 3PG parameters applicable to the model as it is implemented in eCambium) and from the SilviScan data obtained in this study. For example, it was possible to measure maximum and minimum tracheid dimensions and wall thickness. These values were not optimised. The more empirical parameters, e.g. k and m in the wall thickness and tracheid development relationship, were estimated by ad-hoc adjustment that led to best fits at the same time as giving best possible representation of pith-to-bark patterns of variation.

Exhaustive exploration of the parameter space for large numbers of sites is impractical in the eCambium framework, even given the much higher run speed of version 2. It is possible to do piece-meal exploration of certain categories of parameters to get a good indication of best estimates. To test the model's generality across *P. radiata* OWD data from sites across the SE of Australia, a small calibration and validation was done on the "k" and "m" parameters that determine the behaviour of tracheid diameter and wall thickness in relation to the crown control of the tree. 125 sites, from N Tasmania, the Green Triangle, southern and northern Victoria and southern NSW were used (the 53 sites from the present study were included). 60% of these sites were randomly selected for calibration of the k and m variables, and the remaining 40% were left out as validation sites.

Sites

As described above, 53 sites/scenarios were selected for sampling (Table 2). In many cases "sites" were sampled within the same or adjoining compartments to allow silvicultural variations to be compared. Hence, individual site codes essentially represent scenarios, not necessarily different sites, *per sé*.

Soil descriptions

Describing a site for a modelling exercise is typically open to a large amount of subjectivity in defining characteristics such as rooting depth, fertility, even soil texture class. To achieve a consistent approach to soils descriptions for all sites in the study, descriptions were developed from the Soils and Landscape Grid of Australia[6] (see www.asris.csiro.au and http://www.clw.csiro.au/aclep/soilandlandscapegrid/). A soil texture class was calculated from the relative proportions of silt, clay and sand in the top 60 cm. Soil available water holding capacity (AWHC) was calculated for the top 60 cm in each case, and the model maxima and minima for this quantity (field capacity and permanent wilting point) were adjusted accordingly, calculated as a function of texture.

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[5] In these modelling exercises it is easy to get caught up into a false level of precision, and adjust parameters to fit data. However these values do exist as ranges than discrete accurately definable numbers.

[6] In the previous development project and in the initial stages of the current study, the approach to describing a site in terms of soil depth, texture and water holding characteristics was identified as a major issue, owing to the expense of collecting such data and the subjectivity that was likely to exist between different users. Particularly with respect to site fertility, soil depth and texture. In using the ASRIS approach, site descriptions can largely be "automated" based solely on latitude and longitude. It opens the possibility that in future software development, site descriptions could be automatically completed based on geographical position by scraping data from publically available web sites.

As the usefulness of the interpolated soils dataset was considered dubious for the determination of a fertility rating (FR), FR was set at 0.3 for all sites. Overall there was no significant relationship between the N content or C:N ratio in the predicted data from the interpolated soils grids and actual data obtained from the study sites (R^2 = 0.088 and R^2=0.058 respectively) (see below). Rock content was set to zero at all sites, as no information was available for this parameter. Increasing rock content reduces soil water holding capacity. It is expected that a "coarse fragments" estimate will be added to the Australia-wide soils database in the near future.

Taking into account other data and information

As a second step, soil descriptions were made and samples taken from 24 sites (representing 32 scenarios) in April 2015 (Table 8). The following parameters were assessed on soil samples taken from 0- 15 cm and 30 – 60 cm:

- Nitrogen
- Bray Phosphorus
- Texture
- Permanent wilting point and field capacity

Table 8. Summary of soils data obtained in sampling in April 2015

Site code	Soil depth (m)	Sand %	Clay %	Assigned texture	Rock prop. (%)	Max ASW (mm/m)	Min ASW (mm/m)	C (%)	N (%)
BG066	1	49.7	23.2	Sandy clay loam	30	369	154	3.4	0.2
BI104	1.1	44.9	30.4	Clay loam	0	282	123	1.3	0
CB001	1	39.5	30.1	Clay loam	5	273	116	1.5	0.1
GC801	1	62.2	15.2	Sandy Loam	10	390	129	3.1	0.1
GH828	0.8	48.8	27	Sandy clay loam	25	267	113	1.2	0.1
GH845	1	49.2	26	Sandy clay loam	15	247	110	1.5	0.1
GH849	0.8	52.8	21.4	Sandy clay loam	45	300	105	1.3	0.1
MA044	0.9	47.8	26.5	Sandy clay loam	25	267	106	1.7	0.1
SP1181	1	58.4	17.7	Sandy loam	0	195	64	1	0.1
BU019A	1	46.7	27.2	Sandy clay loam	0	268	117	1.3	0.1
EV002	0.7	28.9	35.5	Clay loam	50	425	171	1.4	0.1
GA003	1.5	49.4	25.8	Sandy clay loam	10	288	126	2.2	0.1
HV013	0.8	28.5	35.7	Clay loam	15	320	149	1.7	0.1
HV013a	0.9	28.6	36.3	Clay loam	15	321	160	1.9	0.1
JN058	1	52.5	23.7	Sandy clay loam	10	205	92	1.4	0.1
KO057	1	48.5	25.8	Sandy clay loam	10	247	99	1.3	0.1
ME111	1	33.4	29.9	Clay loam		291	129	1.6	0.1
MG001	1	42.8	26.8	Loam	10	334	124	2.1	0.1
MH001	0.8	50.7	16	Loam	50	263	81	2	0.1
NN001	1	41	26	Loam		299	100	1.2	0.1
TR014	1.2	50.8	22.4	Sandy clay loam	5	340	136	2.3	0.1
TR016	1.2	53.4	20.7	Sandy clay loam	15	338	137	1.9	0.1
WC158	1.2	42	31.9	Clay loam	0	365	167	3.9	0.2

The ex-pasture effect

To cater for the important ex-pasture effect which led to increased fertility, a fertilisation event was added at the beginning of the rotation for all ex-pasture sites in model runs where interpolated soils data were used. Given the strong link between the ex-pasture effect and the diameter of the lower branches, the "Initial fertiliser effect" was calculated as a scaled value of the branch diameters measured at the ex-pasture sites. At sites where actual data on C/N ratio was available (based on samples taken in April 2015), these data were used to calculate fertility rating (Eq. 1)

$FR = 94 \times CNRatio^{-1.73}$…………Equation 1

Silvicultural regimes

Information was provided by FCNSW and HVP and used to set up regimes for modelling (see Appendix 5: Regime descriptions). Regimes were adjusted in cases where inventory, permanent sample plot data, or observations at the sampled locations showed that thinning intensities in records did not match actual stems/ha on the ground at the specific plot location.

Weather data

Weather data for all simulations was obtained from SILO (see www.longpaddock.qld.gov.au/silo/data_available.html). Daily minimum and maximum temperature, total rainfall, incoming solar radiation and relative humidity was extracted for the coordinates of each site rounded to the closest point on the 5 km X 5 km interpolated grid[7].

Simulation runs

Two sets of simulations were undertaken to explore model performance.

- The first was based on the most basic data available directly from interpolated soils grids, which used a constant FR ratio (0.3) and assumed zero rock content.
- The second used data obtained from the field during a targeted set of visits in April 2015 at a subset of sites.

<u>Cabala runs</u>

A set of 25 scenarios were set up in Cabala to compare with runs undertaken using the eCambium IGM. These simulations used the site data derived from the interpolated soils data (soil texture, depth, OC and nitrogen and pH). The regimes were created to be as close as possible to those created in the eCambium runs. In the cases of ex-pasture, heavy fertilisation events were applied. A standard *P. radiata* parameter set was used (provided courtesy of Dr Michael Battaglia and Ms. Jody Bruce (CSIRO)).

SilviScan

Three radial samples from each of 23 sites (Table 9) were sent to FPInnovations, Vancouver, for SilviScan analysis, generating radial profiles of air-dry wood density, cell diameters and wall thickness at 0.025 mm sampling interval and MFA and MOE data at 2 mm sampling intervals. Individual trees from which SilviScan samples were taken were randomly chosen during the

[7] This is quite a coarse grid and will contribute to unexplained variance. Other weather data sources exist (AWAP) but studies suggest they are comparable.

sampling program. A report covering the basic SilviScan analysis was issued by FP Innovations and available to PSC members upon request.

Table 9: Sites for which SilviScan data was obtained

SiteCode	Site & compartment number	Owner
BG066UT	Bago 66	FCNSW
BG587T1	Bago 587	FCNSW
BI104T1	Billo 104	FCNSW
CB001T1	Carabost 001	FCNSW
CB011T1	Carabost 011	FCNSW
GH845T2	GreenHills 844	FCNSW
HL224	Hollands 224	HVP
HV013a	Havilah 013	HVP
KO057	Koetong 057	HVP
MA044UT	Maragle 044	FCNSW
MA053TH	Maragle 053	FCNSW
ME111	Merriang 111	HVP
MG001OP	Magpie 001	HVP
MG001TH	Magpie 001	HVP
MG001UT	Magpie 001	HVP
MH001	Moyhu	HVP
OC1012TH	Oaks Creek	FCNSW
OC1012UT	Oaks Creek	FCNSW
SP1182TH	Splitters	FCNSW
TR014TH	Toorour	HVP
TR016UT	Toorour	HVP
WB026	Warrenbayne 026	HVP
WT001	Wrightleys.	HVP

Assessment of skill

Model performance was primarily assessed against mean wood density of the 50 mm outer-wood cores, as well as acoustic wave velocity (AWV-ST300) measurements (see above). Comparisons used two measures: R-squared and the standard error of the prediction (SEP). While the variance explained in the actual data by the predicted data (r^2) is commonly used a basis for evaluation, it can be misleading if considered in isolation (Downes et al., 2009)[8]. SEP and bias are measures that can be used to assess precision, especially in comparison to the natural variance in the data. For example, the site average outerwood density (OWD) was based on the mean of 30 individual samples (trees). The actual site-based standard deviations obtained in this study ranged from 22.4 to 43.9 kg.m^{-3}. To demonstrate that 2 specific sites are significantly different at the 95% level of confidence, requires that the means are separated by approximately twice the standard deviation. Thus SEP provides a more quantitative method of assessing model predictions. The lower the SEP, the better the model predictions compared to the actual.

[8] See also http://blog.minitab.com/blog/adventures-in-statistics/regression-analysis-how-do-i-interpret-r-squared-and-assess-the-goodness-of-fit

Similarly, r^2 says nothing about any bias in the predicted versus actual measures. If the model consistently over or under-predicts the actual data, the bias (observed – predicted) indicates this.

It is also important to distinguish between statistical and commercial significance. While it is important that the model provides a statistically significant suite of predictions, this is of little value unless it also predicts with commercially significant levels of precision. An r^2 of 20% is probably going to be statistically significant. A commercially useful level of precision is harder to identify[9].

Results

Predictions of mean OWD, AWV, DBH and height

<u>Basic runs</u>

Using data derived from the interpolated Australian soils grids, with a constant site fertility (FR = 0.3) at all sites, and a "fertilisation event" at ex-pasture sites, the model explained over 50% ($p < 0.0001$) of the variation in OWD, with a SEP of 28 kg m^{-3} (representing 5.8% of the mean). The model predicted 37% ($p < 0.0001$) of the variation in ST300 AWV (compared against the mean MOE of the outer 50 mm) (Figure 8).

The model's prediction of OWD was severely affected by over-prediction at Murraguldrie 206 (solid-headed arrow in Figure 8). Removing this site from the analysis increased the R^2 of the actual vs. predicted relationship to 55% and MOE vs AWV to 40%. Also excluding the oldest site in the study (WB026 open-headed arrow) from the analysis, at which the model also over-predicted OWD, increased the R^2 for the OWD relationship to 59%[10]. Accordingly, using the interpolated soils data + information about ex-pasture effects, the model was able to predict nearly 60% of the variation in mean measured OWD for 96% of the scenarios used in the analysis. It is notable in this context that the previous version of eCambium (V1.4) did not significantly predict actual OWD nor did the predicted MOE correlate significantly with AWV in this dataset ($R^2 < 0.1$; $p > 0.8$ for both relationships). A re-development of the modelling approach to handle the different case of the Murray Valley was necessary. The new version of the model did, however, significantly predict variation in OWD and MOE for the sites used in the previous FWPA study ($R^2 = 0.59$ and 0.71 respectively; $p < 0.0001$), using the IGM with interpolated soils data and identical parameter sets to those used for the Murray Valley simulations.

[9] In the authors' discussions with industry representatives, the goal was to achieve an R-squared of 60% as a benchmark for commercial significance in the prediction of DBH and wood density. However, depending upon applications, lower values can be commercially useful (Meder, R., Brawner, J.T., Downes, G.M., Ebdon, N., 2011. Towards the in-forest assessment of Kraft pulp yield: comparing the performance of laboratory and hand-held instruments and their value in screening breeding trials. Journal of Near Infrared Spectroscopy 19, 421-429.)

[10] DBH and height growth was well predicted (compared to PSP and inventory data), although self-thinning at MU206 was not properly captured using the current parameter set.

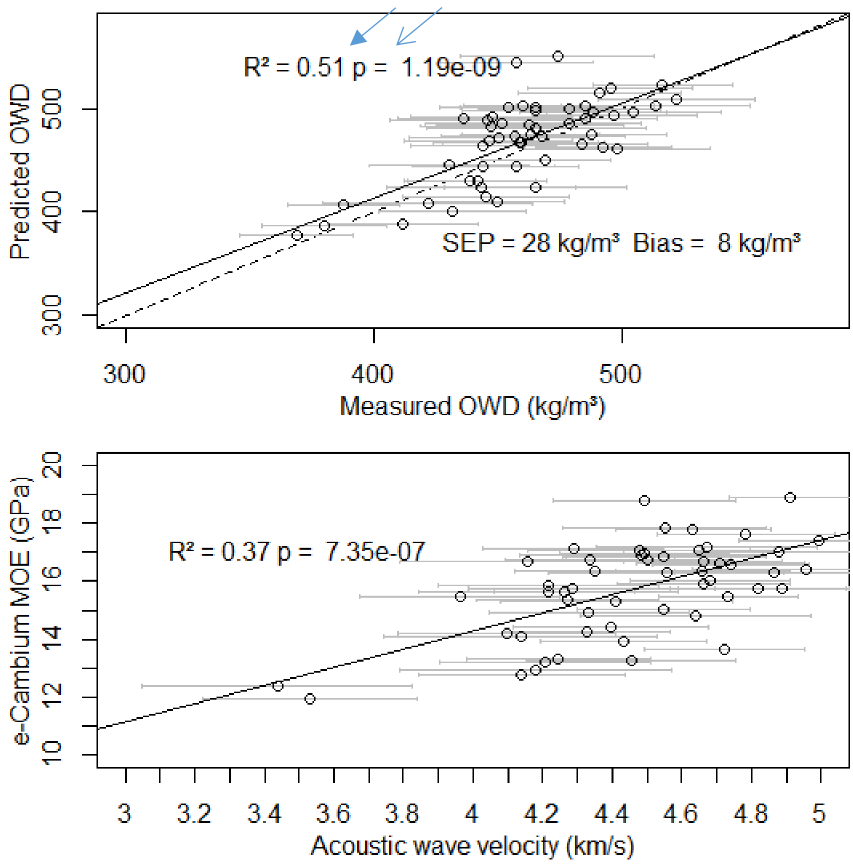

Figure 8: Predicted vs. actual OWD and eCambium MOE vs. AWV using interpolated soils data. The solid line shows the regression and the dashed line shows the one-to-one trend. Mean ± 1 X standard deviation is shown by grey bars.

The model predicted 60% ($p < 0.0001$) of the variation in under-bark DBH (SEP=33mm; 10% of the mean) but only 20% ($p = 0.0005$) of the variation in tree height (SEP=4m; 14% of the mean) (Figure 9). The model severely under-predicted DBH at the ex-pasture site Gardiners 003 and the heavily thinned site at Oaks Creek 1012 (arrow in Figure 9).

The variance in tree height explained by model predictions was low. This appeared to be most strongly driven by under-predictions of height at a group of sites: GO024, the unthinned treatment at OC1012, BG582, HL224 and TR016 (circled in Figure 9). With these points excluded, the model was able to explain nearly 40% of the variation in height, more closely approached the one-to-one line, and SEP dropped to 3 m (10% of the mean). There was no obvious indication of any particular factor at these sites which led to the poor predictions.

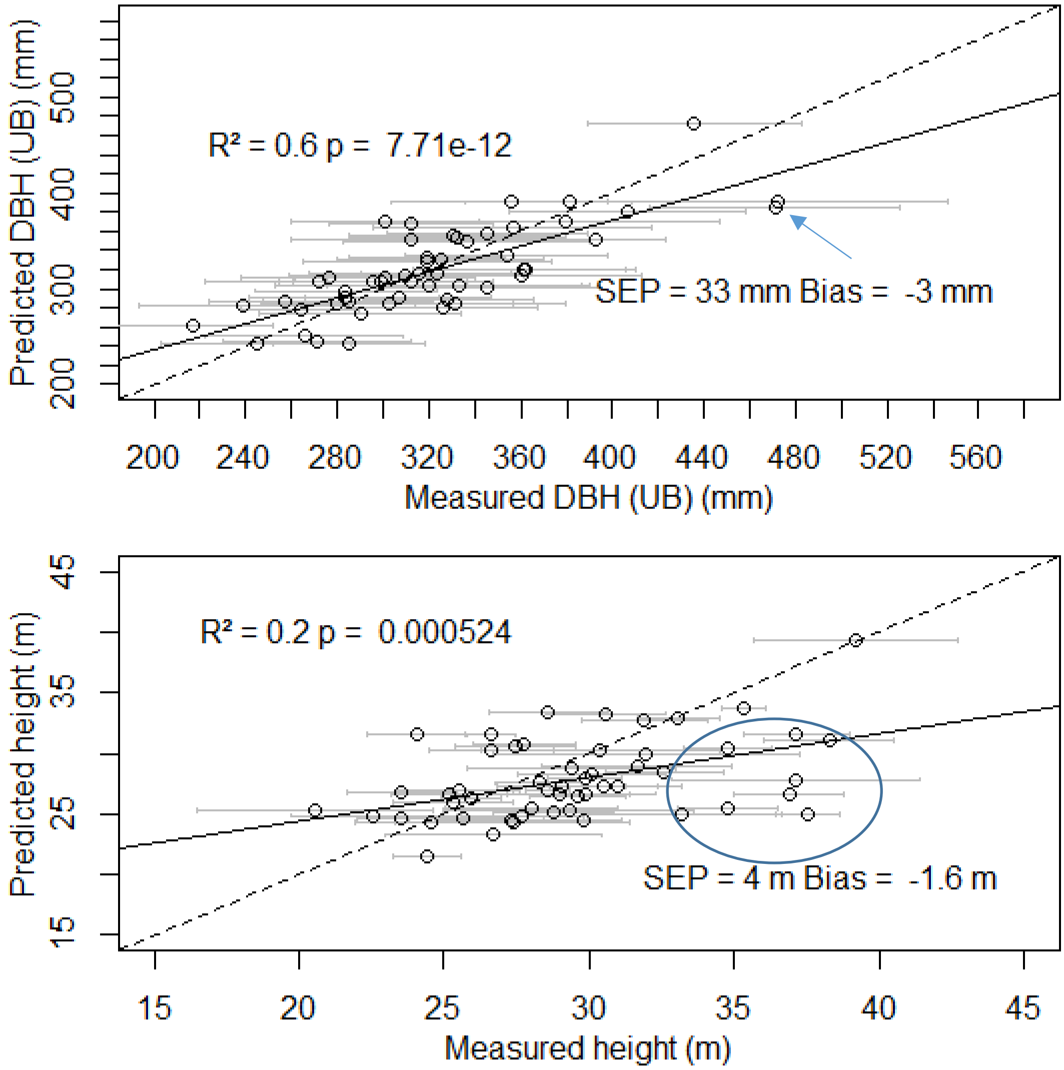

Figure 9: Predicted vs. actual DBH and tree height using interpolated soils data. The solid line shows the regression and the dashed line shows the one-to-one trend. Mean ± 1 X standard deviation is shown by grey bars.

By replacing the relatively simple height model that operates in the current version of the eCambium tool with interpolated height predictions based on measurements at the time of sampling (Eq. 2), the model still significantly predicted actual OWD (R^2 = 0.42, SEP = 32 kg m^{-3}). Diameter predictions suffered, however, with the model predicting only about 30% of the variation in DBH when height was forced to actual data. Forcing DBH in the same way was not undertaken as intra-annual variation in carbohydrate allocation is an important part of the procedure, and significant adjustments would be required to implement such a change.

$$Ht = A(1 - e^{-kt})^m \qquad \text{Equation 2}$$

<u>Comparison with SilviScan</u>

SilviScan measurements made on samples from 3 trees per site at 23 sites/scenarios were compared with the data obtained from outer-50 mm cores, ST300 measurements and in-field DBH measured on 30 trees (Figure 10). Overall, the SilviScan-derived data explained 77% of the variation in OWD, 38% of the variation in AWV (from MOE) and 62% of the variation in DBH. It is interesting that the r^2 of the MOE vs. AWV relationship using SilviScan data was about the same as that of predicted MOE and AWV. There was an increasing bias in the DBH relationship, with increasing tree size, mainly driven by the large difference at WB026. The SilviScan cores taken from the unthinned treatment at Magpie were also much shorter than the average radius for the site based on DBH measurements. The SE for wood density was 19 kg m^{-3}, or about 4.1% of the mean.

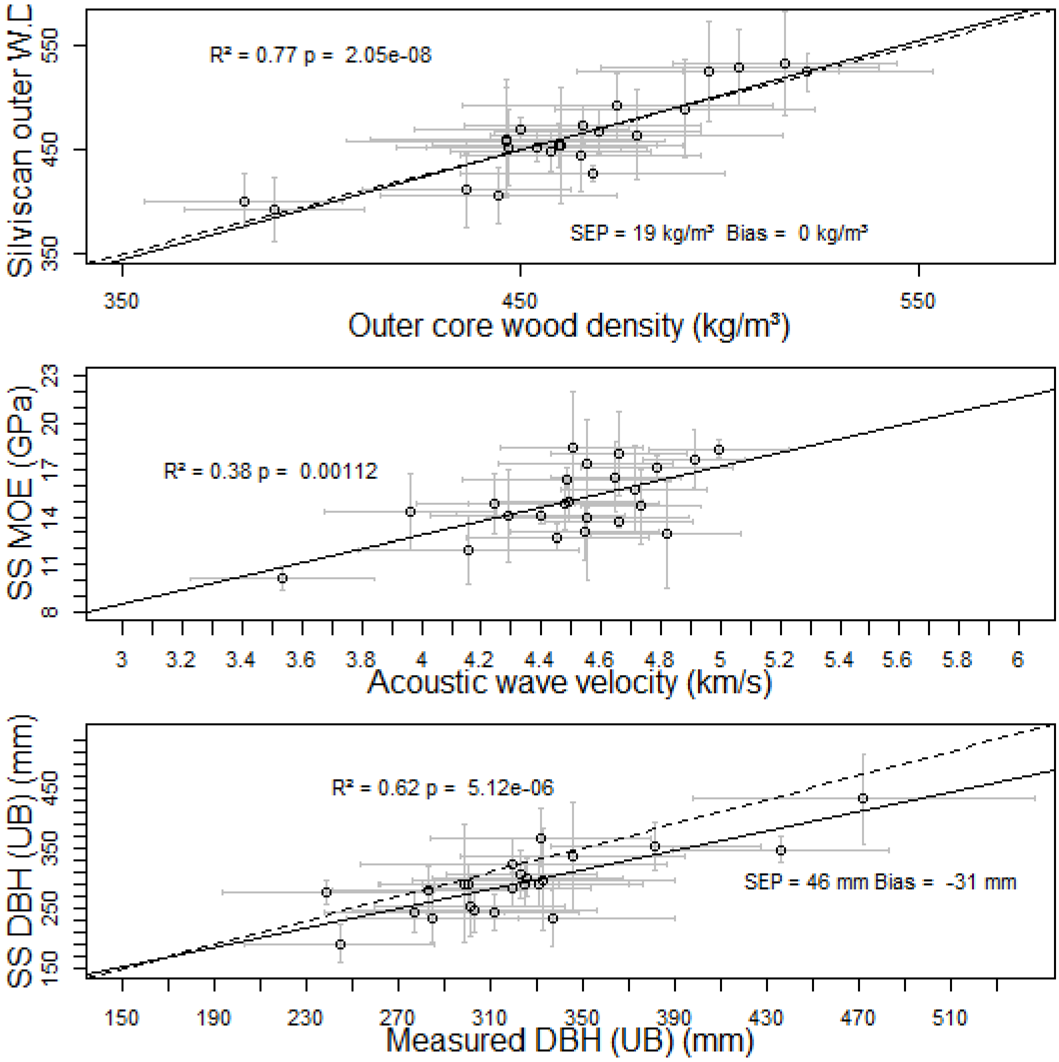

Figure 10: SilviScan-measured wood density of the outer 50 mm, and derived MOE values, as well as DBH calculated from core length vs. actual basic density data on 30 samples and in-field measurements using the ST300 and of DBH.

The predictions of the variation in whole-core and outer-50mm wood density measured by SilviScan on three samples per site was much lower (about 30%) than the correlations achieved when comparing against the outer-50mm cores taken from 30 – 40 trees per site. The predictions improved by excluding the site CB001 (where the SilviScan samples were all of relatively low OWD and the model over-predicted this) or WB026 from the analysis.

Trajectory comparisons

Model predictions of ring mean wood density and MOE and actual values calculated from three individual tree radial samples per site are shown in Figure 11 and Figure 12. The model-predicted wood density trajectory generally provided a good approximation of the actual patterns. At some sites, however, the model under-predicted wood density in the juvenile core (e.g. Billo 104 and Havilah 013) while in other cases the model over-predicted the increase in wood density in the last 5 – 8 rings (e.g. Toorour 016 and WB026). The model over-predicted mid-rotation wood density at some sites (e.g. Bago 066 and Maragle 044).

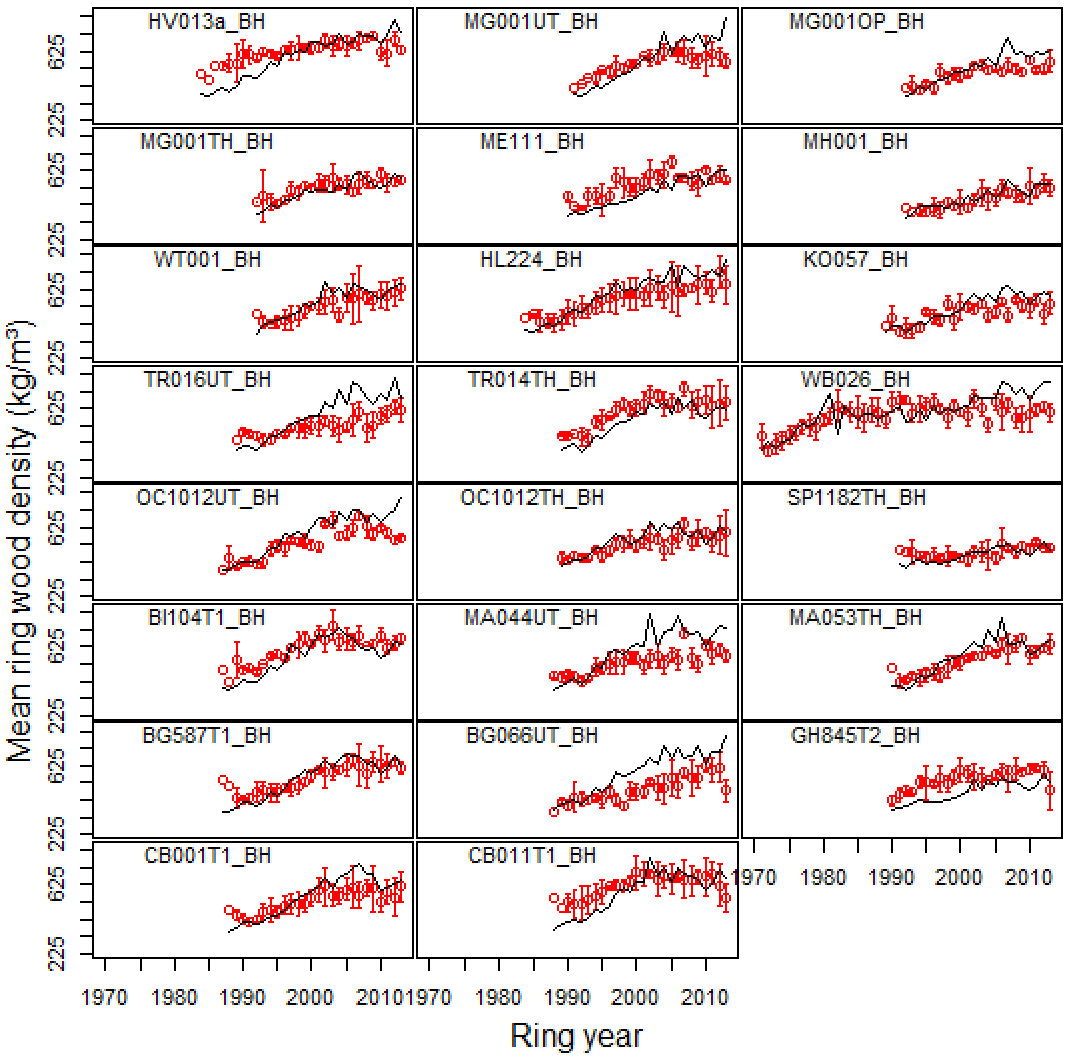

Figure 11: Actual (red) and predicted (black) pith to bark trajectories of mean ring wood density for the 23 scenarios where SilviScan data was obtained. Actual data shows mean ± 1 standard deviation.

With respect to MOE, eCambium tended to over-predict the juvenile core MOE at several sites, but most notably Bago 066 tended to be over-predicted in all but the outer few years. From Table 8 it is evident this site had the highest rock content (30%) based on the soil analyses, whereas these scenarios assumed zero rock content.

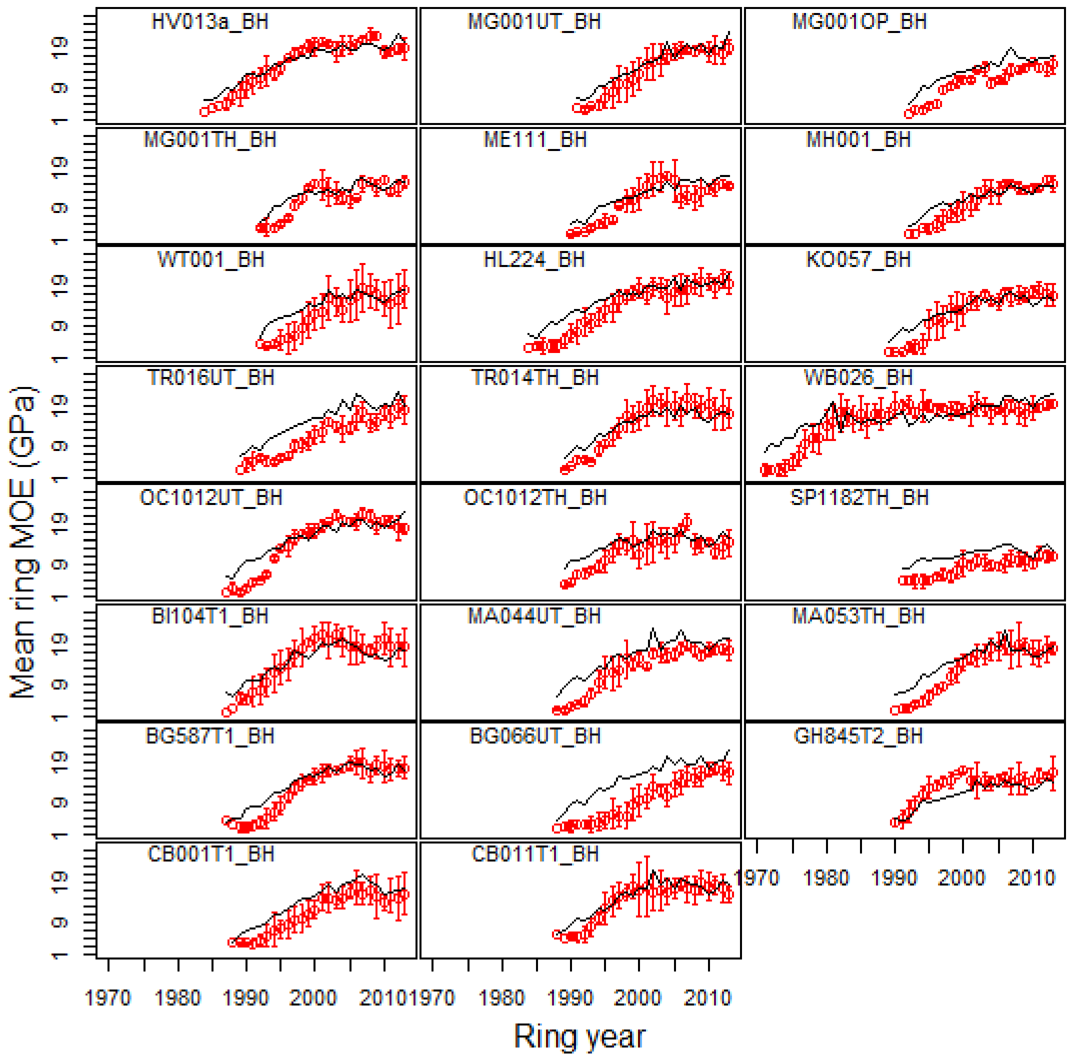

Figure 12: Actual (red) and predicted (black) pith to bark trajectories of mean ring wood MOE for the 23 scenarios where SilviScan data was obtained. Actual data shows mean ± 1 standard deviation.

Predictions based on CaBala inputs

The predictions of OWD when using Cabala inputs for 25 of the sites (CaBala runs used ASRIS interpolated soils data) did not correlate significantly with actual OWD measured at those sites (p = 0.473) nor was the correlation between MOE and AWV significant (p = 0.308). The CaBala model predicted 41% (p = 0.0004) of the variation in under-bark DBH and 30% (p = 0.0023) of the variation in total tree height. By comparison, for the same 25 sites, the eCambium predictions using the IGM predicted 56% (p < 0.0001) of the variation in OWD, 52% (p < 0.0001) of the variation in AWV, 64% (p < 0.0001) in DBH and 20% (p = 0.015) of the variation in tree height. The inability of eCambium to predict OWD when using CaBala inputs was largely due to severe over-prediction of OWD at the very low density sites Splitters and Moyhu. The main source of this discrepancy was different crown dynamics predicted by the two models. eCambium predicted a maximum crown mass more than twice as high as that predicted by Cabala for Splitters and Moyhu. By contrast, at sites such as Carabost 011 and Havilah 013 (where the OWD was high) the two models predicted similar maximum foliage masses.

The models predicted similar pith-to-bark trajectories of wood density at several sites (Figure 13), but in general there was a tendency for Cabala-based runs to predict higher wood densities. At the Gass Creek 801 site (not an ex-pasture site) eCambium predictions of wood density were substantially higher when using CaBala predictions than using the internal stand growth predictions.

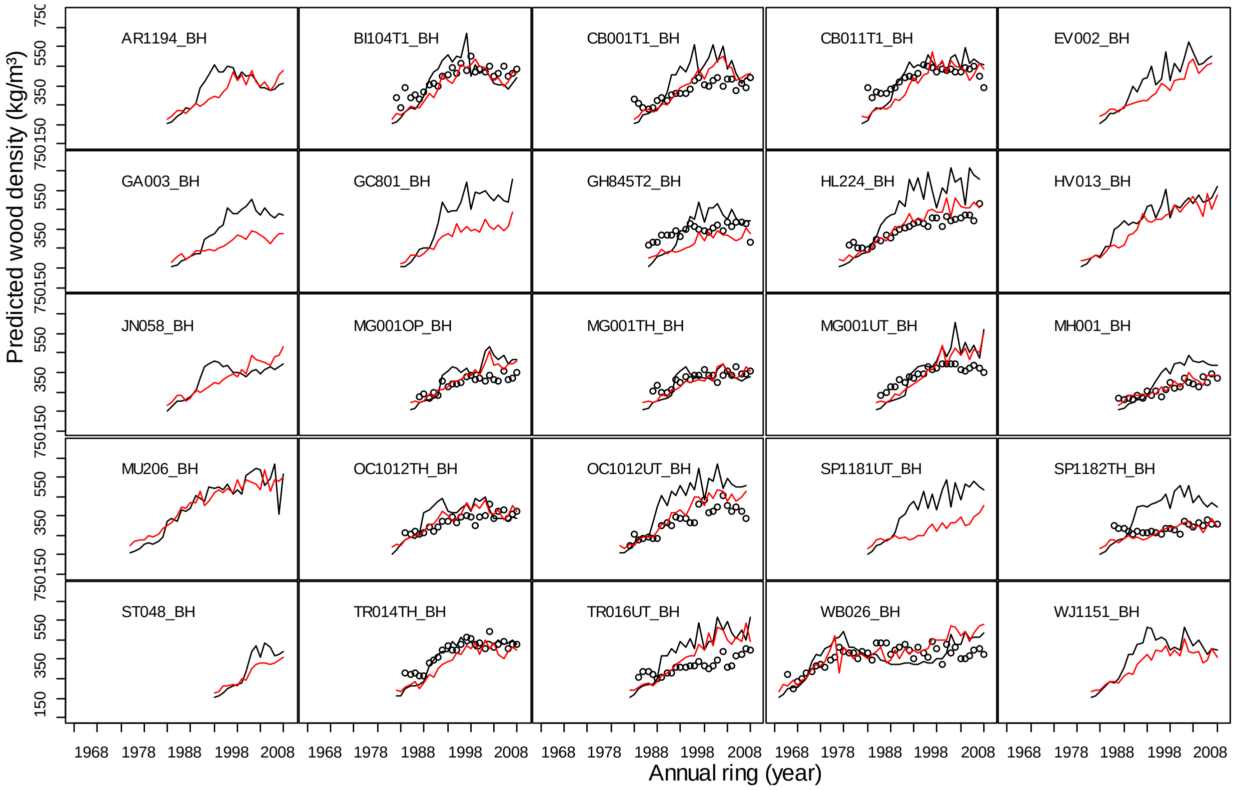

Figure 13: Pith-to-bark trajectories of wood density as predicted by eCambium (red), eCambium using CaBala inputs (black) and actual SilviScan data (where available; black circles).

Runs utilising data obtained in-field

Soil samples were taken from 23 sites in April 2015. Estimates were made of the proportion of coarse fragments in the soil, as well as of likely effective rooting depth. Based on these data, a second set of runs were undertaken with the model on 32 scenarios. The model was able to predict 42% of the variation in OWD (SEP = 32 kg m^{-3}; 7% of the mean) and 40% of the variation in AWV (using MOE) for these scenarios (Figure 14). OWD at the Moyhu site was over-predicted by the model by a large margin in this analysis. Removing that site from the total led to an r^2 of the OWD prediction increasing to 50% (SEP = 30 kg m^{-3}). If eCambium calculated minimum and maximum ASW, as opposed to the numbers estimated by MIR analyses, the predictions were slightly improved (R^2 = 46% and 54% for OWD, with Moyhu included and excluded respectively). By contrast, simulations of just the sites at which soil samples were taken, but using interpolated soils data, correlated with actual OWD with R^2 = 0.59 and predicted MOE vs AWV with R^2 = 0.49 (Figure 14).

