Ministry for Primary Industries
Manatū Ahu Matua

Development of spatially based look-up tables for planted forest species

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Preface

The Ministry for Primary Industries (MPI) Sustainable Land Management and Climate Change (SLMACC) programme provides funding for research to understand the impacts of a changing global climate.

1 Introduction

1.1 BACKGROUND

The Emissions Trading Scheme (ETS) and the Permanent Forest Sink Initiative (PFSI) were created by the New Zealand Government as part of a package of climate change initiatives that will support New Zealand's ratification of the Kyoto Protocol. The ETS and PFSI provide investors and landowners with the ability to earn carbon units from eligible forests (which include planted exotic, and planted and regenerating indigenous tree species). The government allocates carbon units to eligible forests under 100ha in size by using a look-up table approach for key species. Current look-up tables are based either on national or regional averages and may over-estimate carbon sequestration rates for forests planted on more marginal (high, dry, cold) land, or may under-estimate carbon sequestration for forests planted in fertile land. The spatial resolution of default look-up tables for radiata pine can be improved by calibrating the existing radiata pine model (300 Index) to site factors, explicitly including environmental variables as drivers of productivity indices. These indices are used as inputs to the 300 Index growth model together with typical silvicultural regimes, for stands that are known to be intact. The effect of "atypical" low stockings on yield tables can also be modelled. Simple field assessments will dictate whether "atypical" look-up tables are to be applied. Improvements are needed to the current ETS tables to more accurately reflect likely tree growth rates and thus carbon sequestration rates to ensure fair allocation of carbon units for investors, forest owners and the Crown.

This research takes a three staged approach across a range of tree species including radiata pine, other planted species (Douglas-fir, redwood, cypress, Eucalyptus fastigata, Eucalyptus nitens) and key regenerating indigenous species (manuka/kanuka and mixed broadleaf). The research programme involved compiling existing data and acquiring new data to fill knowledge gaps. Radiata pine growth is already well documented throughout most of New Zealand so less research emphasis was placed on this species. In comparison, the growth of other planted species is much less well known. Field based measurement of these species was used to address gaps, although large gaps in coverage still exit because these species are not widely planted. However, moderately strong relationships were found between the growth of radiata pine and the growth of other planted species, so it is possible to predict the growth of other species using radiata pine as a covariate. The growth of indigenous species is reported separately by Landcare Research. The results from this underpinning research programme will form the basis for spatial, empirical and process-based modelling approaches to develop new look-up tables in future, in a format which MAF can readily incorporate into the ETS and PFSI systems.

The vision of the research programme is that by 2016, owners of land afforested under either the PFSI or ETS that are smaller than 100ha are able to use spatially based species specific look-up tables to determine the amount of carbon sequestered by their forests. By providing land owners realistic estimates of the carbon sequestration potential of a range of tree species, afforestation of marginal land is expected to increase, which will help improve New Zealand's future greenhouse gas balance.

1.2 MODELLING RADIATA PINE CARBON STOCKS

In managed radiata pine stands the carbon stock is made up of five pools, including: 1) Above ground biomass, 2) Below ground biomass, 3) Dead wood, 4) Litter, and 5) Carbon in mineral soil. The mineral soil carbon pool is not addressed in this programme. The 4 live and dead biomass pools are modelled by combining stem volume and wood density using the Forest Carbon Predictor. In New Zealand, MPI uses Forecaster Carbon (which is based on Forest Carbon Predictor) to predict carbon stocks annually by pool, using field data that needs to be collected by Forest ETS participants with 100 ha or more of eligible forest. The Field Measurement Approach (FMA) is not used by ETS Participants with less than 100 ha of eligible forest. These participants are required to use Lookup Tables. Lookup tables were developed using the Forest Carbon Predictor, using regional averages of the two "Productivity Indices", the 300 Index, and mean top height (MTH). The 300 Index is defined as the mean annual increment in stem volume under bark of radiata pine at age 30, and assumes plots are managed using a standard regime with a final crop stocking of 300 stems per ha. The mean top height index is the predicted mean height at age 20 years of the 100 largest diameter stems per hectare.

Productivity indices from plots extracted from the permanent sample plot system were used previously to prepare national surfaces of the 300 index and Site indes for NZ's radiata pine plantations (Palmer et al., 2010). Productivity indices were extrapolated spatially using independent variables including air temperature, soil water balance, terrain attributes, and land use history as spatial drivers of productivity. By far the majority of the plots used to develop these surfaces were installed in pre-1990 forest. However, post-1989 forests have resulted from the afforestation of generally more fertile managed grasslands. Unlike site index, the 300 index is strongly influenced by site fertility. There is therefore uncertainty around the applicability of the existing 300 Index surface to ETS participant forests. It was therefore considered important to test the accuracy of the existing surface using field plots installed by ETS participants with >100ha of eligible forest and MfE's post-1989 and pre-1990 LUCAS plots. These plots provide independent data for testing the accuracy of the existing 300 Index surface at planted post-1989 forest site and pre-1990 forest sites. The analysis in this report is intended to provide a basis for improving the 300 Index productivity surface in future, if required.

Wood density is predicted from environmental variables including air temperature and nitrogen fertility, reflected by the adjusted soil C/N ratio (Beets et al., 2007). The soil nitrogen fertility surface layer was improved using soil data from MfE's LUCAS plots, which were installed systematically across NZ's planted forest. These plots provide nationally representative spatial coverage of NZ's planted forests. Improvement of the 300 Index surface and improvement of the nitrogen fertility index surface (C/N ratio) will facilitate the development of improved carbon yield tables for ETS participants with < 100 ha of eligible forest, given the site location and silvicultural regime.

2 Improving look-up tables for radiata pine

Peter Beets and Thomas Paul

2.1 IDENTIFYING GAPS

A GIS gap analysis was carried out to identify environments where exotic forests are currently grown but no growth data exist. The LUCAS LUM (2009) was used to identify existing exotic forests and was overlaid with a data-layer of Permanent Sample Plots (PSP's) with Radiata Pine. To reduce computer time and to match the resolution of rasterized environmental layers all data were gridded to a resolution of 500 x 500 m (25 ha), which was considered sufficient to identify major gaps in PSP coverage.

The following environmental layers acquired from NIWA were used to characterise each 500m x 500m pixel:

- Mean Annual Temperature (°C, normalised data 1970-2000)
- Mean annual rainfall (mm, normalised data 1970-2000)

In addition a separate analysis was carried out to identify areas with extreme exposure, to evaluate the sufficiency of PSP coverage with respect to topographic exposure (TOPEX) and the associated windiness of a site, as exposure is known to affect tree growth and stem form.

Six thousand PSP's currently stocked with radiata pine and with accurate coordinates were used to identify forests with gaps in PSP coverage. Figure 1 shows that forests in cold areas with less than 9 °C mean annual temperature are not well represented. Nor are forests with high rainfall (>3800 mm) or forest on very dry sites (<600 mm). There is also a lack of PSP's in forests that receive more than 2400mm rainfall in areas with a mean annual temperature >13 °C.

The spatial distribution of forests with the described climatic conditions is shown in Map 1 (dark green squares). The distribution is South Island centric as the cool and wetter forests are centred in the hill and high country of Southern Canterbury (with some additional eastern coastal forests), Otago and Southland. It is worthwhile to note that a high percentage of these forests will be stocked with Douglas-fir. Other forests that match the climatic conditions are found in inland Marlborough, around the Central Volcanic Mountains and inland from the East Cape.

To evaluate if the full range of wind conditions in planted pine forest is represented in the PSP dataset, we show a histogram (distribution) of forests with and without PSP's in relation to wind speed (annual monthly average wind speed m/sec classes) (Figure 2). Forests with annual mean monthly wind-speeds >6.2 m/s are not well represented in the PSP dataset. The spatial distribution of these forests is shown in Map 1 (red areas). Non-represented forests are mainly found in the Marlborough Sounds, Wellington Coast and Wairarapa but also in the far North near Cape Reinga and again the north east side of the East Cape. Only a few areas on the East Coast of the South Island (Banks Peninsula, Dunedin and Catlins) have also unsampled forests with high wind speeds. Interestingly none of the previously extreme sites show high wind exposure.

Figure 1: Planted forests (red points) and their distribution along rainfall and temperature gradients in comparison with the distribution of radiata pine PSPs (black crosses).