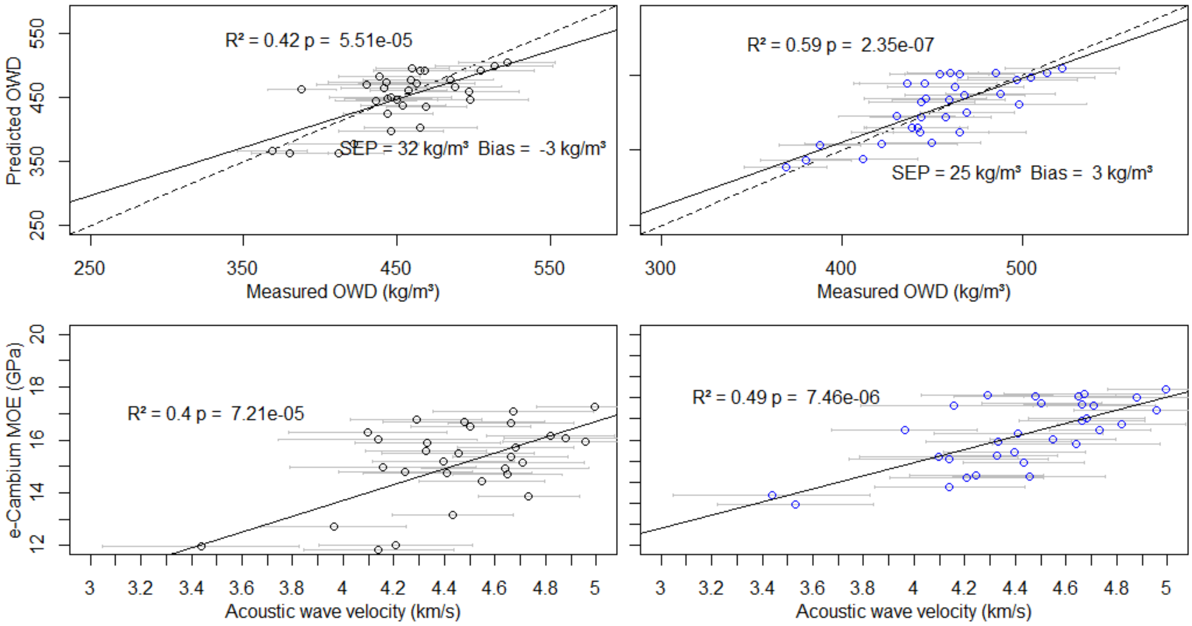

Figure 14: Predicted vs. actual OWD and predicted MOE vs actual ST300 AWV when using site descriptions based on site visits and soil sampling in April 2015 (left; black points) and interpolated soils data (right; blue points)

Based on data obtained from April soil sampling, the model predicted 73% of the variation in DBH (SEP = 28 mm; 9% of the mean) and 37% of the variation in height (SEP = 3m; 10% of the mean) (Figure 15). This was a much stronger prediction than that based on interpolated soils data for that subset of scenarios, particularly for height.

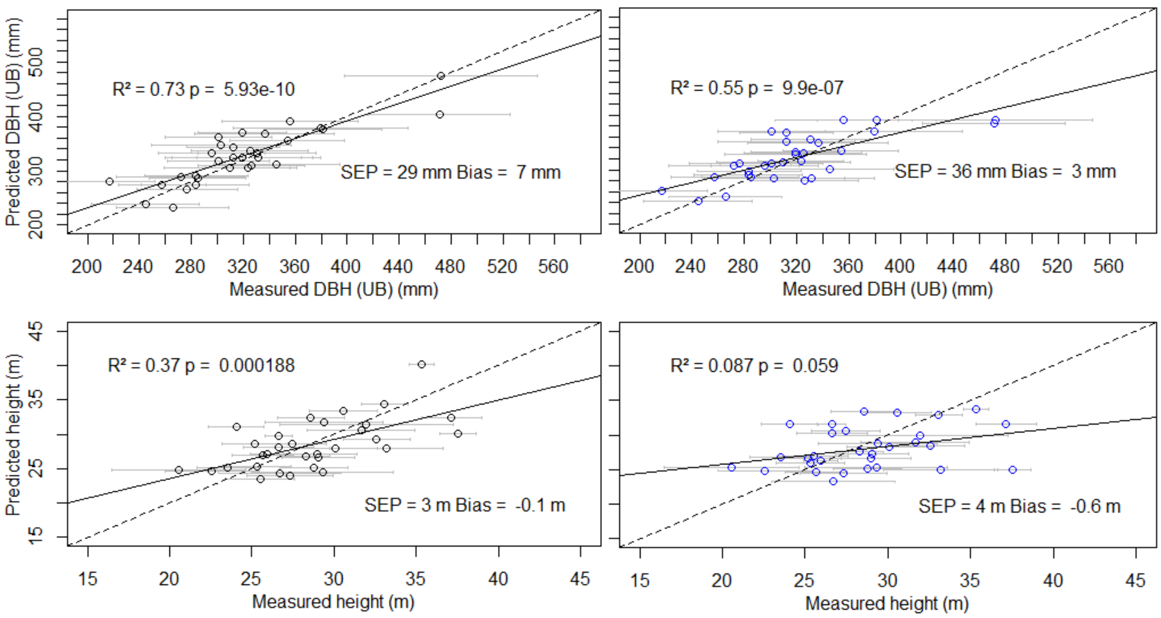

Figure 15: Predicted vs actual DBH and height for runs using site descriptions based on site visits and soil sampling in April 2015 (left; black points) and interpolated soils data (right; blue points)

Prediction of effects of thinning on OWD and AWV

A significant difference in actual OWD was found between UT and thinned at only 3 sites. Of these three, when run using the interpolated soils surfaces data, the model correctly predicted the direction of the thinning of effect at all sites (Table 10). However, the marked difference in density at the Toorour site was not matched. This was to some extent caused by the under-prediction of under-bark growth in the unthinned trees in the last 10 years of the life of the stand.

Table 10: Actual and modelled effects of thinning on OWD.

Site	Actual OWD			Predicted OWD		
	Unthinned/ Lower intensity thinning	Thinned/ Higher intensity thinning	Diff.	Unthinned/ Lower intensity thinning	Thinned/ Higher intensity thinning	Diff.
Burrowye 019*	463	485	22	480	501	21
Lucyvale 018b/015	465	479	14	480	485	5
Lucyvale 018b/018a *	465	488	23	480	496	16
Toorour 014/016 *	446	497	51	489	494	5
Magpie 001	459	467	8	469	472	3
Oaks Creek 1012	453	446	-7	495	461	-34
Splitters 1181/1182	369	380	11	378	385	7
Bago 582/583	447	456	8	493	472	-21
Oaks Creek 1195	452	450	-2	485	471	-14
Green Hills 845	441	450	9	430	474	44
Green Hills 849	443	439	-4	424	441	17

* denotes sites where a significant effect was found in the analysis presented in the MS 2 report.

In order to compare model predictions of the effects of thinning on stiffness, the relative change in AWV (measured) and MOE (predicted) is shown in Table 11 for those cases where a significant effect was found. The model correctly predicted the higher stiffness which was found in unthinned treatments in all cases, and also predicted the "ranking" of the effects between the three cases.

Table 11: Actual and modelled effects of thinning on AWV.

Site	Measured AWV (km/s)		Proportion of change	Predicted outerwood MOE (GPa)		Proportion of change
	Unthinned	Thinned		Unthinned	Thinned	
Oaks Creek 1012	4.65	3.96	14.8%	17.0	15.2	10.6%
Lucyvale 015/018	4.87	4.66	4.30%	16.4	15.9	3.00%
Magpie 001	4.81	4.39	8.70%	15.9	14.4	9.40%

South eastern Australia simulation

Based on a set of 625 runs per site for 74 sites, a total of 46,250 simulation runs, it was possible to estimate 62% of the variation in actual OWD for the calibration sites (with a slope not significantly different from the 1:1 relationship) and 40% of the variation in OWD for the validation sites (both $p < 0.0001$). These simulations all used data taken directly from the TERN interpolated soils surface, holding FR = 0.3, and weather data was taken from the SILO surface. It is perhaps notable that the exclusion of the site MU206, which was identified as an outlier previously, in the validation set, increased the R^2 of the predicted vs. actual relationship from 40% to 44%.

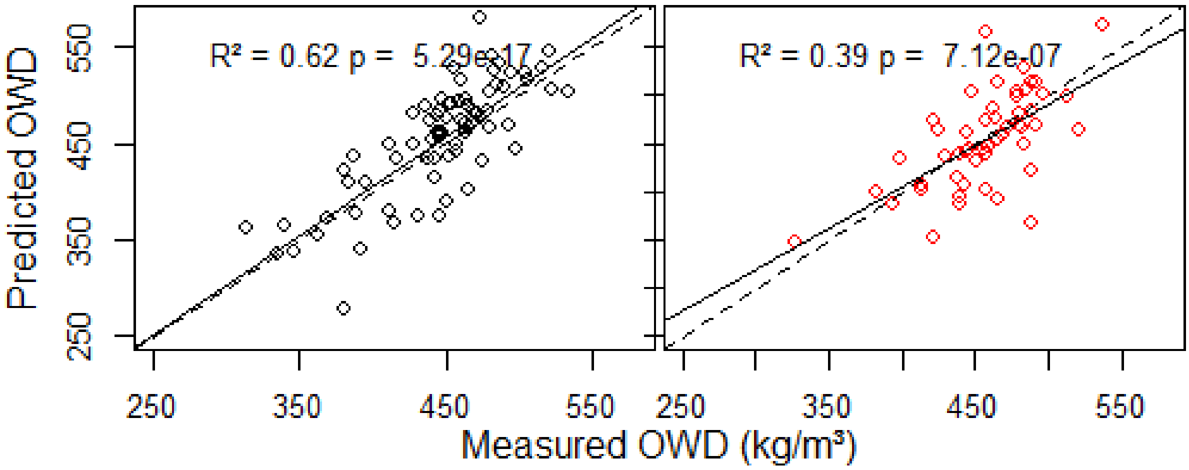

Figure 16: Comparison of modelled and actual data across 125 sites from south eastern Australia, in which the "k" and "m" parameters were roughly optimized for 60% of the sites (left) and the model then fitted against the remaining 40% of the sites as a validation set (right).

An issue that needs to be dealt with in optimisations of this sort is the fact that juvenile wood properties were not included in the analysis (as they were only available for a small proportion of the total of 125 sites). As such, the estimates may not be the best reflection of pith-to-bark behaviour: this needs to be further tested.

Obviously, it is possible to test a number of other combinations of parameters across varied ranges. A small increase in numbers of parameters, however, leads to massive increases in the number of simulations, and is at present not very feasible.

Sensitivity analysis

A sequence of simulations were undertaken to test the effects of changing soil and silvicultural drivers of wood density and DBH variation in the model. Changing fertility rating on its own had the biggest effect on both OWD and DBH (Figure 17). Increasing soil depth and rock content increased DBH but did not lead, overall, to major/trends in changes in OWD. It was evident, however, that at low FR values increasing soil depth led to increasing OWD (Figure 18). In general, increasing soil depth led to an increase in DBH. Increasing clay content led to a modest increase in DBH and decrease in OWD, with the effect becoming somewhat more pronounced at higher FR (Figure 19).

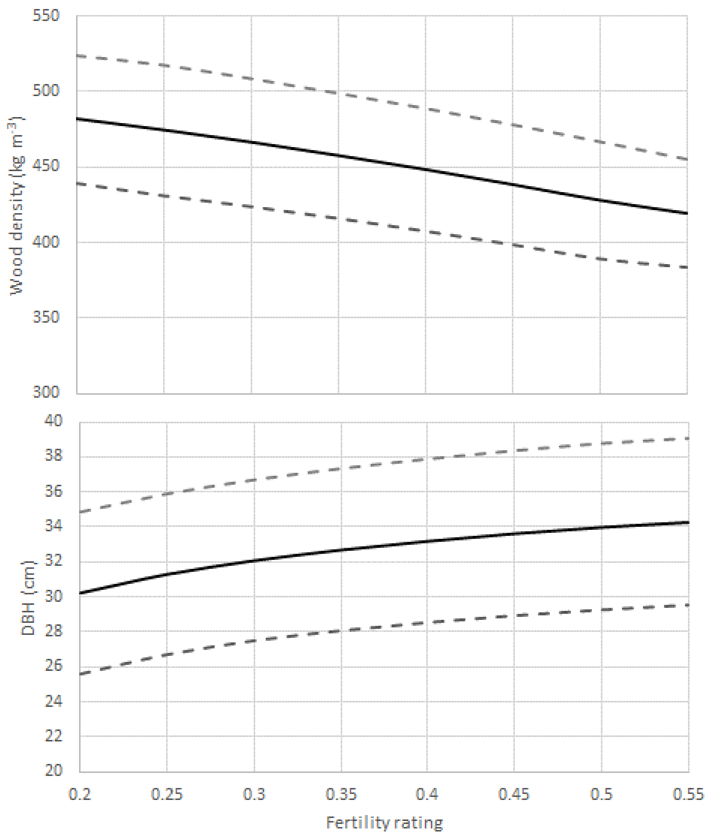

Figure 17: Effects of changing site fertility rating (FR) on mean OWD and mean DBH. Mean ± SD is shown with grey dotted lines

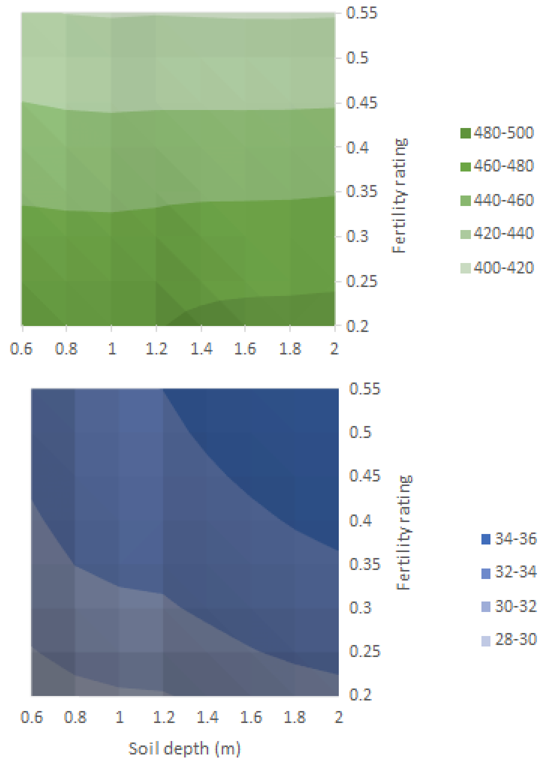

Figure 18: Interactive effects of FR and soil depth on OWD (top, green) and DBH (bottom, blue)

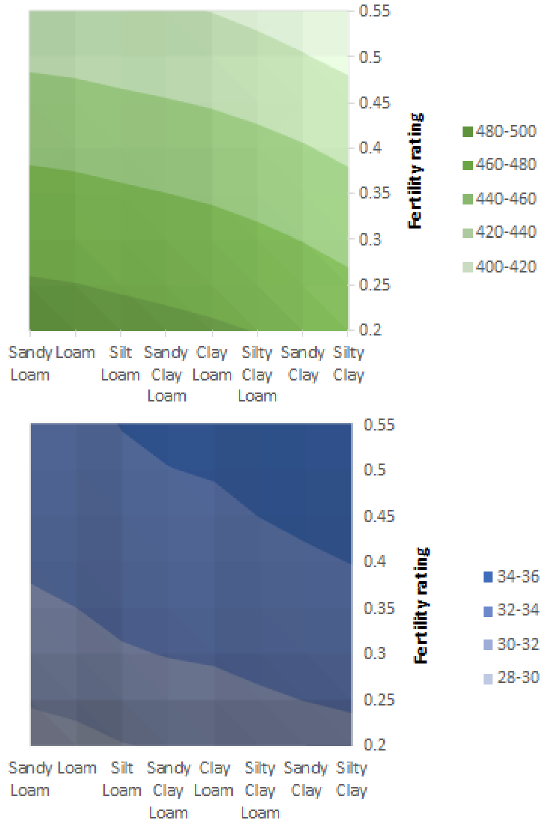

Figure 19: Interactive effects of FR and soil texture on OWD (top, green) and DBH (bottom, blue)

A thinning case study

Model predictions of the effects of thinning intensity in a single thinning, at age 12, and the stand density at planting on OWD are shown for a fairly typical site on a 27.3 year rotation, grown on a clay loam soil of 1.1m depth (Figure 20)[11]. The model predicted that at such a site, on average, lower stocking (sph) at establishment led to higher OWD at "harvest age" (27 years). Imposing thinning treatments could vary this effect. In most instances, increasing thinning intensity at age 12 led to increasing, followed by a decreasing OWD. But there was an interaction between the stand density at establishment and the intensity of thinning, with thinning leading to reasonable gains in OWD at higher establishment stocking, but not when establishment stock levels were lower. Lower stand density and higher intensity thinning both led, invariably, to predicted increases in DBH (Figure 20).

[11] As mentioned in the caption the initial stocking at establishment is shown on the perimeter. The contour lines represent OWD (top) and DBH (bottom). The different lines shaded from dark to light represent different final stocking of a 27 year old stand thinned at age 12. Thus, if the initial stocking was 1900, as thinning intensity at age 12 increases, the OWD at age 27 moves from around 500 kg.m^{-3} to 445 kg.m^{-3} if the final stocking is 400 sph. In comparison an initial stocking at 1100 sph, if left unthinned has an OWD around 485 kg.m^{-3} which increases to around 495 kg.m^{-3} at a final stocking of 700 sph before decreasing to 475 for a final stocking of 400 sph. In contrast DBH tends to consistently increase as thinning intensity increases regardless of initial stocking.

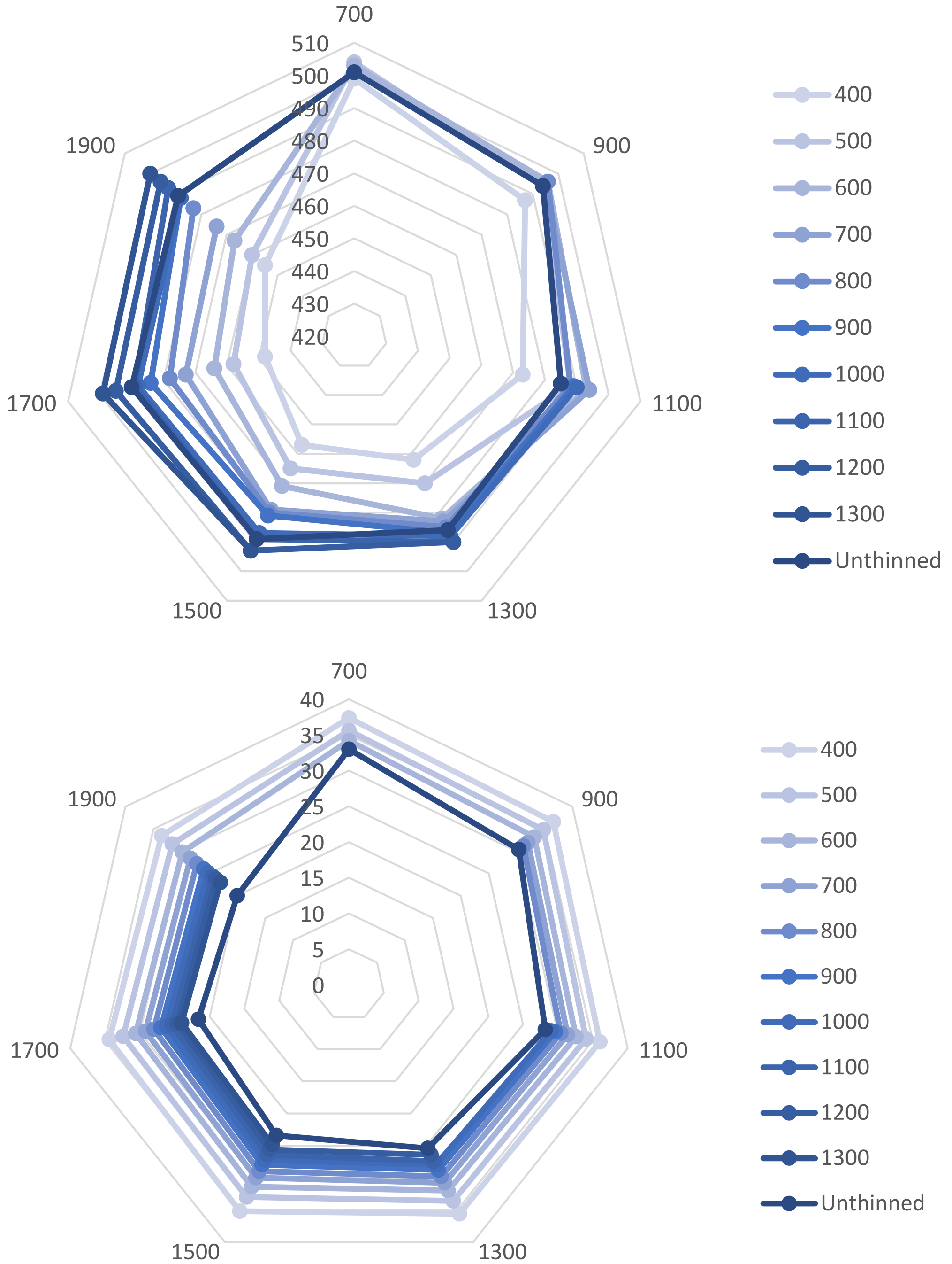

Figure 20: Model predictions of the effects of varied establishment stand density and first thinning intensity (blue shade) on OWD (top) and DBH (bottom). Note the unthinned cases (darkest line). Values on the perimeter indicate SPH at establishment, whereas contour values indicate OWD (kg.m^{-3}) and DBH (cm) respectively.

Predicted board out-turn and product yield

Using a simple virtual sawmill application built in to the eCambium software, the number and predicted stiffness of 100 x 40mm boards produced from each simulated log-end was calculated and compared across sites (Figure 21). This representation provides a different perspective of the combined effect of site, environment and silviculture to impact on productivity. The effect of the fast growth and poorer wood quality on ex-pasture sites such as Splitters (sites 35&36) can be seen, compared to the higher stiffness sites such as Carabost (site 52) and Havilah (sites 1 & 2).

Previous studies have demonstrated the potential of SilviScan data to predict sawn timber properties (McKinley et al., 2003a). Consequently, the predicted sawn board production using radial profiles generated by SilviScan was compared with those using radial profiles generated by eCambium (Figure 22). In general, the model predictions reflected those based on SilviScan data, when expressed as board proportion. Board counts could differ markedly dependent upon the average radius of the SS samples. In some instances, (e.g. site 26: WB026) the three SS radii were markedly smaller than the site average. Whether the trees sampled were smaller or the eccentricity of the stem resulted in a smaller radius, is unclear. It may have been more appropriate to have selected the SS trees less randomly and chosen ones more representative of the site mean. The final scatter plot in Figure 22 shows the site mean board MOE compared between the SS and model populations. The variance explained is statistically significant.

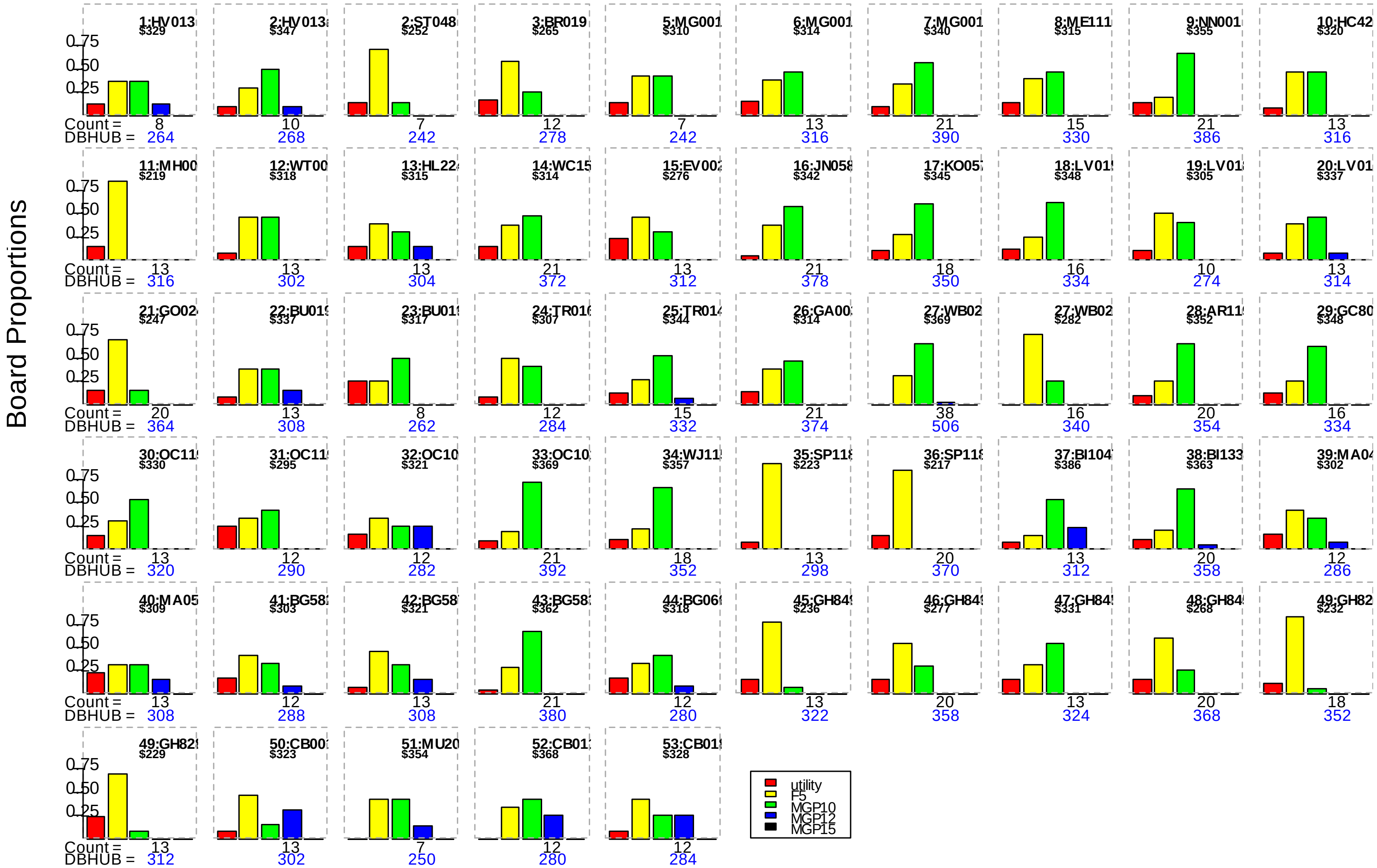

Figure 21. Predicted sawn board proportion (count and grade) at each of the 53 modelled sites. Predicted DBH and board count are noted below each plot. The value of sawn product ($ m^{-3}) is shown based on current approximate grade prices.

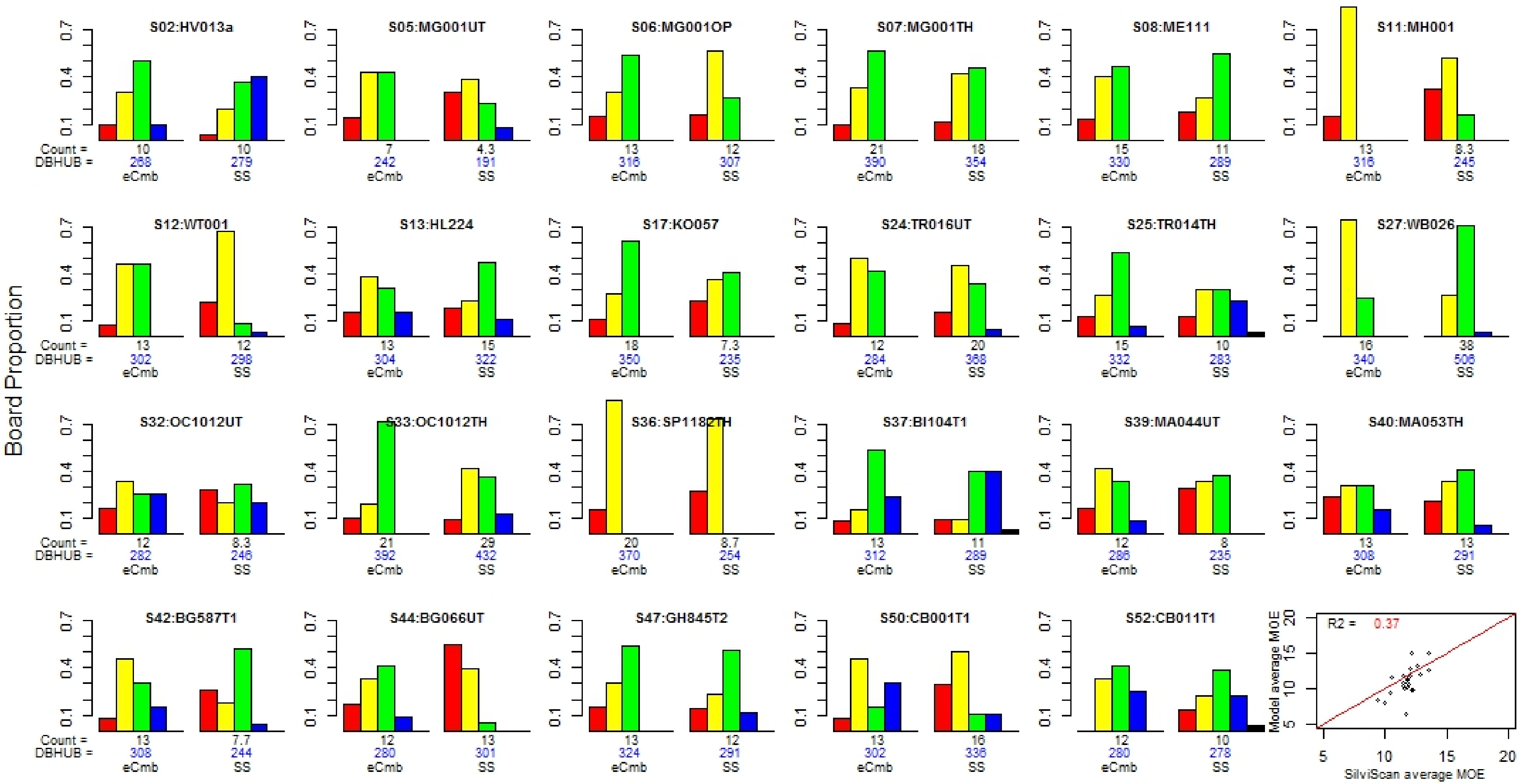

Figure 22. Comparison between SilviScan and eCambium profiles sawn board production. Predicted DBH and board counts are recorded beneath each histogram.

Discussion

Overall, the eCambium tool V2.0 predicted more than 50% of the variation in outer-wood density and 50 to 70% of the variation in DBH measured in all or sub-sets of the sites used in the study. The simulations were achieved using a single set of parameters, which were not "tuned" but which rather reflected a non-optimised set of values. Further adjustment of parameters could lead to increased explained variance. The simulations also used site data that was not adjusted to enable "fitting" in any way. It was surprising that the use of soil characteristics obtained from samples taken at a subset of sites did not improve predictions of OWD over information obtained from the publically-available interpolated soils surfaces. This was partly to do with questions around fertility rating, and particularly, how that relates to wood properties, an issue that is not fully resolved. The use of CN ratio (when available and accurate) as a measure of FR shows promise, but it may not always be the uniformly the best measure. "Fertility rating" as a concept is not a one-size-fits-all parameter, and further work is needed to identify the best way to deal with fertility, growth and wood properties in the context of the eCambium tool. It is notable that using the data obtained from soil sampling led to a marked improvement in the veracity of DBH and height predictions.

The ex-pasture effect

The ex-pasture effect was an important one in this study. Almost all of the ex-pasture sites had below-average OWD. It is generally known that N levels in the stand can be expected to have a deleterious effect on wood density (Beets et al., 2001; Nyakuengama et al., 2001; Turvey et al., 1993). It is important that the model capture this effect. The effect is complex, however, as revealed in the modelling undertaken here. At the Moyhu site, for example, the situation was difficult to predict correctly based on the C/N ratio of soil samples taken in April 2015. Trees at the site had a low wood density, but the soil did not have a high CN ratio. This site was currently being used for cattle grazing, which could suggest that other factors were driving the low OWD at that site, or perhaps the system at Moyhu did not retain nitrogen as well as other sites. It was interesting that the CN ratio at sites like Splitters and Green Hills 828 was still low (i.e. high nitrogen levels relative to OC) nearly 30 years after the stands were established on the previous pasture.

Age effects

The over-prediction of wood density at the oldest site in the study may suggest that, given the current parameter set, the model tends to over-estimate wood density and stiffness in stands much older than about 30 years. However, the model did not over-predict OWD in a preliminary test at a similar aged site in the green triangle (1958 planting at Caroline). This needs more evaluation. The model generally predicts the observed pith-to-bark trend of increasing density and stiffness well. Consequently the amount of explained variance observed in this study could have been increased by including other age classes (e.g. by predicting OWD at early or mid-rotation as well as close to harvest). However, this was intentionally excluded study to provide a more rigorous assessment of model performance, not confounded by age effects.

Effects of disease, slope, wind etc.

In assessing the ability of a tool like eCambium to predict OWD and DBH from basic inputs, it is important to be cognisant of uncontrolled sources of variation. Importantly, for example, eCambium model does not handle the effects of disease, nor does it explicitly handle the effects of slope and aspect. It is notable that many stands in the study were recorded to have had outbreaks of various kinds. There was evidence of aphid infestation in several HVP compartments during site visits in April 2015. Plantation management records indicated *Essigella*, *Cyclaneusma* and *Sphaeropsis* outbreaks of varying levels (sometimes up to 75% of stems with as much as 50% severity) in multiple stands. Particularly notable is the case of Murraguldrie 206, where OWD may have been affected by a major *Essigella* outbreak, not captured by eCambium.

Simulations of height and diameter

The model predictions of height were poor. The model for height is a simple one, relying on the balance of carbohydrate between the increase in diameter at the base and the total volume of the bole, with a basic limitation approach to dealing with stability limits. It was obviously not able to properly handle the variation in height observed across the study. It is notable, however, that height variation in *P. radiata* stands is complex and highly variable even within stands. Ex-pasture sites tend to be shorter (and fatter, proportionally) possibly in part because of apical sway, as well as other factors not captured by the model at present. The effect of ex-pasture on tree form was a major problem when many of these sites were established (Turvey et al., 1993). Previous studies had suggested that the stem deformation ("speed wobbles") commonly observed, resulted in shorter- fatter trees, but susceptibility may have been related to genotypes selected to grow taller and thinner (Downes and Turvey, 1992).

The model also cannot deal with exposure-related height effects. Depending on how the model is being used, a solution in operational use may be to force the model to use height data from pre-harvest or mid-rotation inventories. This is most easily applied to correcting height. However, with further development, it could also be used to modify diameter growth. The latter adjustment is made complicated by the necessity to balance carbohydrate dynamics and intra-annual growth variability which is an important determinant of overall wood properties. Assuming a constant rate of growth by using a growth curve, "forcing" would lose this subtlety. In this same context, additional information on characteristics of the crown, if practical, could benefit model predictions. For example, linking simulations with satellite imagery (as used, for example, in 3PGS). Parameter modification would likely be needed to accommodate this adjusted, data-driven approach.

Model predictions of silvicultural effects

The model was mixed in its ability to predict the subtle effects of thinning on OWD. At the Burrowye site it was accurate, but at Toorour and Lucyvale, it under-predicted the gain in OWD between thinned and unthinned cases. It is notable that at Lucyvale, just a slightly different thinning treatment in the model led to predictions of much higher gain in OWD which shows how sensitive the framework is to thinning specifications. The model did well, however at predicting the consistently higher outerwood stiffness expected from unthinned stands. It is interesting in the context of the results from the thinned/unthinned sites here (where thinned sites typically had high OWD) to note the results of other studies (e.g. (Moore et al., 2015). When simulations were established that replicated the conditions examined by Moore et al. (2015) similar patterns were observed (see Appendix 6 of the milestone 2 report).

SilviScan

The increasing bias with the largest trees seen with the SilviScan data is likely due to the increasing difficulty in accurately "hitting" the pith when taking cores in larger trees. This effect, as well as the much smaller sample size (an order of magnitude), were likely to contribute to the relatively poor correlations between model simulations and means based on three SilviScan samples. The comparisons between OWD and MOE trajectories predicted by eCambium and measured by SilviScan suggests that eCambium, on some sites, is not capturing certain subtleties of variation, particularly in the juvenile core. This may be in part due to the difficulty in capturing site effects in the first 3 – 5 years of the stand as the canopy closes. Further attention to understanding wood formation and optimising the current approach to handling pith-to-bark trends is needed. The large resource of SilviScan data obtained in the FWPA-funded Juvenile Wood Initiative may be useful here.

Using Cabala or the IGM

It appears that in ex-pasture sites, the model does not accurately predict the low wood density when utilising inputs from Cabala. Given the current model structure, this may be due to the higher prediction of maximum crown mass in eCambium runs compared to CaBala. One reason for this is the simpler compartmentalisation in the eCambium framework compared to the more sophisticated approach taken in CaBala, such that foliage and fine branches are not separated, as well as other issues. Further research is needed to fully characterise the accuracy of the approach and the numbers that could be expected. Based on qualitative evidence, the needle mass at the Splitters and Green Hills 828 sites, as well as Moyhu (to a lesser extent) was high, substantially above the normal amount for *P. radiata* plantations. This suggests that the heavier crowns predicted by eCambium were likely correct to some extent, but the margin by which the difference between the models is accurate is not clear.

Conclusions on the performance of eCambium 2.0

Using data direct from off-the-shelf, online interpolated databases, or from samples taken at a subset of sites, the eCambium model explained 50 to 60% of the variation in OWD at the sites used in this study. Standard errors of prediction are similar to the standard errors around the actual site means. Promising is the generality which the model displayed when re-tested across a very broad site set, from across south eastern Australia. On the validation set, the model predicted 40% of the variability in OWD, with little evidence of major over- or under-estimation overall. Although this predictive veracity affects its suitability for fine decision making, in the absence of other streams of data, eCambium shows promise as a low-cost "screening tool", and as a starting point for evaluating broad-scale resource variability. As such, it could find utility as a means of alerting managers to red-flag sites, sitting on the upper or lower ends of the distribution, and enabling targeted sampling campaigns, using infield non-destructive approaches. The possible utility of interpolated soils data available online opens up a promising opportunity to estate-wide simulation approaches, in concert with interpolated weather data and linked silvicultural information.

Stage 1 Conclusions

Purely empirical (fitted) approaches explained significant amounts of OWD and AWV variance in this study. To be an attractive alternative to a statistical, “fitted” model, eCambium needs to explain similar amounts of variability and be applicable across regions. However, it is important to also see the eCambium approach as representing something quite different from the statistically fitted approach in the stricter sense. That is, it is an approach that requires knowledge about only those variables which can be readily obtained from off-the-shelf sources or plantation databases, and which can be generalized to the greatest possible extent. The approach is cumulative, taking into account effects today as a function of events yesterday.

In general, eCambium explained similar amounts of variance in OWD to the purely empirical models, the latter being fitted and not applied in a predictive mode. Whatever approach is used, the variability explained has to be commercially significant as well as statistically significant. A model that predicts only 20% of the variance may be statistically significant, but it is unlikely to be commercially useful. Predictions also need to be accurate as well as precise (Downes et al., 1997). This begs the question as to what a commercially acceptable level is?

Based on discussions with industry, a figure of 60% is one that most potential users would be comfortable with. eCambium predictions were in that range using very general inputs for site descriptions (publically available database values and FR constant at 0.3, rock content constant at zero). As eCambium development continues and as users gain greater understanding of the site variability across their estate, one can expect the target of >60% explained variance to be achievable. Certainly, initial parameter optimization, even across regions as diverse as Tasmania, Green Triangle, Victoria and NSW yielded $R^2 > 60\%$ in calibration. More comprehensive optimization and further model development can be expected to lead to gains in predictive veracity.

Stage 2: Destructive sampling and mill study

The overarching goal of this project is to assess how well the hybrid *eCambium* modelling system predicts commercially meaningful sawlog properties. To this end the ability of eCambium to predict standing tree properties known to relate to sawlog value was addressed in Part 1 of this report. The specific properties of interest, within the context of this project, are log stiffness and volume and ultimately the volume (number) and stiffness grade distribution of the boards they produced.

Part 2 addresses the destructive sampling of 10 trees from 12 of the 53 sites used in Part 1, and the measurement of the properties of the logs and boards produced. In July 2015, a pre-harvest assessment was made of the 12 selected sites was undertaken to mark the trees for destructive sampling and measure height, stem diameter, stem form and average branch diameter in the butt log. Site selections (Table 12) were based on (a) availability (some sites had already been harvested) and then (b) the need to obtain a wide spread of site productivities based on volume and wood density measures made in Stage 1. At each site 12 trees were selected to provide the harvest crews with some flexibility where individual trees were too difficult to extract.

Table 12. Site average summary data

SiteCode	Project site number	Ave DBHOB	Ave Tree Height	Ave Tree Slenderness	Ave AWV	Ave Bark Thickness	Ave Branch Diam.	Ave outerwood density	Site average Ht / Dia	No. Logs
HV013a	2	317.9	29.3	90.6	5.0	17.4	14.7	521.9	92.2	25
ME111	8	372.7	32.6	87.6	4.5	23.9	21.0	469.2	87.4	34
MH001	11	319.3	25.5	76.9	4.5	21.3	30.3	388.0	79.8	25
LV015	18	425.0	37.1	83.1	4.7	31.9	23.6	479.0	87.3	41
LV018b	19	338.3	27.4	86.1	4.9	24.1	26.7	465.4	80.9	25
LV018a	20	419.0	31.0	77.1	4.5	29.1	26.4	488.3	74.0	25
BI104T1	37	356.5	29.0	79.6	4.5	27.8	25.0	504.8	81.2	34
MA053TH	40	347.9	29.9	82.5	4.5	24.5	35.0	478.9	85.8	32
BG587T1	42	375.3	28.6	72.8	4.5	31.7	38.3	465.3	76.1	33
BG066UT	44	372.3	25.7	72.1	4.2	23.2	42.0	436.3	68.9	28
GH845T2	47	379.7	27.4	66.4	4.2	24.5	31.7	450.0	72.3	28
CB011T1	52	296.1	24.6	80.7	4.6	28.8	21.7	516.3	83.0	24
Average		360.0	29.0	79.6	4.5	25.7	28.0	471.9	80.7	29.5
Max		425.0	37.1	90.6	5.0	31.9	42.0	521.9	92.2	41.0
Min		296.1	24.6	66.4	4.2	17.4	14.7	388.0	68.9	24.0
Range		128.9	12.5	24.2	0.8	14.5	27.3	133.9	23.2	17.0

Ideally the 10 trees harvested for Stage 2 would have been selected from among those sampled in stage 1, and on most of the sites this was the case. However, at

- Havilah 013a (site 2) the commercial harvest of this site was underway at the time of the study. The stage 1 trees were on a steep, south-facing slope and many were too far downslope for a safe (non-commercial) harvest. Only 3 of the initial 30 trees were able to be included in the stage 2 study and additional adjacent trees were selected to make up the required number.
- Moyhu (site 11) 3 of the selected 12 trees were not harvestable due to their proximity to monitoring equipment. The harvesting crew selected 3 additional trees which were not measured during the pre-harvest visit.

- Lucyvale 15 (site 18), the originally sampled site was too difficult to access at the time of harvesting, and a separate set of harvest trees was selected. These were approx. 200 metres from the stage 1 site, and the trees for the mill study were measured for DBHOB, branch diameter and form.

Of the trees sampled in stage 1, 95 were included as part of the sawmill trial. In total 121 trees were harvested, generating 357 logs.

Description of the Sawmill study

Appendix 6: Overview of the mill study protocol provides a textual and photographic record of the sequence of steps followed to allow individual logs and boards to be tracked back to the site and tree from which each was sourced. In summary logs were

- coded in the forest after felling by the harvesting co-ordinator using a site code, tree code and log code (1 -5 to identify log sequence from the base). Harvesting crews were asked to apply a normal sawlog protocol for deciding the length of the log and the removal of any portion that did not meet specification.
- In the log yard, logs were laid out on beams with (generally) the basal end on the same side, and log codes checked and recorded.
- Each log was given a unique number starting from 300 to match the number from prepared barcode sheets.
- Log length, large end and small end diameters were recorded along with heartwood diameters, while also collecting HM200 acoustic velocity measures.
- Log ends were trimmed (squared) and a 50mm disc removed from the small end for DiscBot analysis at Scion.
- Log numbers were stenciled onto the SED and a sheet of barcodes glued to the LED and coated with 2 coats of a clear satin varnish.
- Logs were then moved into a single stack and each log weighed to obtain a green weight and used to calculate log MOE as per the following equation
    - LogMOE = Acoustic velocity^2 * Green log density
- Logs were then stacked prior to mill processing.

It was evident during log measurement, that some would not meet sawlog specifications, containing ramicorn or other defects, such as excessive sweep. Some trees only produced a single log, while in some instances from the more productive sites, up to five logs were generated. In this study, the evaluation of the RESI tool as well as eCambium, only buttlogs were considered.

Preharvest IML-Resistograph analysis

In July 2015, a new NDE technology became available for assessment in the project, via development work within the New Zealand Solid Wood initiative (SWI). The work being funded by the SWI involved the application of the IML-Resistograph (RESI) (http://www.imlaustralia.com/en/wood-testing-systems/products/iml-resi-systems/iml-resi-pd-series/) as a means of predicting log acoustic velocity as typically obtained from the use of the HM200 tool. Given the extensive dataset already obtained in the project, and the investment planned in the harvesting and processing of logs, the ability to evaluate the RESI tool was opportune.

This section describes the relationship between

(a) Stage 1 standing tree data (OWD & AWV-ST300), and mean outerwood resistance (OWR) at the site average level and at individual tree level.
(b) predicted HM200 values obtained from processing the RESI trace and the actual HM200 and log MOE values measured on 120 butt logs.

Methods

A pith-to-bark RESI trace was taken from each of the 30 trees originally sampled in Stage 1 from the 12 sites selected for Stage 2 harvest. The variability in wood properties used to select sites can be seen in Figure 23. In addition, where selected trees were not sampled in Stage 1 (as per above), a RESI trace was also collected. In one case, a non-sawmill (stage 1) site (Maragle 044) was located adjacent to a selected sawmill study site (Maragle 053), and the 30 trees from this site were also sampled using RESI. Table 12 records the details of the sites sampled together with their mean outerwood density and ST300 values. These selected sites represented the range of available variance of stands that were currently standing

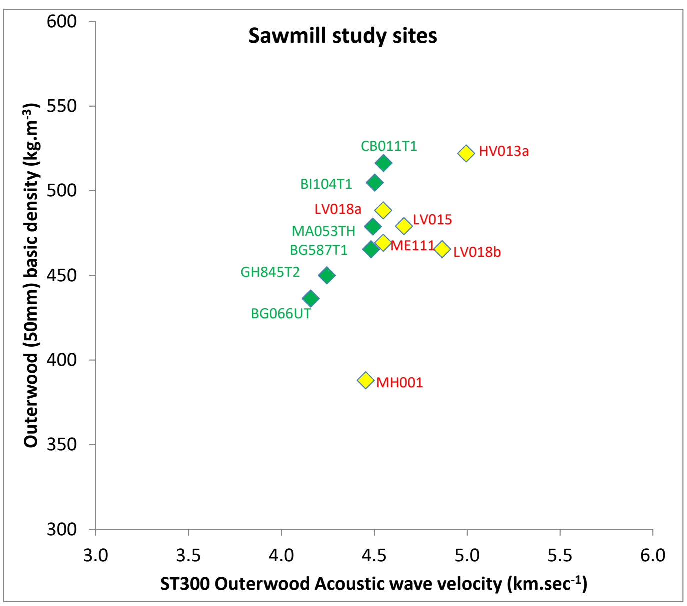

Figure 23. The selected sites covered the widest range available of density and AWV values.

RESI traces were also obtained from the small end diameter (SED) of each log.

Individual RESI traces were uploaded into a database and combined with tree and site data to match individual traces with source data. Two data sets were generated representing

(1) pre-harvest RESI traces

(2) SED log-based RESI traces.

Individual tree average OWD (outer 50mm) and AWV data was available from the stage 1 study where trees were sampled between late August and early October 2014. Individual RESI traces were processed using a procedure written in the R statistical programming language (R-Core-Team, 2013a) to detect the position of the cambial zone, and from this point generate an average resistance value for the outer 50 mm (e.g. Figure 24).

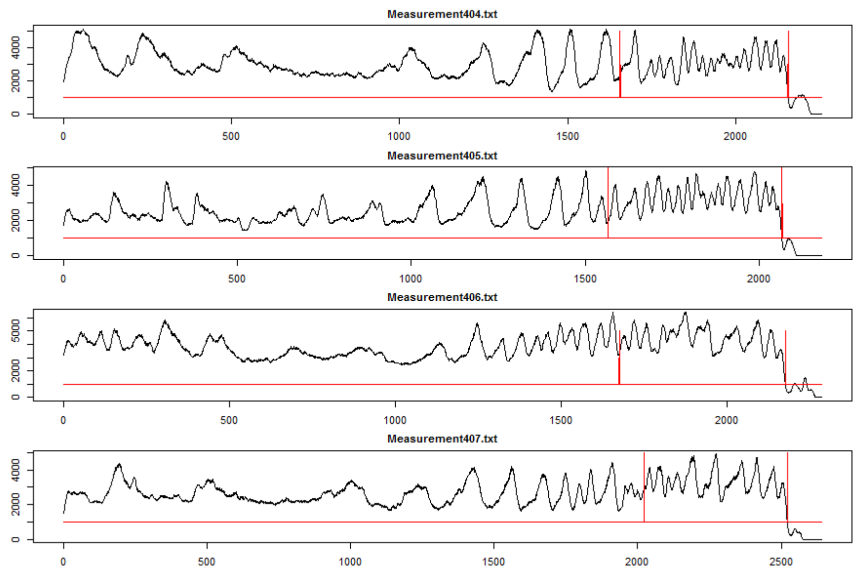

Figure 24. Four RESI traces, indicating the region over which mean and maximum OWR values were calculated.

The position of the pith, cambial zone and annual ring boundaries were marked and annual summaries of a range of variables calculated. These were reduced to a single value for each variable per RESI trace. Using the pre-harvest RESI traces, predefined regression equations[12] based on earlier work in New Zealand were used to predict HM200 values and compared with values for butt logs only. The ability of the RESI traces to explain additional variance in the log HM200 data was assessed by generating new regressions fitted to the data set using R (R-Core-Team, 2013b).

Results

Relationship with OWD, OWR and AWV-ST300

Despite the two sampling programs being almost 12 months apart, site average OWD was strongly correlated with site average OWR, with OWR explain 88% of the variance in OWD (Figure 25). Site average OWR only accounted for 29% of the variance in ST300 values, and this increased by 2% to 31% if the maximum value in the outer 50 mm of the RESI trace was used (Figure 25b). Further analysis to improve the correlation with ST300 values will be explored at a later date if warranted.

[12] The initial study involved 100 logs from the KPP sawmill in NZ. The regression defined there was used in this study as an initial step. Subsequent work by the NZSWI has broadened this data set and a multi-site calibration is being developed.

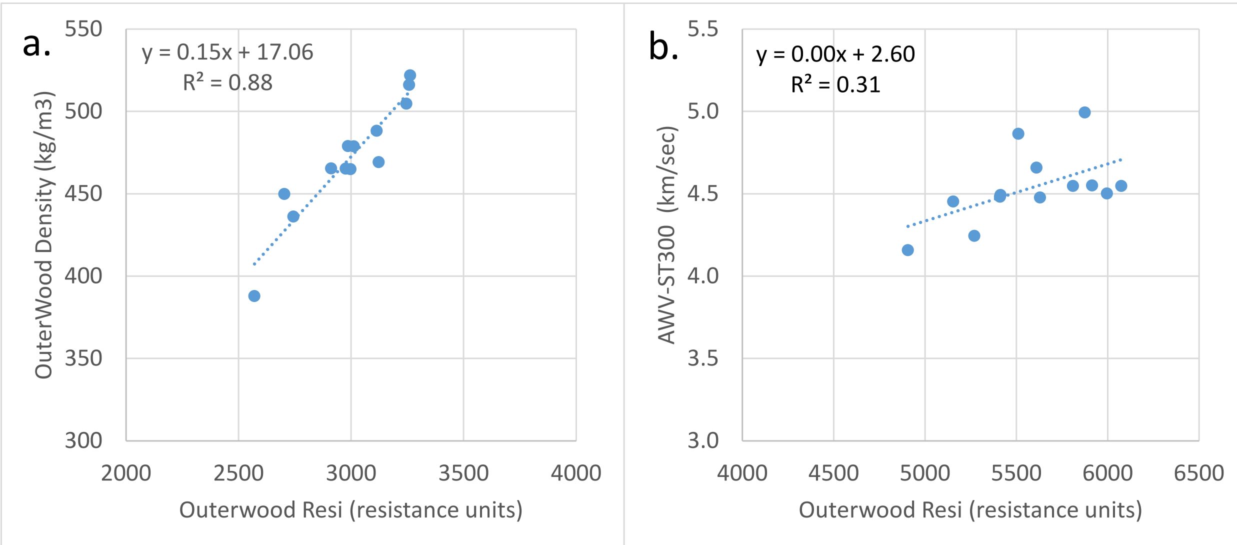

Figure 25. Relationships between site average (a) OWD & OWR and (b) AWV & maximum Resi in outerwood.

At the individual tree level, the relationship was weaker with an r^2 of 34% (Figure 26a). Given the large within-tree variation, the need to take the RESI trace some distance from the OWD sampling point and the time difference between the sampling times, this is consistent with other studies comparing data at the individual tree level. Relationships between the mean RESI values and the acoustic velocity values were considerably weaker (Figure 26b).

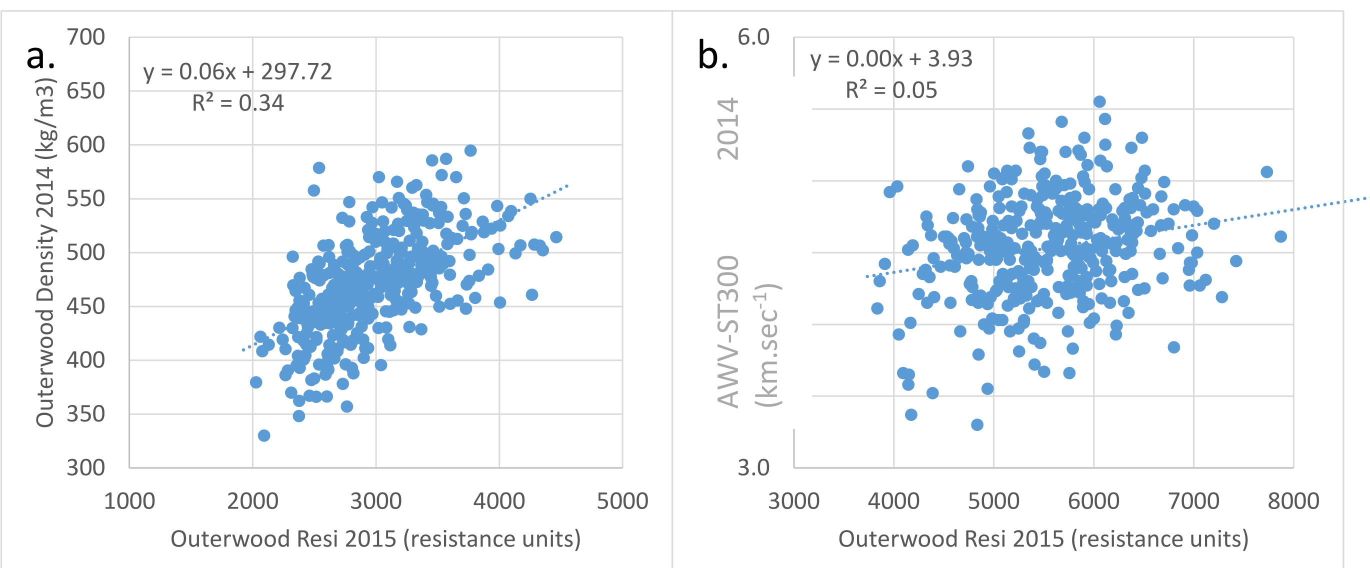

Figure 26. Relationships between individual tree (a) OWD & OWR and (b) AWV & maximum RESI in outerwood.

These data support the value of the IML-Resistograph as a means of ranking sites in terms of outerwood density variance.

Relationship between RESI-predicted and actual log AWV

<u>Site average comparisons.</u>

The high degree of between-tree variability is such that main application of the RESI tool will be at the site or sub-population level. Across the 12 sites considered here, the RESI-predicted HM200 values (default KPP regression) explained 47% of the variance in actual buttlog HM200 values (Figure 27a). Breaking this down to the Victoria and NSW site sub-categories, we find most of the unexplained variance is in the Victorian sites (r^2 = 0.28) rather than the NSW sites (r^2 = 0.91). Overall the NZ-based default prediction of HM200 tended to over-predict the actual values. As can be seen in Figure 23, there was generally more scatter in the actual wood property data relationships also. Moyhu is an ex-pasture site with heavy branching and poor form. Havilah is a high elevation, relatively dry site.

The sawmill study included the weighing of logs allowing the calculation of log green density, from which log stiffness (MOE) was calculated (MOE = $HM200^2$ x density). This means of adding density into the log properties, reduced much of the HM200 scatter (Figure 27b). The scatter amongst the Victorian sites is reduced, largely by bringing Moyhu (low density and stiffness) closer to the general population. These suggests that RESI-predicted HM200 value is a better indicator of log stiffness than acoustic velocity.

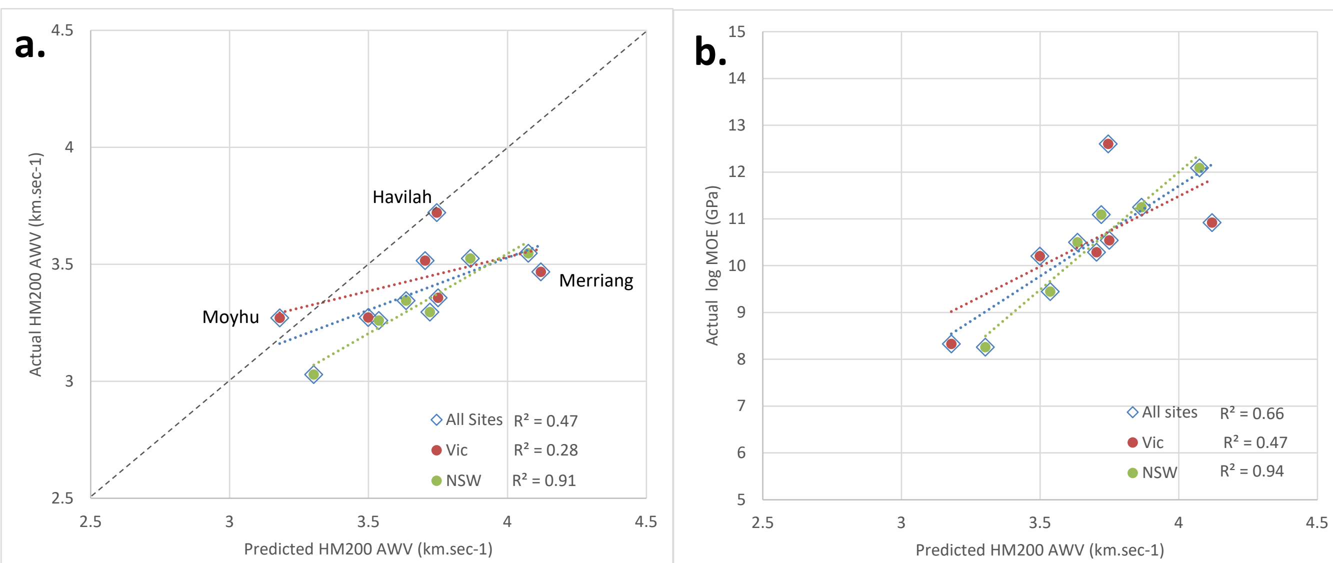

Figure 27. Predicted versus actual site average values for all 12 sites, as well as values describing the precision and accuracy of the predictions. The relationship within the mature sites only is also shown (solid blue points)

On an individual tree basis, the RESI-predicted HM200 values (based on the preliminary New Zealand KPP log study) explained 23% of the variance in the actual data with a standard error of prediction of 0.38 $km.sec^{-1}$. The PrHM200 consistently explained more of the variance in log MOE than in acoustic wave velocity.

This application of the RESI tool is at an early stage of development and the data from this project will contribute to the development of a more robust and widely applicable relationship. A regression fitted to the data from this project (Figure 28c&d) explained 83% and 58% of the variance in the site average and individual tree values.

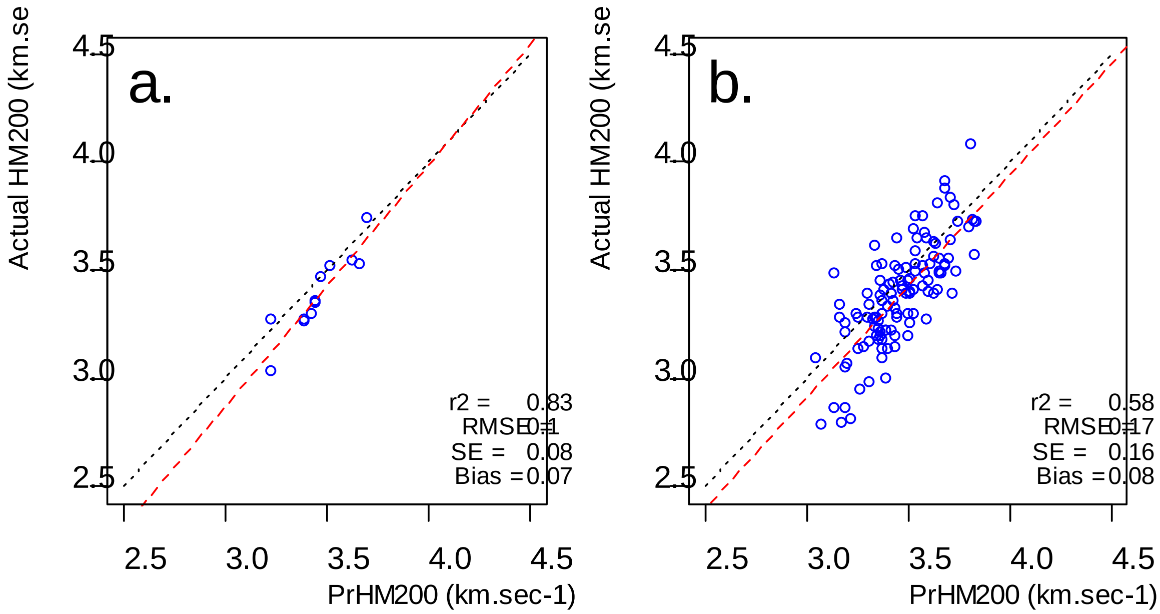

Figure 28. Predicted versus actual HM200 values. (a) Site-average and (b) individual tree predictions respectively based on a fitted relationship between Actual HM200 values and RESI data from this study

Empirical relationships between Stage 1 measures and Stage 2

The overarching goal of this project is to assess how well the hybrid *eCambium* modelling system predicts commercially meaningful sawlog properties. As a basis for comparison it is valuable to assess whether, independent of eCambium predictions, the pre-harvest (Stage 1) data significantly explained variability in the log level data.

In the following section we quantify how other wood property and tree growth measures predicted log stiffness and volume, and ultimately the volume and stiffness grade distribution of the boards they produced. Pre-harvest (stage 1) data is summarized and compared with sawlog properties at (a) a site average level and (b) an individual tree level. Of the trees sampled in stage 1, 95 were included as part of the sawmill trial.

Results

Before considering the empirical analysis of log quality as a function of pre-harvest measures, it is of interest to put this into a commercial context. Because of the detailed nature of the study and the ability to track each individual board back to its log and site of origin, it was possible, by assigning each board grade a commercial value, to obtain an average value of the properties of lumber from each site.

Figure 29 compares the value of lumber produced from each site as a function of the acoustic velocity of the logs as measured in the log-yard[13]. From this it is possible to infer that 0.1 km per second of AWV equates to approx. $10 per cubic metre of lumber. The 12 study sites spanned a value range of $75 per cubic metre of processed lumber. If recoveries are around 50%, this equates to ~$40 per cubic metre of log volume. Similarly increasing the log MOE by 1 GPa equates to ~$14 / m^3 of sawn lumber value.

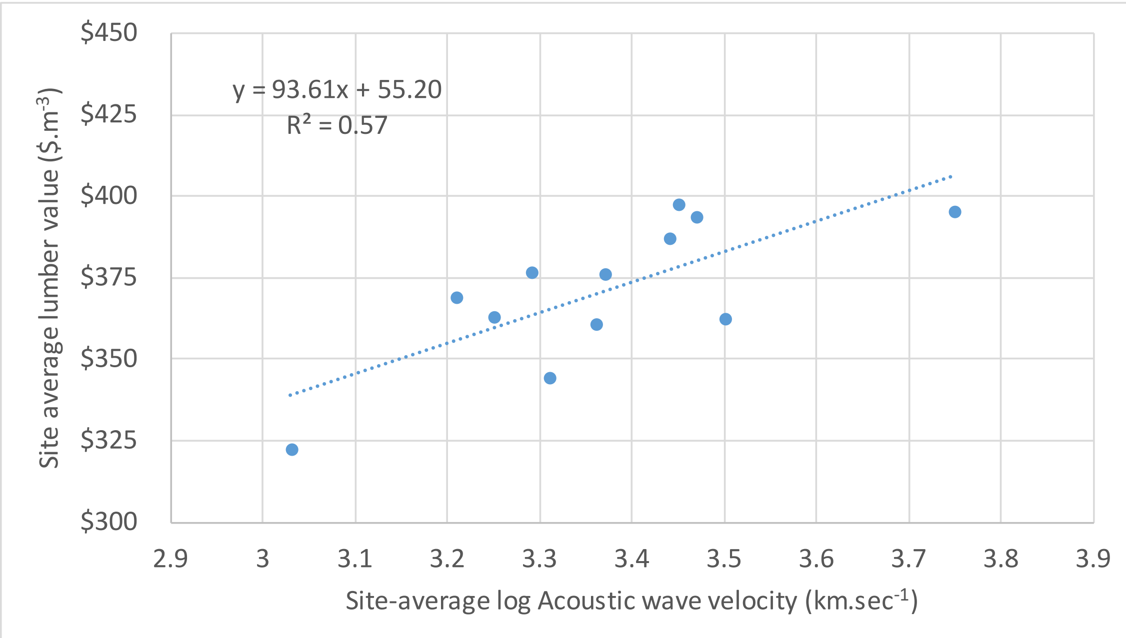

Figure 29. Commercial value of lumber relative to sawlog acoustic velocity.

Within-tree variation.

It is also valuable to obtain some indication of within-tree variation between logs before assessing the relationships between stage 1 and stage 2 data,. As the stage 1 measures were obtained from sampling around breast height, it is expected that these would relate most precisely to buttlog (log 1) values. However, as the majority of trees produced more than one log, and some trees produced up to five logs per tree, the relationship between butt log and other logs is of interest.

In the log-yard each log was assessed for

- large and small end diameter
- large and small end heartwood diameter
- length (depending on individual tree characteristics, butt logs were shorter than the target 6 – 6.5 m)

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[13] The following values were used and relate to a cubic metre of lumber

Low - $250, MGP10 - $400, MGP12 - $440, MGP15 - $480.

- Acoustic velocity (HM200)
- Green density
- Log MOE ($HM200^2$ * green density)

Table 13 records the correlation between acoustic velocity (HM200) and log MOE for the different logs up the stem at an individual tree level, removing trees where direct comparisons were not available. The strength of the correlation reduces as the spatial separation between the logs increases. However, the correlations are still statistically significant and while one would expect the correlations between the pre-harvest data and log 1 to be strongest, the relationships with the butt logs should be informative for the other logs. The data suggests that 80% of the variance in log 2 can be explained by variance in log 1.

Table 13. Pearson correlations (r NOT r^2) between log properties within trees. Shaded cells above the diagonal record the number of logs available to generate the correlation.

Acoustic Velocity (HM200)				
	log 1	log 2	log 3	log 4
log 1	1	118	96	19
log 2	0.88	1	93	20
log 3	0.67	0.78	1	19
log 4	0.63	0.51	0.45	1
Log MOE				
	log 1	log 2	log 3	log 4
log 1	1	118	96	19
log 2	0.89	1	93	20
log 3	0.66	0.74	1	19
log 4	0.39	0.56	0.47	1

Site-average.

Site average data from stage 1 (based on the 30 trees sampled) was compared with the site average data from the logs generated (Figure 30). DBHOB measured a year previously explained 72% of the variance in large end diameter (LED) of buttlogs. There was a weaker negative relationship between LED and outerwood density, and similarly weak relationships between DBHOB and log HM200 and MOE values. Site average branch diameter was a strong predictor of log MOE. Consistent with similar findings in New Zealand (Watt et al., 2008; Watt et al., 2006b; Watt and Zoric, 2010), the site average tree slenderness (Tree height / DBHOB based on 6 trees per site) was a reasonably strong predictor of site average HM200 and log MOE. Site average outerwood density was a good predictor of log MOE but not as good for HM200 values. Site average ST300 was a reasonable predictor of log MOE and a good predictor of HM200.

Average log MOE was also calculated as a volume-weighted average of all boards produced. The board MOE value was calculated in the mill using the green density (based on weighbridge green weight and volume calculated from mill-based measures of board dimensions) and acoustic velocity (E-grader). This measure was strongly correlated with the log-yard measure ($R^2 = 0.88$)[14]. Given that the measure based on boards includes proportionately more of the inner juvenile (low stiffness) wood, it was consistently lower than the log-yard measure.

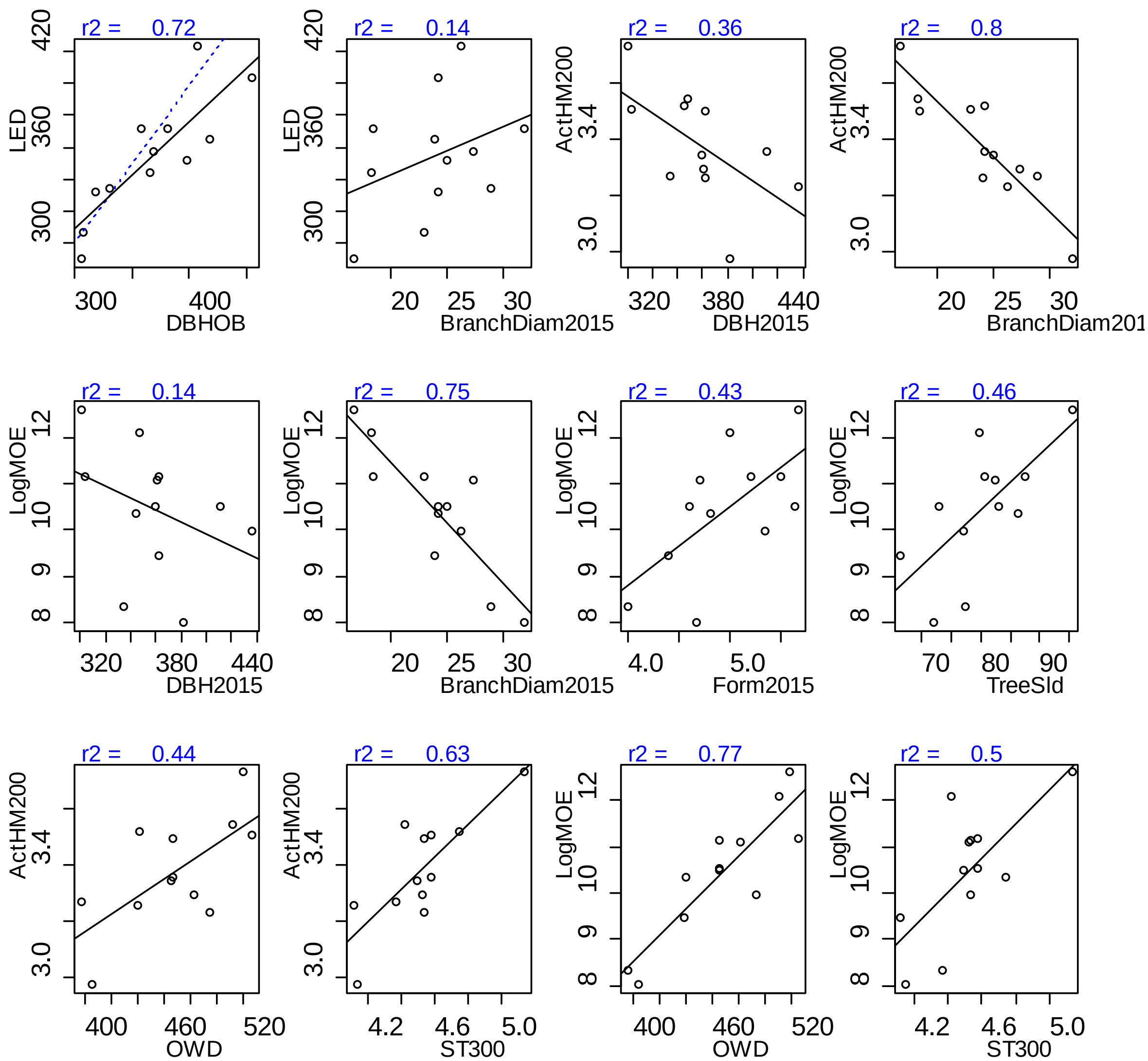

Figure 30: Correlation plots between site averages obtained from pre-harvest and log yard data. Only buttlog data was used here.

Individual tree

Of the 121 trees harvested in stage 2, 95 had been individually sampled in stage 1. Figure 31 illustrates the main correlations among the stage 1 and stage 2 variables. DBH, as would be

[14] Logyard MOE = 2.954 + (0.87 * BoardLogMOE)

expected, gave a good measure of log LED, whereas there was no relationship between OWD and log diameter. The negative effect of increasing branch diameter on reducing log HM200 and MOE is also evident. OWD and ST300 values had a moderate relationship with HM200 and log MOE.

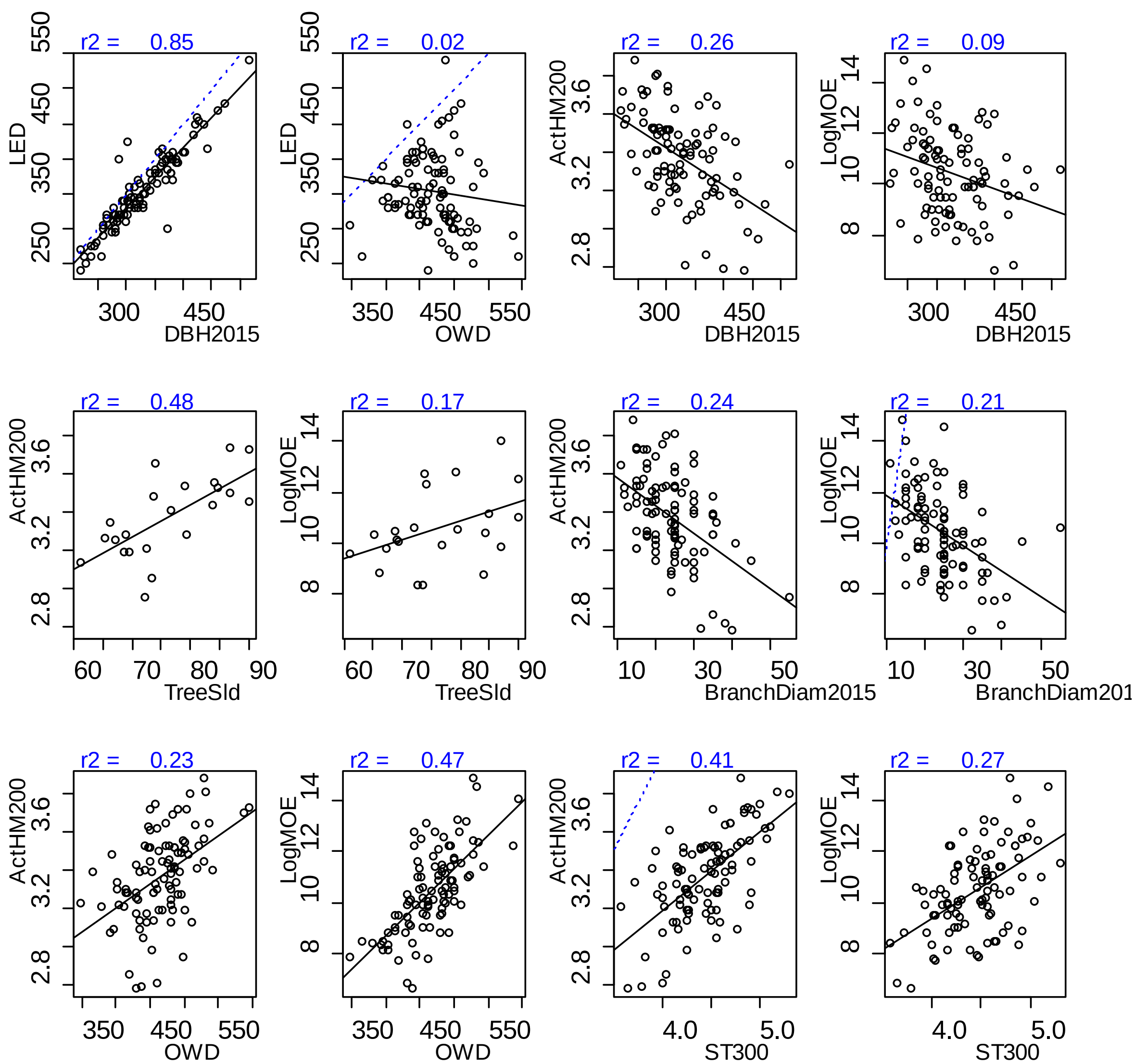

Figure 31: Relationships among Stage 1 (x-axis) and Stage 2 (y-axis) data. Note in stage 1 only 6 out of 30 trees per site were measured for height (and therefore tree slenderness), bark thickness and branch diameter. Dashed line indicates the 1:1 line in appropriate plots.

<u>Regression analysis of log MOE and HM200 values</u>

From Figure 31 it is evident that OWD had a better predictive capability for log MOE, whereas ST300 had a stronger relationship with HM200 values. Combining these into a regression explained 48% of the variance in HM200 values and 57% of the variance in log MOE

- Log HM200 = 1.026 + (0.00166 * OWD) + (0.354 * ST300)
- Log MOE = -7.062 + (0.0223 * OWD) + (1.593 * ST300)

Combining all available data from the pre-harvest measurements allowed 61% of the variance in HM200 and 62% of the variance in Log MOE values to be explained using the following fitted[15] regressions. These regressions did not include tree slenderness as tree height was only measured on 6 of the 30 trees sampled per site in stage 1 and not all these were selected as harvest trees. Consequently, including tree slenderness would have reduced N markedly. The inclusion of branch diameter in the equation indicates the importance of this variable that is not being captured by covariance with DBHB, OWD or ST300.