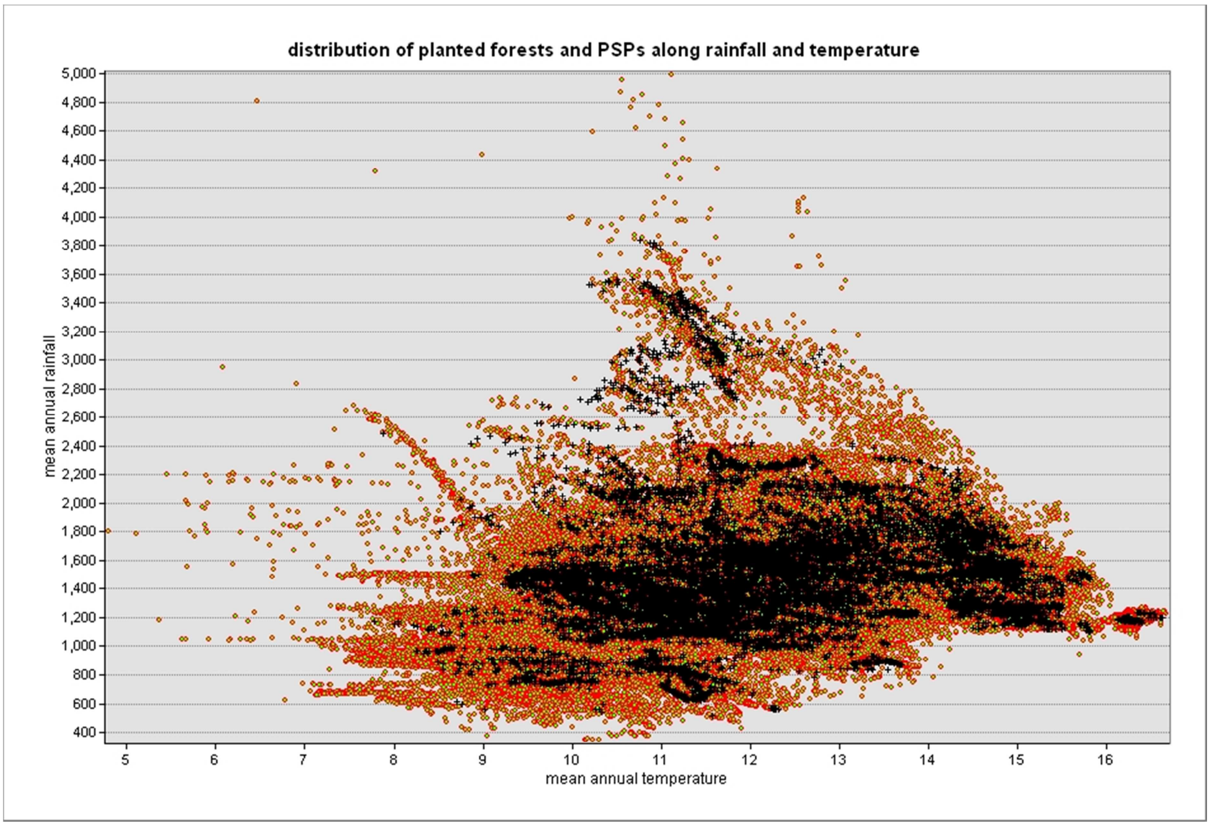
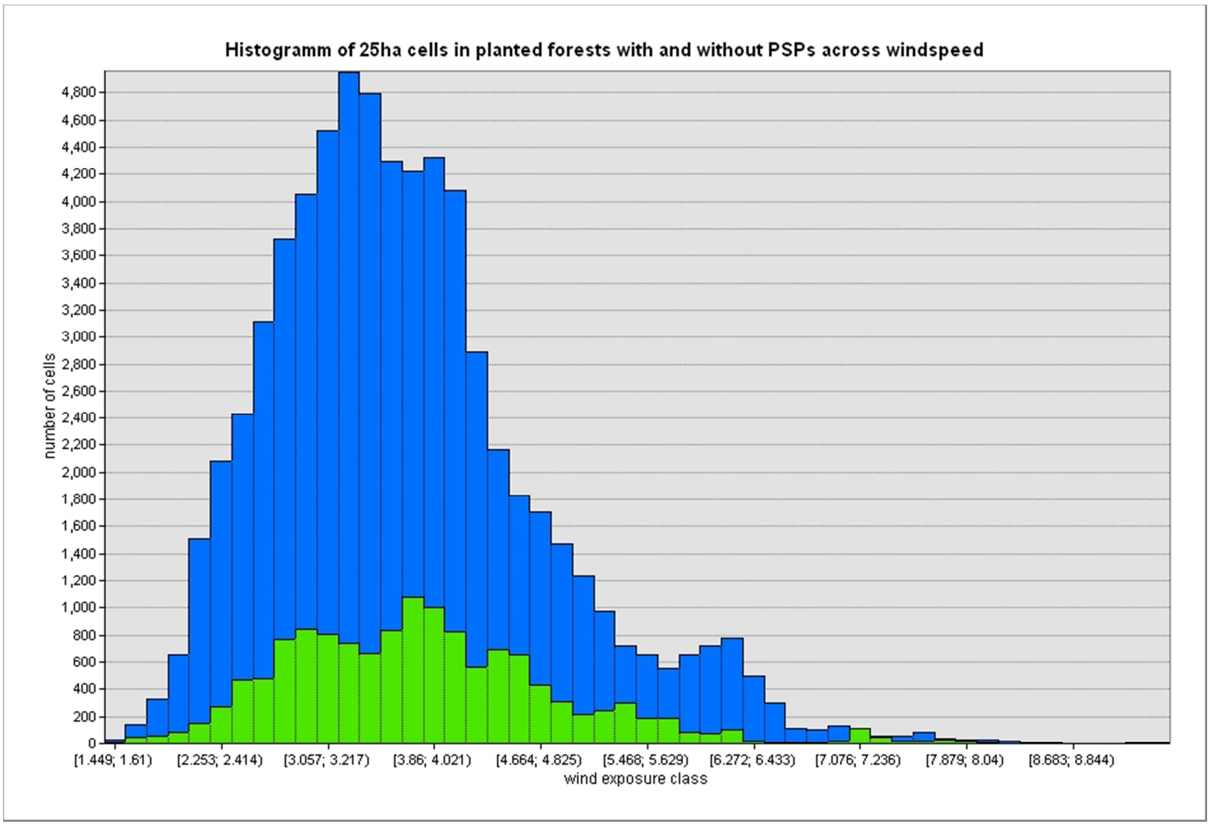
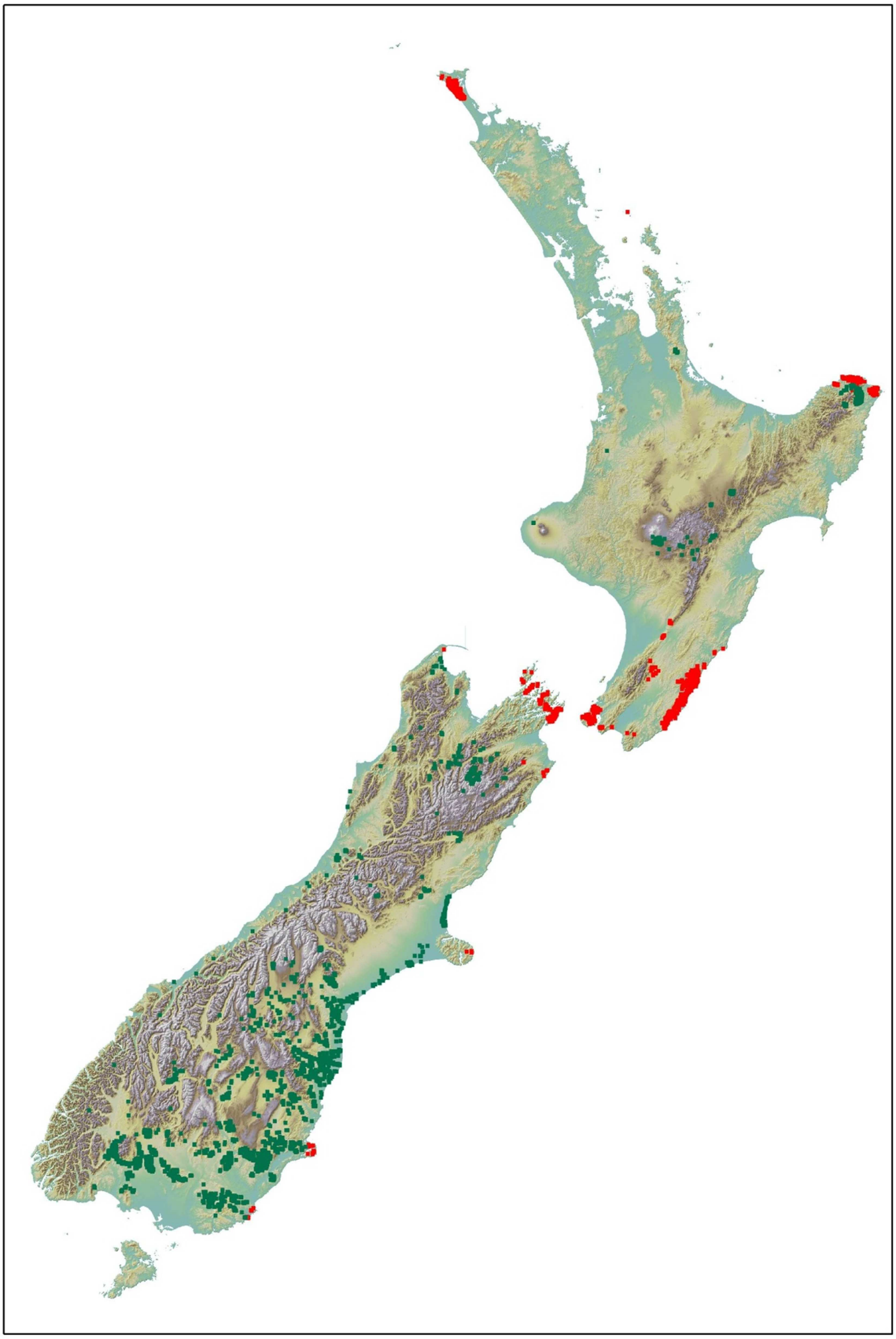


Figure 2: Frequency of forest cells with (green) or without (blue) PSPs along a wind gradient (annual average m/s).



Map 1: Distribution of forests in climatic environments not well represented by current Radiata Pine PSPs. Dark green: forests with “extreme” climates (rainfall and temperature); Red: forests exposed to high winds (>6.2 m/s, annual average).



2.2 SOIL NITROGEN FERTILITY INDEX (ADJUSTED C/N RATIO)

The Ministry for Primary Industries requires soil fertility estimates for Post-1989 land registered under the ETS and would also like estimates for Pre-1990 planted forest land, in order to estimate carbon stocks and sequestration. Carbon stocks and sequestration are being estimated using the Forest Carbon Predictor that has been implemented in Forecaster-Carbon, which includes a wood density model that predicts radiata pine outer wood density as a function of the site mean annual air temperature and the soil nitrogen fertility (C/(N – 0.014) index (Beets et al.,2007). The nitrogen fertility index of a site can be determined by sampling the mineral soil (0 – 5 cm depth) and measuring the total carbon (C) and nitrogen (N) concentrations. Because there is no provision under the Field Measurement Approach (FMA) to directly measure soil fertility at sites registered under New Zealand's Emission Trading Scheme (ETS), it will be necessary to predict soil fertility at participant's site(s) indirectly from existing spatial information. Likewise, improved lookup tables will require density estimates derived from a spatial soil fertility layer.

Soil fertility varies spatially, depending on soil type and farm management activities such as past fertilisation and the use of legumes (nitrogen fixing clover). In general, soil fertility improvement can be expected to be greatest on high quality flat land, least on steep remote farmland, and virtually non-existent on forest land without a pasture history. While stand age is not expected to affect the soil fertility index (based on Scion trial results with repeated measures of the adjusted C/N ratio), soil disturbance (mixing with subsoil) owing to historical harvesting activities may have occurred at Pre-1990 planted forest land. Post-1989 planted forest is unlikely to have been harvested, and soil disturbance will therefore be minimal. The Ministry for the Environment (MfE) Land Use Map (LUM, 2011) categorises grassland into subcategories that are likely to differ in soil fertility. In addition, soil fertility was directly measured in LUCAS plots installed in planted forest, using a defined protocol.

As part of LUCAS, a systematic grid-based assessment of soil fertility across NZ's planted forest land was undertaken by sampling soil at plots that intersected post-1989 (4-km grid) and pre-1990 (8-km grid) planted forest. In addition to the fertility index, these plots provide information on the species and planting date of the stand (i.e. stand age), and whether the site was harvested. The LUM provides the mapped land-use subcategory as at 1990 for each plot. LUCAS soil data provide national coverage of planted forests, and have the added advantage of ensuring that wood density estimates for ETS will be consistent with estimates for LUCAS (for national reporting purposes).

Grassland subcategories in the LUM that were afforested since 1990, and land that was already in forest as at 1990 include:

- High Producing Grassland;
- Low Producing Grassland;
- Grassland with Woody Biomass;
- Natural forest;
- Pre-1990 planted forest.

In this context, natural forest will likely be naturally regenerating shrubland located within areas of planted forest. It may have transitioned from Grassland with Woody Biomass, and hence the soil fertility of this category is unlikely to be equivalent to that of primary natural forest.

Some pre-1990 forests were established on farmland in the 1970's and 1980's, while most others were established on cutover natural (native) primary or secondary forest. The fertility of pre-1990 planted forest can be expected to differ from site to site, depending on the level of improvement when the land was still under pasture.

2.2.1 Fertility index

The soil fertility index is calculated from the total carbon (C) and nitrogen (N) concentration in surface mineral soil (from 0-5cm depth) following Beets et al. (2007) as follows:

$$C/(N-0.014)$$

This ratio, which is referred to as the adjusted C/N ratio, was calculated for each LUCAS plot intersecting post-1989 and pre-1990 planted forest.

2.2.2 Soil fertility objectives

(1) Develop a regression model to predict soil fertility on a spatial basis, taking into account soil type and past farm management factors, as reflected by the LUM subcategories as at 1990.
(2) In addition to the LUM, incorporate data from the Vegetation Cover Map of New Zealand to partition out pre-1990 forests established on pasture in the 1980's, and assess whether this improves the soil fertility model.
(3) Develop a soil fertility layer for New Zealand based on the best model.

The number of planted forest plots (all species) is shown by soil order and LUM category in Table 1. Soil samples covered a range of soil orders and LUM categories. Most soil orders were represented by twenty or more samples (Table 1), however Gley, Granular, and Organic were represented by only 1 or 2 samples each, and Oxidic, Semi-Arid, and Anthropogenic were not sampled at all.

Table 1. Number of soil samples per LUM category (or subcategory) and soil order based on planted forest plots (i.e. all species).

Soil Order	Grassland High producing	Grassland Low producing	Grassland with woody biomass	Natural Forest	Other	Planted Forest Pre-1990	Total
Allophanic	2	7	3			6	18
Brown	24	69	23	6		60	182
Gley						1	1
Granular	1		1				2
Melanic	3	4		1		2	10
Organic		1					1
Pallic	5	25	5	1	1	8	45
Podzol	3	3	6			11	23
Pumice	13	17	7			58	95
Raw		2				5	7
Recent	2	35	5	2	1	22	67
Ultic	7		5	1		19	32
Oxidic							0
Semiarid							0
Anthropic							0
Total	**60**	**163**	**55**	**11**	**2**	**192**	**483**

The corresponding mean adjusted C/N ratios for these categories are given in Table 2. Poorly sampled soil orders were amalgamated into a single class called "Other Soils" for regression analysis purposes. Fertile soils (High producing grassland) have the lowest ratios, while infertile soils (pre-1990 planted forest) have the highest ratios, on average.

Table 2. Average adjusted C/N ratio of soil summarised by LUM category (or subcategory) and soil order.

Soil Order	Grassland High producing	Grassland Low producing	Grassland with woody biomass	Natural Forest	Other	Planted Forest Pre-1990	Overall Average
Allophanic	13.3	12.9	13.5			18.1	14.8
Brown	14.7	15.0	16.7	17.2		21.5	17.4
Gley						14.7	14.7
Granular	13.8		19.5				16.7
Melanic	12.9	15.8		18.4		17.7	15.6
Organic		21.1					21.1
Pallic	13.7	14.5	13.8	23.8	17.2	19.7	15.6
Podzol	13.4	21.7	20.0			21.0	19.8
Pumice	13.6	14.5	15.8			20.9	18.4
Raw		28.8				40.0	36.8
Recent	13.0	14.6	14.6	14.1	14.1	21.2	16.7
Ultic	15.1		16.7	15.5		23.6	20.4
Average	**14.2**	**15.1**	**16.3**	**17.2**	**15.6**	**21.7**	**17.8**

2.2.3 Data analysis

The GLM procedure in SAS was used to examine the relationship between the adjusted C/N ratio and various independent variables. Variables assessed included the LUM Land use category as at 1990 (i.e. it included the three grassland subcategories, Pre-1990 planted forest, Natural forest, and "Other"), and variables from other sources, including stand age, rotation number, soil order, and wood supply region. Independent variables were examined individually and in combination. Rotation number and stand age were added to test various assumptions. Specifically, while we do not expect fertility to change within a rotation (i.e. age not likely to be significant based on Scion trial data), it is expected that pre-1990 forest planted relatively recently (and therefore 1st rotation) on a mix of grassland and cutover forest sites will be on average more fertile than Pre-1990 forest planted predominantly on cutover forest sites prior to the 1970's (and therefore 2nd rotation or higher).