- Log HM200 = 2.085 + (0.0014 * OWD) + (0.262 * ST300) + (-0.00093 * DBHOB) + (-0.00762 * Branch Diameter)
- Log MOE = -3.956 + (0.020 * OWD) + (1.391 * ST300) + (-0.054 * Branch Diameter)

Including the Resistograph data

The ability of the RESI tool to explain variance in log properties was described above. This involved the combination of a range of RESI trace properties into a predicted HM200 value. The predicted HM200 value (PrHM200) was added to the pre-harvest data regression and increased the variance explained to 64% for log HM200 and 67% for log MOE.

Given that the RESI tool is being evaluated as an alternative to “traditional” outerwood density and ST300 approaches, a regression that replaced these with the RESI value explained 45% of the variance in HM200 and 37% for log MOE.

- Log HM200 = 3.25 + (0.21 * PrHM200) + (-0.0013 * DBHOB) + (-0.0069 * Branch Diameter)
- Log MOE = 4.36 + (1.99 * PrHM200) + (-0.053 * Branch Diameter)

Note that the PrHM200 value generated from the RESI trace is still a work in progress[16]. The RESI data can also be used to generate a predicted outerwood density (PrOWD) value which in this data was strongly correlated with the actual outerwood density ($r^2 = 0.7$). Adding this PrOWD into the above regression increased the variance explained to 50% for the HM200 value and 57% for log MOE. These are relationships at the individual log level; they will be markedly stronger at the site-average level.

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[15] Regression coefficients are fitted to the available dataset and would be expected to generate weaker relationships when applied to an independent dataset.

[16] Other studies indicate the RESI predictions should be able to account for better than 50% of the variance in HM200 on a consistent basis. When grouped into site averages, RESI predictions should account for >80% of the variance between sites.

Regression robustness

The above equations represent regressions fitted to the data and do not describe its performance in application to an independent data set. To assess the relationship further a form of cross-validation analysis was undertaken where the data was randomly divided into a training set (75% of samples) and a test set (25% of samples). Regressions of the form described above were fitted to the training set and the resultant regression used to predict the values in the test set. This process was repeated through 25 iterations (Figure 32), and the variance explained and standard errors of prediction recorded for each iteration and summarized (Table 14).

Table 14: Summary of cross-validation equation for the prediction of log HM200 from pre-harvest (standing tree) measurements.

		Regression coefficients					Fitted		Validation			
		Intercept	PrHM200_ Manual	PrOWD	DBHOB	Branch Diameter	r^2	SEE	r^2	RMSEP	SEP	Bias
HM200	Average	3.187	0.134	0.00066	-0.00137	-0.00651	52%	0.159	51%	0.170	0.170	-0.009
	stdev	0.117	0.024	0.00009	0.00017	0.00154	4%	0.008	12%	0.024	0.025	0.036
	CV	4%	18%	13%	-12%	-24%	7%	5%	23%	14%	15%	
	Max	3.378	0.178	0.00080	-0.00099	-0.00211	60%	0.171	76%	0.231	0.235	0.072
	Min	2.920	0.090	0.00043	-0.00175	-0.00870	45%	0.135	29%	0.130	0.128	-0.070
	Range	0.458	0.088	0.00036	0.00077	0.00659	15%	0.036	47%	0.101	0.106	0.141
		Regression coefficients					Fitted		Validation			
		Intercept	PrHM200_ Manual	PrOWD	DBHOB	Branch Diameter	r^2	SEE	r^2	RMSEP	SEP	Bias
LogMOE	Average	4.766	0.908	0.00918	-0.00388	-0.05089	59%	1.058	56%	1.127	1.113	-0.099
	stdev	0.882	0.183	0.00100	0.00092	0.01124	3%	0.044	8%	0.146	0.139	0.278
	CV	19%	20%	11%	-24%	-22%	5%	4%	14%	13%	13%	-2.812
	Max	6.865	1.426	0.01093	-0.00222	-0.03720	65%	1.162	74%	1.335	1.332	0.341
	Min	3.257	0.644	0.00725	-0.00550	-0.07826	54%	0.982	43%	0.706	0.705	-0.721
	Range	3.608	0.782	0.00368	0.00328	0.04106	11%	0.180	32%	0.629	0.627	1.063

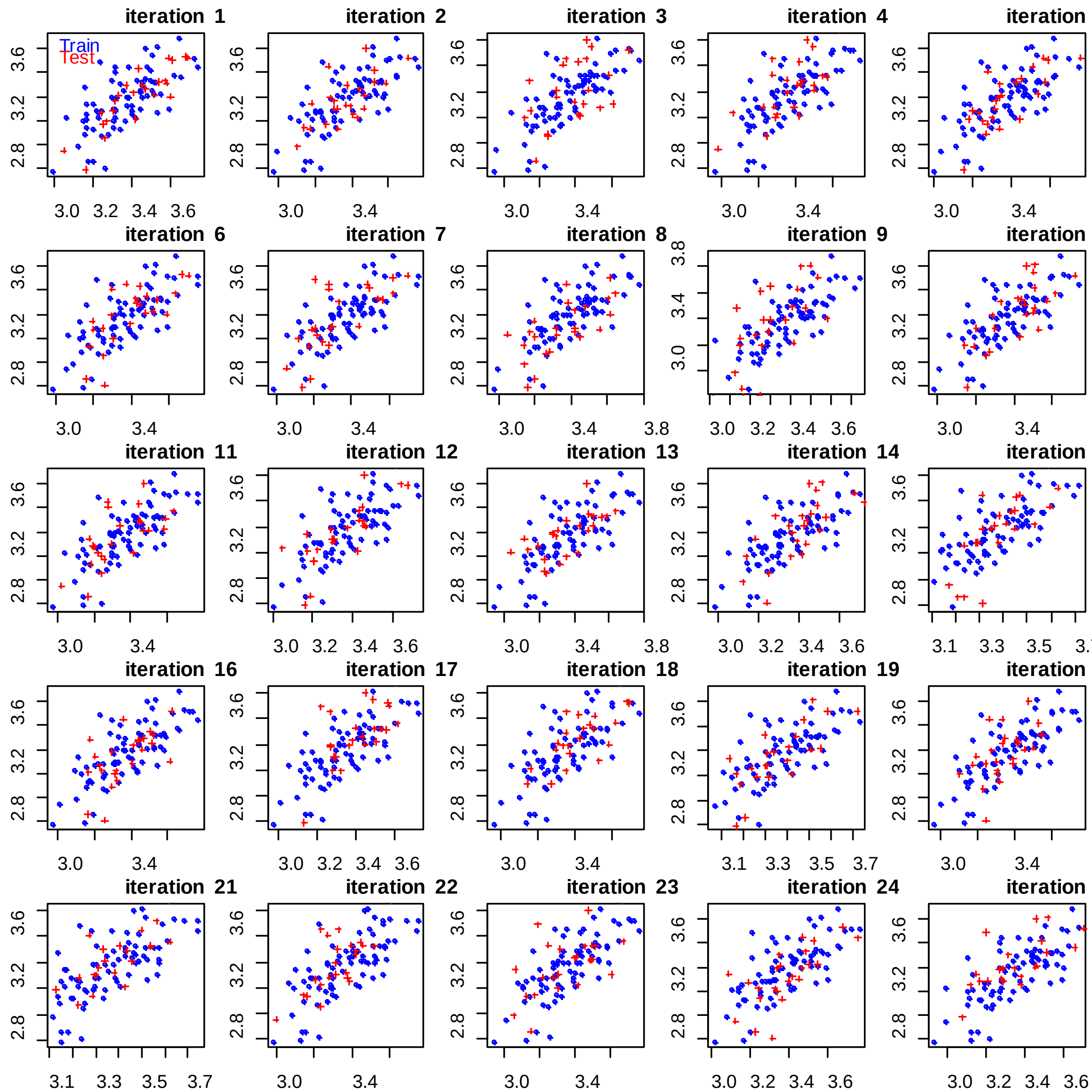

Figure 32: Iterative fitting of a regression to the randomly selected training set (blue) and applied to the test set (red).

Summary

Independent of eCambium, the analysis above describes the variability in log acoustic velocity (HM200) and log MOE as a function of variables measured from standing trees made one year prior to harvest. At a site average level, individual tree characteristics (average branch diameter, outerwood density) were able to account for 60-70% of the variance in log acoustic velocity and stiffness (MOE). Standing tree measures (OWD, ST300, DBHOB, Branch diameter) were able to account for > 50 % of the variance in individual log acoustic velocity and MOE.

eCambium as a predictor of log and board values

A major objective for the overall project was the validation and further development of the eCambium model as a predictor of commercially useful sawlog properties (value). This section assesses the accuracy and precision with which the eCambium predictions made previously (e.g. Figure 21) accounted for variance in actual sawlog data. To a large extent the known relationships between OWD and log quality have already demonstrated eCambium's potential in this regard through its ability to predict OWD in standing trees.

For commercial purposes, the ability of eCambium to predict log properties (MOE) is primary. However, the relationship between predicted and actual board properties is valuable to assess to provide an appropriate level of confidence to the predicted distribution of grade recovery.

Comparisons based on actual and predicted board numbers confounds the effects of variation in growth (stem diameter and height) with wood property variation; larger logs produce more boards and their outer boards are more likely to contain less of the low-stiffness juvenile core. Presenting comparisons in terms of board proportions, where the volume of each board is a proportion of the total (all proportions summing to 1), to some extent removes the confounding effects of volume.

The data presented previously (Figure 21) has been reproduced here with only the 12 sawmill study sites (Figure 33). The predicted values were based on five grades (utility, F5, MGP10, MGP12, MGP15) whereas actual sawn boards at the green mill stage, were classified in only four grades (low, MGP10, MGP12, MGP15). The dollar value of the low grade was used for calculating the value of both "utility" and "F5" classes

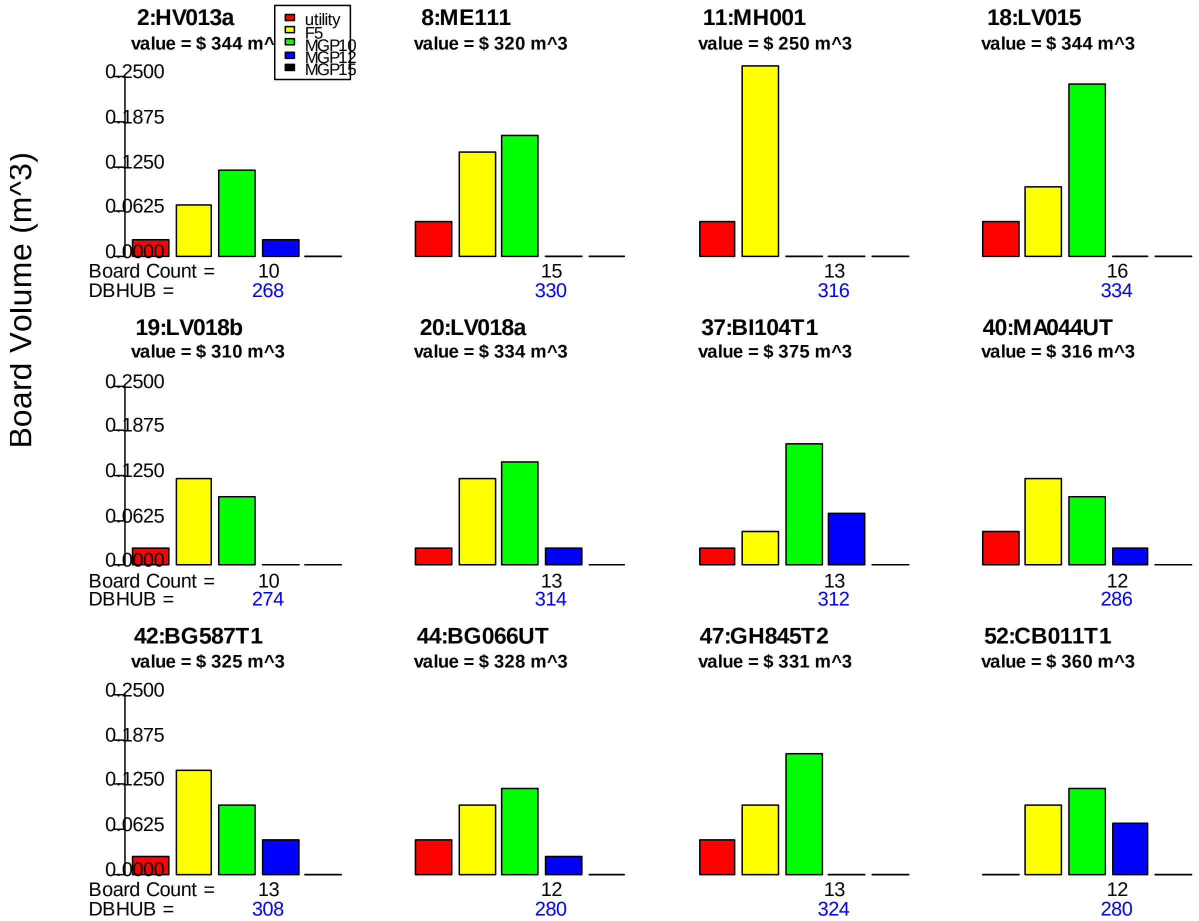

Figure 33. Predicted lumber value based on eCambium scenarios prepared for the milestone 3 report

Predicted vs actual log MOE and value

Based on the actual sawn board volumes recovered from the sawmill study, an actual value ($\$/m^3$) was calculated and compared with the predicted values (Figure 34). At the site-average level, eCambium predictions explained over 60% of the variance in the actual data if one obvious outlier (Site 44: Bago066) was excluded.

Bago compartment 066 is a high elevation site (1000m) and the local region has considerable topographical variability. eCambium utilizes publicly available weather data on an approximately 5km by 5 km grid. Because of this relatively coarse resolution, Bago 066 (site 44; elevation 1000 m) uses the same weather data as Bago 587 (site 42; elevation 850 m) and consequently the resolution of the weather data may not properly reflect the actual differences (eCambium does not include an elevation effect on temperature, but uses the weather data to capture its effect). It is notable from Figure 12, of all the sites for which SilviScan data was obtained, Bago 066 had the greatest tendency for MOE to be over-predicted compared to the actual trajectories in MOE. This relative to the other sites, eCambium markedly over-estimates the value of the logs.

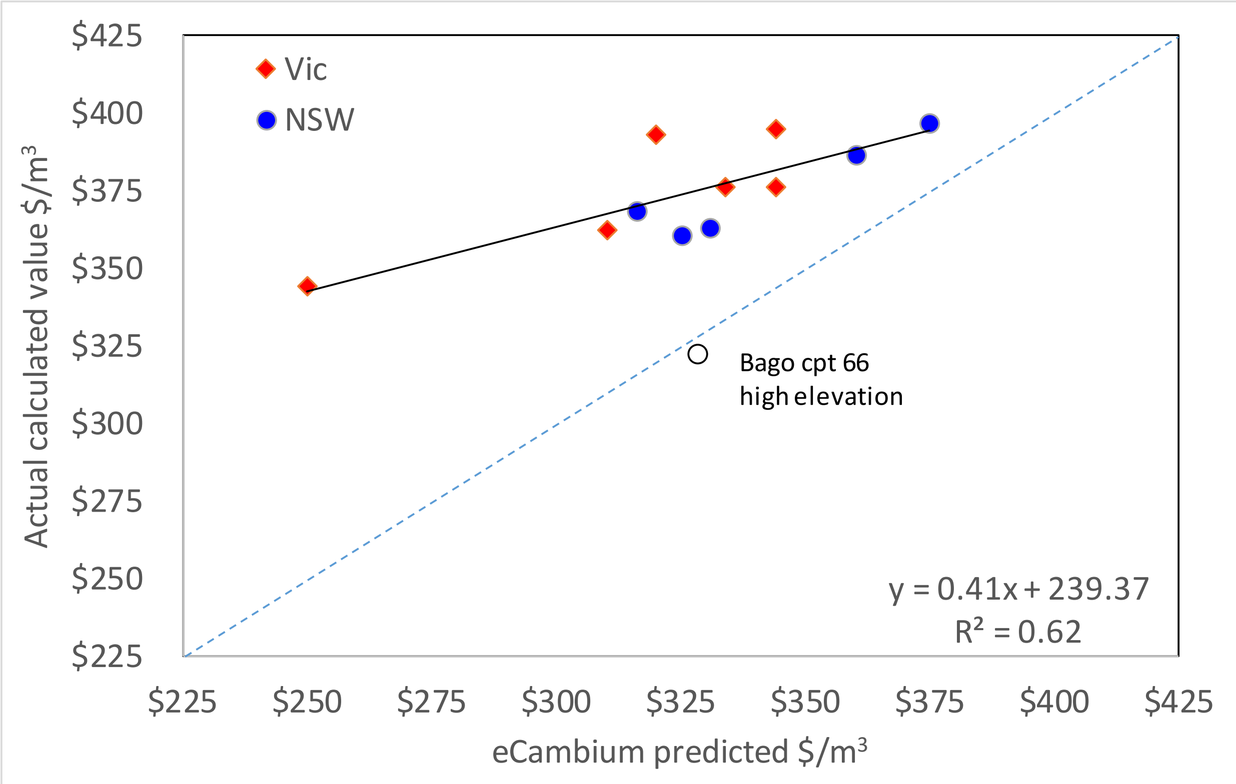

Figure 34. Predicted vs actual lumber value expressed as $ /m^3. Note one site (Bago 066) was left out of the relationship shown. Including this site reduced the r^2 from 0.62 to 0.33.

It should also be remembered that the eCambium predictions from Figure 33 represent scenarios based on no attempt to vary the FR among the sites. Modelled MOE at Bago 066 was improved markedly (a reduction of 0.3 GPa) by adding a fertilization event (increasing fertility from 0.3 to 0.5) to cater for likely higher fertility than assumed. The soil samples taken from Bago 066 (April 2015) had a high Nitrogen content, and a moderate C:N ratio (19.4), which suggests that this site may even have had ex-pasture characteristics. In all likelihood, fertility was higher at time of establishment in that case. Changing mean minimum and maximum temperature (altitude effects) did not lead to noticeable changes in MOE (max 0.1 GPa), but by increasing rainfall by 20%, MOE at BG066 decreased by 0.2 GPa. Higher site fertility combined with higher rainfall than that was used for the simulations would be expected to lead to a lower predicted MOE of at least 0.4 GPa, which would mean that the R^2 value based on all 12 sites would increase to approximately 66%.

In general, eCambium tended to over-predict MOE in the juvenile core. This is to a large extent a problem associated with the overly steep predicted MFA decline at some sites. The improvement of the MFA model in eCambium is currently underway as part of a student project at the University of Stellenbosch. It is also evident that eCambium generally over-predicted lumber value, part of which effect is the threshold values used to assign a particular board to a particular stress grade.

Predicted versus actual log MOE

Similar to Figure 34, the comparison of predicted radial breast height MOE versus actual mean log MOE yielded similar results (Figure 35). Bago 066 was the largest outlier and if left out of the relationship, eCambium predictions explained 50% of the variance in the 11 remaining sites. The two Victorian sites Me111 and Hv013a had the next largest residual difference between the predicted and actual values. Overall there was little bias between the predicted breast height radial (core) average and the average log MOE.

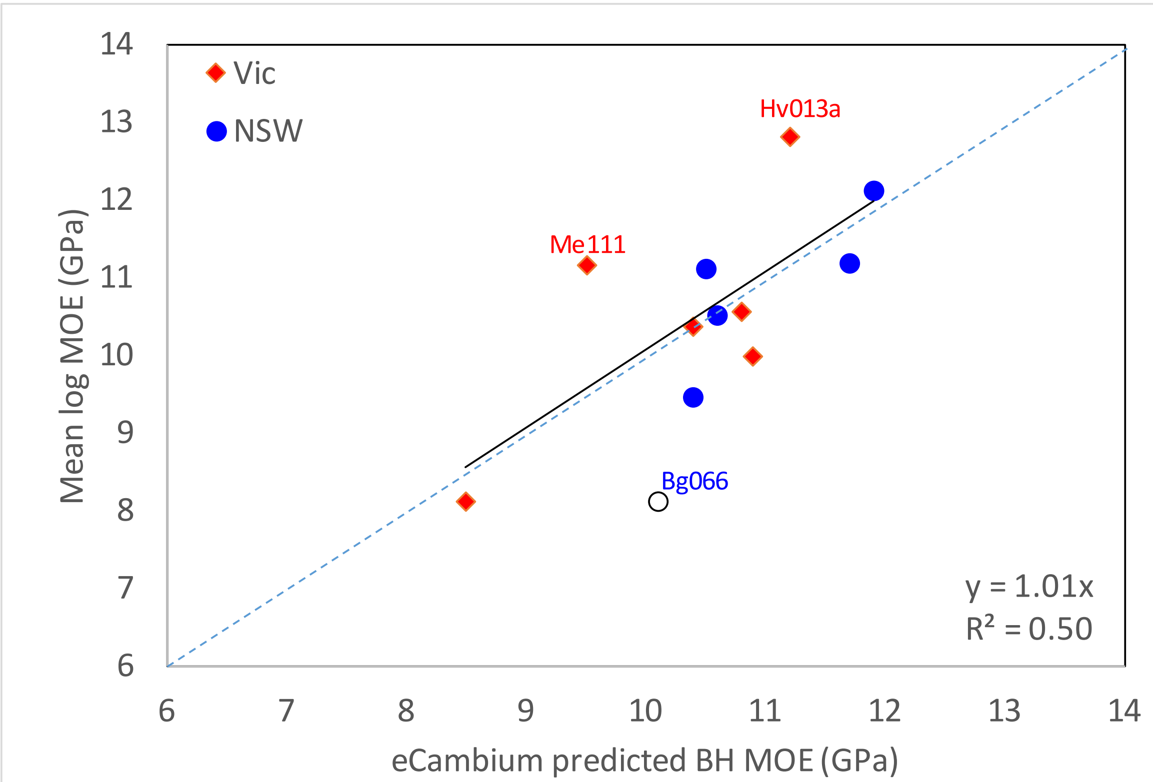

Figure 35. Predicted vs actual log MOE. Log MOE is the site average calculated from the Hm200 and green log density values, measured on individual logs in the log yard.

Grade thresholds

From Figure 34 eCambium generally tended to over-predict the value. In contrast the relationship with log MOE is close to the 1:1 line (Figure 35). Boards are allocated to grades based on board MOE values and specific thresholds. The threshold MOE values used in the preceding value comparisons, had been estimated from a previous FWPRDC 2004 project in the Green Triangle[17]:

- Utility 6.3
- F4 12
- MGP10 16.6

[17] FWPA Project PNC-196-1011 Predicting wood quality to improve sawlog value in radiate pine, Figure A3.24

- MGP12 20
- MGP15 >20

The actual MOE of the sawn boards produced in the study was recorded in the mill along with the grade class they were allocated to, based on the measured green density and the acoustic velocity of each board. This allowed the identification of the actual thresholds used to allocate boards to different grades (Table 15).

Table 15. The actual thresholds used in the allocation of boards to stiffness grades. Note these are done at the green mill stage. During the drying stage the boards would be regraded and the "low" grade would be replaced with "utility" and "F4".

Grade	MOE ranges	No. boards	eCambium upper-threshold value
Low	0-6.79	902	7.9
MGP10	6.80-11.00	1693	16.25
MGP12	11.01-13.94	489	17.05
MGP15	13.95 -17.81	47	>17.05

Using the upper values of the MOE ranges in Table 15 (i.e. 6.79, 11.00, 13.94, 17.81) as threshold values in eCambium resulted in an over-prediction of the number of higher grade boards. This may be due to eCambium predicting "clearwood" MOE and consequently the MOE-reducing effects of knots and other features are not accounted for. eCambium predictions had been optimized to relate to those generated by SilviScan, and as SilviScan MOE is in turn calibrated against dynamic MOE (Evans et al., 2000) it tends to be higher than that observed in measurements of actual lumber. As a result, the threshold range was optimised to bring the predicted versus actual value close to the one-to-one line (cf Figure 34), to give the values presented in Table 15, right hand column. Note this did not explain the greatest variance (r^2). The fitted threshold values resulted in an r^2 of 36% between predicted and actual value (Figure 36) if Bg066 was excluded.

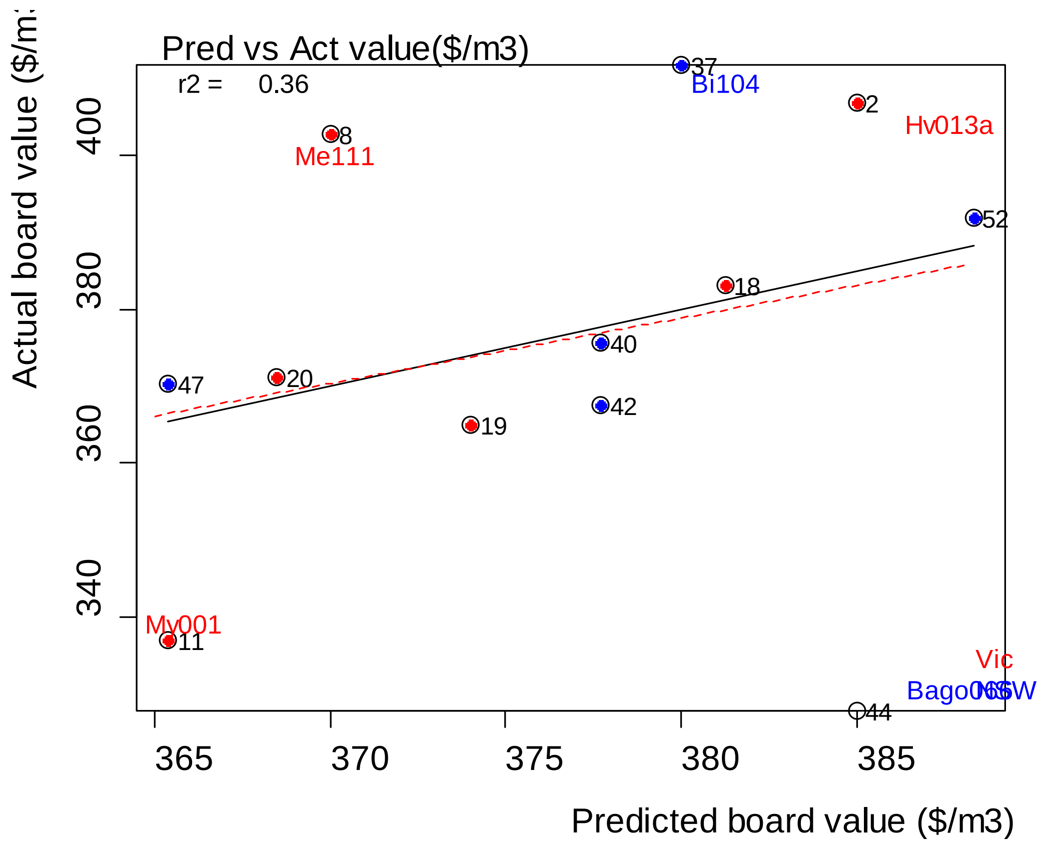

Figure 36. Combining the board volumes and grades with their value generated a comparison of predicted versus actual value shows eCambium predicted 36% of the value per cubic metre using thresholds optimised to minimize prediction bias. [Bago 066 excluded]. Black dotted line shows the 1:1 line; red dashed line shows the line of best fit.

The strength of the relationship is very sensitive to changes in these threshold values and essentially this process is one of trying to manage the combined effects of volume and stiffness. As diameter is the major determinant of board volume, to the extent that eCambium under predicts volume it will under-predict value. Likewise, if eCambium over-predicts volume but under-predicts stiffness, then the predicted vs actual value might be similar.

As such a better assessment of eCambium's predictive performance with respect to wood quality is (a) its ability to predict log MOE (Figure 35) a property of known commercial significance and (b) the relative distribution of boards within each grade. Ideally the predicted proportions within each grade would be the same as those actually obtained.

Comparing predicted vs actual of board distributions

In Figure 37 the predicted and actual histograms of board volumes within each grade, based on the thresholds shown in Table 15 are presented where the y axis records the relative volume of boards in each grade[18]. Some confounding can be expected in this presentation of the data, with the interaction between log volume (predicted log diameter) and wood variability. The distributions were normalized to offset this effect. Using these thresholds, 10 of the 12 sites (all except sites 8 and 52) had board distributions that were significantly different (at α=0.05) from the actual distributions (based on a chi-square test for differences in probabilities on a 2 x 4 contingency table). For this test, instead of normalising the data, the number of boards as predicted from eCambium was merely multiplied by 10, effectively comparing boards from 10 identical (simulated average) trees with boards from the 10 actual (and varied) trees.

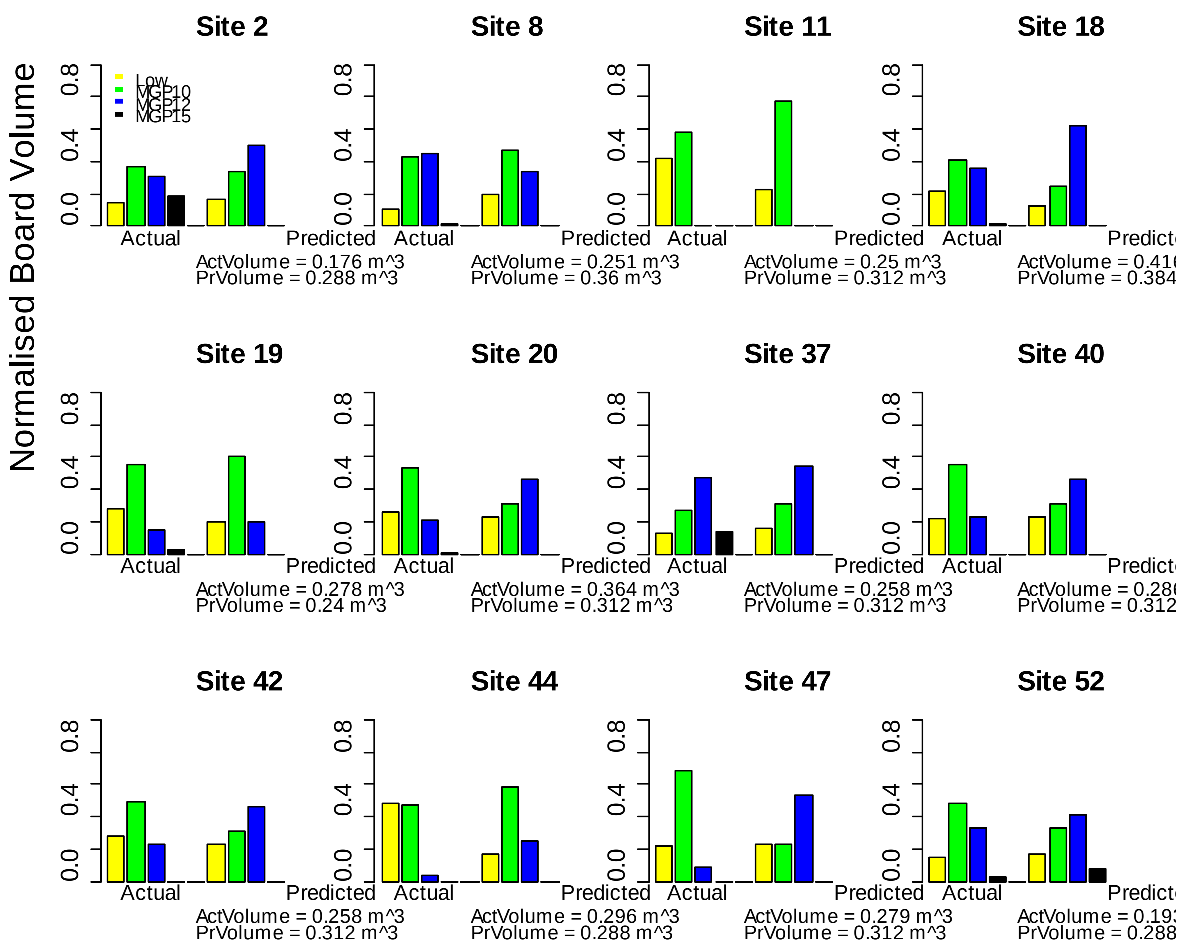

Figure 37 Comparison of actual and predicted board grade distributions by site using the predicted data generated for Figure 34 using the following thresholds of stiffness for the predicted values. "Low: 7.9", "MGP10: 16.25","MGP12: 17.05". The difference in actual versus

[18] Note that this is done assuming a standard log length (board length) of 6 metres. In calculating this from the actual board data only the width and thickness of the boards was used.

predicted volumes are recorded at the base of each plot and a function of diameter. To minimize this effect on the histograms the volume data has been normalized.**

It is clear that the thresholds chosen make a large difference. By running an optimisation procedure on these thresholds for varied distributions achieved, a new set of thresholds was identified which led to a major improvement in this metric, such that only 4 of the 12 sites (2, 8, 37 and 44) were found to have board distributions that *were* significantly different (at α=0.05) from the actual distributions. Interestingly these 4 sites exhibited the greatest difference between actual and predicted value in Figure 36, resulting in a lower r^2 than would otherwise have been found.

Using these new thresholds, 67% of predictions were the same as actually observed (Figure 38). These revised upper thresholds used in eCambium were Low = 9.2, MGP10 = 15.5 and MGP12=17.3. These higher thresholds likely relate to the effects of unmodelled variables such as knots and compression wood.

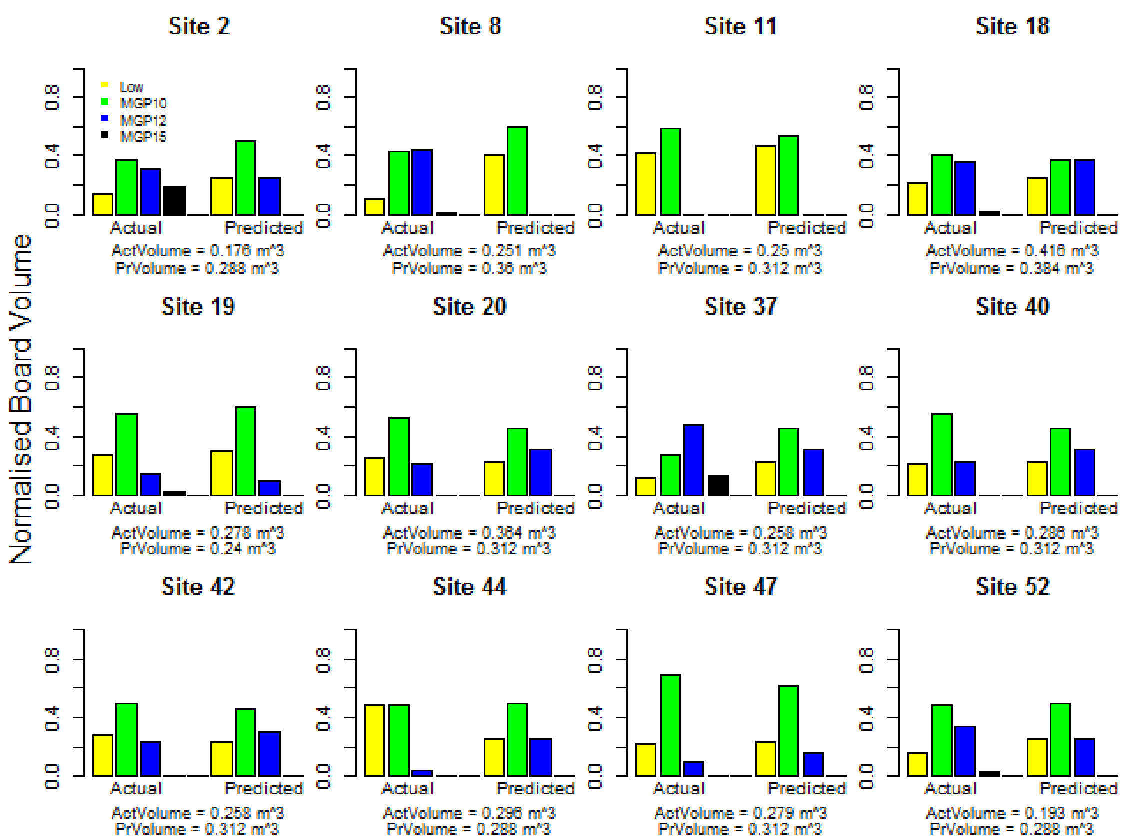

Figure 38. Comparison of actual and predicted board grade distributions by site using the predicted data generated in the milestone 3 report using altered thresholds of stiffness for the predicted values: "Low: 9.2", "MGP10: 15.5","MGP12: 17.2".

It is also of significance that in the actual board data, a variety of dimensions were produced[19], as the sawing process optimizes volume recovery in a way that the current sawn-board simulator in eCambium does not. However, as eCambium's virtual logs are perfectly round, there is going to be an over-estimate of recovery volumes compared to actual data.

An idea of the variability in wood properties within the logs as compared to the variability in MOE predicted by eCambium (at 0.3 m) is shown in Figure 39. The simulation at site 44 (Bago 066) predicts particularly narrow outer rings, as compared to the actual log end shown, which was one reason for the over-prediction of MOE at that site. Note also the poor ring structure at site 11 (Moyhu 001) and the concomitant structure in the predicted board end (which also shows the lower MOE values). The strong response to the two thinnings at the Lucyvale 015 and Green Hills site 845 is clear in the simulated log end.

[19] 100 x 40, 100 x 25,150 x 50, 100 x 50, 75 x 40, 75 x 50, 200 x 50

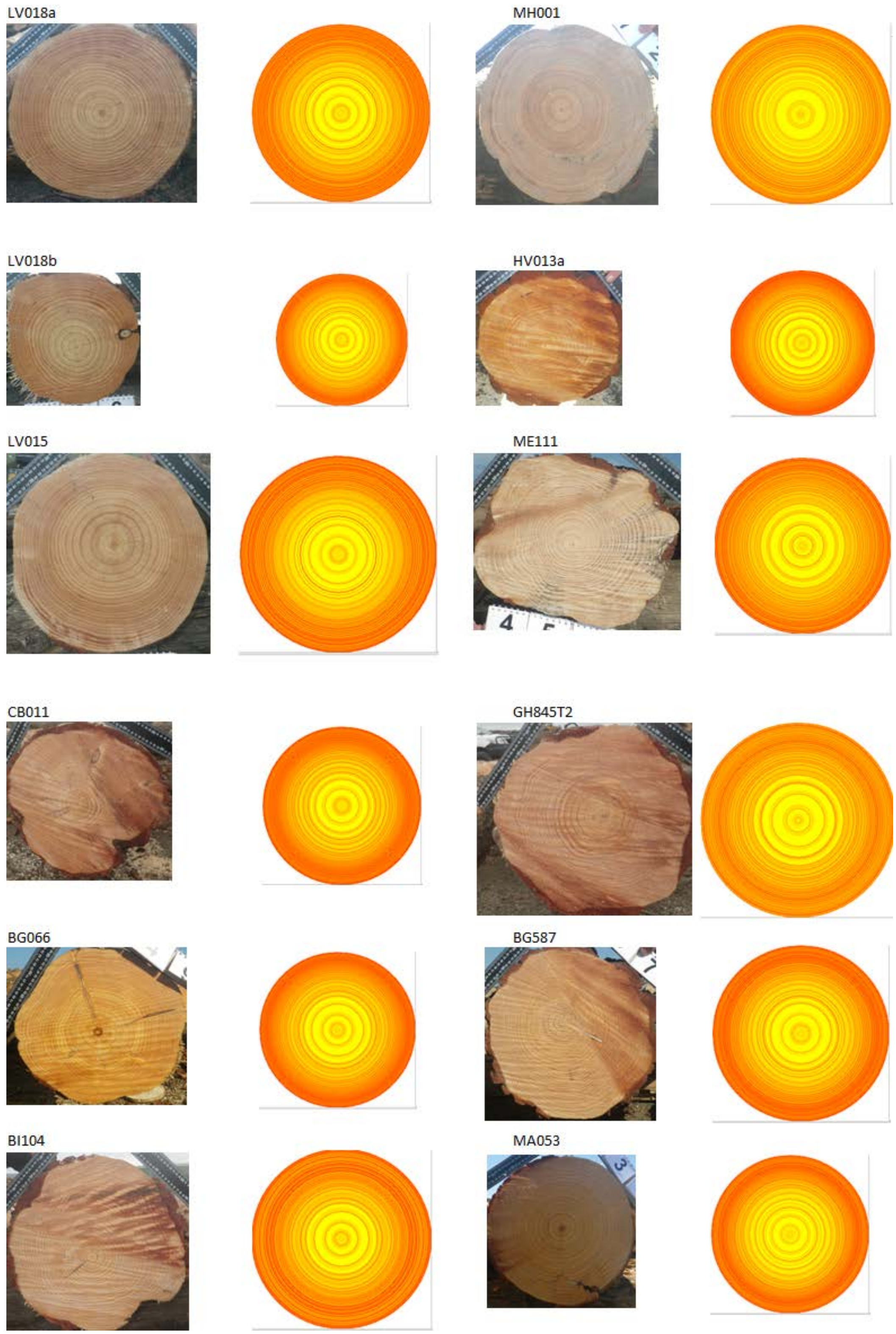

Figure 39: Images of actual and simulated log ends. The actual ends were chosen to match the simulated tree sizes, and images are scaled relative to each other. Yellow indicates low MOE and red indicates high MOE in the simulated images.

Stage 2 Conclusions

- The current version of eCambium provides a useful, low-cost means of assessing expected wood variability across the estate allowing more targeted in-field assessments and a means for assessing alternative management strategies.
- eCambium predictions made prior to the mill study explained over 60% of the variance in actual site value and 50% of log MOE if one of the 11 sites was excluded as an obvious outlier (Bago 66). Me111 also stood out as a “problematic” site. However, whereas Bago 066 produced less stiff logs than predicted, Me111 produced logs stiffer than predicted.
- It is important to understand results in this report in the context of the standardised site characterisation used. This involved the assumption of constant fertility rating except where “previous pasture” was known to be the case, as well as constant (zero) rock content. These assumptions were made in the absence of better information and to validate eCambium in its most commercially-robust form. If and as the software is applied commercially, users will often lack information on these 2 attributes particularly.
- *Post-priori* changes of site conditions would be expected to improve predictions. At Bago 066, for example, the high N content, rapid early growth and large diameter knots suggest it may have been ex-pasture. Taking this into account and assuming higher rainfall due to its higher elevation led to markedly lower predicted MOE. Given the mandate upon the eCambium tool, however, for predictions to be as “un-tuned” as possible, with site descriptions and weather data from off-the-shelf databases, some sites were poorly predicted.
- Despite this, the model significantly predicted actual values, and certainly broadly discriminated between high and low value sites with a moderate degree of accuracy (8 out of 12 cases, depending on thresholds). The thresholds used for grade allocation, reflecting the important effects of non-modelled properties such as knots, is an important part of optimising model performance.
- We would expect ongoing development of eCambium to improve volume predictions. Accumulated experience will provide users with more informed insight into site and regime conditions. These should serve to improve the precision and accuracy of predictions over time.

Recommendations

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Appendices

Appendix 1: eCambium user guide updated for Version 2.1

eCambiumis an integrated hybrid modelling system that predicts stem diameter growth as well as pith-to-bark variation in tracheid radial diameter and wall thickness, wood density, microfibril angle, modulus of elasticity (stiffness). It is available as standalone executable file.

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 commercially-important wood properties. The version described in this manual is a developed version of software produced from a previous project (Drew and Downes, 2013a), and is distributed with an access database containing scenarios related to the sites used in the study decribed in the main body of this report.

Installing eCambiumon your computer

The software is designed to run on Microsoft Windows, and has been tested on Windows 7 and 10.

How the model works

eCambiumincorporates 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:

- Carbohydrate available to the stem
- Maximum (pre-dawn) leaf water potential
- Tree height
- Foliage mass

Two options to provide this data to the wood formation model are possible. The user can select and import pre-run scenarios from a CaBala data file (*.mbc). Alternatively, users can define their sites, silvicultural regimes and weather datasets in the eCambium software interface and run the internal stand growth model (IGM) to produce their own eCambium scenarios.

The eCambium software is designed to read from "project" files. Each project is a stand-alone (Access database) 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 user-defined combination of site, regime and weather data, and a parameter (genotype) set. For a detailed description of the model itself, refer to Drew and Downes (In Prep)[20].

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[20] Drew, D.M. and Downes, G.M. (In Prep). The eCAMBIUM process-based model for wood property prediction in *Pinus radiata.*

To create a new Access database project

Access was chosen as the database, despite various minor shortcomings, because the Windows operating system comes with the necessary drivers to allow the database to be created and used, even if the Access software is not installed.

The 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 the objective of the modelling exercise.

To create a new project click on "Create a new project" on the main window (Figure 40). 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 eCambiumdata 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 eCambiumwhile this happens as the data file may become corrupted. Until a project created, or a pre-existing one loaded, various buttons on the user interface will not be activated.

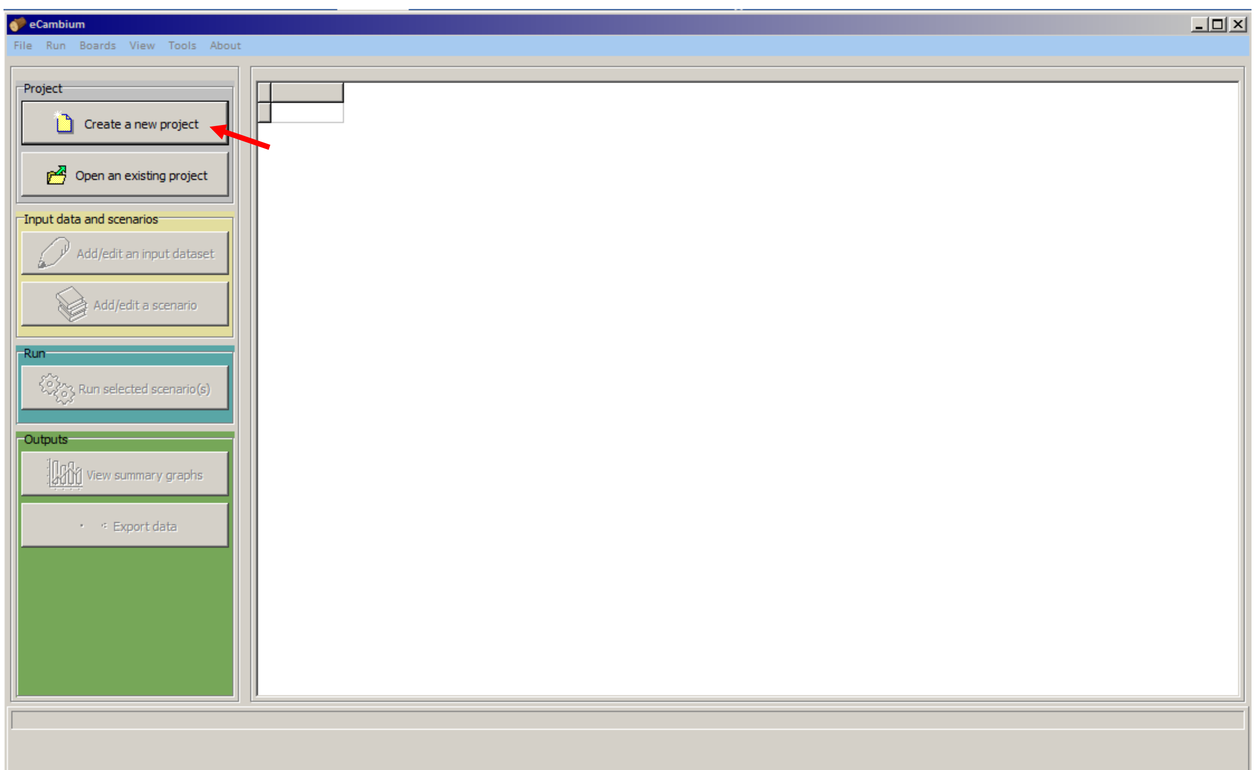


Figure 40. Click on "Create a new project" to create a new eCambiumdata file

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 ".eCambium" 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 *.eCambiumextension 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.

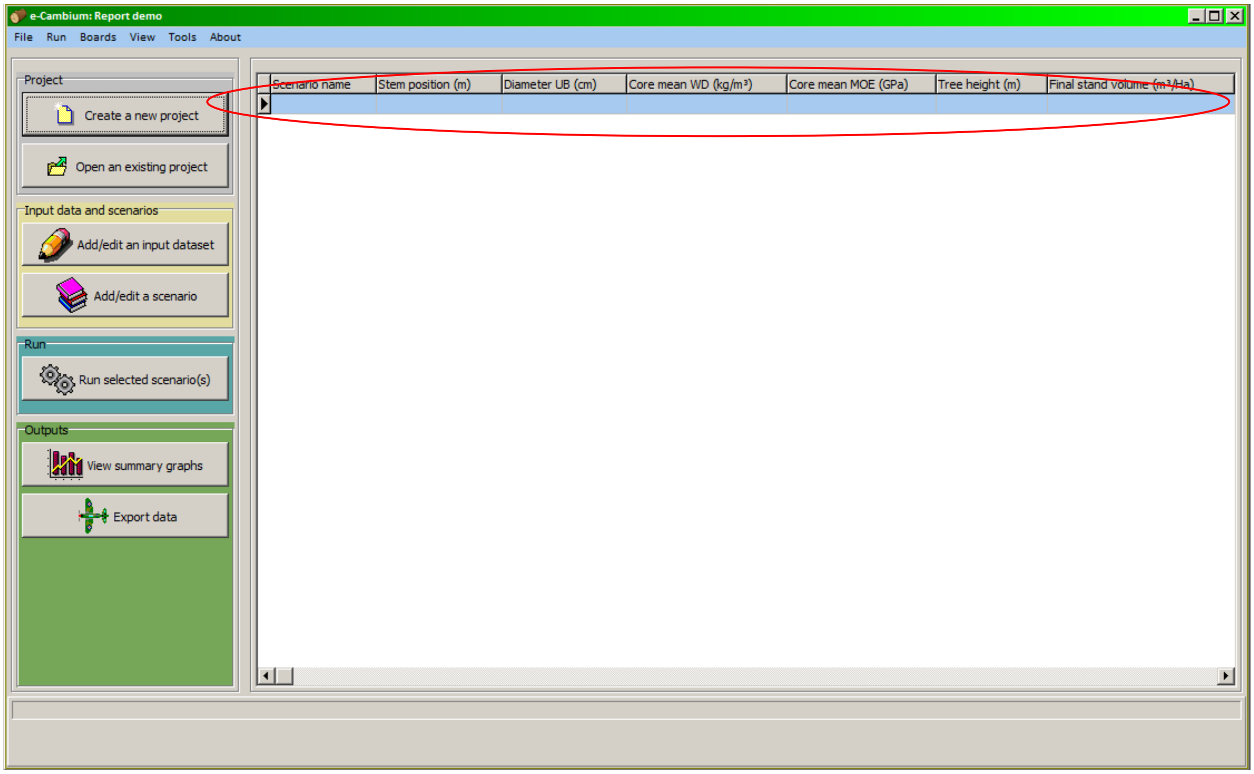
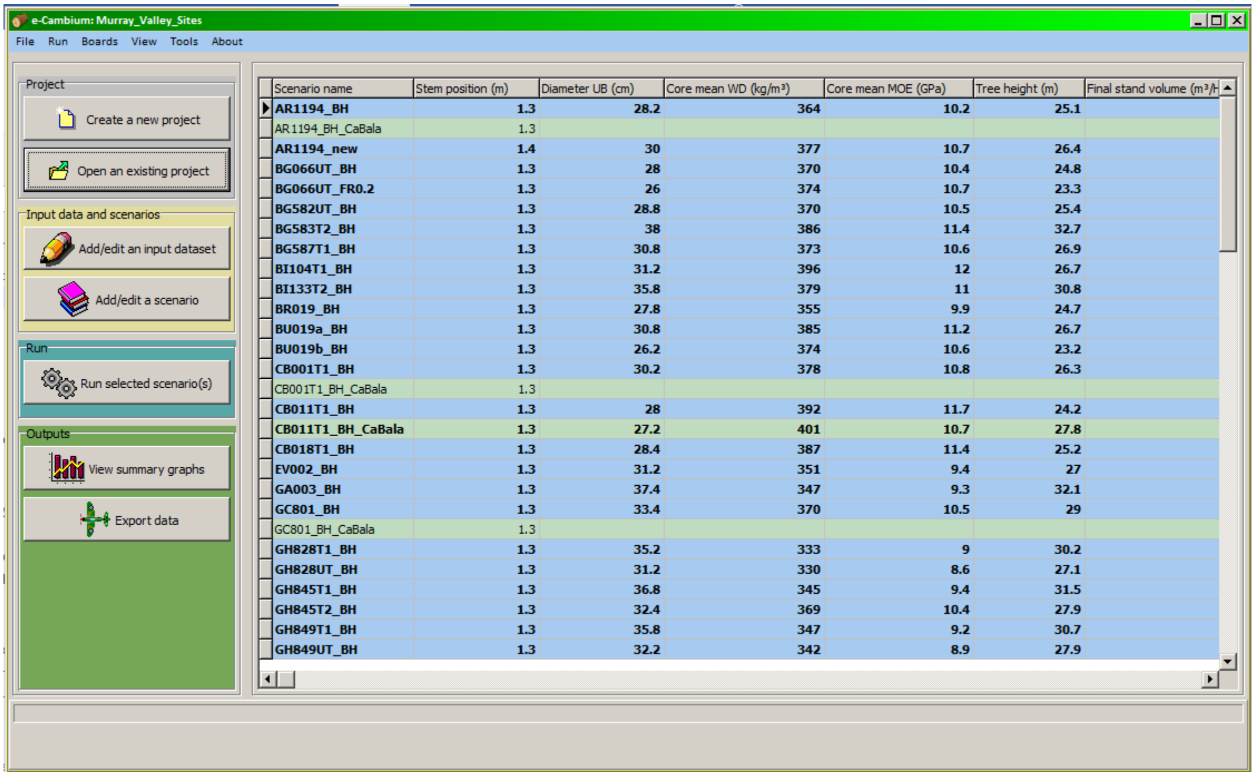


Figure 41. The empty first line indicating that the current open project has no scenarios

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 and the name of the project file will appear in the title bar of the user interface. Scenarios that link to an existing CaBala database have a green background. Native eCambium scenarios (using the eCambium IGM) are blue. Scenarios that have successfully been run will display in bold text, showing a variety of predicted values and other information. Otherwise, the data columns will be blank. Both growth and development data and wood properties data will be written to disk at the end of a run. Only the last day of each month, for growth and development data, is written by default. If the user wants to write data from every day of the simulation, it is necessary to specify this under the "run" option on the main menu. The resolution of the written wood properties data can also be altered here by selecting "Set segment length". By default, the software will order the scenarios alphabetically in ascending order of scenario name. The table can be sorted (in ascending order) on other fields by clicking on the applicable column heading.



Scenario name	Stem position (m)	Diameter UB (cm)	Core mean WD (kg/m³)	Core mean MOE (GPa)	Tree height (m)	Final stand volume (m³/H
AR1194_BH	1.3	28.2	364	10.2	25.1	
AR1194_BH_CaBala	1.3					
AR1194_new	1.4	30	377	10.7	26.4	
BG066UT_BH	1.3	28	370	10.4	24.8	
BG066UT_FR0.2	1.3	26	374	10.7	23.3	
BG582UT_BH	1.3	28.8	370	10.5	25.4	
BG583T2_BH	1.3	38	386	11.4	32.7	
BG587T1_BH	1.3	30.8	373	10.6	26.9	
BI104T1_BH	1.3	31.2	396	12	26.7	
BI133T2_BH	1.3	35.8	379	11	30.8	
BR019_BH	1.3	27.8	355	9.9	24.7	
BU019a_BH	1.3	30.8	385	11.2	26.7	
BU019b_BH	1.3	26.2	374	10.6	23.2	
CB001T1_BH	1.3	30.2	378	10.8	26.3	
CB001T1_BH_CaBala	1.3					
CB011T1_BH	1.3	28	392	11.7	24.2	
CB011T1_BH_CaBala	1.3	27.2	401	10.7	27.8	
CB018T1_BH	1.3	28.4	387	11.4	25.2	
EV002_BH	1.3	31.2	351	9.4	27	
GA003_BH	1.3	37.4	347	9.3	32.1	
GC801_BH	1.3	33.4	370	10.5	29	
GC801_BH_CaBala	1.3					
GH828T1_BH	1.3	35.2	333	9	30.2	
GH828UT_BH	1.3	31.2	330	8.6	27.1	
GH845T1_BH	1.3	36.8	345	9.4	31.5	
GH845T2_BH	1.3	32.4	369	10.4	27.9	
GH849T1_BH	1.3	35.8	347	9.2	30.7	
GH849UT_BH	1.3	32.2	342	8.9	27.9	

Figure 42. Listed scenarios in an open project.

Warning: sometimes, when the computer is already busy with other write operations, opening medium to large eCambium data files can take some time. 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:

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

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 (Figure 43).

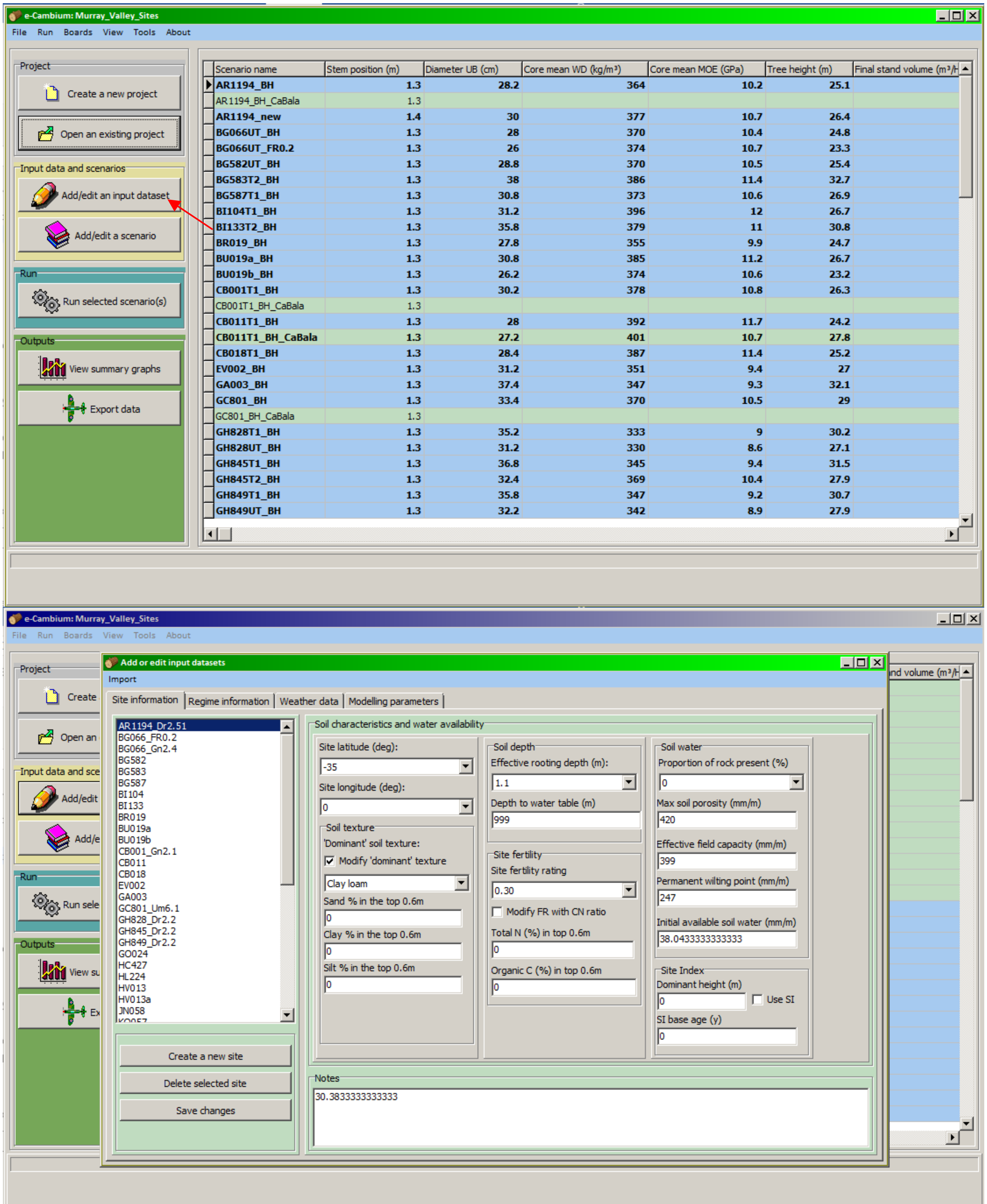


Figure 43. To create a new site, regime, weather dataset or parameter set, click on "Add/edit an input dataset".

Site information

The Site information interface (Figure 43) is displayed as the first tab in the data input section under the form headed by the “Site information”. Prior to entering site and regime information, a standard set of data needs to be known (Table 16). It is helpful to compile this for the planned exercise beforehand. Describing the site is probably the component of the modelling exercise where the greatest subjectivity occurs. In general the cost of obtaning detailed soil information is prohibitive. The eCambum software has been designed to operate from a minimum of descriptive data and parameterised (as much as possible) against publically available soils data (see Appendix 3 for instructions on how to collect this information). The publically available soils data is weighted heavily to the more studied agricultural landscapes.

Table 16. List of essential site and regime information required by the eCambium 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		0.3
	Soil depth (m)	m	1.2
	Rock content	%	10
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, 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. 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.

<u>Dominant soil texture</u>

Eleven soil texture types are given that provide a range of textural classes, ranging from soils with virutally no clay (sand) to soils that are predominantly clay. These are called dominant, in the sense that this is the texture type that should be considered to be the main texture of soils which the tree roots are able to explore. Determining soil texture can be subjective and consequently the model allows this to be defined by the percentages of sand, silt and clay. These numbers need to add to 100%, and once entered they can be used modify the texture class. These percentages are defined on publically available databases. The estimated percentages of sand, silt and clay are given for each grid point in the TERN soils database for Australia.

In addition many of the variables related to water holding capacity are calculated automatically by the model using known relationships based on soil texture. However, these can be over-ridden by manually inserting new values (if known) in the appropriate text boxes.

- Minimum available soil water (mm/m) provides a lower limit, beyond which any water in the soil is inaccessible to the plant.
- Initial available soil water (mm/m) is the starting value for the model and as such will be only important for the initial growth phase.
- Maximum available soil water (mm/m) is analogous to field capacity and will vary according to the soil type and physical and chemical properties.

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. For most sites in an estate this has to be estimated and is consequently subjective. "Fertility" as a concept is hard to quantify or define, and will be related to different variables at different sites (e.g. N, P, K or micronutrients limitations). eCambium has an inbuilt capacity to calculate fertility from the "Total N" and "Organic C" data if known, based on data obtained in the Murray Valley region, where FR appeared to correlate to C/N ratio. Typically these numbers are less than 0.5% for Total N and less than about 10 % for Organic C. However, the appropriateness of using this calculation needs to be considered according to local knowledge and experience.

Soil depth (m)

An estimate of soil depth is required to limit and control root exploration by the model. "Effective rooting depth" can exhibit considerable localised variance, but publically available databases provide a figure which can be used as a starting point.

Site Index

If Site Index (dominant height at a given age) of the stand is known, the height (m) and age (y) can be inserted for the site. This will then limit maximum growth for the modelled scenario to that expected at the appropriate age is calculated with a height/age curve. If this data is not entered, and/or the "Use SI" checkbox is not checked, no over-ride will occur.

Saving the Site description

Ensure all fields have numbers: a blank is not an acceptable character. If a blank is left a message may appear stating that *"" is not a valid integer*.

After the site description data entry has been completed, select the "Create a new Site" button (Figure 43) and enter a descriptive site name in the dialog that appears (Figure 44). Specify a new, unique name for the site in the edit box. Once the "Create a new site" button is clicked, the new site is automatically saved and added to the list on the left side of the window. 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.

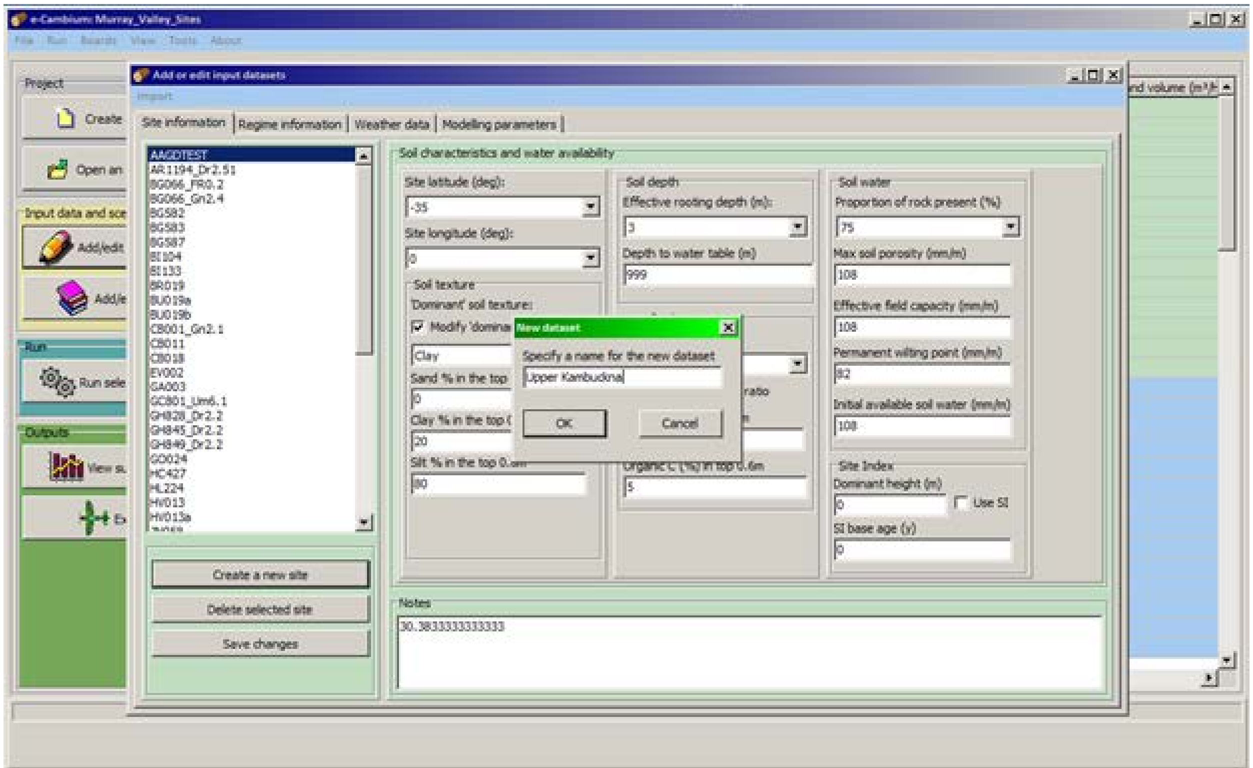


Figure 44. Saving the site information for the IGM

Regime information

To create a new regime, select the “Regime information” tab to the right of the “Site information” tab just completed (Figure 45). 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.

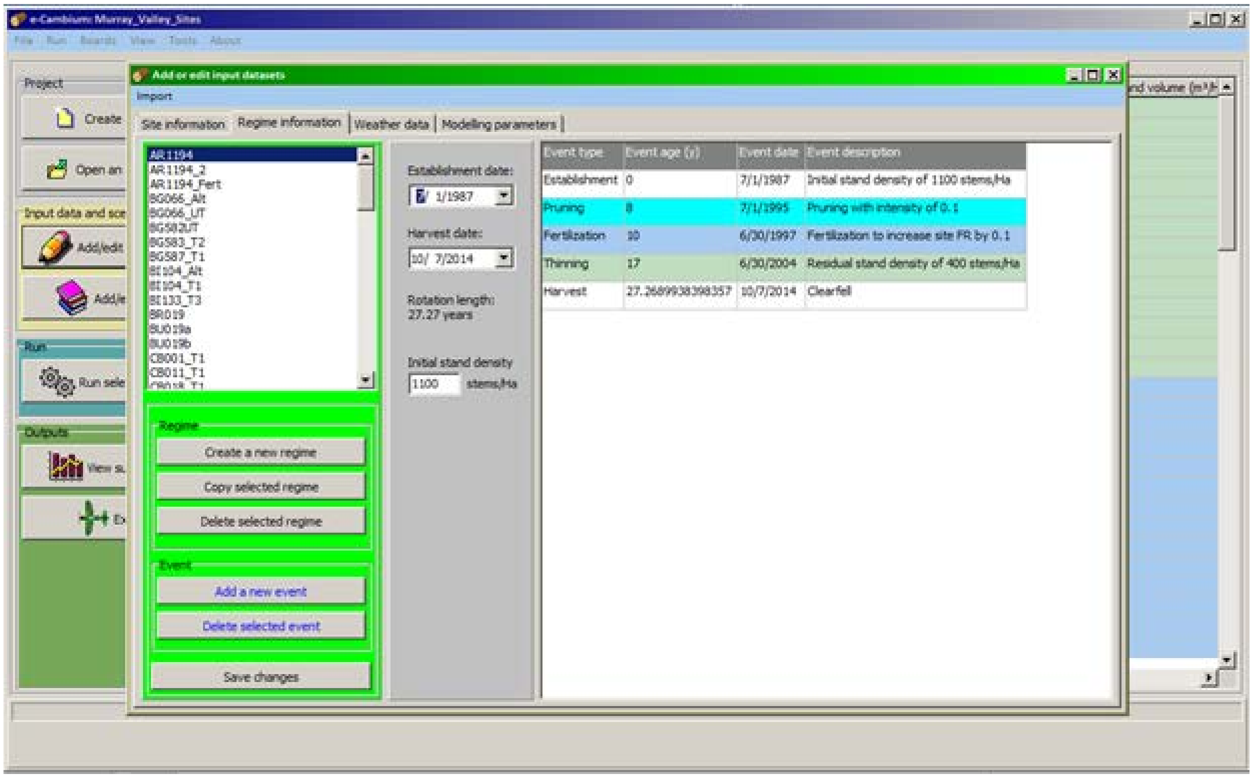


Figure 45. The main window for editing regime information for the IGM. Planting and harvesting events are shown in white; other events are indicated in colour.

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 fertilisation, 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.

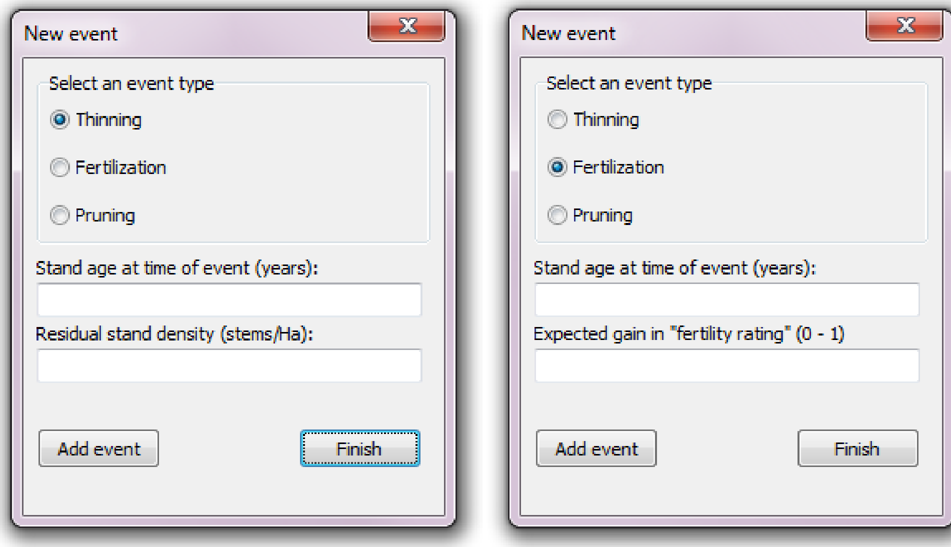


Figure 46. The regime event window, showing selections of "thinning" or "fertilization".

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

At present 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 (Figure 47). 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 47. Example of the header of standard SILO output required for successful eCambiumdata 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.

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 (Figure 48). To zoom in on data, click with the left mouse button and drag down-and-to-the-right.

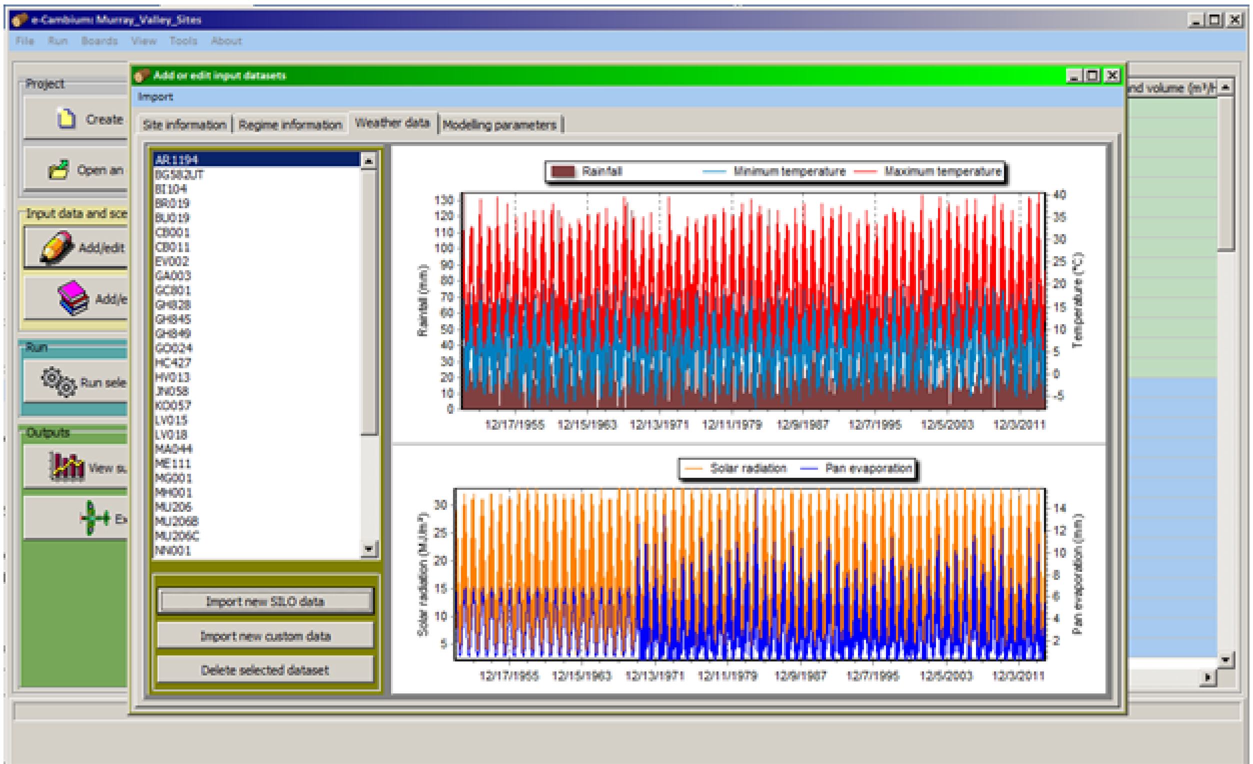


Figure 48. The main window for importing and viewing weather data for the IGM with imported data for the selected dataset shown.

To import weather data in csv format, use the “Import data from external files” feature which is available under “File” on the main menu (See section below on Importing data).

Model parameters.

The software provides the option of creating a default parameter dataset, which will be generated for both the IGM and the wood formation component. If a Cabala simulation is being used as the basis for a wood development simulation the former 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. As such we refer to these parameters as “Genotype”.

A major part of model development is optimising these parameters. In general, for a given species, these parameters should remain relatively constant. However, there may be scope for further refining them for genotypic variation within a species. Consequently multiple parameter sets could be created for testing. The default parameters are a suggested radiata pine set for the wood formation model (Figure 49) and the IGM (Figure 50), established by testing the model across a wide variety of sites. For most purposes these parameter sets should not be altered. Changing values needs to be undertaken with caution and some understanding of the physiological and calculation implications.