The regression model that was developed to predict soil fertility has two independent variables: 1) The LUM land use category as at 1990 (which included the Grassland subcategory (High Producing, Low Producing, GWB) and Planted Forest category, and, 2) the soil order. Data for all plots containing planted species were included in the model.

The Vegetation Cover Map of New Zealand was then used to partition out pre-1990 planted forests established on pasture in the mid-1980's, and the regression model refitted to determine whether the VCM provided useful information. This analysis was based on radiata pine plots in the LUM.

2.2.4 Assumptions

1. Site nitrogen fertility remains constant within a rotation - The statistical analysis supported the assumption that "Stand Age" was not significantly associated with the fertility index (prob >F = 0.13).
2. The statistical analysis showed that second rotation stands had on average higher C/N ratios (so were less fertile) than first rotation stands. This supports the view that the more recently planted (and therefore currently still 1st rotation) stands were established on grassland, whereas older forests were established on less fertile cutover forest sites.

2.2.5 Nitrogen fertility model

The Grassland land use subcategories and Forest Land use based on the LUM, as at 1990, explained significant variation in the soil C/N ratio (Table 3). The average adjusted ratio was lowest (i.e more fertile) for High Producing Grassland, intermediate for Low Producing Grassland, and highest (i.e. less fertile) for Grassland with Woody Biomass – in line with expectations. Substantial variation within a grassland subcategory was evident. Variation within grassland subcategories was expected, because management inputs are likely to vary spatially, both between and within farms. Pre-1990 planted forest soil was on average the least fertile (highest adjusted C/N ratio), however soil fertility varied substantially within this land use as well.

Soil order on its own explained slightly less variation in the soil C/N ratio than the land use subcategory at 1990 (Table 3). This was mainly due to the effect of raw sand, with an adjusted ratio averaging around 45 for this soil order compared with averages ranging from 15 – 21 for other soil orders. Model coefficients are given in Table 4. Note that Wood Supply Region was not tested at the time the C/N soil fertility map was prepared. However, the regression model in Table 3 with Region is superior to models without region. We interpret this to mean that Regional differences in afforestation captured some of the improvement in soil fertility. Despite this improvement in the model R^2, rotation was significant, with C/N decreasing from 22.2 in 2nd rotation stands to 19.95 in first rotation stands (which implies that the more recent plantings (i.e. 1st rotation stands) were on more fertile (Lower C/N) sites.

Table 3: Percentage variance in the adjusted C/N ratio (R2) explained by selected independent variables in multiple regression models.

Number of Independent Variables	Variables in regression model	All Plots (Pre-1990 and Post-1989 R^2
1	LUM Landuse subcategory	36
	Soil order	35
2	LUM Landuse subcategory, Soil Order	59
3	LUM Landuse subcategory, Soil Order, Rotation	62
4	Region, LUM Landuse sub-category, Soil Order	65
5	Region, LUM Landuse sub-category, VCM, Soil Order	68

The model based on Land use category as at 1990, based on the LUM and Soil Order (i.e. model with 2 variables), has an R^2 of 59% (Table 4). It was used to develop the adjusted C/N ratio fertility map of New Zealand. Some additional improvements in the soil fertility surface are possible using additional sources of data, such as region, and VCM, and rotation number.

Table 4: Regression model for predicting soil fertility index (C/(N – 0.014)) for planted forest (all species) using LUM layer and soil order.

	All Planted Forest	
Coefficient	**Estimate**	**s.e.**
Intercept	22.07	0.654
Allophanic	-3.728	1.050
Brown	-1.298	0.697
Melanic	-2.052	1.291
Other soil	-0.712	1.869
Pallic	-2.133	0.847
Podzol	0.433	0.970
Pumice	-1.512	0.731
Raw	23.86	1.698
Recent	-3.322	0.795
Ultic	0	.
High Producing	-6.553	0.528
Low Producing	-5.434	0.404
GWB	-4.332	0.548
Natural Forest	-3.217	1.104
Other	-3.715	2.520
Planted forest	0	.
R^2 (%)	59	
RMSE	3.51	

2.2.6 Spatial soil fertility layer

The national adjusted C/(N – 0.014) ratio layer for the North and South Island of New Zealand are shown in Figures 1 and 2.

When implementing the final regression model, note that:

- Soil orders grouped in "Other Soil" include the following: Oxidic, Semiarid, Anthropic, Gley, Granular, and Organic soil.
- Land classified as Natural forest as at 1990 did not include primary natural forest.

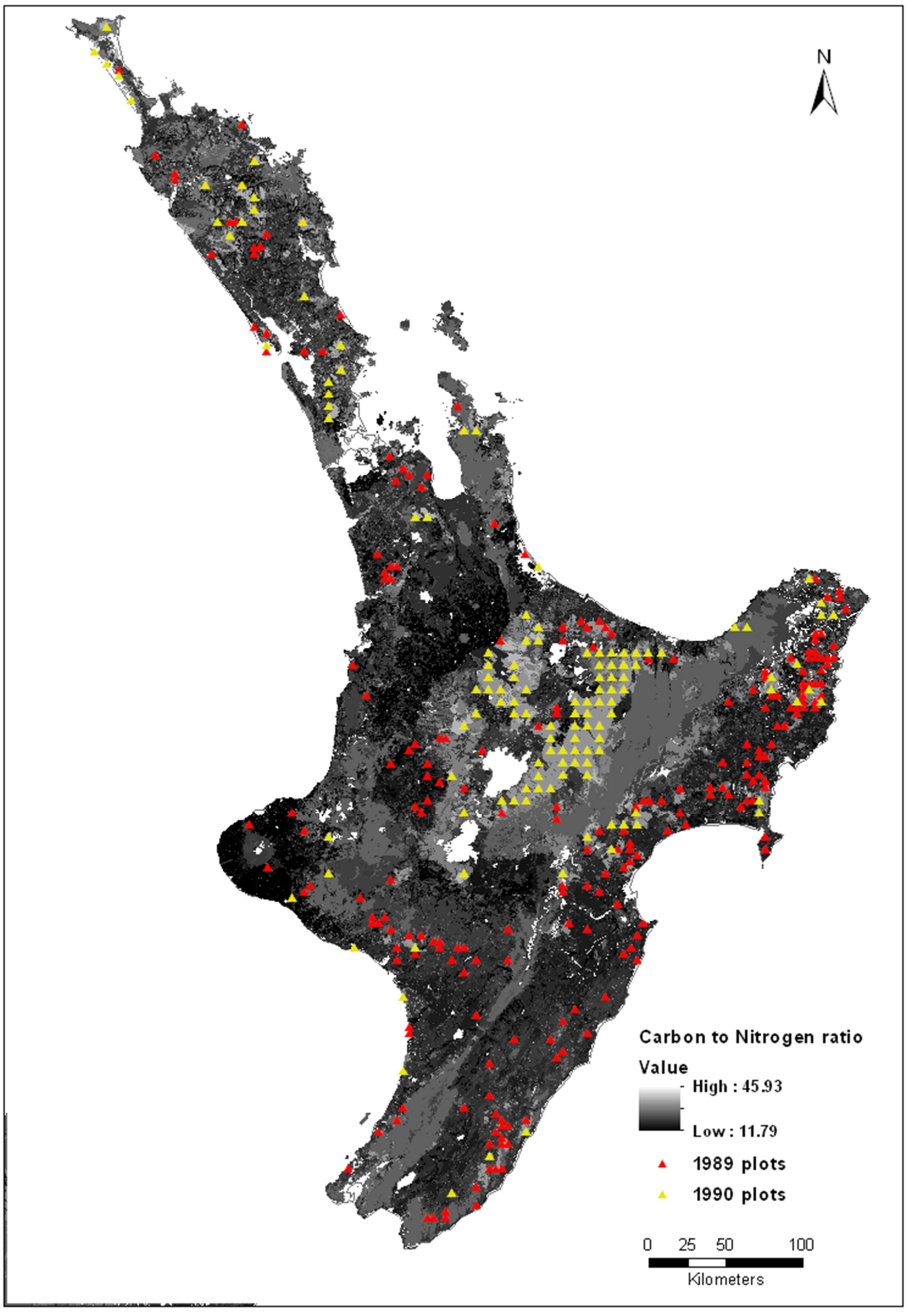


Figure 1. Soil fertility layer (adjusted C/N ratio) for the North Island of New Zealand.

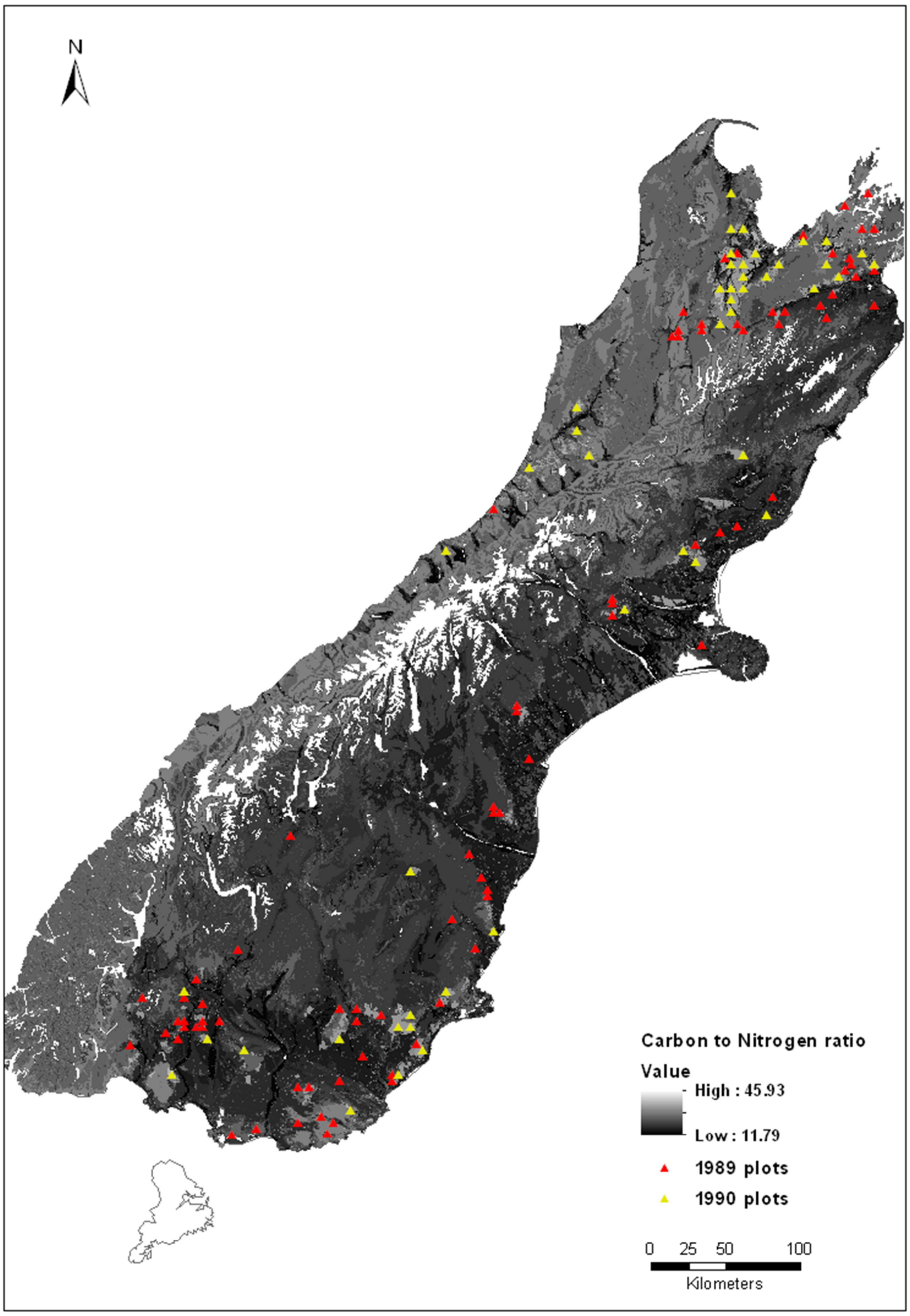


Figure 2. Soil fertility layer (adjusted C/N) ratio for the South Island of New Zealand.

2.2.7 Discussion of soil fertility

The implementation of the Forest Carbon Predictor as Forecaster-Carbon for ETS purposes requires spatial predictions of soil fertility to allow accurate predictions of outer wood density. Factors influencing soil fertility in LUCAS plots with soil data included grassland subcategories (High Producing Grassland, Low Producing Grassland, and GWB) as mapped within the LUM and soil order. Use of these factors will facilitate more accurate wood density predictions at specific sites for participants using the FMA. Likewise, wood density can be more accurately calculated in future for participants using the Look-Up table approach.

The use of the LUM in this way will help ensure that wood density predictions of land afforested after 1st January, 1990 reflect the level of soil fertility improvement that has occurred as a result of farm management activities prior to afforestation of the site. Furthermore, consistency with carbon stock estimates from LUCAS will be maintained, which will help ensure that carbon credits under ETS are not likely to be over or underestimated using the FMA. Nevertheless, the effects of periodic improvements to the LUM will need to be incorporated within Forecaster-Carbon.

2.2.8 Summary

- New Zealand's Land Use and Carbon Analysis System (LUCAS) plots provide national coverage of soil fertility measurements in post-1989 and pre-1990 planted forest. Plots were installed and measured in 2007/2008 and in 2011, and will reflect improvements in nitrogen fertility that had occurred by that time.
- The NZ LUM grassland subcategories (High Producing Grassland, Low Producing Grassland, and Grassland with Woody Biomass) as at 1990 and soil order explained a significant proportion of the variation in soil Carbon/(Nitrogen - 0.014) ratio (an index of nitrogen fertility) measured in the national network of LUCAS plots in planted forest.
- Averaged across soil orders, High Producing Grassland had a low ratio (14.2), Low Producing Grassland had an intermediate ratio (15.1), and Grassland with Woody Biomass had a moderately high ratio (16.3). Pre-1990 forest had the highest ratio (21.7).
- Land Use Category as at 1990 and Soil order explained approximately 60% of the variation in the adjusted C/N ratio.
- Pre-1990 planted forest has transitioned from either grassland prior to 1990 or from forest land, which differ in soil fertility. The VCM post-dated the period when major new plantings commenced in the early 1970's. New planting had decreased markedly by the mid-1980's, and therefore the VCM did not improve on the LUM significantly.
- The use of the LUM will help ensure that wood density predictions of land afforested after 1st January 1990 reflect the level of soil fertility improvement that occurred as a result of farm management activities prior to1990. Furthermore, consistency with carbon stock estimates from LUCAS will be maintained, which will help ensure that carbon credits under ETS are not over or underestimated using the FMA. Nevertheless, the effects of periodic improvements to the LUM will need to be incorporated within Forecaster.

3 300 Index for radiata pine in relation to LUM land-use category and nitrogen fertility

3.1 LUCAS PLOT 300 INDEX ANALYSIS

The 300 Index was derived using LUCAS planted forest plots with radiata pine. The number of plots, n and the mean and range in the 300 Index, and the mean soil fertility index (adj C/N) are shown by Wood Supply Region and LUM category in Table 1. Due to mapping resolution limitations, some planted forest plots were classified as "Natural Forest" and "Other".

Table 1. LUCAS plots mean, minimum and maximum 300 Index by region and LUM category, and associated mean soil C/N ratio.

Region and LUM category	n	Mean 300 Index	Min 300 Index	Max of 300 Index	Mean adj C/N
Auckland Northland	**48**	**27.7**	**16.5**	**40.5**	**20.2**
Grassland - High producing	15	30.8	24.8	38.3	14.8
Grassland - Low producing	11	29.1	23.1	37.4	17.8
Grassland - With woody biomass	8	25.6	17.2	40.5	23.1
Natural Forest	6	26.4	21.5	38.0	22.3
Other	1	17.0	17.0	17.0	33.9
Planted_Forest	7	24.0	16.5	35.4	28.5
BOP	**41**	**28.4**	**7.2**	**52.7**	**19.5**
Grassland - High producing	1	27.7	27.7	27.7	13.2
Grassland - Low producing	10	29.7	20.6	34.3	15.9
Grassland - With woody biomass	5	35.9	26.2	52.7	15.3
Natural Forest	4	29.8	27.4	31.1	21.0
Planted_Forest	21	25.8	7.2	35.0	22.3
Canterbury West Coast	**19**	**19.4**	**10.1**	**29.2**	**16.6**
Grassland - High producing	2	21.0	20.9	21.1	13.2
Grassland - Low producing	7	15.4	10.1	20.3	13.1
Grassland - With woody biomass	6	22.2	15.7	27.5	15.7
Natural Forest	1	29.2	29.2	29.2	20.2
Planted_Forest	3	18.8	15.2	24.5	27.8
Gisborne	**66**	**30.3**	**3.3**	**48.8**	**14.3**
Grassland - High producing	2	25.9	21.8	30.1	14.5
Grassland - Low producing	48	31.6	10.7	48.8	14.1
Grassland - With woody biomass	9	23.2	3.3	34.1	15.1
Natural Forest	4	33.2	21.4	38.9	14.4
Planted_Forest	3	30.4	22.1	38.3	15.1
Hawkes Bay/southern NI	**139**	**30.1**	**5.1**	**51.6**	**15.0**
Grassland - High producing	24	32.5	21.4	49.1	13.7
Grassland - Low producing	74	30.4	9.9	51.6	14.1
Grassland - With woody biomass	22	30.5	16.8	40.8	15.0
Natural Forest	9	27.3	11.0	38.9	17.8
Planted_Forest	10	24.1	5.1	33.9	21.7
Nelson	**46**	**23.9**	**5.0**	**41.3**	**20.6**
Grassland - High producing	1	36.4	36.4	36.4	17.0
Grassland - Low producing	14	23.8	13.0	41.3	17.7
Grassland - With woody biomass	16	26.1	16.5	39.2	20.4
Natural Forest	5	15.4	5.0	30.4	20.4
Planted_Forest	10	23.6	18.1	28.7	25.3
Otago	**26**	**21.2**	**3.9**	**36.2**	**16.9**
Grassland - High producing	5	22.4	3.9	36.2	13.4
Grassland - Low producing	8	19.9	16.1	25.0	17.1
Grassland - With woody biomass	6	20.4	14.1	27.2	15.1
Natural Forest	1	34.0	34.0	34.0	17.0
Other	1	23.1	23.1	23.1	17.2
Planted_Forest	5	20.1	10.2	26.1	22.5
Southland	**10**	**18.8**	**2.2**	**30.9**	**21.3**
Grassland - Low producing	7	17.6	2.2	23.9	20.5
Grassland - With woody biomass	2	23.4	15.9	30.9	22.0
Planted_Forest	1	18.0	18.0	18.0	25.9
Waikato	**41**	**27.3**	**14.4**	**37.2**	**19.5**
Grassland - High producing	5	33.0	29.7	35.6	12.8
Grassland - Low producing	5	25.7	15.1	30.8	18.3
Grassland - With woody biomass	4	27.0	17.6	37.2	14.7
Planted_Forest	27	26.7	14.4	34.8	21.7
Grand Total	**436**	**27.6**	**2.2**	**52.7**	**17.2**

Wood Supply Region and LUM subcategory jointly explain only 24% of the between plot variation in 300 Index. The low R^2 of the models in Table 2 is somewhat surprising, and is reflected by the wide range in values of the 300 Index within each of the categories (see minimum/maximums in Table 1). Soil order and other factors such as temperature were not significant after the effects of Region and LUM landuse subcategory were taken into account. Region and soil C/N_{adj} (Table 3, 4) explained slightly more variation in 300 Index than Region and LUM Landuse subcategory (Table 1, 5), which indicates that the LUM landuse subcategories are serving as useful surrogates for soil fertility. Other factors including LUM land use subcategory, rotation number, temperature, soil order, and elevation were not significant after the effects of Region and soil C/N_{adj} were accounted for.

Table 2: Percentage variance in 300 Index of LUCAS planted forest plots explained by selected independent variables in multiple regression model.

Number of Independent Variables	Variables in regression model	R2
1	Region	0.20
	LUM Landuse subcategory	0.05
2	Region, LUM Landuse subcategory	0.24

Table 3: Percentage variance in 300 Index of LUCAS planted forest plots explained by selected independent variables in multiple regression model.

Number of Independent Variables	Variables in regression model	R2
1	Region	0.20
	C/N_{adj}	0.09
2	Region, C/N_{adj}	0.25

However, the R^2 of the model based on Region and soil C/Nadj is still very low. Variation in the 300 Index clearly depends on factors related to Region (average climate, rainfall) and soil fertility, however other factors must also be very important, for example, solar radiation (the 300 index varies appreciably with aspect), weed competition early in the life of a stand, and possibly the type of planting stock.

3.2 WITHIN STAND VARIABILITY IN 300 INDEX

To improve understanding about variability in the 300 Index, 30 plots each 0.05 ha horizontal area (which is the same area as a LUCAS planted forest plot) were installed in a post-1989 radiata pine plantation in the Bay of Plenty Region. At this forest (Figure 3), the 1990 land use mapped as 74 = Grassland - with woody biomass, 75 = Grassland – high producing, 76 = Grassland – low producing. 71 is a small amount of Natural forest, which can be ignored. The 2008 land use is post-1989 forest (current). The soil C/N_{adj} ratio, based on transects across the forest, averaged 13.

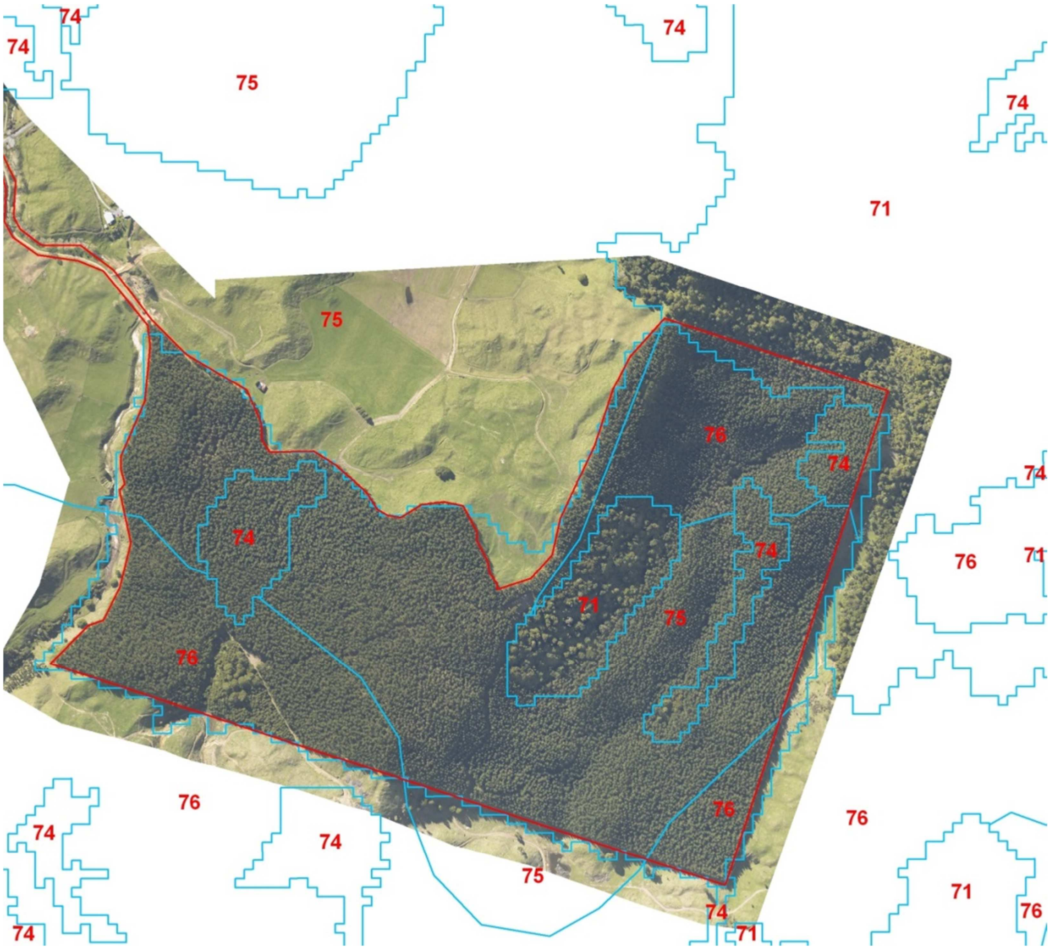


Figure 3. MfE's Land Use Map (LUM) sub-categories for a post-1989 planted forest stand in the Bay of Plenty.

The 300 Index, which was estimated for each of the 0.05 ha plots, averaged 32.1 (and ranged from 27.6 – 38.5. The existing 300 Index surface gave predictions that ranged from 32 – 33 (1 ha resolution) for this forest, with an average 300 Index of almost 33. At the scale of a LUCAS plot 0.05 ha, the field data for this BOP forest, which had a planted forest area of approximately 63 ha, shows that the 300 Index can range between wide limits. A major influencing factor was aspect (the 300 Index was up to 36% higher on sunny aspects than shady aspects), with the lowest 300 Indices found in shaded gully microsites, and the highest 300 Indices found in sunny sheltered microsites.