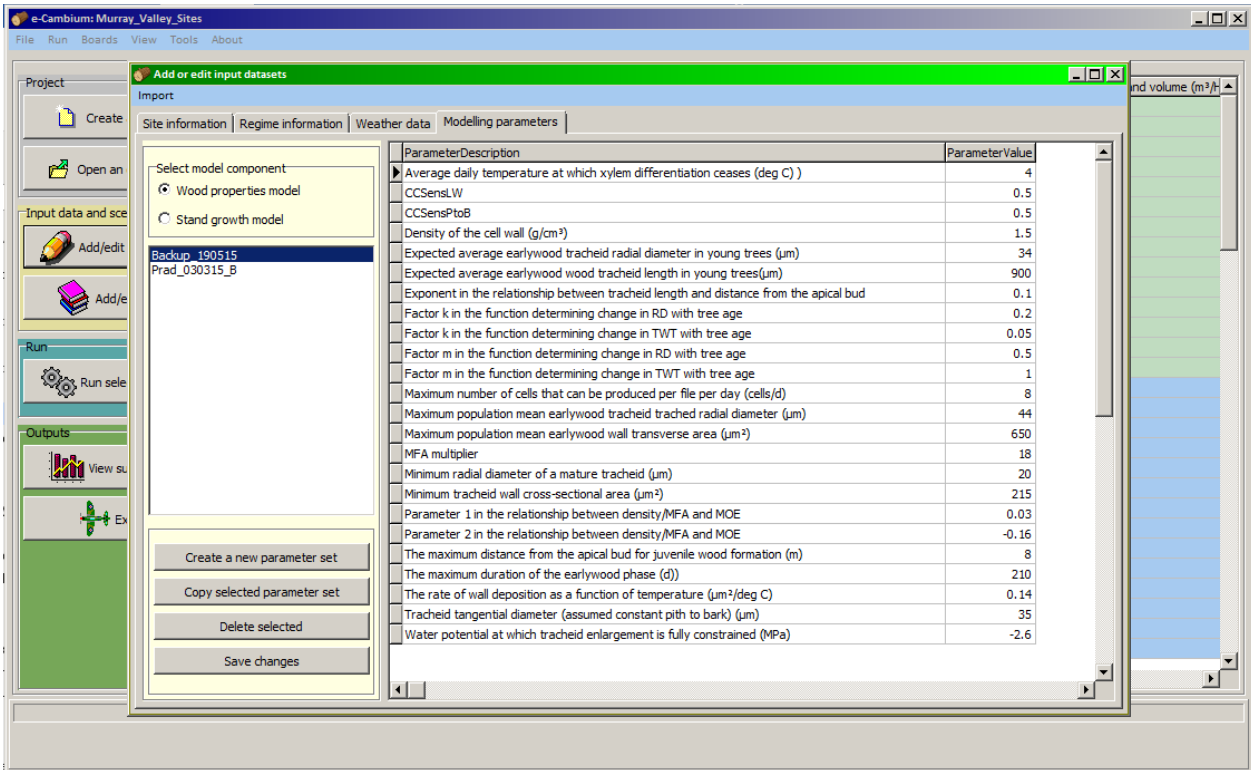


Figure 49. Wood development parameters with default values

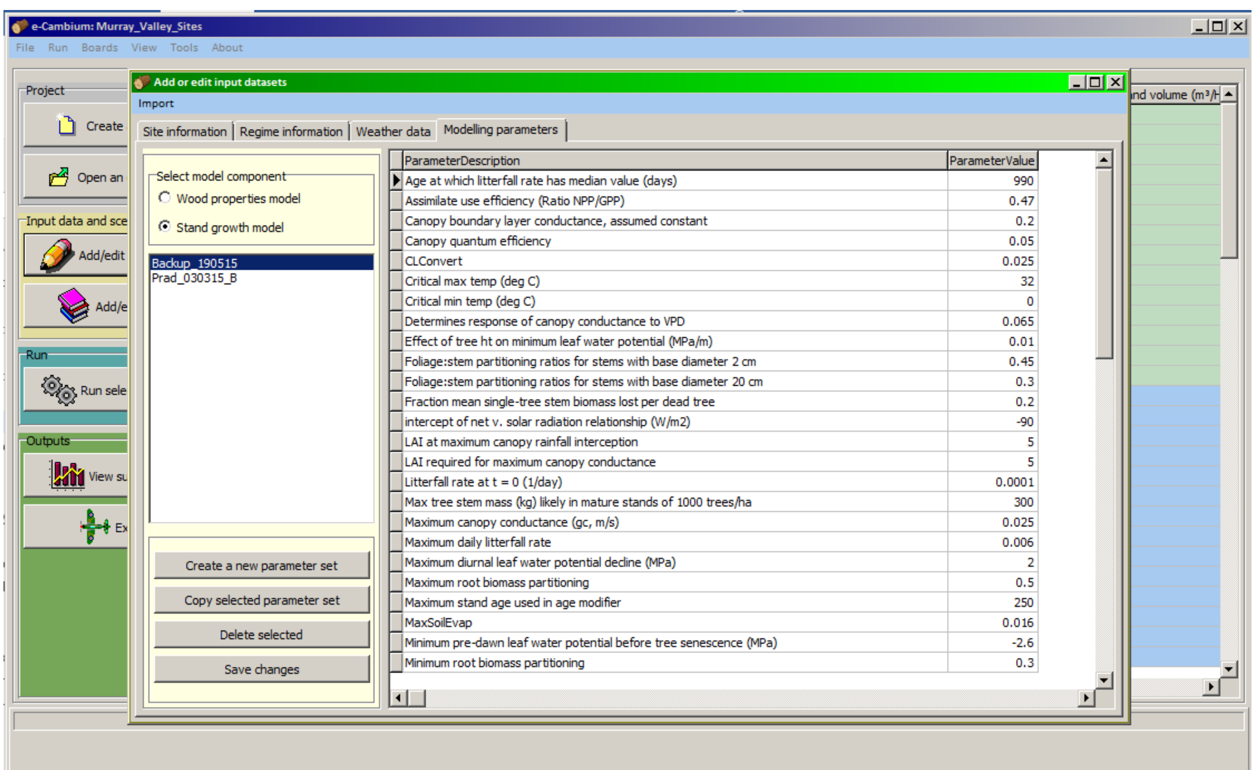


Figure 50. IGM parameters with default ranges

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_FCNSW”). 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. wood model or IGM) will display in the adjacent table. The parameter values can be edited. To ensure values are saved, after editing a value, click on another cell, to move the cursor, and “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”.

This completes the sequence for generating the components required to build a scenario to run. Close the open window 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 eCambiumparameter 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” (Figure 51).

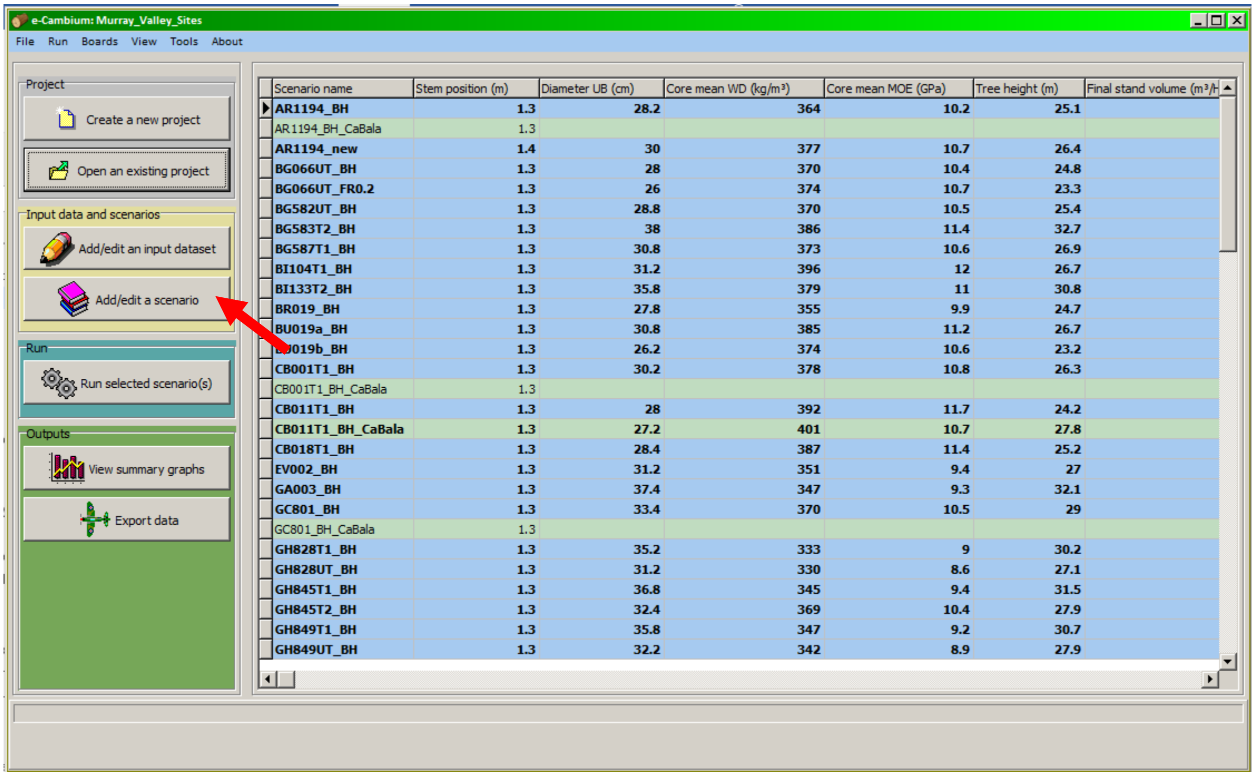


Figure 51. The eCambiumGUI with the "Add/edit a scenario" button indicated

If a scenario is selected on the adjacent grid listing the scenarios, the appropriate edit dialog will automatically display with values already updated on the drop-down lists (Figure 52b). 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 (Figure 52a). **To deselect any scenario/s already selected**, simply click somewhere on the main eCambiumwindow (aside from the table of scenarios). If the user selects "Create a new eCambiumscenario", then a blank dialog form of Figure 52b will appear.

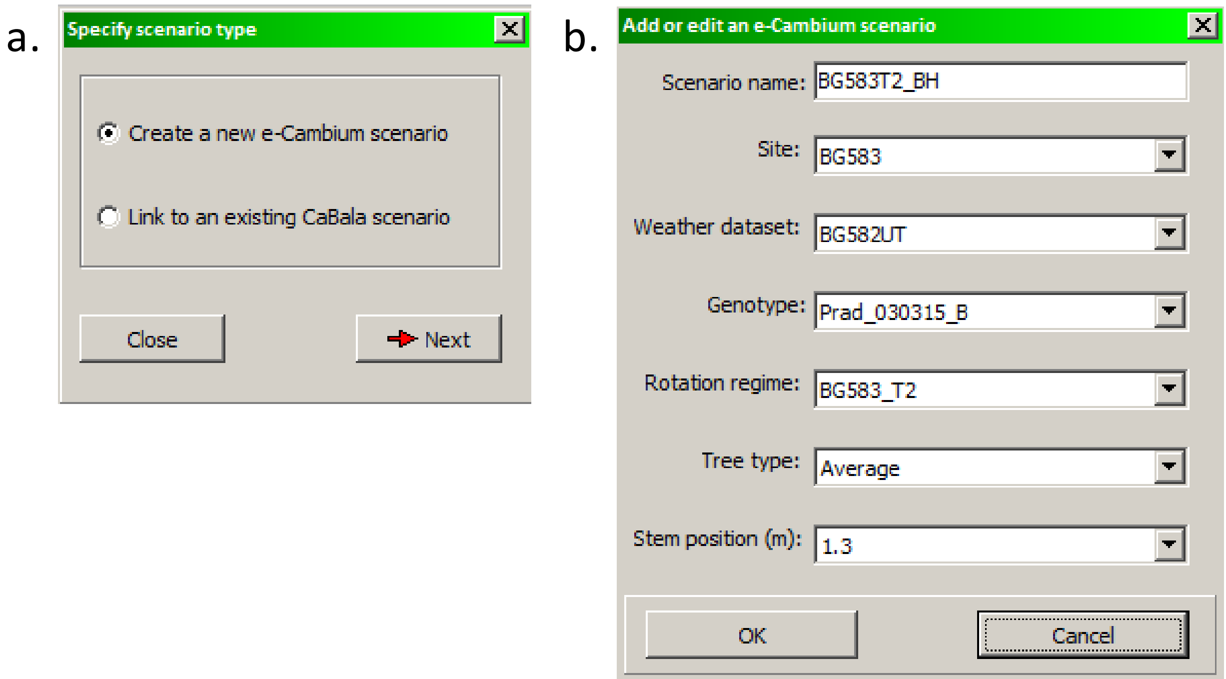


Figure 52. The eCambiumscenario building dialog for scenarios using the IGM. (a) the dialog appears if no existing scenarios have been selected. In (b) this dialog appears when a specific scenario has been selected showing all input datasets already specified, as well as a name for the scenario

First, specify a 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. 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”. Basically these deletes all previous simulations for that scenario.

If, after selecting “Add/edit a scenario” the user selects to “Link to an existing CaBala scenario”, the following dialog displays:

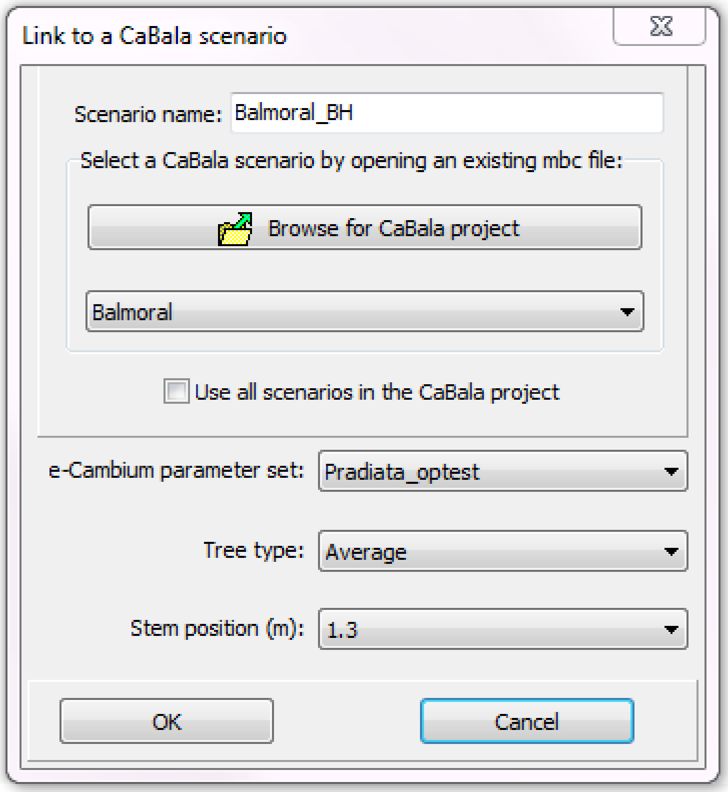


Figure A3.15: The eCambiumscenario building dialog for scenarios using Cabala inputs.

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 eCambiumscenario that will link to the CaBala scenario, and eCambiumwill 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 eCambiumparameter 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 populate 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

Once a scenario is defined it can be run by simply selecting the "Run selected scenarios(s)" button on the left hand panel (Figure 51). Each run typically takes a second or two to run and then a couple of seconds to write the data to the database. Once completed the summary data tableis populated with

However, before running the model, various run conditions can be defined which affect the way the data is stored and then displayed.

- Run | Set segment length
  Selecting this brings a dialog where the user can stipulate the radial length over which wood property data is averaged ranging from 0.5mm to 1.0mm. Selecting a coarser sampling interval (e.g. 1mm) will store the predicted wood properties at that resolution. Finer resolutions result in longr profiles and therefore more time is needed to write the data to the database.
- Run | Write daily data to disk
  The daily write option: Should data from each day of the model run be written to disk or only the (default) month-end values of the growth data? All daily data takes much longer to write, but provides a resolution that might be useful. Click on Run|Write daily data to disk.

If at least one scenario exists, the model can run. 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 (Figure 53), 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.

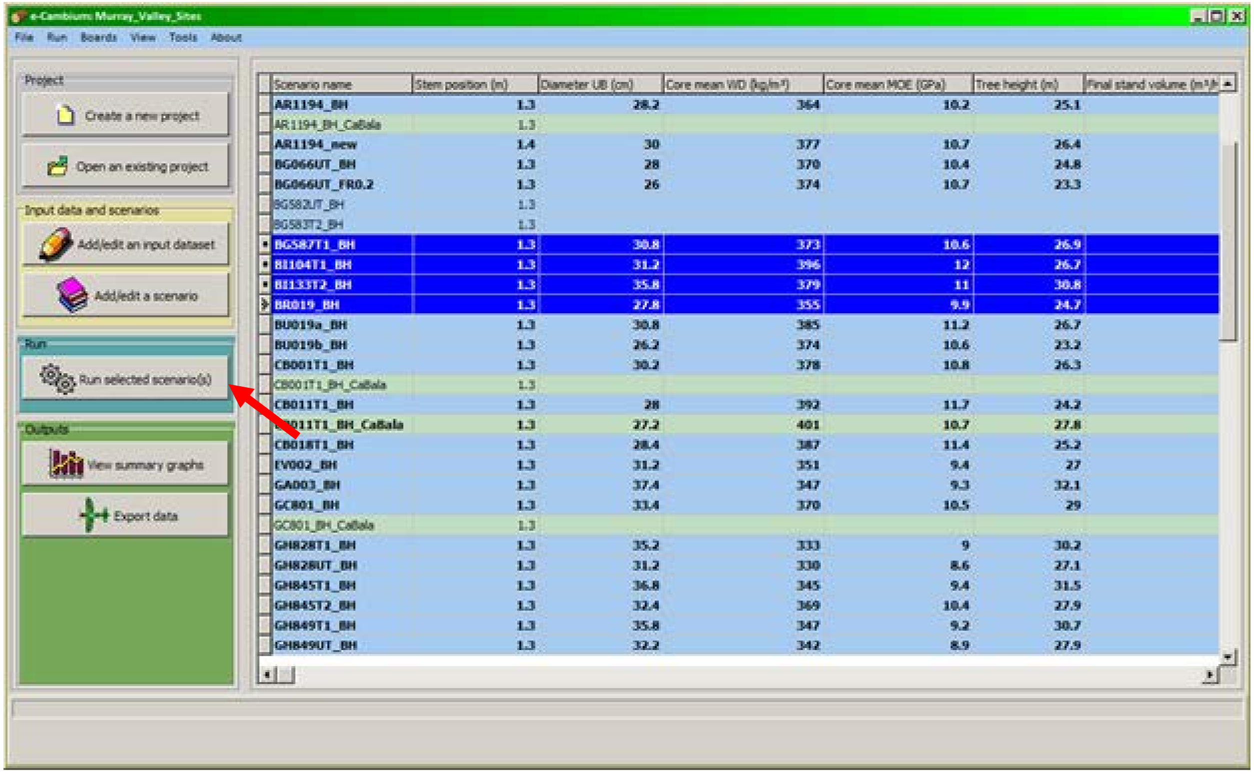


Figure 53. Click on "Run selected scenarios" to initiate one or a set of model runs.

Once at least one scenario is selected, click on "Run selected scenarios" (Figure 53). 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 databse 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>

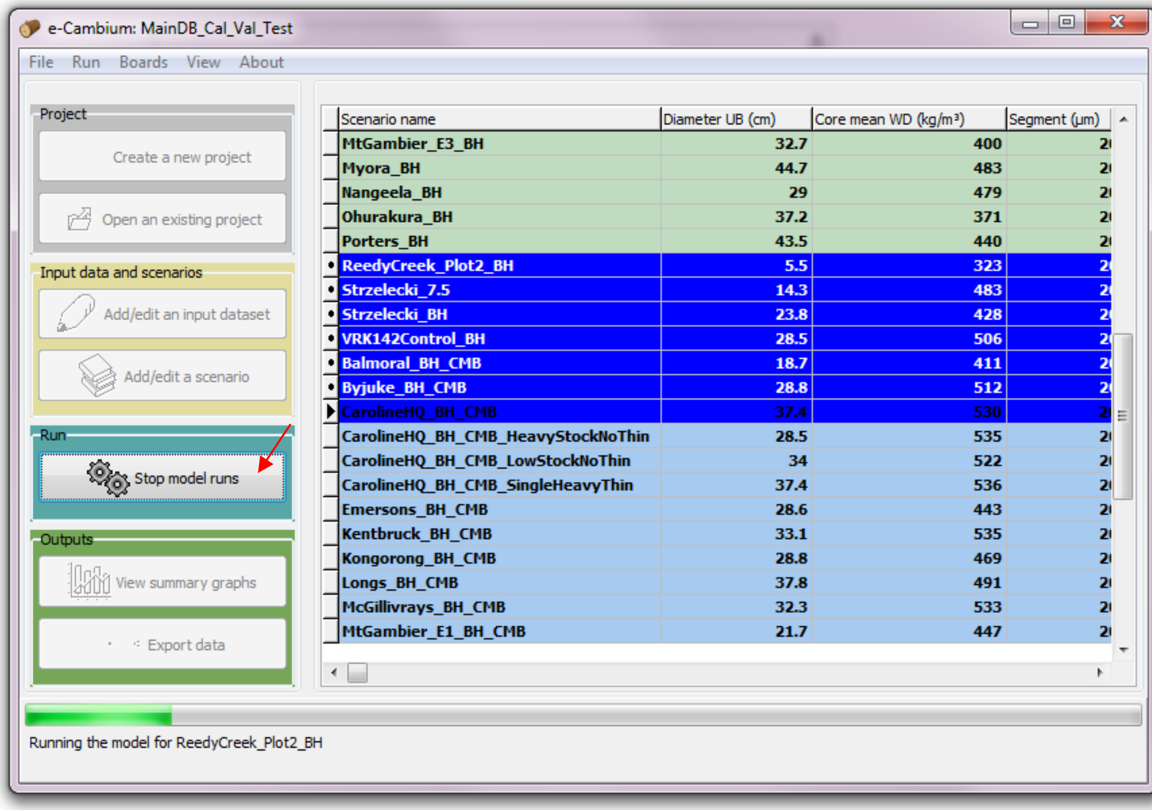


Figure 54. Click on "Stop model runs" will exit the current loop.

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).

- 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. The user can also choose to see density data summarized as an "air-dry" or "oven dry" estimate, relevant for comparing to SilviScan density data, or basic density respectively.

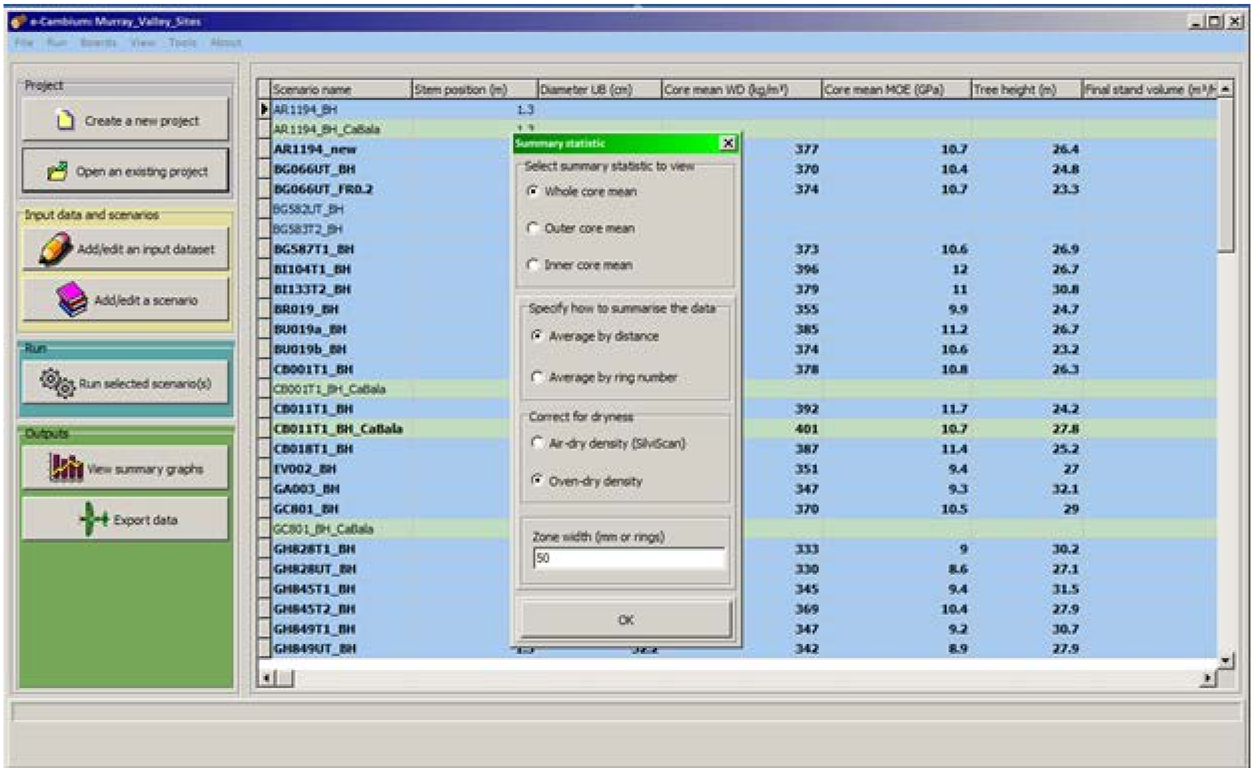


Figure 55. Window to change summary statistics shown in main table.

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" button on the left hand panel of the main user interface.

A dialog will appear and the user can specify whether to view

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

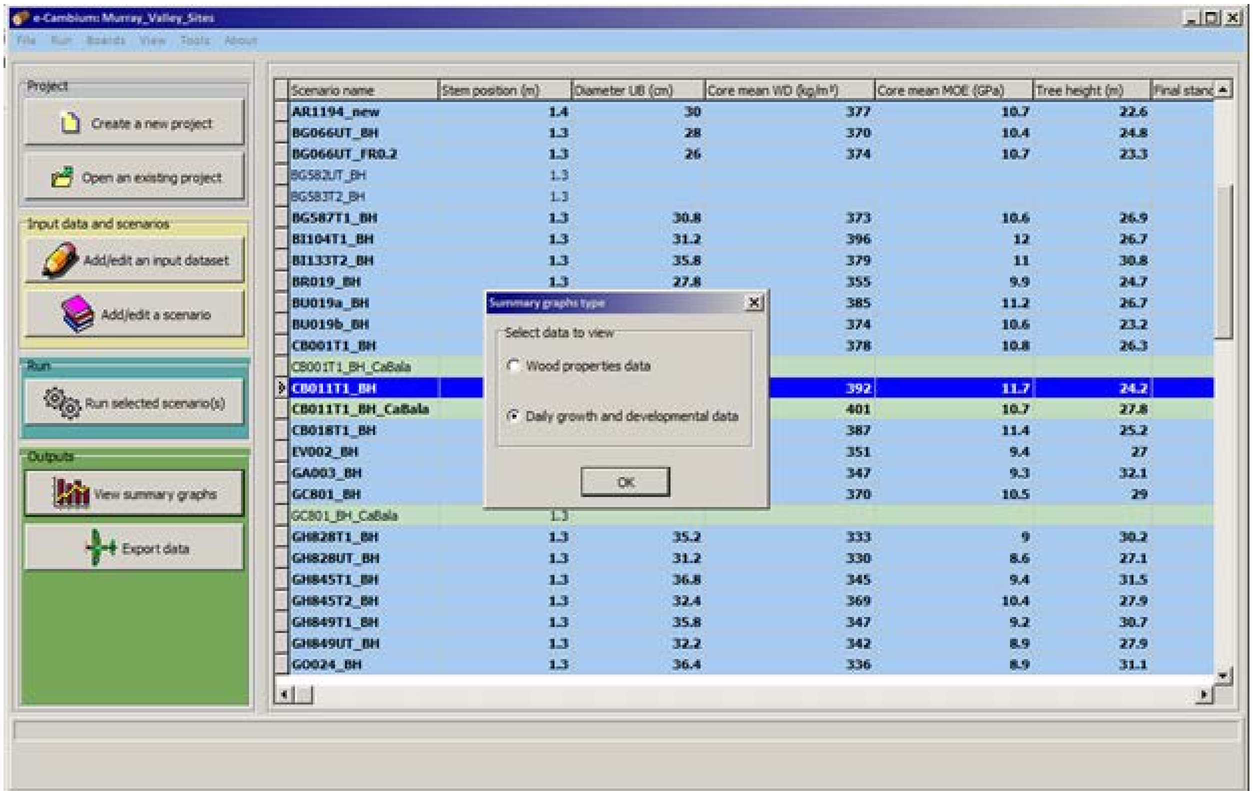


Figure 56. Selecting the button "View summary graphs' when a scenario is highlighted, or double clicking on a scenario which has been run will call up the dialog box to explore the detailed model predictions.

<u>Viewing wood property summaries</u>

By selecting the first option, the window shown in Figure 57 will display. The first tab shown is a summary tab where a radial trajecotry of annual MOE (stiffness) is shown in the top panel. In the lower panel the hypothetical log end is shown, firstly as a simple disc image and secondly with boards superimposed colur coded according to the predicted stiffness grade. The third plot in the lower panel shows a histogram of the predicted boards. This is 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.

The default optionis to display this as a count of baords within each grade. Alternatively this can be changed by selecting the "Board summary options" (circled in Figure 57).

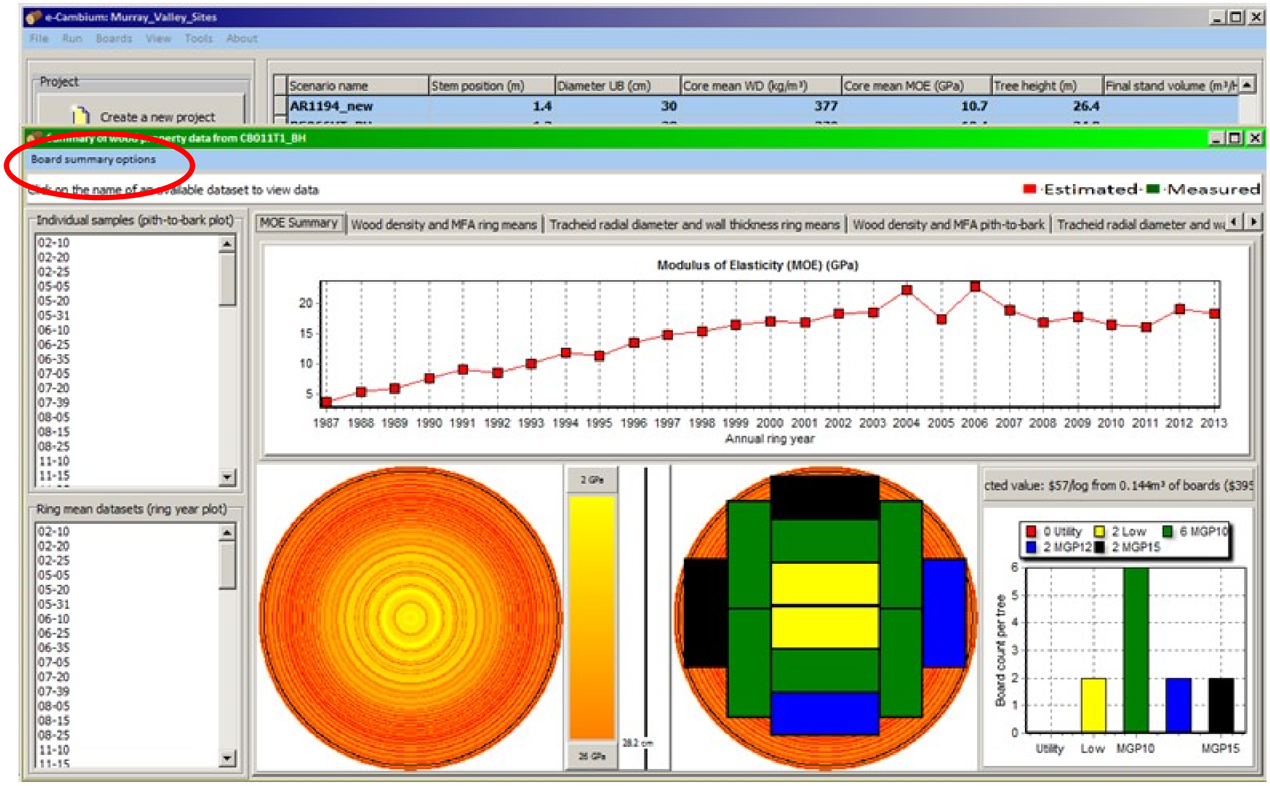


Figure 57. Graphical output of predicted ring average MOE and hypothetical potential board quality

The following options for this display are possible

- Board count (default)
- Board proportion: the proportion of boards within each grade by number not volume
- Total Board volume in m3/ha using the stocking information from the regime input modified by any mortality predicted by the model
- Total Board value in $ / ha
- Total board value in $/log

These various calculations are made based on various user defined inputs. On the main user interface selecting “Boards | Set board dimensions” the dimensions of the boards to be “sawn” from the central cant and wind boards can be defined, as shown in Figure 58.

Similarly, by selecting “Boards | Set board grade thresholds” the user can define the various grades produced in the sawing simulation, as well as the value of those grades. In the example in Figure 59, only 4 grades are being produced as the threshold of the first grade (Utility) is set to zero. Therefore, in this case, no utility grade boards will be produced. By changing the specified thresholds the user can dictate the number and volume of boards in each grade.

Returning to the display interface in Figure 57, 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 (eg. Figure 60).

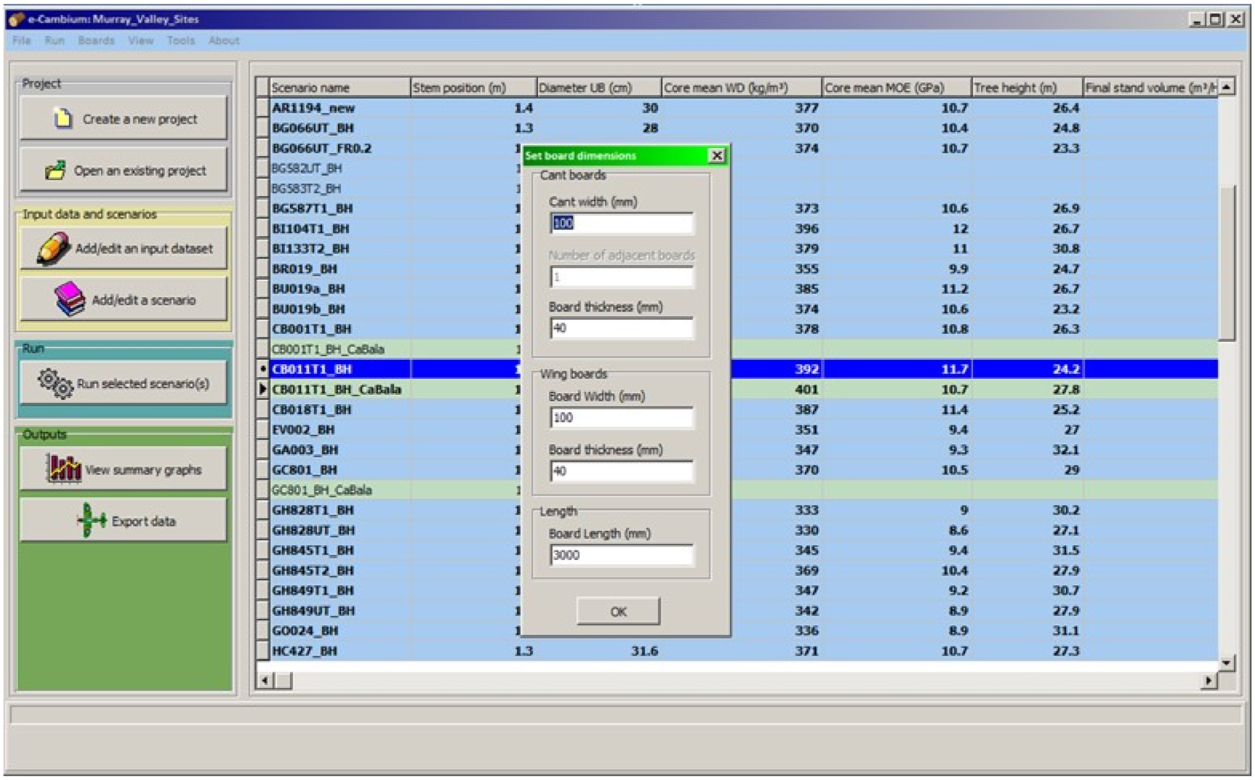


Figure 58. By selecting "Boards | Set board dimensions" on the main interface the dimensions of the boards to be "sawn" from the central cant and wind boards can be defined.

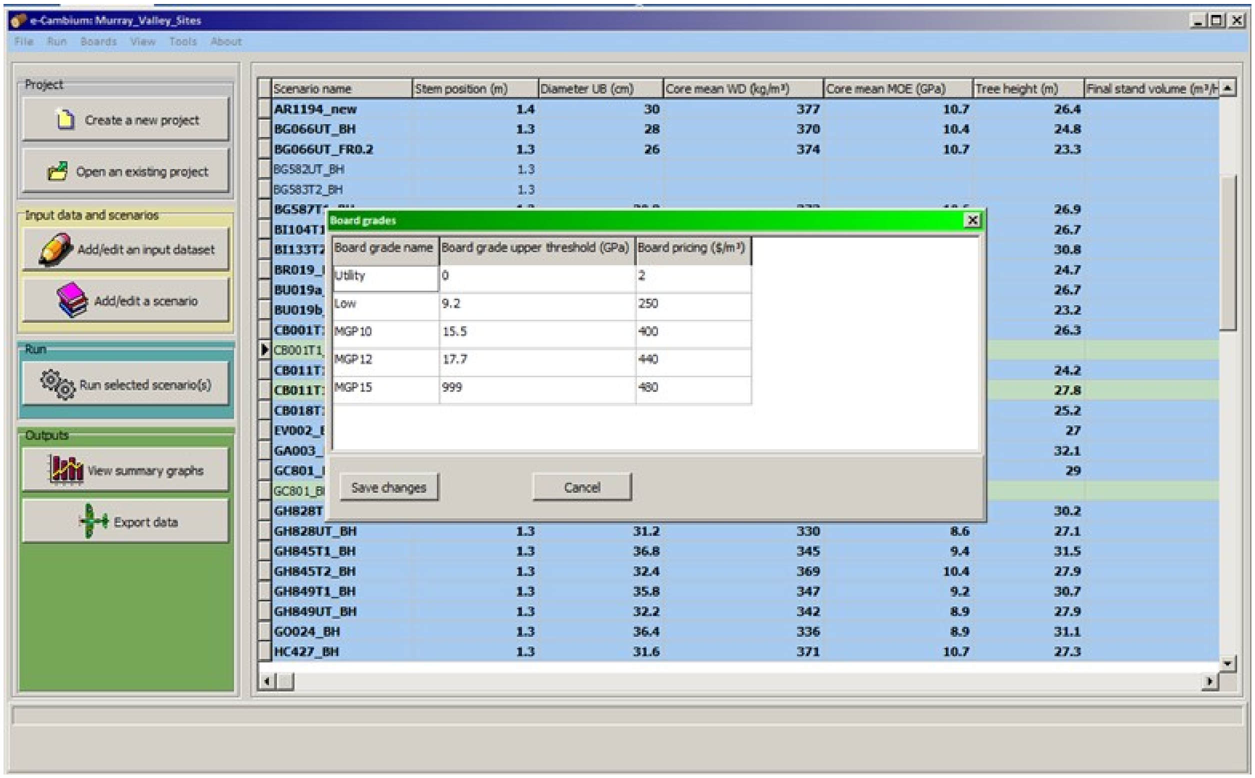


Figure 59. Selecting "Boards | Set board grade thresholds" the user can define the various grades produced in the sawing simulation, as well as the value of those grades

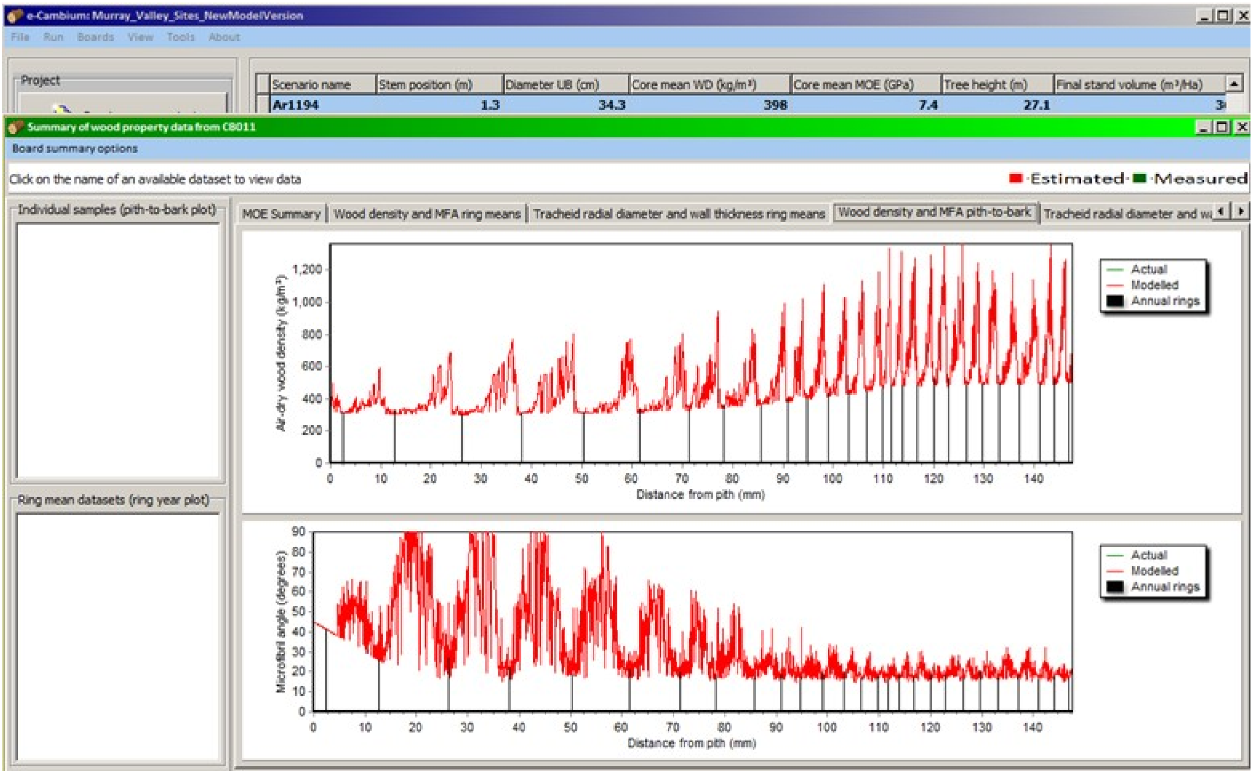


Figure 60. Graphical output of predicted pith-to-bark variation in wood density and microfibril angle.