The LUCAS derived model (Table 4) was used to predict the 300 Index at the BOP forest site which had a C/N_{adj} ratio = 13. The predicted mean 300 Index was 30.6.

Table 4: Regression model for predicting the 300 Index from Region and soil fertility (C/(N – 0.014)) for planted forest.

	All Planted Forest	
Coefficient	**Estimate**	**s.e.**
Intercept	33.92	1.659
Auckland Northland	0.633	1.437
BOP	1.089	1.491
Canterbury West Coast	-8.938	1.883
Gisborne	1.633	1.389
Hawkes Bay Southern NI	1.261	1.236
Nelson	-3.035	1.452
Otago	-6.985	1.701
Southland	-7.893	2.385
Waikato	0	-
C/(N-0.014)	-0.338	0.0658
R^2 (%)	25	
RMSE	6.75	

Table 5: Regression model for predicting the 300 Index from Region and LUM landuse sub-category for planted forest.

	All Planted Forest	
Coefficient	**Estimate**	**s.e.**
Intercept	26.02	1.116
Auckland Northland	-1.302	1.541
BOP	1.020	1.523
Canterbury West Coast	-9.371	1.956
Gisborne	1.892	1.506
Hawkes Bay Southern NI	1.019	1.338
Nelson	-4.337	1.539
Otago	-7.467	1.776
Southland	-9.886	2.481
Waikato	0	-
Grass - high producing	5.371	1.275
Grass – low producing	2.953	1.029
Grass – woody biomass	3.142	1.149
Natural forest	1.376	1.514
Other	-1.547	4.964
Planted forest in 1990	0	-
R^2 (%)	24	
RMSE	6.828	

3.3 ETS PLOT 300 INDEX ANALYSIS

A substantial number of plots in forest established on ex-pasture sites were recently installed as part of the ETS. Participants with post-1989 planted forests exceeding 100 ha in area are required to have carbon yield tables for their forest(s) derived from plots assessed using the field measurement approach. MPI provided Scion with the resulting 300 Indices per plot, to test the accuracy of the existing 300 Index surface in Forecaster Carbon. The ETS plots were intersected with MfE's LUM, to extract the grassland subcategory for each plot. Because of mapping resolution limitations, approximately 500 ETS plots were not classified as grassland by the LUM. The plots incorrectly classified as pre-1990 planted forest were assigned to a grassland subcategory based on other ETS plots nearby, for subsequent data analysis. Plots with a mix of crop tree species and a small number of plots that appeared to be outliers were not used. The accuracy of the existing surface was assessed by comparing the measured 300 Index of acceptable plots with the value at the plot x,y coordinate predicted by the 300 Index surface.

The measured 300 Indices showed strong regional differences (Table 6). The Bay of Plenty region had the highest mean value (300 Index = 32.8), while Canterbury, the West Coast, and Marlborough had 300 Indices that averaged 25 or less. The 300 Index surface slightly overpredicted measured values by 0.2% when averaged nationally across all plots (Table 6). Regional differences were apparent, with 300 Index mean values overpredicted by more than 10% in Canterbury and underpredicted by more than 10% in Otago and Southland. Predictions in other regions mostly averaged within 5% of measured mean values.

Table 6. Mean 300 Index values by region measured in ETS and LUCAS plots, corresponding predictions from 300 Index surface in Forecaster Carbon, and prediction error.

Region	n	Measured 300 Index	Predicted 300 Index	Prediction error %
Auckland	145	29.3	29.2	-0.3
Bay_of_Plenty	453	32.8	32.4	-1.5
Canterbury	871	22.7	26.3	13.1
Gisborne	2343	31.8	32.8	2.6
Hawkes_Bay	2986	32.4	33.3	2.1
Manawatu_Wanganui	1898	31.2	29.8	-4.9
Marlborough	951	25.1	26.7	5.2
Nelson	23	28.4	29.5	3.6
Northland	606	28.3	30.0	5.0
Otago	1070	28.2	25.0	-13.4
Southland	241	29.4	26.7	-10.4
Taranaki	554	30.7	30.9	-0.1
Tasman	426	28.7	27.0	-6.9
Waikato	755	29.4	31.0	4.1
Wellington	790	29.7	28.8	-3.2
West_Coast	11	22.5	22.9	1.3
Overall Total or Mean	14123	30.0	30.3	0.2

Summaries by LUM subcategory are given in Table 7 and by LUM subcategory within region in Table 8. Ex-pasture sites had measured 300 Indices on average 19% greater than pre-1990 forest sites. There was some bias evident in the 300 Index surface. Over-prediction was on average more apparent at less productive sites (Table 7), as evident from the ranking: Grassland with Woody Biomass > pre-1990 Planted Forest > Other > Natural Forest > Grassland – High producing > Grassland – Low Producing. Only Grassland – Low producing was underpredicted.

Table 7. Mean 300 Index values by LUM subcategory measured in ETS and LUCAS plots, corresponding predictions from 300 Index surface in Forecaster Carbon, and prediction error. The mapping resolution is 1 ha, so in this and following table plots classified as "Natural Forest" and "Other" can be interpreted as grassland.

LUM subcategory	n	Measured 300 Index	Predicted 300 Index	Prediction error %
Grassland - High producing	3223	30.9	31.6	1.3
Grassland - Low producing	8651	30.3	30.1	-1.4
Grassland - With woody biomass	1958	27.4	29.0	4.9
Natural Forest	93	29.0	29.6	1.6
Other	59	26.0	27.1	2.3
Planted Forest - Pre-1990	139	25.9	27.3	4.5
Overall Total or Mean	14123	30.0	30.3	0.2

The effect of site fertility (implied by the grassland subcategory) on the 300 Index varied by region. In most regions, the 300 Index was on average appreciably higher in grassland subcategories than Pre-1990 forest, although this needs to be interpreted with caution because the sample size based on LUCAS plots was small for some regions. 300 Indices for pre-1990 planted forest plots were similar on average to those obtained for grassland subcategories in areas such as Gisborne, which was expected because pre-1990 forests in that region were generally also established on ex-pasture sites.

Table 8. Mean 300 Index values by LUM categories within region based on ETS and LUCAS plots, corresponding predictions from 300 Index surface in Forecaster Carbon, and prediction error.

Region/LUM subcategory	n	Measured 300 Index	Predicted 300 Index	Prediction error %
Auckland				
Grassland - High producing	61	30.8	30.2	-2.0
Grassland - Low producing	42	27.9	28.8	3.3
Grassland - With woody biomass	37	29.1	28.1	-4.0
Planted Forest - Pre-1990	5	23.7	29.2	19.4
Bay_of_Plenty				
Grassland - High producing	152	33.7	33.3	-1.3
Grassland - Low producing	231	33.1	32.4	-2.6
Grassland - With woody biomass	40	30.9	32.0	3.3
Other	2	34.4	31.6	-9.6
Planted Forest - Pre-1990	28	28.0	28.1	0.1
Canterbury				
Grassland - High producing	287	22.6	25.2	9.5
Grassland - Low producing	353	22.7	26.7	14.2
Grassland - With woody biomass	221	22.7	27.1	15.9
Natural Forest	2	20.4	20.7	1.4
Other	5	19.0	25.7	22.1
Planted Forest - Pre-1990	3	21.8	25.1	12.9
Gisborne				
Grassland - High producing	62	32.4	33.1	1.8
Grassland - Low producing	2086	31.9	32.8	2.2
Grassland - With woody biomass	168	30.4	32.8	6.7
Natural Forest	15	29.7	32.4	7.5
Other	3	22.0	35.4	39.2
Planted Forest - Pre-1990	9	29.8	32.7	7.0
Hawkes_Bay				
Grassland - High producing	1507	32.9	34.2	3.5
Grassland - Low producing	1247	32.0	32.3	-0.3
Grassland - With woody biomass	206	31.1	33.6	7.3
Natural Forest	2	30.0	27.2	-8.5
Other	16	26.7	25.4	-7.1
Planted Forest - Pre-1990	8	30.0	32.1	6.4
Manawatu_Wanganui				
Grassland - High producing	69	31.3	28.9	-8.7
Grassland - Low producing	1607	31.5	29.9	-5.8
Grassland - With woody biomass	195	29.2	30.0	1.7
Natural Forest	13	28.8	30.8	6.5
Other	8	17.1	22.2	22.7
Planted Forest - Pre-1990	6	19.9	23.5	15.9
Marlborough				
Grassland - High producing	8	25.6	27.3	6.4
Grassland - Low producing	620	25.6	26.1	1.5
Grassland - With woody biomass	316	24.4	27.9	11.8
Natural Forest	3	18.3	26.8	32.1

Planted Forest - Pre-1990	4	19.2	27.5	29.0
Nelson				
Grassland - Low producing	16	28.9	30.1	4.2
Grassland - With woody biomass	5	27.2	28.5	4.5
Natural Forest	1	30.4	29.3	-4.0
Planted Forest - Pre-1990	1	26.4	25.7	-2.6
Northland				
Grassland - High producing	436	29.2	30.7	4.3
Grassland - Low producing	92	25.9	26.5	1.1
Grassland - With woody biomass	69	25.4	30.5	16.1
Planted Forest - Pre-1990	9	29.2	28.9	-2.8
Otago				
Grassland - High producing	294	29.7	26.0	-15.0
Grassland - Low producing	517	27.6	24.3	-14.4
Grassland - With woody biomass	232	27.7	25.3	-9.8
Natural Forest	13	28.1	27.6	-1.8
Other	6	29.9	24.3	-23.9
Planted Forest - Pre-1990	8	22.8	22.6	-0.5
Southland				
Grassland - High producing	47	33.5	28.3	-18.7
Grassland - Low producing	168	28.6	26.4	-8.7
Grassland - With woody biomass	20	27.7	25.6	-7.9
Natural Forest	2	29.6	30.1	1.4
Other	2	28.2	26.6	-4.5
Planted Forest - Pre-1990	2	19.2	19.7	2.3
Taranaki				
Grassland - High producing	28	35.4	35.8	0.5
Grassland - Low producing	466	30.4	30.5	-0.4
Grassland - With woody biomass	45	30.4	32.4	5.6
Natural Forest	11	31.3	28.2	-11.0
Other	1	35.2	27.0	-30.4
Planted Forest - Pre-1990	3	32.2	32.3	2.1
Tasman				
Grassland - High producing	33	27.7	27.9	-0.9
Grassland - Low producing	253	29.9	27.3	-10.7
Grassland - With woody biomass	122	26.8	26.2	-2.8
Natural Forest	4	30.2	28.1	-10.4
Other	1	28.5	24.6	-15.8
Planted Forest - Pre-1990	13	23.0	27.3	14.8
Waikato				
Grassland - High producing	185	30.5	31.2	0.9
Grassland - Low producing	415	29.5	31.6	5.6
Grassland - With woody biomass	89	27.1	29.8	8.2
Natural Forest	21	31.8	30.8	-3.1
Other	14	30.1	31.1	2.1
Planted Forest - Pre-1990	31	26.3	25.8	-2.2
Wellington				
Grassland - High producing	54	29.2	30.5	4.4

Grassland - Low producing	538	30.4	28.8	-5.7
Grassland - With woody biomass	186	28.1	28.4	0.6
Natural Forest	6	22.8	28.6	20.9
Other	1	20.0	27.2	26.6
Planted Forest - Pre-1990	5	25.2	26.6	5.4
West_Coast				
Grassland - With woody biomass	7	23.1	22.7	-2.0
Planted Forest - Pre-1990	4	21.4	23.1	7.1
Overall Total or Mean	14123	30.0	30.3	0.2

3.4 SUMMARY

- A comparison of 300 indices derived from ETS plots with predictions from the existing 300 surface in Forecaster Carbon has provided information on the accuracy of the existing surface regionally and with respect the level of grassland improvement prior to afforestation of the site.
- The existing 300 Index surface has an overall prediction error of 0.2% although the surface overpredicts in Canterbury (13%) and underpredicts in Otago (13%), Southland (10%) and Tasman (7%), with prediction errors in other regions of 5% or less.
- The existing surface on average overpredicts at less fertile sites (Pre-1990 forest and grassland with woody biomass), and provides acceptable predictions at more fertile sites (low producing grassland and high producing grassland).
- Work on improve the 300 Index surface and incorporating the new surface in Forecaster Carbon is planned to occur in 2016.

4 Improving look-up tables for other planted species - Species Productivity

C.L. Todoroki

4.1 EXISTING MODELS

Tools currently available at Scion for calculating stand carbon cover a range of tree species, including Douglas-fir (Pseudotsuga menziesii), the eucalypts, the cypresses, redwood (Sequoia sempervirens), totara (Podocarpus totara), and kauri (Agathis australis).

The most prevalent model for predicting carbon content is C_Change (Beets, 1999). Although developed for P. radiata, it can be used in conjunction with other species with input of species-specific volume and growth models and density data. C_Change is implemented in the Forest Carbon Predictor (FCP), was implemented in the Douglas-fir calculator in 2008, and has linkages with the E. fastigata web tool. For kauri, and as part of his Master’s thesis, Greg Steward with the help of Peter Beets, developed an Excel spreadsheet for predicting carbon (Steward, 2011). This is not incorporated in the kauri calculator.

Look-up tables have also been derived for various forest types (i.e. groupings of species) based on results derived from C_Change and averaged across the country and across management regimes .A summary of the calculators is given in the box below:

Species	Calculators	Look-up table (Forest type, thinning assumption)
D. Fir	C_Change, FCP, Douglas-fir calculator: Excel	Douglas-fir, common thinning regimes
Eucalypts	C_Change *E. fastigata* web tool (MAF) FFR EUFAS web calculator	Exotic hardwoods group, no thinning
Cypress	*	Exotic softwoods group, as for *P. radiata*
Redwood	*	Exotic softwoods group, as for *P. radiata*
Totara	*	Indigenous forest group, no thinning
Kauri	Excel worksheet	Indigenous forest group, no thinning

*C_Change possible with input of species-specific data.

Apart from Douglas-fir, carbon calculations for the other species are based on limited information, and cannot be used to accurately represent stand in all regionals. In order to achieve improved accuracy, greater geographical coverage of models is required. This in turn will necessitate additional sample plot measurements, and further planting and management of the species.

4.2 IDENTIFYING GAPS

The first stage of the ETS look-up table research plan aimed to determine gaps in existing knowledge across a range of tree species. The species investigated here include Douglas-fir (*Pseudotsuga menziesii)*, eucalypts (*Eucalyptus fastigata*, *E. nitens*, *E. regnans*), and poplar (*Populus* species). Species of secondary interest included the cypresses (including *Cupressus lusitanica* and *C. macrocarpa*), redwood (*Sequoia sempervirens*), totara (*Podocarpus totara*), and kauri (*Agathis australis*).

A literature review and analysis of data and models currently available for each of the selected species was conducted. The literature review examined climatic and environmental factors necessary for the growth and sustained productivity of the tree species. A global approach was applied first, followed by a local approach which examined data held on the Permanent Sample Plot (PSP) system, volume and taper models available, and published and unpublished reports.
In general, the geographic spread of the PSPs is heavily weighted to the Central North Island. This is particularly true for *E. fastigata*, *E. regnans*, and *C. lusitanica for which more than 40% of plots established in these species are located in the Bay of Plenty*. Douglas-fir has the greatest representation in terms of models, indices, data, and sites within New Zealand. However, development of a productivity map at the national level for Douglas-fir, using averaged climatic values (e.g. mean annual temperature, total annual rainfall) has been unsuccessful (Watt et al. 2009b). Causes for weak correlations (R^2 <0.1) between productivity indices and environmental variables were speculated to be due to Swiss needle cast infestation, and/or to the provenance of the material. Another reason proposed here is that the variables were based on averages, rather than on climatic extremes. The latter have been shown to be important to productivity (Waring et al. 2008) and help explain why New Zealand grown Douglas-fir produces up to 40% more wood

volume annually than that recorded on the best sites in the Pacific Northwest (PNW) of the United States.

The least represented species in terms of models, indices, data, and sites are the poplars which are geographically scattered, have had little long-term research trials, but have been highly recommended by Shelbourne and Wilkinson (1997) as a promising species for both production forestry and soil conservation.

The cypresses are grown throughout New Zealand. However, the majority of sample plots are established with *C. macrocarpa*, followed closely by *C. lusitanica* and models have been developed for each species, and as a combined model.

Our current knowledge of species productivity in terms of climate, soil, geographic coverage, and density studies is summarised in the table below. The greatest body of research, information, models, and PSPs are associated with Douglas-fir. The least represented species is the poplars. However, even in cases where there is a compelling body of information, knowledge gaps, caused by bias in the underlying data, still exist. For example, models developed for *C. lusitanica* (CULUS) and *C. macrocarpa* (CUMAC) are biased towards younger trees. Growth models for *E. fastigata* are based on data that is predominantly from the Central North Island, and due to the limited amount of data, the model (incorporated in the *E. fastigata* calculator) has not been subjected to validation with independent data. There is no calculator for totara, though growth curves for the species have been developed. However growth curves (for the basal area and volume) ignore mortality, thus estimates would be expected to be over-estimated, particularly at higher ages.

Note that in those cases where productivity is defined using environmental (climate, soil) data, mortality caused by disease or other abiotic factors has, in general, not been integrated within the models.

Figure 3.1: Summary of current state of knowledge of selected alternative species

Species	Productivity index	Productivity defined by climate & soil	Calculator	Soils supporting PSPs #Soil orders (of 15)	PSP geographic coverage #Regions (of 15)	Density studies #Regions (of 15)
Douglas-fir	✓		✓	11	14	7
Cypresses	✓	CULUS	✓	10 CULUS/CUMAC	15	9
E. fastigata			✓	9	10	2
E. nitens				9	9	4
E. regnans				7	11	6
Redwood	✓	✓	✓	9	10	6
Poplar				3	3	1
Totara				7	6	2
Kauri			✓	4	6	4

Key:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

SI = Site Index; SBAP=Site Basal Area Potential

4.3 IMPLICATIONS OF RESULTS

The models identified in this review are the best available for predicting productivity, however none (including those for Douglas-fir) can accurately predict growth for the combination of all environmental (temperature, rainfall, soil, altitude, wind) gradients.

To improve the accuracy of look-up tables that provide pre-calculated carbon stock tables for key species, this report analyses our current state of knowledge, and hence determines gaps in existing knowledge.

A literature review and gap analysis was conducted of our current understanding of productivity of alternative (species apart from *Pinus radiata*) forestry species in New Zealand. Priority species for this gap analysis comprised Douglas-fir (*Pseudotsuga menziesii)*, eucalypts (*Eucalyptus fastigata*, *E. nitens*, *E. regnans*), and poplar (*Populus* species). Species of secondary interest included the cypresses (including *Cupressus lusitanica* and *C. macrocarpa*), redwood (*Sequoia sempervirens*), totara (*Podocarpus totara*), and kauri (*Agathis australis*).

The review for each species covered the current status of species site productivity. This included whether or not productivity indices, site indices, volume equations, taper equations, wood density equations, and growth models had been developed. If developed, the limitations of the datasets upon which they were developed (for example in terms of age or site limitations) were examined.

The distribution of the current network of Permanent Sample Plots (PSPs) associated with each species was also examined, and summarised by region. In addition climatic (temperature, rainfall) and biophysical (soil classification) data were also obtained, and summarise by region.

For Douglas-fir, the review was extended to determine what research had been performed in investigating the extent and impact of the Swiss-Needle Cast disease on the species. Of particular interest, were estimates on the impact of Swiss-needle cast on productivity via reduction of volume production, growth rate or other measures of productivity.

There are various measures of productivity, including primary productivity (net and gross), site productivity or site index. Productivity can be measured by tree growth in terms of height, basal area, and volume.

Primary productivity is the rate at which energy is bound or organic matter created by photosynthesis, per unit of the earth's surface per unit time (Whittaker 1975). Productivity is expressed as oven dry organic matter in g/m^2/yr, or energy in kCal/m^2/yr. In contrast, the amount of organic matter present at a given time, per unit of the earth's surface, is standing crop or biomass, and is usually expressed as g/m^2 or kg/m^2, or as t/ha.

On the other hand, site productivity provides a measure of height growth; and for a stand is expressed as site index. Site index, a commonly used method for indicating productivity of a range of plantation species throughout the world, is the mean top height of the 100 largest-diameter trees per hectare. For *P. radiata* the base age for site index is 20 years, and for Douglas-fir 40 years, whereas a base age of 30 years was used by Berrill (2004) for *C. lusitanica* and *C. macrocarpa*.

Productivity, in its various forms, differs from one species to another and from one site to another and is influenced primarily by moisture and temperature, and secondarily by nutrients and succession (Whittaker 1975). Other factors that influence productivity include density or spacing, i.e. the number of trees per unit area (Evans 1992), disease, pests, drought, fire, and mortality.

Productivities generally increase with increased precipitation (Fig. 1a) and increase with increasing temperature (Fig. 1b), although for Douglas-fir productivity does not necessarily increase with increasing temperature. Douglas-fir and species other than radiata pine tend to have more specific microsite requirements for growth (Ledgard et al. 2005). For *C. lusitanica*, Watt et al. (2009a) found productivity to be influenced by potential root depth, summer frosts, date of planting, and vegetation cover.

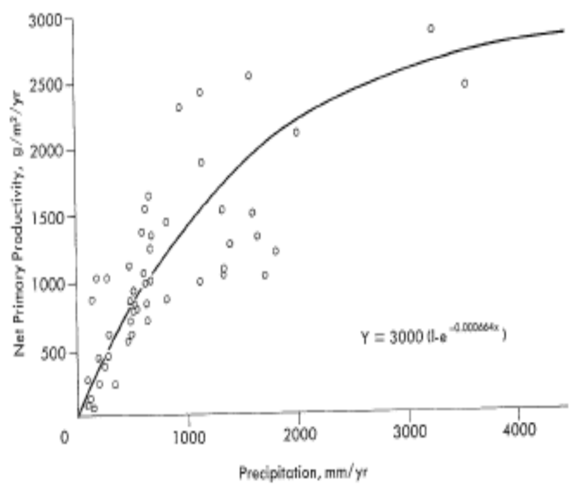


Fig. 1a. Net primary productivity, above & below ground, in relation to mean annual precipitation.
Source: Lieth (1973).

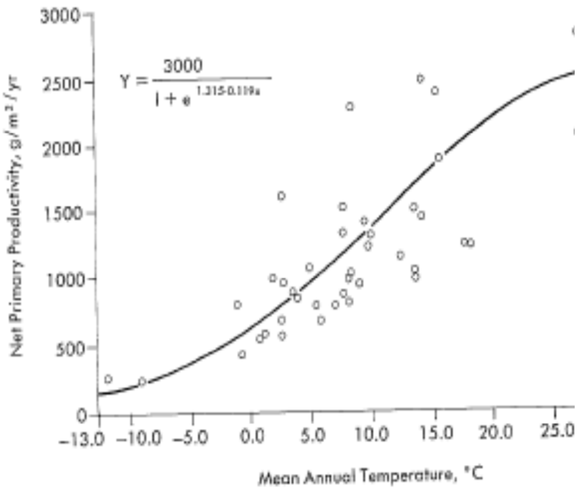


Fig. 1b. Net primary productivity, above & below ground, in relation to mean annual temperature.

$$NPP(rainfall) = 3000 \cdot (1 - e^{-0.000664x}) \quad [1]$$

where x is measured in mm/yr

$$NPP(temperature) = \frac{3000}{1 + e^{1.315-0.119x}} \quad [2]$$

where x is measured in °C.

Typical climatic criteria used to aid the selection and siting of tree species include rainfall, mean annual temperature, maximum and minimum seasonal temperature, and length of dry season. An example of climate data being used to identify the environmental limits of species is the world climatic mapping program (WORLD, Booth et al 2002). The software uses data derived from a global 0.5°×0.5° dataset and includes data for 67,477 locations. The data is compatible with that found in the Forestry Compendium (CAB 2010) for rainfall and temperature ranges, though changes to the data ranges can also be made as illustrated in the example for *P. taeda* (loblolly pine) by Booth et al. (2002). WORLD provides world-wide coverage of major landmasses excluding Antarctica.

Environmental limits (rainfall, temperature, and altitude) for selected tree species were obtained from global accounts available within the Forestry Compendium (CAB 2010, Table 1).