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. These data appear in the panels on the left hand side of Figure 60. Pith-to-bark SilviScan profiles will be listed n the top panel, and annual ring means listed in the lower panel. Typically they will be named according to site and the one relevent to the modelled data can be selected by clicking the appropriate item in those panels.

Daily outputs

In the main user interface window, double clicking a scenario that has been run brings up the Selecting to view "Daily growth and developmental data" (Figure 56) will display the window shown below (Figure 61). 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. These data can consist of inventory measurements made at specific times, or annual ring width measurements that made be obtained from radial profiles arising fro SilviScan or RESI data. 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.

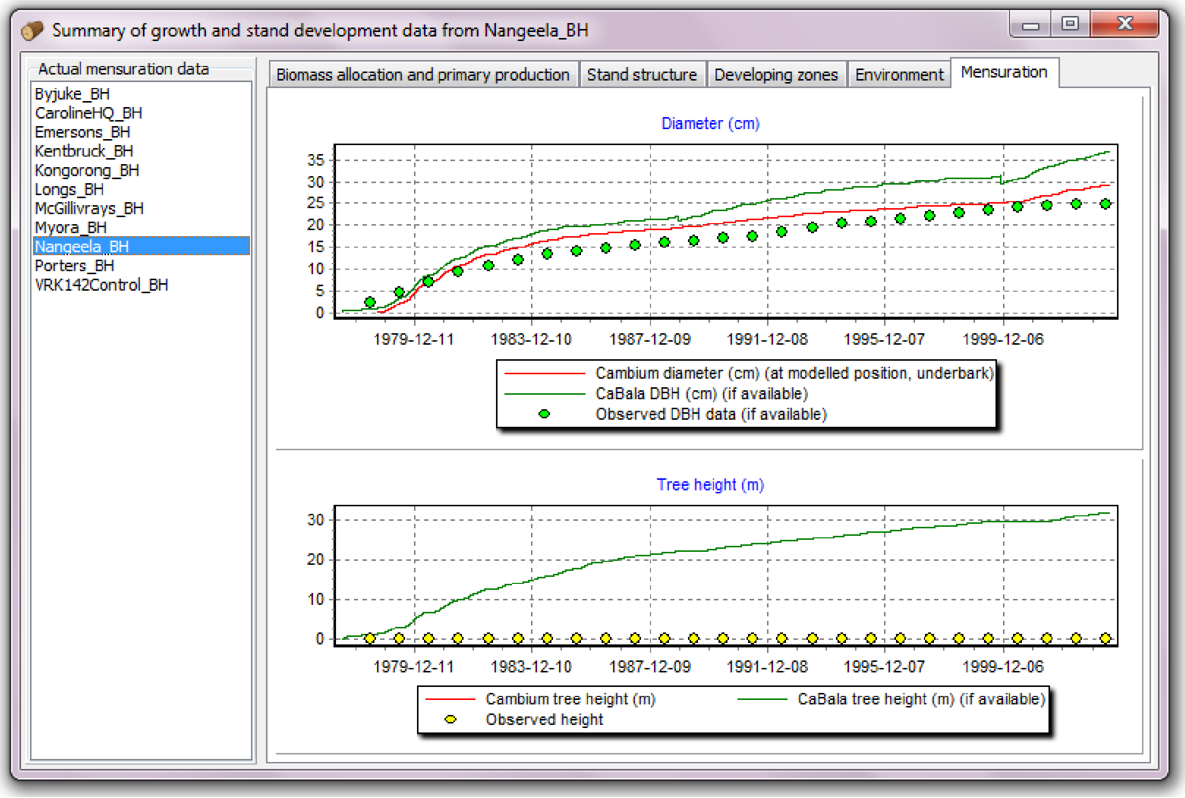


Figure 61. Daily outputs of simulated stem diameter (eCambium prediction of underbark diameter at 1.3 m), tree height with measured underbark diameter from ring positions (SilviScan or RESI data).

Importing data

Uploading data from external files

It is possible to import data into the eCambiumdatabase from external comma-delimited (*.csv) files. Selecting the “File|Import data” from the main menu (Figure 62) allows data of four different types to 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)

(5) Site information with columns for:

a. Site name
b. Site latitude (deg)
c. Site longitude (deg)
d. Fertility rating
e. Max ASW field (mm/m)
f. Min ASW field (mm/m)
g. Water table depth (m)
h. Soil texture
i. Soil depth (m)
j. Rock proportion field (%)
k. Clay, sand and silt percentage (%)
l. Nitrogen, OC and Phosphorus percentage (%)
m. Site index (m)
n. Site index base age (y)
o. Site notes

(6) Regime information with columns for:

a. Regime name
b. Regime type
c. Regime date
d. Regime value

(7)

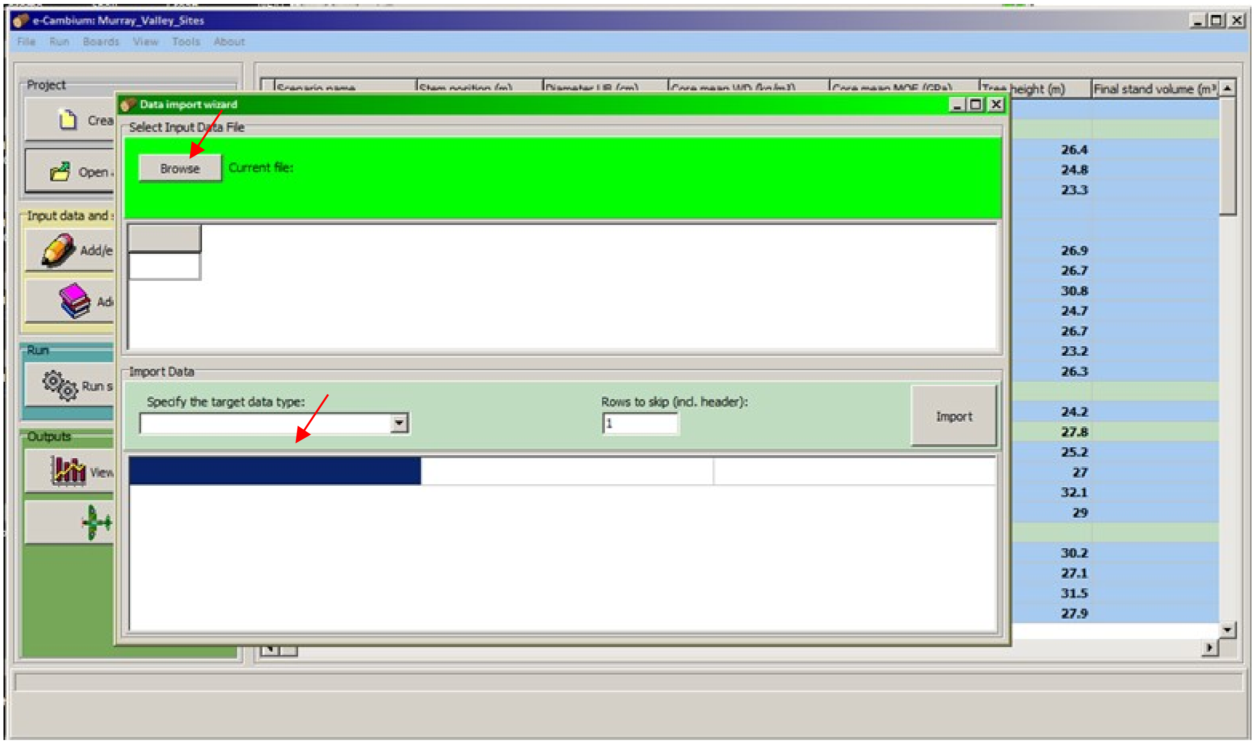


Figure 62. First select a csv file to import, followed by a data type table into which to import the data.

All data types require that a name for the dataset either be read from the input file, or specified as a constant value. Once an input comma-delimited file has been selected, columns in the file will be numbered (Figure 63). The type of data it contains needs to be selected from the dropdown list in the “Import Data” panel, to allow the lower table to be populated with the appropriate field names. 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 (“Import Data” panel) with the appropriate column in the input data file (“Select Input Data File” panel). 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.

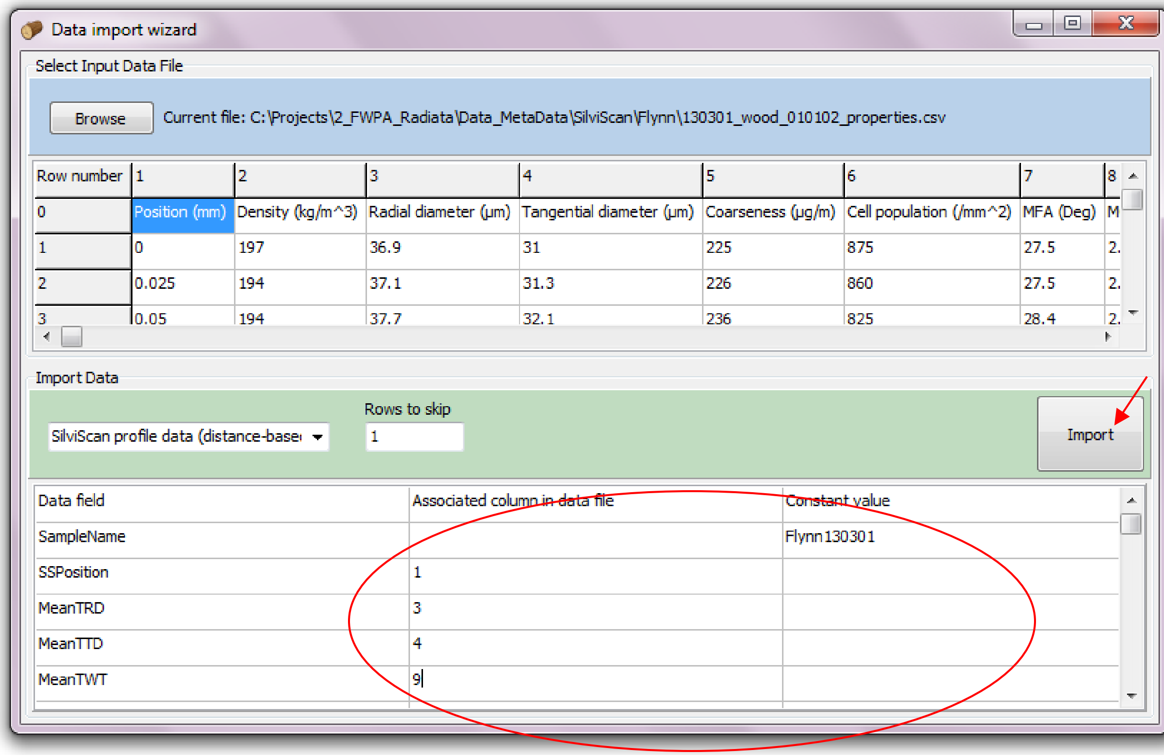


Figure 63. Specify which columns in the csv data file correspond to which field in the eCambiumdata table (e.g the SilviScan distance-from-pith is in column 1 of the csv file, and corresponds to the field "SSPosition" in the selected target data file). Note that in this example the SampleName field has been specified as "Flynn130301" and is not read from the csv file.

Note: using this feature can make the setting up of sites and regimes a lot easier. If site descriptive data can be collated for a range of sites using Excel (for example), this can then be imported allowing all sites to be set up quickly. GIS-based data can potentially be scripted to export regime information into an eCambium-ready format for a large number of sites..

Importing data from another eCambiumdata file

It is also possible to import parameter sets, weather data, site descriptions and regime information from other eCambiumfiles (*.cambium). This feature is found by clicking on the menu bar: "*File|Import data from another eCambiumproject*". First select a file by clicking on "Browse" (Figure 64). 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". As the weather data sets tend to be large, importing these can take time.

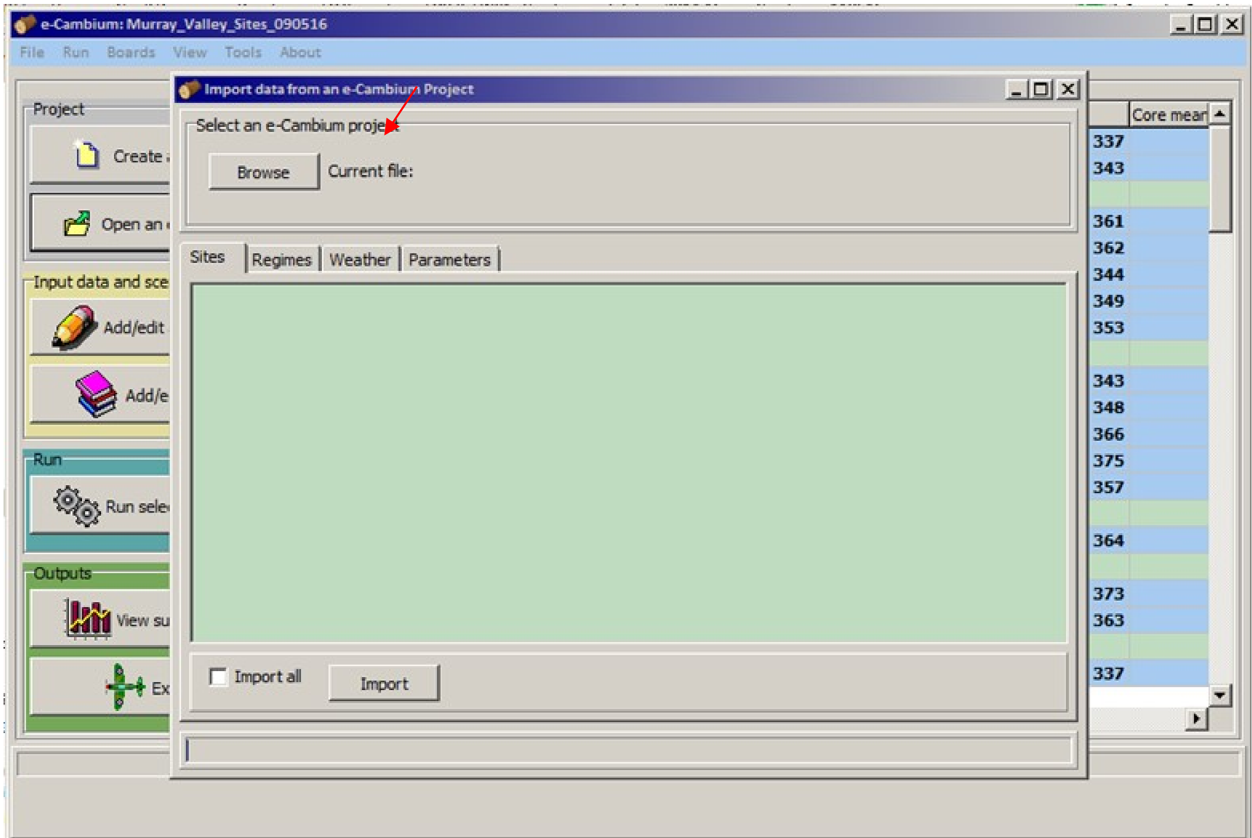


Figure 64. Select an eCambium data file from which the import data and information

Exporting data to comma-delimited files

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

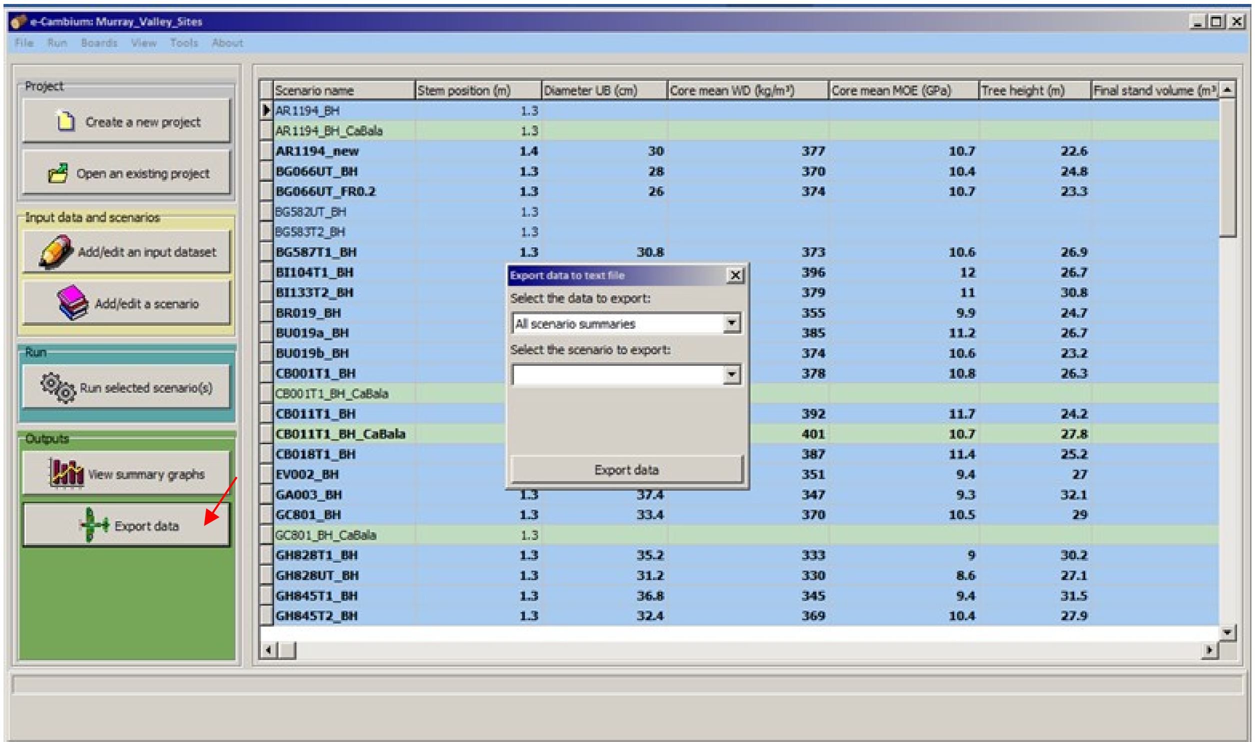


Figure 65. Click on "Export data" to save simulation datasets as CSV files. Select a data type and a scenario from which to export

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 that available from a system like SilviScan.
- 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 eCambiumGUI 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 **Error! Reference source not found.**).

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.

Appendix 2: Accessing online weather data

Weather data can be obtained from a various sources and needs to be prepared in a text file (e.g. csv file saved from Excel). The eCambium software has an input facility that allows the user to assign particular columns to the specific weather variables it needs.(link to user guide at the appropriate point)

In practice the easiest input is using files generated by the online SILO data.

https://www.longpaddock.qld.gov.au/silo/datadrill/index.php

At present this is not a free service at the moment and a license is required.

(https://www.longpaddock.qld.gov.au/silo/silopricelist.html

However, the system is currently in the process of being transferred to an open access platform which will provide the information freely.

eCambium is setup to read in the Silo-derived text file. The user has the option to name the data according to their specific needs. We have found it useful to use a file name that matches a site or compartment of interest.

SILO Future State Product Map

The future state SILO system will provide three products:

	Spatial Datasets	Patched Point Datasets	Data Drill Datasets
Description	Gridded, continental-scale daily climate surfaces derived by interpolating observational data. The grid will span 112°E - 154°E, 10°S - 44°S with resolution 0.05° latitude by 0.05° longitude (approximately 5 km × 5 km).	Continuous daily time series at point locations. Missing observational data will be "patched" using interpolated estimates. PPDs will be constructed for all stations (approximately 20,000).	Daily time series of data consisting entirely of interpolated estimates. The data will be taken from the gridded Spatial Datasets and will be available at any grid point over the land area of Australia, including some islands.
Format	NetCDF, JSON and KML A copy of the spatial datasets will be mirrored on a disk array managed by DNRM for internal use. The internal copy will be in NetCDF and DSITI's proprietary DRR formats.	CSV and JSON text files in either: • one of SILO's predefined formats. SILO currently provides datasets in 15 tailored formats, suitable for direct input to a number of biophysical models. Some formats may be withdrawn following consultation with users. • a custom user format consisting of columns containing: date, station number (if appropriate), latitude, longitude, elevation, and two columns of data for each climate variable selected by the user. The two columns are the value and the source of the data.	

<table>
<tr><td>Error estimate</td><td>KML formatted datasets will contain the error estimate at each station used in the construction of the given dataset.</td><td>Same as for Data Drill except an error estimate will only be provided for patched values i.e. the interpolated estimates, not the observed values.</td><td>An additional column containing the error estimate will be added for each climate variable selected. This column will only be added if requested by the user via a customised format (not available in predefined formats).</td></tr>
<tr><td>Access method</td><td colspan="3">All three products will be available via:
• Web interface: a new self-service web site. Users will specify the data they require and be provided with a link to download the data once it is ready for collection.
• Web API: users will encode their data request in a URL. The data will be streamed directly back to the user for display in their browser, consumption by a user application or download via command line HTTP tools. The API will be similar to the Enterprise Services Bus system currently provided by SILO. Project staff will assist users in adapting to the new web API as part of transition activities.</td></tr>
<tr><td>Variables</td><td colspan="3">All three products will be available for the following climate variables on a daily timestep over the period 1889-present:
• rainfall (a monthly accumulation will also be provided). Units: mm
• maximum and minimum temperatures. Units: °C
• vapour pressure and vapour pressure deficit. Units: hPa
• mean sea level pressure. Units: hPa
• evaporation (class A pan and a synthetic estimate). Units: mm
• solar radiation (total incoming downward shortwave radiation on a horizontal surface, derived from estimates of cloud oktas and sunshine duration, and radiometer data). Units: MJ/m^2
• relative humidity at the times of maximum and minimum temperatures. Units: %
• evapotranspiration (FAO56 short crop and ASCE tall crop estimates; and Morton's actual, potential, wet and lake estimates). Units: mm</td></tr>
</table>

Notes:

- Independent cross validation will be used to provide users with an indication of data quality. The error estimate will be obtained from the interpolation system and provided for each product as described above.
- Gridded estimates of long term mean errors will be constructed and made available to users at a later date (post-project).
- All three products will derived from observational data provided by the BoM, however additional data suppliers may be incorporated at a later date (post-project).

Appendix 3: Accessing site description databases

Instructions for obtaining data from the TERN soils grid and inputting into eCambium 2.1

eCambium Version 2 has been designed to make use of off-the-shelf input datasets wherever possible. The use of the SILO interpolated weather data set has been used since version 1. However, since the release of the national soils grid for Australia (see http://www.clw.csiro.au/aclep/soilandlandscapegrid/index.html) it has been possible to access high quality information about soils for any position in the country. A number of options exist for users to be able to find the relevant information in order to create a site for simulation using the eCambium tool. These can be considered in two categories. The first would be at a relatively coarse level, using easily accessed visually online mapping products provided through the TERN website. The second is to access the data through GIS products or R.

In eCambium version 2.1, an estimate of the fertility rating (FR) value can be obtained from the C: N ratio of the site. This is based on the findings from site sampling done as part of milestone 3 of the current FWPA project (***). It is important to note the limitation of this approach, however. It may be that this is a suitable approach only under limited circumstances. Furthermore, these data do not necessarily reflect accurately conditions at the site (e.g. in cases where plantations are ex-pasture sites), and furthermore, the FR value, as it pertains to a growth limitation, may be influenced in a more complex way and by other variables.

The eCambium tool can calculate soil maximum and minimum ASW from texture or it is possible to use the AWHC estimates also available on the TERN soils database if preferred.

Category 1

If only setting up a small number of sites, it is feasible to use to use the online viewing facility or (preferably) Google Earth to obtain estimates of the key inputs.

<u>Online viewing system</u>

The online viewing facility can be accessed at http://www.clw.csiro.au/aclep/soilandlandscapegrid/ViewData-Portal.html, and works best using the Internet Explorer browser. It is necessary to have Microsoft Silverlight installed on your computer and to be running MS Windows.

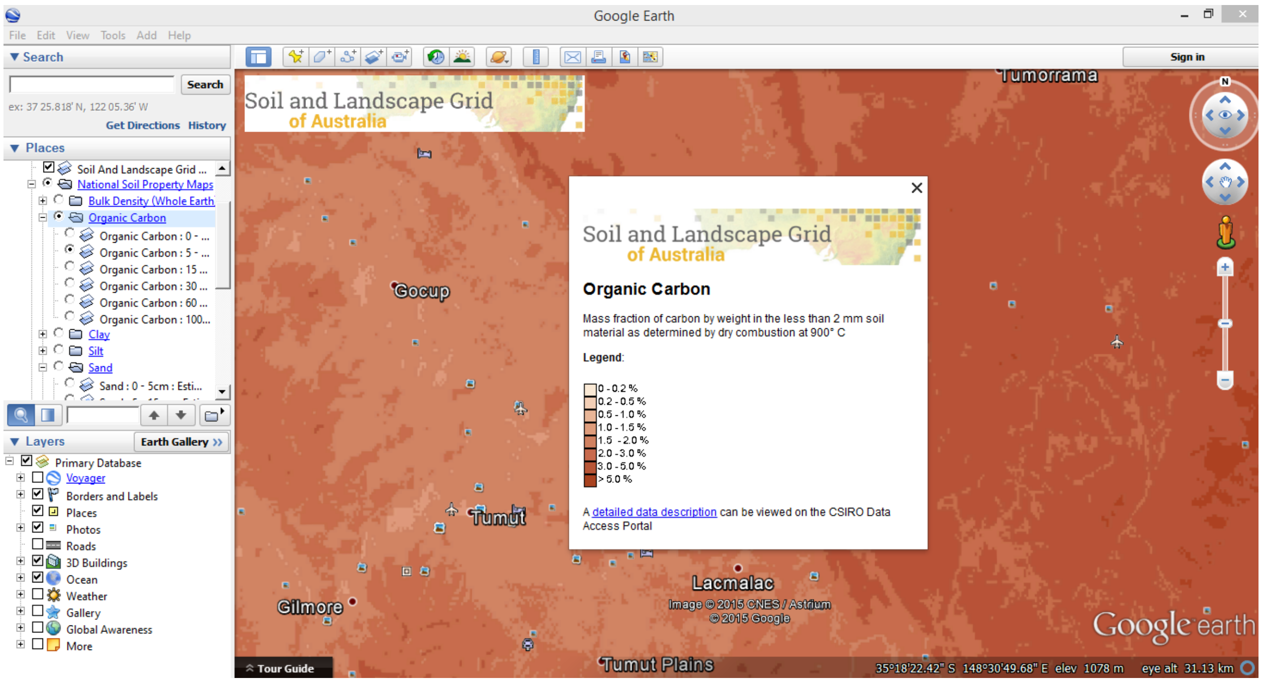
<u>Google earth</u>

Google earth can be downloaded at https://www.google.com/earth/.

Once the software is installed, download the soils and landscape grid kml file from http://www.clw.csiro.au/aclep/soilandlandscapegrid/ViewData-KML.html and open in Google earth.

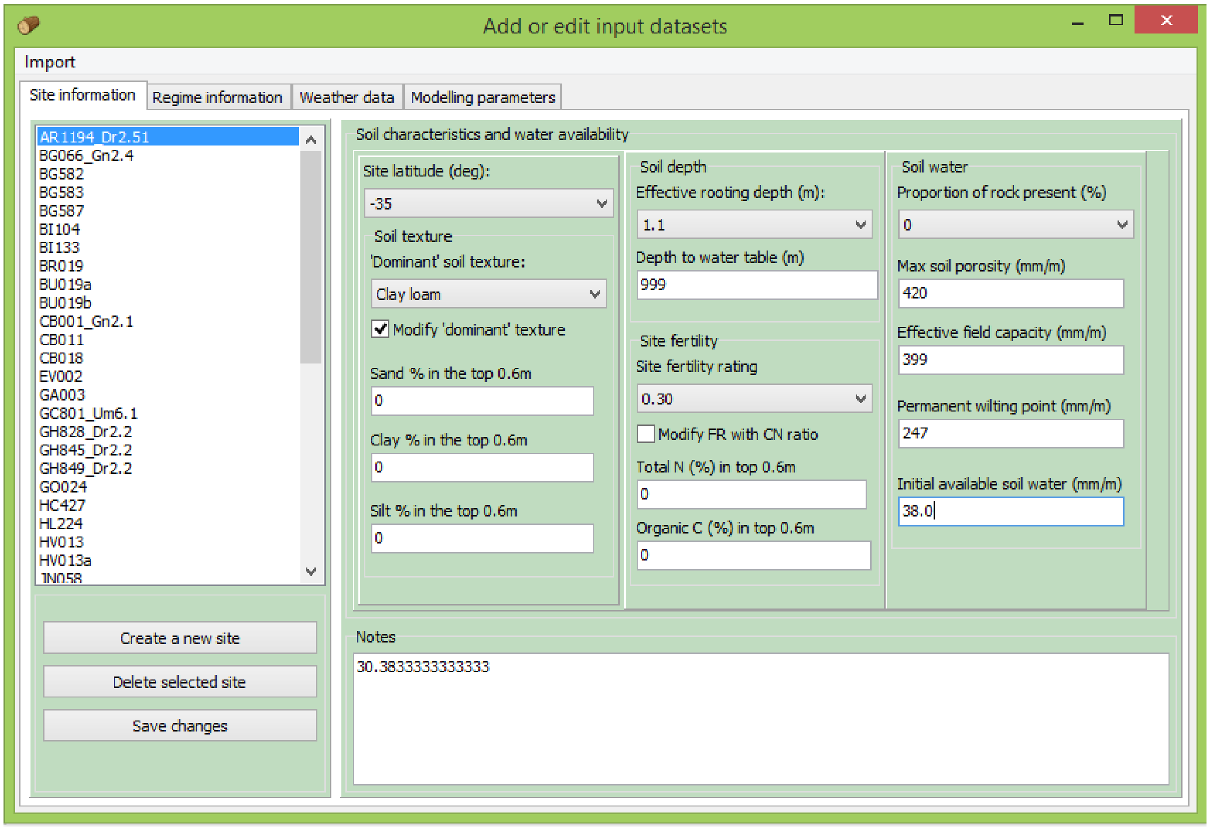
Under the “Places” menu, select “National Soil Property Maps”. Click to drop down, then select the layer of interest (e.g. “Clay”). Again, drop down, and then select the depth of interest (e.g. “5 – 15 cm”). This layer will now be displayed on the map (see below).

Zoom into the area of interest (double click on the map or use the + and – slider) and navigate to the geographical position where data are required. This can be easily done by looking at the latitude and longitude of the cursor position shown below the map. A legend can be displayed showing the ranges represented by the colours by clicking on the category (e.g. “clay”). Using this approach, only ranges can be determined, rather than the precise value estimated for each point.



Soil depth can be immediately read. For soil texture variables (sand, clay and silt %, total N and organic C) a weighted average for the depth to 60 cm needs to be calculated. Ascertain the values for 0 – 5, 5 – 15, 15 – 30 and 30 – 60 cm and work out the weighted average for that position. Do the same for “Total Nitrogen” and “Organic carbon”.

The findings for the point can be manually entered into the revised eCambium user interface for setting up sites (See below). eCambium can then estimate “dominant texture” and fertility rating from the entered values, or the user can choose to over-ride this automatic calculation by un-checking the relevant check boxes in the interface. In this case, the simulation run will still use the dominant texture class and FR regardless of sand, silt and clay % or C and N contents.



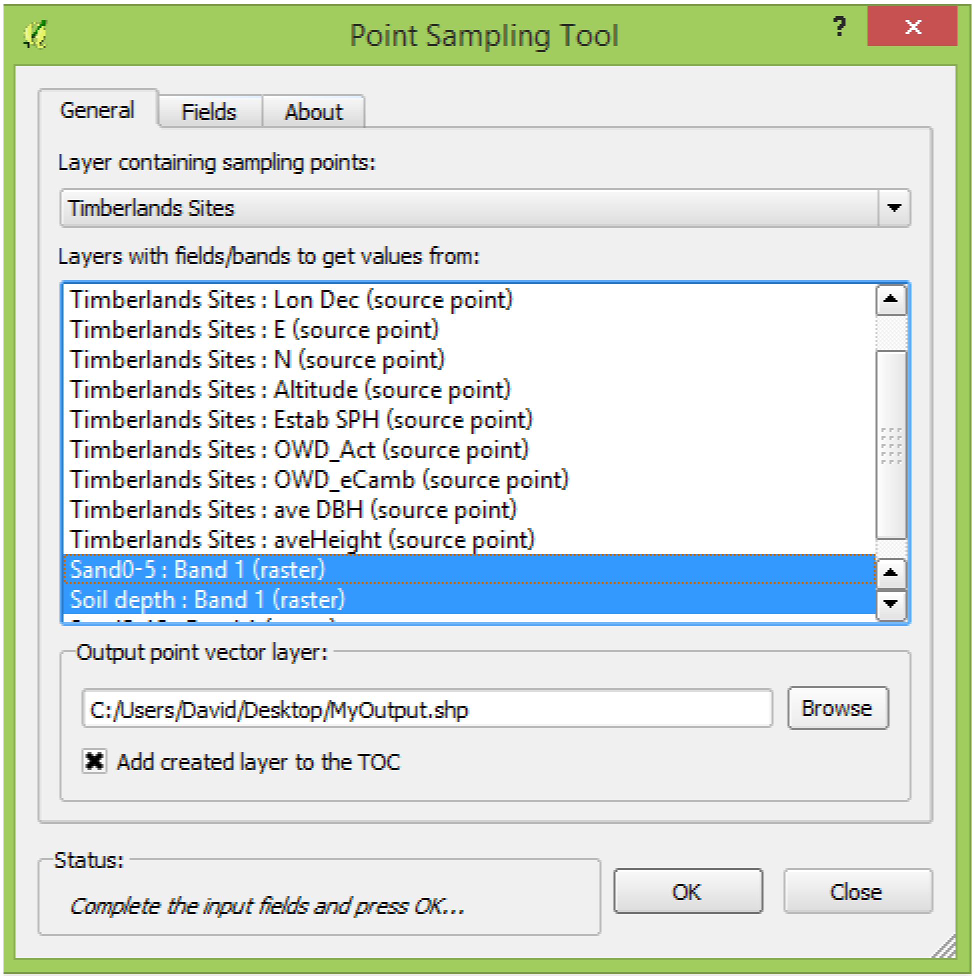
Category 2

Alternatively, a much more finessed approach is possible using GIS software such as ArcGIS and QGIS (the latter being freely available). Instructions for accessing the TERN data via these GIS tools can be found at http://www.clw.csiro.au/aclep/soilandlandscapegrid/GetData-GIS.html.

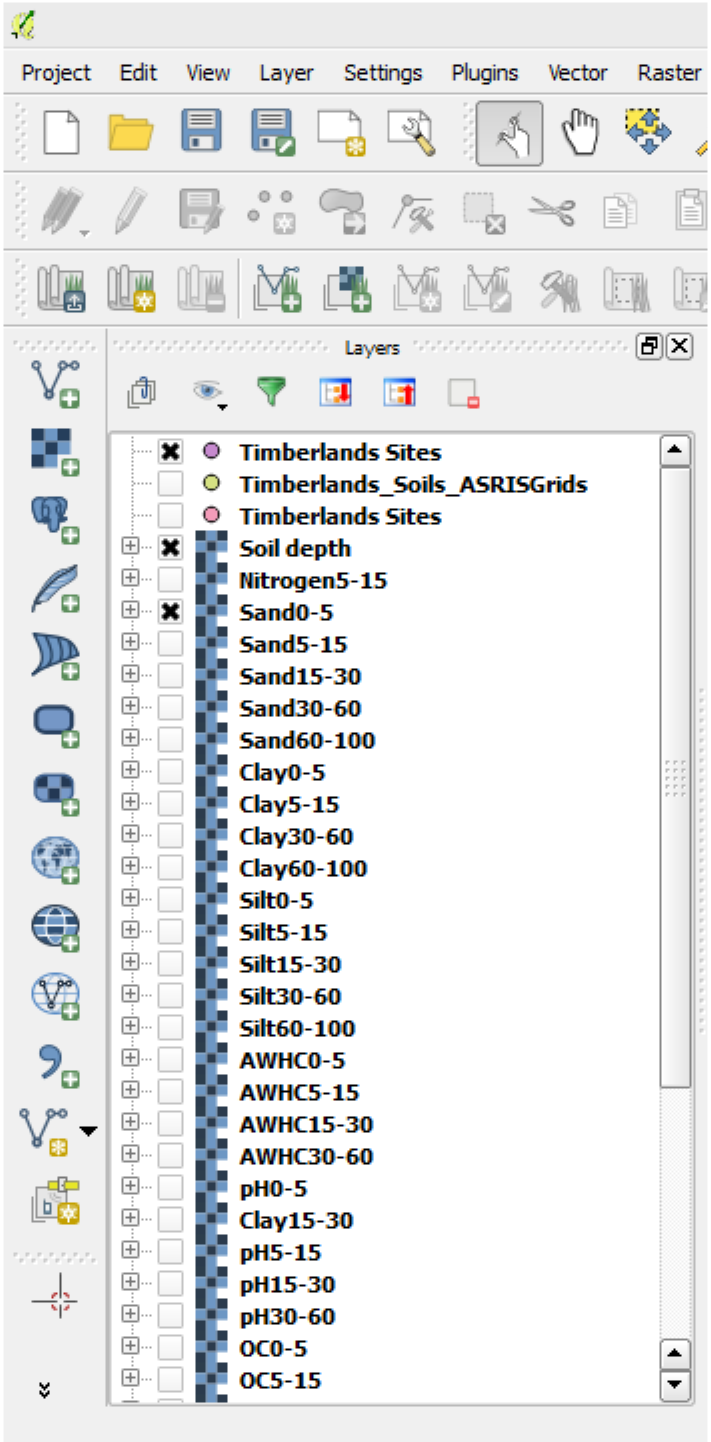
Extracting data using QGIS and the point sampling tool

Once the surfaces are loaded and available, the easiest way to extract the soils properties of interest for a number of points is to use the plug in available in QGIS called the "Point Sampling Tool" and the equivalent functionality in ArcGIS. Use this tool to create, for each point in a list, a file of the relevant variables.

Click on the variables of interest in the listing under "layers" on the left side of the displayed map (see the example below where only the sites listing, soil depth and sand 0 – 5 are selected). Then open the Point Sampling Tool dialogue and select all the variables to extract for the selected sites listing. It is necessary to specify a new shp file as an output, which will contain the new listing. Once this is done, click "OK".