Table 1. Environmental limits for the alternative species under review

Species	Mean annual rainfall (mm)	Dry season (months with <40mm rain)	Mean max temp hottest month (°C)	Mean min temp coldest month (°C)	Mean annual temp (°C)	Absolute min temp (°C)	Altitude (m)
A. australis	1000-2500	0-?	27-28	13-16	13-16	-3	0-700
C. lawsoniana	1000-2250	6-8	20-33	-2-5	5-11	-22	0-1950
C. arizonica	300-600	0-4	18-40	-9-2	6-20	-35	0-2400
C. leylandii	450-1800	0-6	13-24	2-12	6-15	-20	0-350
C. lusitanica	600-1500	4-?	24-33	0-6	12-20	-15	0-3000
C.macrocarpa	500-1000	4-8	20-24	5-5	12-15	3	0-100
E.fastigata	750-1900	0-5	22-29	-1-6	12-18	-10	300-1400
E. nitens	750-1500	0-6	20-28	-1-7	9-18	-12	600-1780
E. regnans	700-2000	0-5	18-29	0-10	10-20	-7	0-1100
P. menziesii	350-1750	0-3	7-30	-10-5	0-11	-35	0-3260
P. deltoides	380-3000	0-1	22-30	-10-12	12-16	-45	0-3000
P. eugenie	300-1500	0-1	15-30	-5-15	9-20	-29	0-3000
P. nigra	300-1000	2-3	18-31	-5-12	9-17	-29	0-4000
P. totara	700-2000	0-0	26-32	-5-3	9-15	-9	0-650
S. sempervirens	640-3100	2-4	25-35	-9- -1	10-16	-12	0-915

Source: CAB (2010) Note: highlighted ranges indicate corrected values.

4.4 NEW ZEALAND CLIMATE AND ESTIMATED NET PRIMARY PRODUCTIVITY (NPP)

According to the National Institute of Water and Atmospheric Research (NIWA 2012), “most areas of New Zealand have between 600 and 1600 mm of rainfall, spread throughout the year with a dry period during the summer”. However mean annual rainfall varies considerably between regions (Fig. 2a), as does mean annual temperature which ranges from 10°C in the south to 16°C in the north (Fig 2b).

This is equivalent to a range in net primary productivity (NPP) of 990-1960 $g/m^2/yr$ (from Eqn 1) and 1410-1930 $g/m^2/yr$ (from Eqn 2). Based on these results one would expect NPP to be in the range of about 1000-2000 over much of NZ. This range (1000-2000 $g/m^2/yr$) is regarded as being the normal range of NPP for most forest communities (Whittaker 1975). However, a drop in temperature of 0.7°C occurs for every 100 m of altitude (NIWA 2012). With altitudes of up to 910 m being considered to be within the range of commercial planting for exotic species (Weston 1957) NPP would be expected to fall as illustrated in Fig. 3.

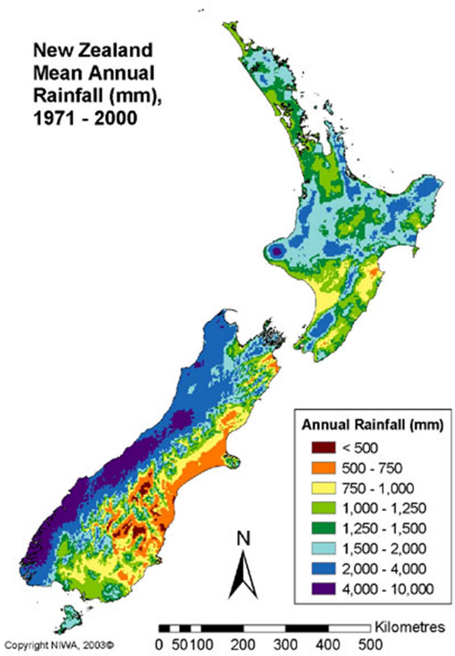


Fig. 2a. Mean annual rainfall

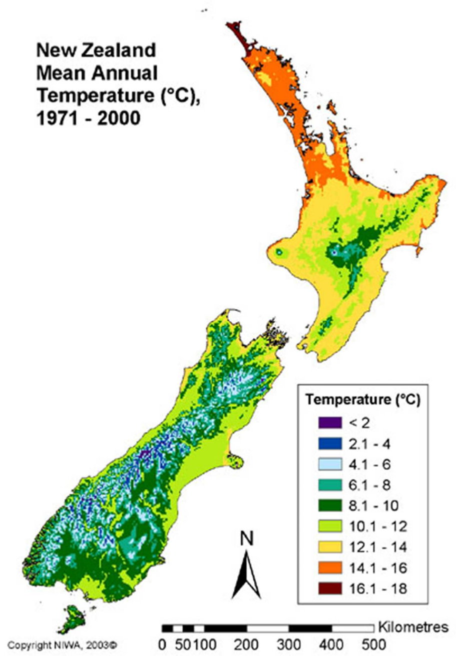


Fig. 2b. Mean annual temperature

Source: NIWA (2012)

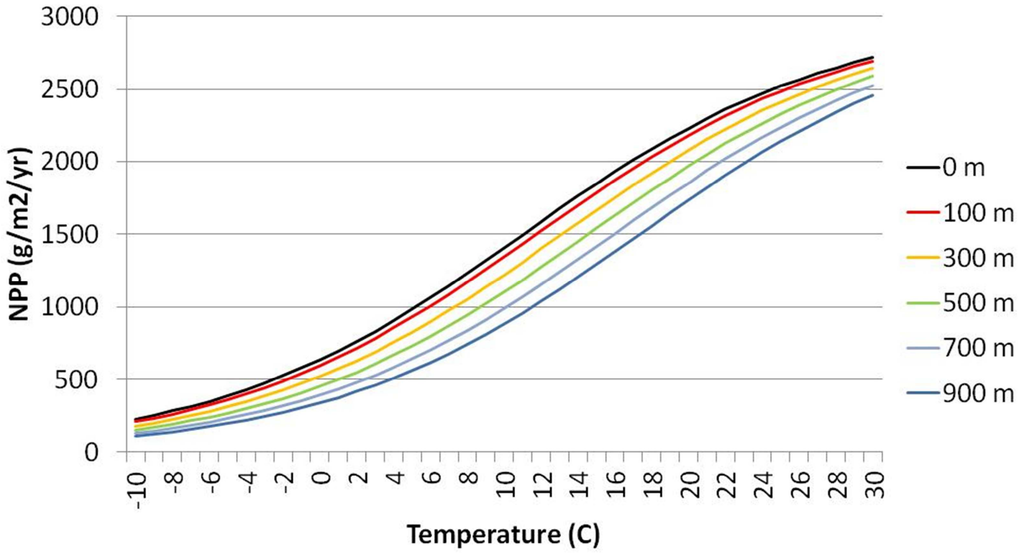


Fig. 3. Net primary productivity above & below ground, in relation to mean annual temperature at altitudes ranging from sea level to the maximum considered suitable for commercial planting.

4.5 CURRENT STATE OF ALTERNATIVE SPECIES IN THE PSP DATABASE

There are some 3694 plots associated with Douglas-fir, the cypresses, eucalypts (*E. fastigata*, *E. nitens*, and *E. regnans*), coast redwood, poplar, totara, and kauri (Fig. 4). Nearly half (1764 plots) are associated with Douglas-fir (10 mixed, 1754 pure stands) and a further quarter (934 plots) with the three eucalyptus species (39 mixed, 895 pure). The cypresses (including hybrids) account for about one-fifth of the plots (16 mixed, 750 pure) while coast redwood, totara, kauri, and poplar (including hybrids) are associated with 114, 60, 43, and 13 plots respectively. Breakdown of the plots by individual species is given in Table 2.

Regional breakdown of the PSP plots is shown by species in Table 3 and mapped, also by species, in Figs (5a to 5f). Gaps are evident for all species, including Douglas-fir for which there are no PSP plots located in Nelson/Tasman region (refer NN, PSMEN, Table 3).

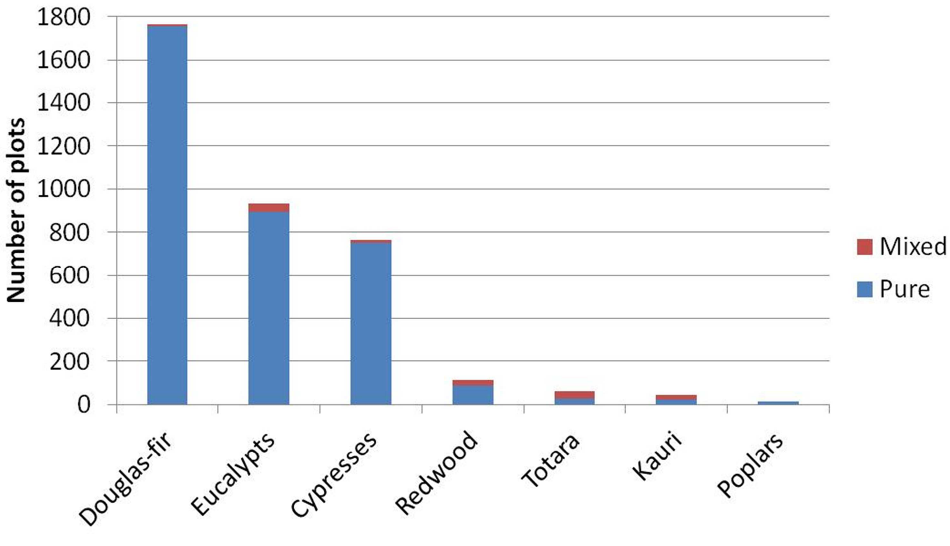


Fig. 4. Alternative species in Permanent Sample Plot database

Table 2. Number of plots of each of the species under review.

PSP Code	Species	Common name	# plots	#pure
AGAUS	*Agathis australis*	Kauri	43	23
CCLHG	*x. Cupressocyparis leylandii*	Haggerston Grey leyland cypress	2	1
CCLLG	*x. Cupressocyparis leylandii*	Naylors Blue leyland cypress	11	8
CHLAW	*Chamaecyparis lawsoniana*	Lawson cypress	35	35
CUARZ	*Cupressus arizonica*	Arizona cypress	22	22
CULEY	*Cupressus leylandii*	Leyland cypress	10	10
CULUS	*Cupressus lusitanica*	Mexican cypress	239	232
CUMAC	*Cupressus macrocarpa*	Monterey cypress	419	414
CUMIX	*Cupressus* mixture	Cypress mixture	28	28
EUFAS	*Eucalyptus fastigata*	brown barrel	174	160
EUNIT	*Eucalyptus nitens*	shining gum	356	351
EUREG	*Eucalyptus regnans*	mountain ash	404	384
PCTOT	*Podocarpus totara*	totara	60	26
PODEL	*Populus deltoids*	eastern cottonwood	1	1
POEUG	*Populus eugenei*	hybrid black poplar	2	2
POMIX	*Populus* mixture	Poplar mixture	3	3
POREG	*Populus regenerata*	*	2	2
POROB	*Populus robusta*	*	2	2
POSER	*Populus serotina*	*	2	2
POXRU	*Populus x rumford*	Rumford poplar	1	1
PSMEN	*Pseudotsuga menziesii*	Douglas-fir	1764	1754
SQSEM	*Sequoia sempervirens*	Coast redwood	114	87

*not listed on CAB forestry compendium

Table 3. Number of plots, by region for which measurements are held in the Permanent Sample Plot database.

Species	AK	BP	CY	GS	HB	MB	NN	NT	OT	SD	TR	WC	WK	WM	WN
AGAUS	20	5			2			4			8		4		
CCLHG			1						1						
CCLLG			5			5								1	
CHLAW			18				2		1	8		1		5	
CUARZ			22												
CULEY		1	1											8	
CULUS	6	99	10	22	10		3	35			1	13	34	3	3
CUMAC		55	45	5	8	9	10	175	56	7	1	9	23	10	6
CUMIX	8	12	4		4										
CU-all	14	167	106	27	22	14	15	210	58	15	2	23	57	27	9
EUFAS		80		4	1		2	15		1	5		48	15	3
EUNIT		135	5		2		5	62	38	52		6	51		
EUREG		181	1	2	43		3	1		13	3		150	5	2
PCTOT	2	10		1	1			45					1		
PODEL									1						
POEUG		2													
POMIX								3							
POREG		2													
POROB		2													
POSER		2													
POXRU									1						
PO-all		8						3	2						
PSMEN		473	354	6	156	16	270		221	82	3	45	89	26	23
SQSEM		20	29	20	22				8	1	1	1	5	7	

AK=Auckland BP=Bay of Plenty CY=Canterbury GS=Gisborne
HB=Hawkes Bay
MB=Marlborough NN=Nelson/Tasman NT=Northland OT=Otago
SD=Southland
TR=Taranaki WC=West Coast WK=Waikato WM=Wanganui /Manawatu
WN=Wellington