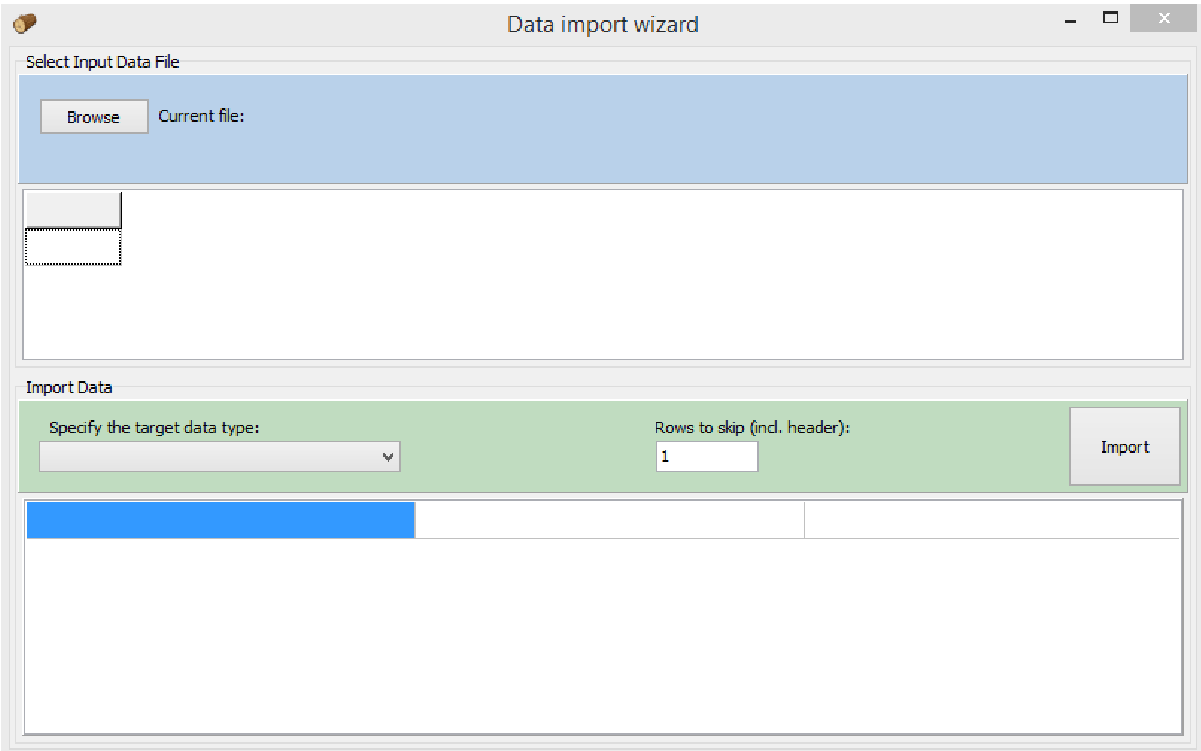


This layer will automatically be added to the project. At this point, it can be saved as a CSV format, or the Attributes table viewed, and the data copied and then pasted into a spreadsheet.

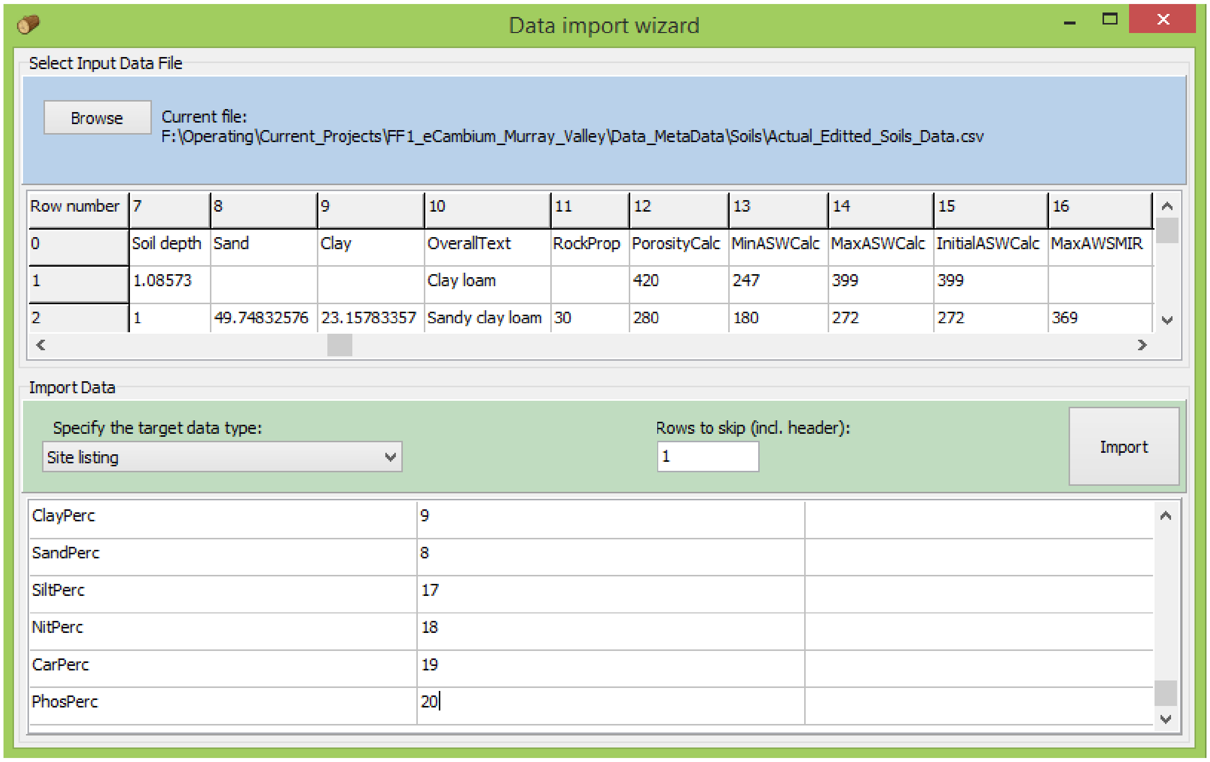


On this file, it is necessary to first pre-process by calculating the mean value for 0 – 60 cm for soil texture and N and OC content data. That is, eCambium requires a single number estimating the clay, silt and sand and total N and OC content for 0 – 60 cm soil depth. It is important that each "site" should have a unique name, which is reflected in a column of this file, with each name corresponding the various points.

Once the necessary variables have been calculated, these data can be uploaded to eCambium using the import Wizard feature. Select “File | Import Data from External Files”. The window below will open:



Browse for the input CSV file that you have previously created with the soils data. Select “Site listing” from the target data drop-down menu. In the lower table it is necessary to specify which column number in the data file (shown in the top table) corresponds to the required fields in the eCambium data file. Type the column number (shown as headers in the top table) into the second column of the lower table (as shown). If no column for the variable of interest exists, it is necessary to type in a constant. For example, for Fertility rating (FR) a constant of 0 can be typed in. If Total N and OC values are uploaded, eCambium will estimate FR from these latter two variables at run time.



Once all columns are matched to the required data fields in the lower table, or a value is estimated for those variables where no input data is available, click on "Import". If the data imports successfully, the sites, with names as they were given in your input data file, will appear in the available list for scenario creation and editing.

Soil Sampling Protocol

As a basis for comparison with the TERN data, soils were sampled from 24 of the 53 sites according to the following protocol. The data was used to obtain descriptive data for soil texture, site fertility and water holding capacity.

Work plan for each site

1. Auger approximately 10 holes to ~60 cm depth. These can be laid out sequentially to examine the pattern of change and the depth to different layers. Auger 2 – 3 holes to a depth of at least 80 cm, to get a minimum soil depth
   Photograph and describe the "laid out" profile
2. Take the A horizon sample (0-15 cm after removing humus layer) and B horizon sample (30-60 cm) and place in separate buckets
3. Bulk the A and B samples over the 10 holes and mix well in their separate buckets
4. Assess, describe and estimate rock content from augered samples or roadside profiles
5. In a wet strength paper bag subsample each of the A and B horizon samples to obtain ~ 1 kg sample
6. Record the site details / code, date and Horizon on each bag along with details to allow the analysis laboratory to identify the customer

7. If necessary store the samples in air-dry conditions that allow samples to dry. Do not over dry.

Laboratory Analyses

Deliver the samples for analysis. Analysis include

- Mid- Infrared (texture, Total N, Total C.)
- Bray P

Contact and Address of Laboratory

George Croatto
Agriculture Research and Development Division
Department of Economic Development, Jobs, Transport and Resources
Centre for Applied Sciences
Terrace 4, Ernest Jones Drive, Macleod 3085 | DX: 212 871
T: +61 (0)3 8458 2607 | M: +61 (0)428 577 523 | E: matt.kitching@ecodev.vic.gov.au
www.economicdevelopment.vic.gov.au

Equipment list for fieldwork

- Auger(s)
- Wet strength paper bags
- Spade
- Camera / Ipad (record site significant details and photographs)
- 4 buckets (soil mixing)
- Gloves
- Tag pen / marker
- Wet weather gear
    - Pants, Jacket, towel
- Protective clothing
    - Hi Vis vest
    - Footwear
    - Helmet

Appendix 4: Model parameter values and description

ECambium IGM parameters

ParameterDescription	ParameterValue
Canopy quantum efficiency	0.05
Canopy boundary layer conductance, assumed constant	0.2
The maximum rate of upward movement of the base of live crown (m/d)	0.025
Determines response of canopy conductance to VPD	0.065
Maximum diurnal leaf water potential decline (MPa)	2
Rate of decay of fertilisation effect (1/d)	0.000033
Tree physiological sensitivity to site fertility	0.25
Litterfall rate at t = 0 (1/day)	0.0001
Maximum daily litterfall rate	0.006
Root turnover rate per day	0.0005
Radiation extinction coefficient	0.5
LAI required for maximum canopy conductance	5
LAI at maximum canopy rainfall interception	5
Maximum stand age used in age modifier	250
Maximum canopy conductance (gc, m/s)	0.025
The maximum height/base diameter ratio (m/cm)	1.1
Rainfall interception in a canopy with LAI for maximum interception (mm)	2
Maximum rate of direct evaporation from the top 10 cm of soil (mm/d)	0.016
The minimum crown length (m)	3
The minimum height/base diameter ratio (m/cm)	0.8
Fraction mean single-tree stem biomass lost per dead tree	0.2
Power of relative age in function for fAge	0.5
Foliage:stem partitioning ratios for stems with base diameter 2 cm	0.45
Foliage:stem partitioning ratios for stems with base diameter 20 cm	0.3
Minimum root biomass partitioning	0.3
Maximum root biomass partitioning	0.5
Minimum pre-dawn leaf water potential before tree senescence (MPa)	-2.6
intercept of net v. solar radiation relationship (W/m2)	-90
slope of net v. solar radiation relationship	1.8
The rate of root vertical growth per unit root mass (m/kg)	1
Specific leaf area at age 0 (m^2/kg)	5

ParameterDescription	ParameterValue
Specific leaf area for mature leaves (m^2/kg)	5
Modifier for DBH/Ht Relationship (Stems/Ha)	1500
Age at which litterfall rate has median value (days)	990
Power in self-thinning law	1.5
Critical max temp (deg C)	32
Critical min temp (deg C)	0
Optimum temperature (deg C)	18
Effect of tree ht on minimum leaf water potential (MPa/m)	0.01
Stand age (years) for SLA = (SLA0 + SLA1)/2	3
Max tree stem mass (kg) likely in mature stands of 1000 trees/ha	300
Assimilate use efficiency (Ratio NPP/GPP)	0.47

eCambium xylem parameters

Parameter Description	Parameter estimates/ranges
Parameter 1 in the relationship between density/MFA and MOE	0.03
Parameter 2 in the relationship between density/MFA and MOE	-0.16
The sensitivity of latewood formation to crown control	0.5
Exponent in the relationship between tracheid length and distance from the apical bud	0.1
The maximum distance from the apical bud for juvenile wood formation (m)	8
Expected average earlywood wood tracheid length in young trees(µm)	900
Factor k in the function determining change in RD with tree age	0.2
Factor k in the function determining change in TWT with tree age	0.05
Maximum number of cells that can be produced per file per day (cells/d)	8
The maximum duration of the earlywood phase (d))	175-210
Maximum population mean earlywood tracheid trached radial diameter (µm)	44 - 46
Maximum population mean earlywood wall transverse area (µm²)	635 -660
MFA multiplier	16 -18
Expected average earlywood tracheid radial diameter in young trees (µm)	32 - 34
Water potential at which tracheid enlargement is fully constrained (MPa)	-2.6
Average daily temperature at which xylem differentiation ceases (deg C))	4
Minimum radial diameter of a mature tracheid (µm)	20 – 24
Minimum tracheid wall cross-sectional area (µm²)	215 - 240

Parameter Description	Parameter estimates/ranges
Factor m in the function determining change in RD with tree age	0.5
Factor m in the function determining change in TWT with tree age	0.75 - 1
Tracheid tangential diameter (assumed constant pith to bark) (μm)	35
Air-dry density of the cell wall (g/cm^3)	1.5
The rate of wall deposition as a function of temperature (μm^2/deg C)	0.12 - 0.14

Appendix 5: Model input data

Soil descriptors derived from interpolated soils surfaces

Site	Latitude	Soil Depth	Min ASW	Max ASW	Soil texture	Porosity
AR1194	-35	1.1	273	416	Clay loam	420
BG066UT	-36	1.1	258	396	Sandy clay loam	400
BG582UT	-36	1	272	416	Clay loam	420
BG583T2	-36	1	257	396	Sandy clay loam	400
BG587T1	-36	1	270	416	Clay loam	420
BI104T1	-35	0.9	287	416	Clay loam	420
BI133T2	-35	0.9	287	416	Clay loam	420
BR019	-37	1.1	256	396	Sandy clay loam	400
BU019A	-36	0.9	201	337	Loam	340
BU019B	-36	1	261	396	Sandy clay loam	400
CB001T1	-36	1	267	416	Clay loam	420
CB011T1	-36	1	279	416	Clay loam	420
CB018T1	-36	1.1	276	416	Clay loam	420
EV002	-36	1	260	396	Sandy clay loam	400
GA003	-37	1	279	416	Clay loam	420
GC801	-35	1	260	396	Sandy clay loam	400
GH828UT	-35	1	241	396	Sandy clay loam	400
GH845T1	-35	1	278	416	Clay loam	420
GH845T2	-35	0.9	213	337	Loam	340
GH849T1	-35	0.9	206	337	Loam	340
GH849UT	-35	0.9	293	416	Clay loam	420
GO024	-36	1.1	260	396	Sandy clay loam	400
HC427	-37	1.1	286	416	Clay loam	420
HL224	-37	1.1	262	396	Sandy clay loam	400
HV013	-37	1.1	279	416	Clay loam	420
HV013a	-37	1.1	276	416	Clay loam	420
JN058	-36	1	255	396	Sandy clay loam	400

Site	Latitude	Soil Depth	Min ASW	Max ASW	Soil texture	Porosity
KO057	-36	1.1	253	396	Sandy clay loam	400
LV015	-36	1.1	251	396	Sandy clay loam	400
LV018A	-36	1.1	258	396	Sandy clay loam	400
LV018B	-36	1.1	259	396	Sandy clay loam	400
MA044UT	-36	1	274	416	Clay loam	420
MA053TH	-36	1	279	416	Clay loam	420
ME111	-37	1.1	287	416	Clay loam	420
MG001OP	-36	1.1	276	416	Clay loam	420
MG001TH	-36	1.1	274	416	Clay loam	420
MG001UT	-36	1.1	276	416	Clay loam	420
MH001	-37	1.1	291	416	Clay loam	420
MU206	-35	1	260	396	Sandy clay loam	400
NN001	-37	1.2	286	416	Clay loam	420
OC1012TH	-35	1	254	396	Sandy clay loam	400
OC1012UT	-35	1	256	396	Sandy clay loam	400
OC1195TH	-35	1	256	396	Sandy clay loam	400
OC1195UT	-35	1	255	396	Sandy clay loam	400
SP1181UT	-35	1	264	396	Sandy clay loam	400
SP1182TH	-35	1	284	416	Clay loam	420
ST048	-36	1.1	271	416	Clay loam	420
TR014T2	-37	1.1	277	416	Clay loam	420
TR016UT	-37	1	265	396	Sandy clay loam	400
WB026	-37	1	283	416	Clay loam	420
WC158	-37	1.2	277	416	Clay loam	420
WJ1151	-35	1	260	396	Sandy clay loam	400
WT001	-37	1	270	416	Clay loam	420

Regime descriptions

Summary of planting dates and fertilisation and thinning events applied to simulations. Level for establishment is stems/Ha, for pruning is relative intensity, for thinning is remaining stems/Ha and for Fertilisation is relative gain in fertility rating.

Regime name	Month	Type	Level	Notes
AR1194	Jul-87	Establishment	1100	
AR1194	Jul-95	Pruning	0.1	
AR1194	Jun-04	Thinning	400	
AR1194	Oct-14	Harvest	1	
BG066_UT	Jul-85	Establishment	1100	
BG066_UT	Oct-14	Harvest	1	
BG582UT	Jul-84	Establishment	1100	
BG582UT	Oct-14	Harvest	1	
BG583_T2	Jul-84	Establishment	1100	
BG583_T2	Jan-99	Thinning	486	
BG583_T2	Sep-07	Thinning	200	
BG583_T2	Oct-14	Harvest	1	
BG587_T1	Jul-86	Establishment	1100	
BG587_T1	Jul-95	Pruning	0.1	
BG587_T1	Feb-98	Pruning	0.1	
BG587_T1	Jun-07	Thinning	500	
BG587_T1	Oct-14	Harvest	1	
BI104_T1	Jul-85	Establishment	1400	
BI104_T1	Dec-04	Thinning	400	
BI104_T1	Oct-14	Harvest	1	
BI133_T3	Jul-86	Establishment	1100	
BI133_T3	Dec-04	Thinning	350	
BI133_T3	Jan-11	Thinning	206	
BI133_T3	Oct-14	Harvest	1	
BR019	Jul-88	Establishment	1100	
BR019	Sep-14	Harvest	1	
BU019a	Jul-88	Establishment	1100	
BU019a	Sep-01	Thinning	650	
BU019a	May-11	Thinning	250	
BU019a	Sep-14	Harvest	1	
BU019b	Jul-88	Establishment	1100	
BU019b	Sep-14	Harvest	1	
CB001_T1	Jul-87	Establishment	1100	
CB001_T1	Sep-95	Pruning	0.1	
CB001_T1	Apr-97	Pruning	0.1	
CB001_T1	Jul-99	Pruning	0.1	

Regime name	Month	Type	Level	Notes
CB001_T1	Jun-09	Thinning	400	
CB001_T1	Oct-14	Harvest	1	
CB011_T1	Jul-86	Establishment	1333	
CB011_T1	Dec-04	Thinning	625	
CB011_T1	Oct-14	Harvest	1	
CB018_T1	Jul-84	Establishment	1196	
CB018_T1	Nov-11	Thinning	400	
CB018_T1	Oct-14	Harvest	1	
EV002_Fert	Jul-87	Establishment	850	
EV002_Fert	Aug-87	Fertilization	0.44	To simulate the ex-pasture effect Not used in cases where actual C/N data was available
EV002_Fert	Sep-14	Harvest	1	
GA003_Fert	Jul-88	Establishment	900	
GA003_Fert	Aug-88	Fertilization	0.4	To simulate the ex-pasture effect Not used in cases where actual C/N data was available
GA003_Fert	Jul-04	Thinning	350	
GA003_Fert	Jul-09	Thinning	250	
GA003_Fert	Sep-14	Harvest	1	
GC801	Jul-87	Jul-87	1100	
GC801	Sep-95	Pruning	0.1	
GC801	Jun-01	Thinning	400	
GC801	Oct-14	Harvest	1	
GH828_Fert	Jul-84	Establishment	1100	
GH828_Fert	Aug-84	Fertilization	0.8	To simulate the ex-pasture effect. Not used in cases where actual C/N data was available
GH828_Fert	Jan-05	Thinning	550	
GH828_Fert	Oct-14	Harvest	1	
GH845_T1_Fert	Jul-86	Establishment	1100	
GH845_T1_Fert	Aug-86	Fertilization	0.5	To simulate the ex-pasture effect Not used in cases where actual C/N data was available
GH845_T1_Fert	Jan-95	Pruning	0.2	
GH845_T1_Fert	Jan-00	Thinning	500	
GH845_T1_Fert	Oct-14	Harvest	1	

Regime name	Month	Type	Level	Notes
GH845_T2_Fert	Jul-89	Establishment	1100	The compartment sampled was actually 844, but the planting dates and silvicultural history were as assumed for compartment 845. Fertiliser is to simulate the ex-pasture effect Not used in cases where actual C/N data was available
GH845_T2_Fert	Aug-89	Fertilization	0.5	
GH845_T2_Fert	Jan-95	Pruning	0.2	
GH845_T2_Fert	Jun-05	Thinning	500	
GH845_T2_Fert	Jul-10	Thinning	325	
GH845_T2_Fert	Oct-14	Harvest	1	
GH852_T1_Fert	Jul-87	Establishment	875	
GH852_T1_Fert	Aug-87	Fertilization	0.5	To simulate the ex-pasture effect Not used in cases where actual C/N data was available
GH852_T1_Fert	Jan-07	Thinning	400	
GH852_T1_Fert	Oct-14	Harvest	1	
GH852_UT_Fert	Jul-87	Establishment	875	
GH852_UT_Fert	Aug-87	Fertilization	0.5	To simulate the ex-pasture effect Not used in cases where actual C/N data was available
GH852_UT_Fert	Oct-14	Harvest	1	
GO024_Fert	Jul-88	Establishment	1000	
GO024_Fert	Aug-88	Fertilization	0.5	To simulate the ex-pasture effect Not used in cases where actual C/N data was available
GO024_Fert	Jul-00	Thinning	500	
GO024_Fert	Sep-14	Harvest	1	
HC427	Jul-87	Establishment	1100	
HC427	Feb-03	Thinning	550	
HC427	Sep-14	Harvest	1	
HL224	Jul-81	Establishment	900	
HL224	Sep-14	Harvest	1	
HV013	Jul-83	Establishment	1200	
HV013	Sep-14	Harvest	1	
HV013a	Jul-82	Establishment	1200	
HV013a	Sep-14	Harvest	1	
JN058_Fert	Jul-87	Establishment	1100	

Regime name	Month	Type	Level	Notes
JN058_Fert	Aug-87	Fertilization	0.31	To simulate the ex-pasture effect. Not used in cases where actual C/N data was available
JN058_Fert	Jul-01	Thinning	550	The stand density at the sampling location was higher than inventory data suggested
JN058_Fert	Sep-14	Harvest	1	
KO057_Fert	Jul-87	Establishment	1100	
KO057_Fert	Aug-87	Fertilization	0.33	To simulate the ex-pasture effect. Not used in cases where actual C/N data were available
KO057_Fert	Nov-03	Thinning	500	
KO057_Fert	Jul-10	Thinning	250	
KO057_Fert	Sep-14	Harvest	1	
LV015	Jul-86	Establishment	1100	
LV015	Jul-02	Thinning	500	
LV015	Jun-10	Thinning	400	Some question about intensity of final thinning
LV015	Sep-14	Harvest	1	
LV018a	Jul-86	Establishment	1100	
LV018a	May-03	Thinning	500	
LV018a	Sep-14	Harvest	1	
LV018b	Jul-86	Establishment	1100	
LV018b	Sep-14	Harvest	1	
MA044_UT	Jul-84	Establishment	1100	
MA044_UT	Jan-93	Pruning	0.1	
MA044_UT	Oct-14	Harvest	1	
MA053_T1	Jul-87	Establishment	1100	
MA053_T1	Jul-07	Thinning	450	
MA053_T1	Oct-14	Harvest	1	
ME111_Fert	Jul-89	Establishment	1100	
ME111_Fert	Aug-89	Fertilization	0.32	To simulate the ex-pasture effect. Not used in cases where actual C/N data were available
ME111_Fert	Apr-04	Thinning	550	
ME111_Fert	Sep-12	Thinning	350	
ME111_Fert	Sep-14	Harvest	1	
MG001OP	Jul-89	Establishment	1100	
MG001OP	Jun-00	Thinning	600	
MG001OP	Jun-08	Thinning	450	
MG001OP	Jul-13	Thinning	300	
MG001OP	Sep-14	Harvest	1	
MG001TH	Jul-89	Establishment	1100	
MG001TH	Jun-00	Thinning	330	
MG001TH	Jun-08	Thinning	160	
MG001TH	Sep-14	Harvest	1	
MG001UT	Jul-89	Establishment	1250	

Regime name	Month	Type	Level	Notes
MG001UT	Sep-14	Harvest	1	
MH001_T1_Fert	Jul-91	Establishment	1100	
MH001_T1_Fert	Aug-91	Fertilization	0.5	To simulate the ex-pasture effect Not used in cases where actual C/N data were available
MH001_T1_Fert	Apr-07	Thinning	500	
MH001_T1_Fert	Sep-14	Harvest	1	
MU206_UT	Jul-79	Establishment	1400	
MU206_UT	Oct-14	Harvest	1	
NN001_Fert	Jun-85	Establishment	1111	
NN001_Fert	Jul-85	Fertilization	0.25	To simulate the ex-pasture effect Not used in cases where actual C/N data were available
NN001_Fert	Jun-01	Thinning	300	
NN001_Fert	Sep-14	Harvest	1	
OC1012_T2	Jul-84	Establishment	1100	
OC1012_T2	Apr-95	Pruning	0.1	
OC1012_T2	Oct-97	Thinning	495	
OC1012_T2	Jul-06	Thinning	200	
OC1012_T2	Oct-14	Harvest	1	
OC1012_UT	Jul-84	Establishment	1100	
OC1012_UT	Apr-95	Pruning	0.1	
OC1012_UT	Oct-14	Harvest	1	
OC1195_T2	Jul-87	Establishment	1100	
OC1195_T2	Mar-95	Pruning	0.05	
OC1195_T2	Jun-06	Thinning	500	
OC1195_T2	Aug-11	Thinning	180	
OC1195_T2	Oct-14	Harvest	1	
OC1195_UT	Jul-87	Establishment	1100	
OC1195_UT	Mar-95	Pruning	0.05	
OC1195_UT	Jun-02	Thinning	700	
OC1195_UT	Oct-14	Harvest	1	
SP1181_UT_Fert	Jul-87	Establishment	1100	
SP1181_UT_Fert	Aug-87	Fertilization	0.75	To simulate the ex-pasture effect Not used in cases where actual C/N data were available
SP1181_UT_Fert	Apr-96	Pruning	0.1	
SP1181_UT_Fert	Oct-14	Harvest	1	

Regime name	Month	Type	Level	Notes
SP1182_T1_Fert	Jul-87	Establishment	1100	
SP1182_T1_Fert	Aug-87	Fertilization	0.75	To simulate the ex-pasture effect Not used in cases where actual C/N data were available
SP1182_T1_Fert	Apr-96	Pruning	0.1	
SP1182_T1_Fert	Feb-09	Thinning	250	
SP1182_T1_Fert	Oct-14	Harvest	1	
ST048	Jul-97	Establishment	1100	
ST048	Feb-11	Thinning	600	
ST048	Sep-14	Harvest	1	
TR014TH	Jul-86	Establishment	900	
TR014TH	Sep-03	Thinning	400	
TR014TH	Apr-12	Thinning	300	
TR014TH	Sep-14	Harvest	1	
TR016UT	Jul-86	Establishment	900	
TR016UT	Sep-14	Harvest	1	
WB026_T1	Jul-68	Establishment	1650	
WB026_T1	Sep-83	Thinning	250	
WB026_T1	Sep-14	Harvest	1	
WC158	Jul-85	Establishment	960	To simulate the ex-pasture effect Not used in cases where actual C/N data were available
WC158	Jul-85	Fertilization	0.47	
WC158	Aug-04	Thinning	400	
WC158	Sep-14	Harvest	1	
WJ1151_T2	Jul-85	Establishment	1100	
WJ1151_T2	Jul-02	Thinning	450	
WJ1151_T2	Sep-09	Thinning	250	
WJ1151_T2	Oct-14	Harvest	1	
WT001	Jul-88	Establishment	1100	
WT001	Jun-09	Thinning	450	
WT001	Sep-14	Harvest	1	

Appendix 6: Overview of the mill study protocol

The purpose of this appendix is to provide a textual and photographic record of the mill trial to assist in the analysis of the data, as well as guide potential future studies. The following sequence was followed to prepare and process logs in the log-yard prior to mill processing. The final steps include a description of the milling process and a visual record of what was required to obtain the necessary data.

1. Logs were unloaded and delivered to the preparation area

2. In the log stack, the butt ends were marked to allow logs to be laid out consistently to facilitate measurement and markup
3. An excavator was used to lay logs out and align them on bearers

4. A log number starting from 301 was assigned to each log, which matched with prepared barcode sheets to be glued to the large end. The log number was sprayed onto the SED end of each log. Log numbers were matched with the assigned project log code (e.g.44-1-2 for site 44, tree 1, log 2), checking that the logs had the same code each end. Coding

done during harvest was clarified by the number from the other end. Good confidence that logs were correctly identified and marked during harvest.

5. The end of each log was cleaned and squared with a fresh chainsaw cut to both ends. The log number was written at the top of the SE end and a 40 mm cross-sectional disc taken. This upper end marking helps to align the disc image with the log barcode during processing, with the DiscBot data. This needed to be as clean and square as possible to minimise preparation time for the DiscBot system at SCION.
6. Underbark and heartwood diameters from SED and LED of logs were measured. Logs were quite dry, especially from HVP, and given they had been harvested a couple of weeks previously, picking the sapwood / heartwood boundary was often difficult. Wetting the end helped.

7. Log length was measured and HM200 acoustic velocity obtained. (This included a measure of the resonance spectrum from the HM200 for each log)
8. A RESI trace was obtained from the SED of each log.
9. Each log end was wetted and an image taken, which included the log number, a set square with metric measurements and a small plumb-bob hanging from the apex of the

square. The 3 points of the set square are used to correct the plane of the image. Initially the SE and LE images were intended to be distinguished by the sequence (SE first then LE) however (around image 520) LE or SE was included in each image, as the sequence of imaging varied between batches.

10. Discs taken were labelled with two prepared barcodes on the tangential longitudinal face. The barcode number was then read with a scanner into a spreadsheet and linked to the log number which was manually typed in. Each disc was then cut radially through the pith into 2 halves with a circular saw, with each disc clamped to a work bench. By aligning the disc such that the log number written onto the transverse surface was towards the saw, each half was then separated with a single barcode on each. The orientation of each disc was then relatable to the barcode orientation applied in the next step. The log number on the disc was written before being cut, and was therefore the upper surface.

11. Glue was applied to the large end of each log (compressed air driven glue gun, powered by compressor powered by petrol generator), allowing a minute before applying the barcode sheet such that 'North' was towards the top of the log and the centre of the sheet was aligned with the pith. The glue was sourced by Scion who had undertaken various studies to identify the optimal glue to minimize the loss of barcode during the

sawing process. It was a urea formaldehyde-based product and as such required careful handling. The sheet was trimmed to just inside the outer, under-bark diameter using a kraft knife. The sheet needed to be pressed onto the surface to allow good contact between the sheet and the wood to make sure there were no unglued areas that would come off during sawing. After the first day, labels were pretrimmed to the appropriate dimensions before application as this was found to be quicker and produce a better result, especially when wind was strong enough to blow labels off while being trimmed.

12. The barcode label end was coated with 2 coats of satin water-based varnish to help protect it from weather.

13. After all was dry, the logs were stacked on bearers ready for weighing.

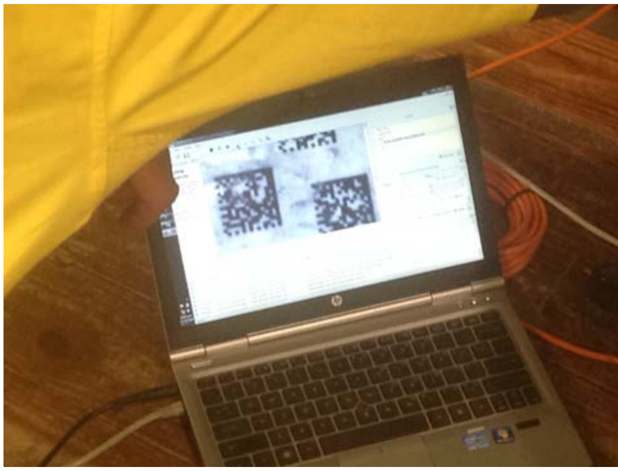
14. A weighing rig, supplied by CHH, was positioned such that the excavator could, with as little movement as possible, take a log from the pile, swing to load it on the rig, and then place it onto a new pile. A person was located such that he could read the weighing rig screen, out of excavator range and also out of the sun. The display screen was therefore removed from the rig and placed in the cabin of a car for reading.

<u>This concluded the tasks required for log preparation. The following pertains to the setup and testing of the camera in the mill, for imaging sawn board ends</u>

15. A camera was set up and tested in the mill to capture board end images of barcodes. This was the critical step that allowed the identification of each board, back to log and tree to be cross-matched with the mill generated data on board stiffness, density and shape. Boards with glued barcodes were run past the camera after the shift finished. Lighting was an issue and the focal depth. The need to keep board ends within a narrower range of distances from the camera was identified.


16. The mill replaced load cells on the board weighbridge associated with the ecoustic grader to ensure accurate measures of density and hence MOE. The supplier of the ecoustic grader was on site to prepare and monitor the performance of the log and board acoustic measurement.

17. The mill study was scheduled for Friday 16th October at 11am. No logs were loaded into the mill after10:30 and the mill was cleared by 11am. The camera system was set up from 9am, and the image capture system tested.




18. At 11am 8 test logs were loaded which had barcodes attached. The camera picked the barcodes from these and the log details decoded. If the system failed, the mill trial would have been delayed until we could get the image capture approach working.
19. A mechanical failure of the debarker delayed the start of the trial logs.
20. The loader driver was asked to load logs into the bin centrally to minimize the risk of the barcode ends scraping against the side of the bin.
21. Logs started being processed around 12:30 pm and the entire batch was processed by 1:45 pm. The sequence of log numbers as they entered the Royalty scanner was recorded. This was largely the sequence with which they went through the mill, however there was an opportunity for the sequence to change as the logs entered the system from the tri-deck. A second camera system (GoPro) was set up to monitor flow just before the ELI scanner to assess the ability to track log numbers pre-sawing. However image resolution was inadequate to read the log numbers. Changes in order will need to be tracked from log length and diameter records.

22. There were a couple of log breakages, which resulted in some boards coming through without barcodes, and therefore unable to be identified. Barcoded boards were

consistently clear. To facilitate the matching of barcodes and mill ID, the travel of the boards past the camera was kept to batches of 3 minutes with a 20 second gap. In many cases the gap was natural and the batch less than 3 minutes owing to sawing process flow. A small proportion of boards had the label soaked off by the water/oil spray used during cant sawing. A less water absorbent barcode paper may alleviate this. Mill staff worked to clean the barcode ends with compressed air followed by someone wiping the ends with a cloth as they passed. Other staff worked to keep the distance from the camera reasonably constant.

23. At the end of the trial all the various data sources were collated from the log-yard measurements, board photos, log sequence data and mill data (board measures, log measures, cant measures).

Appendix 7: Comparison of soils data

The project involved an analysis of the soils from 25 of the 53 sites involved in the study. This provided an opportunity to compare the actual soils data obtained with that available on the publicly-available TERN soils surface. This database is biased towards agricultural soils given the greater availability of data compared to forestry sites.

There was no relationship ($p > 0.1$) between the soil depth as determined by in-field augering and the soil depth (or the regolith depth) available from the TERN database (Table 17). It is of importance to note, however, that the augering could not determine depth of any more than about 1.5 m below the soil surface. It is also notable that the soil depth estimates, both in field and from the TERN database were fairly homogenous, varying only between 0.9 and 1.2 m. At one site, Oak Creek, the soil did seem substantially deeper than the TERN database suggested.

There was evidence that the estimated sand content of sampled soils was correlated (R^2 = 14%; $p = 0.061$) with the average sand content extracted for 0 – 60 cm depth from the TERN database. This was, however, not the case for the clay content, for which no significant ($p = 0.800$) correlation was found. This was primarily because of 4 sites (Moyhu, both Splitters sites and Gass Creek) where the actual (or at least, MIR-determined) clay content was substantially less than the TERN soils surface estimates. There was a better (R^2 = 28%; $p = 0.007$) relationship between soil carbon content measured at the sites and the organic carbon(OC) content of the 0 – 30 cm soil depth from the TERN soils surfaces. No relationship existed ($p = 0.937$), however, between total N measured on soil samples and the total N for 0 – 30 cm soil depth from the TERN soil surfaces. Notable here, however, was the very high total N still present at certain sites, some (but not all) were known to be ex-pasture sites. A particularly interesting instance is Bago 066, which was difficult to simulate accurately. On average the actual N content was around half that obtained from the TERN database. This would affect site fertility estimates, but it should be noted that in the evaluation described in this report, site fertility was kept constant at 0.3.

Table 17. Summary of estimates of soil properties made from soil samples obtained from study sites and from TERN soils surfaces

	Measurements/estimates from field visits						Estimates from TERN soils surface					
SITE_ID	Soil depth	Sand %	Clay	Overall texture class	Soil carbon (%, w/w)	N (%, w/w)	Estimated soil depth	Estimated sand % (0 – 60 cm)	Estimated clay % (0 – 60 cm)	Soil class	OC (%, w/w)	N (%, w/w)

HV013	0.8	28.5	35.7	Clay loam	1.7	0.06	1.1	40	30	Clay loam	5.1	0.19
HV013a	0.9	28.6	36.3	Clay loam	1.9	0.06	1.1	40	30	Clay loam	4.9	0.20
EV002	0.7	28.9	35.5	Clay loam	1.4	0.05	1.0	50	20	Sandy clay loam	2.4	0.13
ME111		33.4	29.9	Clay loam	1.6	0.07	1.1	50	20	Clay loam	3.7	0.18
OC1012UT	> 1.5	39.4	33.6	Clay loam	3.2	0.17	1.0	50	30	Sandy clay loam	3.3	0.16
CB001T1		39.5	30.1	Clay loam	1.5	0.06	1.0	40	30	Clay loam	2.3	0.15
NN001	1.0	41.0	26.0	Loam	1.2	0.07	1.2	40	30	Clay loam	3.7	0.19
WC158	1.2	42.0	31.9	Clay loam	3.9	0.20	1.2	50	30	Clay loam	4.2	0.16
MG001OP		42.8	26.8	Loam	2.1	0.07	1.1	40	30	Clay loam	5.0	0.19
BI104T1	1.1	44.9	30.4	Clay loam	1.3	0.05	0.9	50	30	Clay loam	3.5	0.16
BU019A		46.7	27.2	Sandy clay loam	1.3	0.05	0.9	50	20	Loam	2.8	0.14
MA044UT	0.9	47.8	26.5	Sandy clay loam	1.7	0.07	1.0	40	30	Clay loam	4.1	0.16

KO057	1.0	48.5	25.8	Sandy clay loam	1.3	0.07	1.1	50	20	Sandy clay loam	2.1	0.14
GH828UT	0.8	48.8	27.0	Sandy clay loam	1.2	0.08	1.0	50	30	Sandy clay loam	2.4	0.13
GH845T2		49.2	26.0	Sandy clay loam	1.5	0.07	0.9	40	20	Loam	3.2	0.18
GA003	1.5	49.4	25.8	Sandy clay loam	2.2	0.13	1.0	50	30	Clay loam	3.2	0.15
BG066UT	1.0	49.7	23.2	Sandy clay loam	3.4	0.18	1.1	50	20	Sandy clay loam	5.1	0.15
MH001	0.8	50.7	16.0	Loam	2.0	0.08	1.1	50	30	Clay loam	1.9	0.15
TR014T2	1.2	50.8	22.4	Sandy clay loam	2.3	0.10	1.1	50	30	Clay loam	3.7	0.16
JN058	1.0	52.5	23.7	Sandy clay loam	1.4	0.06	1.0	50	30	Sandy clay loam	2.4	0.17
GH849T1	0.8	52.8	21.4	Sandy clay loam	1.3	0.05	0.9	50	20	Loam	2.1	0.13
TR016UT	1.2	53.4	20.7	Sandy clay loam	1.9	0.09	1.0	50	20	Sandy clay loam	4.0	0.17
SP1181UT		58.4	17.7	sandy loam	1.0	0.07	1.0	50	30	Sandy clay loam	2.3	0.13
SP1182TH		58.4	17.7	sandy loam	1.0	0.07	1.0	50	30	Clay loam	2.3	0.13

GC801		62.2	15.2	Sandy Loam	3.1	0.12	1.0	50	30	Sandy clay loam	4.0	0.16