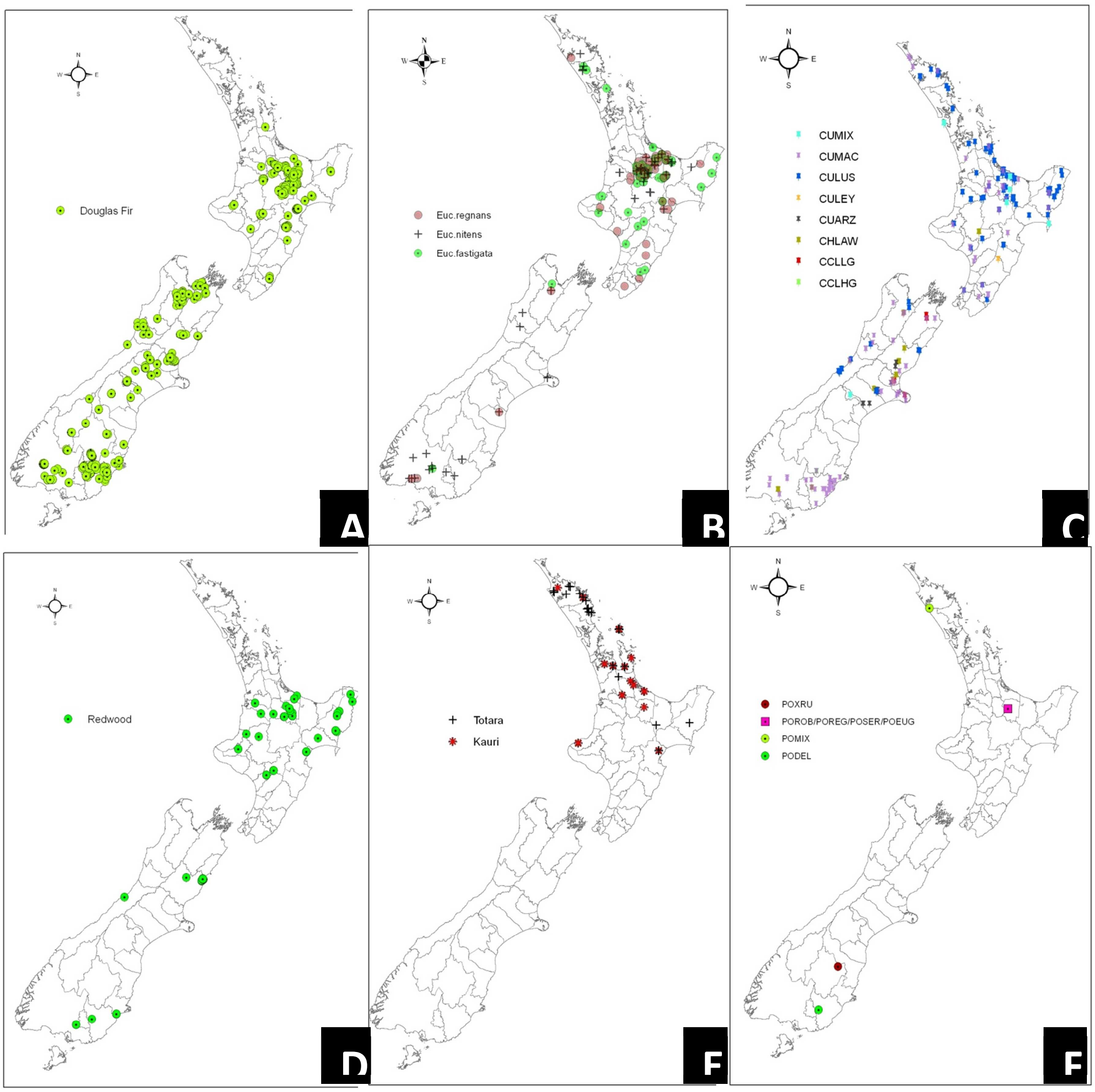


Figure 5. Regional distribution of species for which measurements are held in PSP database.

4.6 CLIMATIC CONDITIONS OF PSPS

Mean annual rainfall at the PSP plot locations located as indicated in Fig. 5 ranged from 480 to 4380 mm. The cypresses were located on plots with the greatest mean annual rainfall. Totara and kauri demonstrated the least variability in rainfall, while *E. nitens*, with the largest interquartile range, grew on plots with wide variability in rainfall (Fig. 6). From Equation 1, NPP is estimated at 820-2840 g/m^2/yr.

Mean annual temperature at the PSP plots ranged from 6.6 to 15.9°C. Minimum temperature ranged from -0.8 to 12.2°C, and maximum temperature from 12 to 20°C. Again, *E. nitens* demonstrated the greatest variability in climatic conditions, as shown by the interquartile range. *S. sempervirens* also had a large interquartile temperature range (Fig. 7). From equation 2, NPP is then expected to be within the range of 1110-1920 g/m^2/yr.

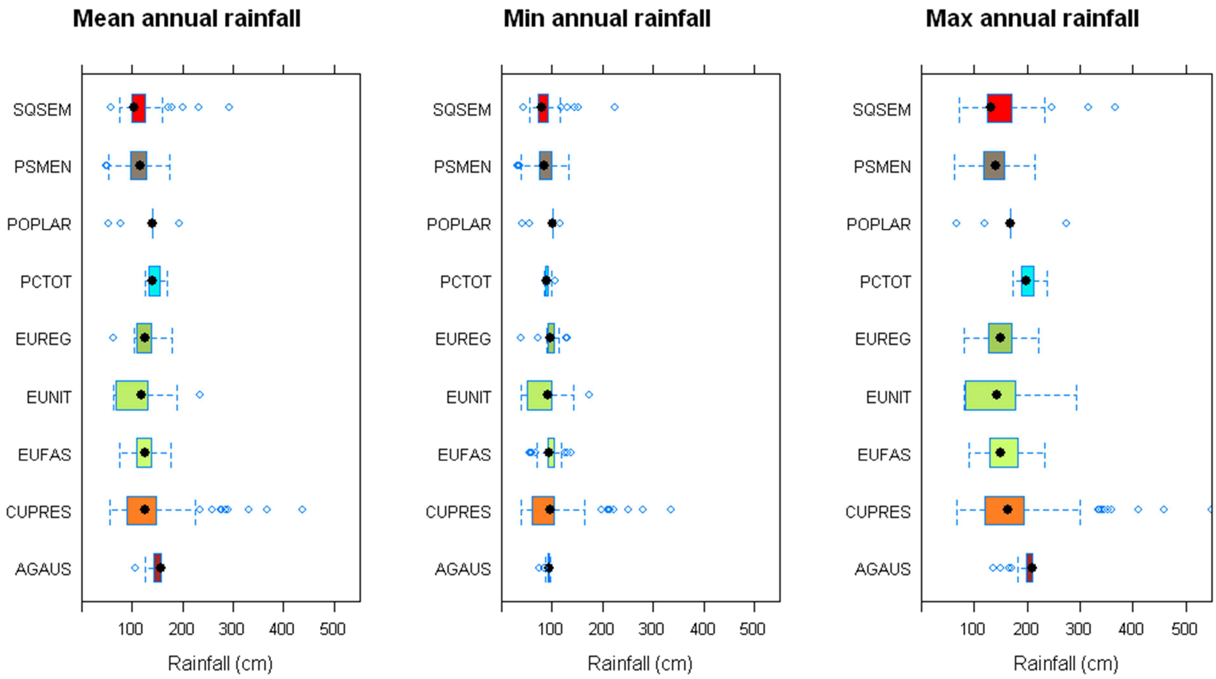


Figure 6. Annual rainfall at Permanent Sample Plot sites.

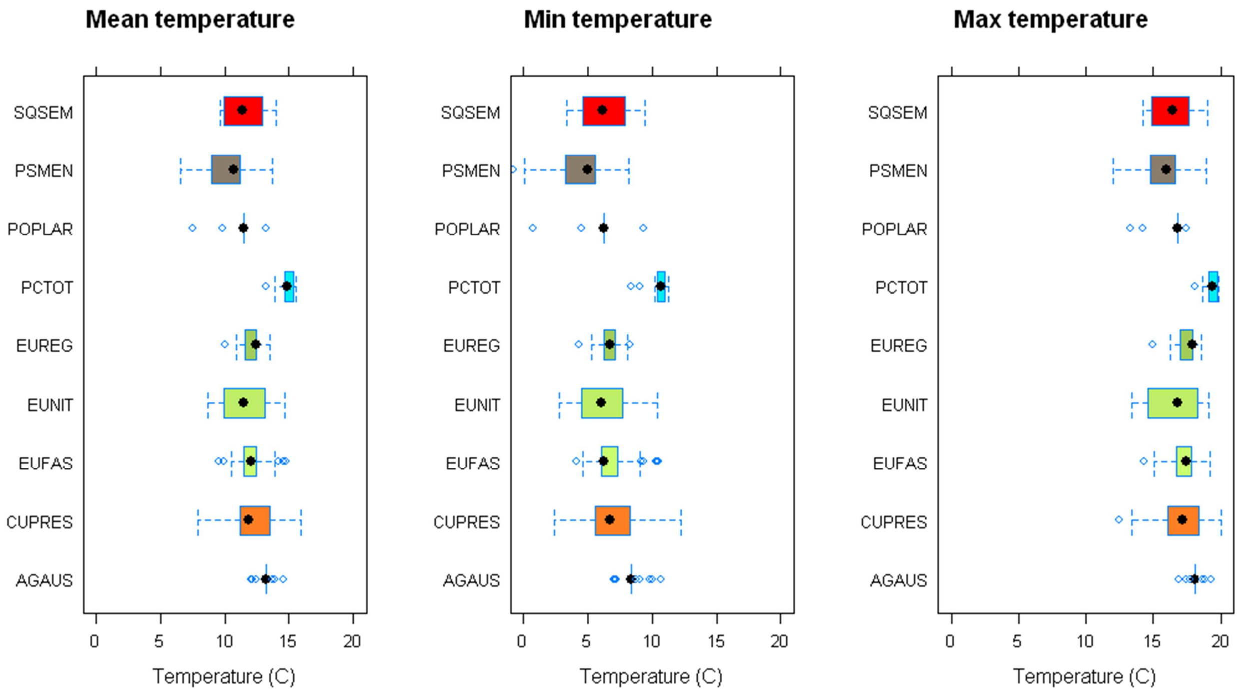


Figure 7. Temperature at Permanent Sample Plot sites.

4.7 SOILS UNDERLYING PSPS

Many of the PSPs are established on Brown soils, the most extensive soils covering 43% of New Zealand and occurring in places where summer drought is uncommon and which are not waterlogged in winter. Brown soils are one of the 15 New Zealand Soil Classification (NZSC) soil orders. The two least extensive soils (Anthropic and Semiarid) were absent from the PSPs. The former (which are found in urban areas and areas that have been mined) covers less than 1% of New Zealand, while the latter (which occur in inland Otago and southern Canterbury, where annual precipitation is less than about 500 mm) covers about 1%. The NZSC soil classification for soil groups where PSPs are established is shown in Table 4. The soil orders underlying each species in the PSP plots is given in Table 5.

Table 4. New Zealand soil classifications associated with each of the Permanent Sample Plot locations. Anthropic and Semiarid soils are intentionally omitted.

Soils	Group				
B:Brown	**BO** Orthic Brown	**BL** Allophanic Brown	**BS** Sandy Brown	**BM** Mafic Brown	**BF** Firm Brown
E:Melanic	**EO** Orthic Melanic				**BA** Acid Brown
G:Gley	**GO** Orthic Gley	**GR** Recent Gley			
L:Allophanic	**LO** Orthic Allophanic	**LI** Impeded Allophanic			
M:Pumice	**MO** Orthic Pumice	**MI** Impeded Pumice			
N:Granular	**NO** Orthic Granular				
O:Organic	**OM** Mesic Organic				
P:Pallic	**PI** Immature Pallic	**PJ** Argillic Pallic	**PP** Perch-Gley Pallic	**PX** Fragic Pallic	
W:Raw	**WO** Orthic Raw	**WF** Fluvial Raw	**WH** Hydrothermal Raw	**WS** Sandy Raw	**WX** Rocky Raw
R:Recent	**RO** Orthic Recent	**RF** Fluvial Recent	**RS** Sandy Recent	**RT** Tephric Recent	
U:Ultic	**UD** Densipan Ultic	**UE** Albic Ultic	**UY** Yellow Ultic		
X:Oxidic	**XO** Orthic Oxidic				
Z:Podzols	**ZO** Orthic Podzol	**ZP** Perch-Gley Podzol	**ZX** Pan Podzol		

Table 5. New Zealand soil classifications by species.

	NZSC Classification Key for Soil Orders (defined in Table 4)												
Species	**B**	**E**	**G**	**L**	**M**	**N**	**O**	**P**	**R**	**U**	**W**	**X**	**Z**
AGAUS	BO			LO	MO				RO				
CULEY					MO			PP	RO				
CULUS	BF,BL BO		GO,GR	LI,LO	MI,MO		OM	PI	RO,RS RT	UD,UE UY	WO WF		ZO,ZP ZX
CUMAC	BF,BL BO,BS		GR	LO	MI,MO		OM	PI,PJ Pl,PP,PX	RF,RO RS,RT	UE	WS		ZP
EUFAS	BA,BF BO	EM	GO	LO	MI,MO		OM		RF,RO RT	UY			ZO
EUNIT	BA,BF BL,BO	EO		LO	MI,MO		OM	PP,PX	RF,RT	UE,UY			ZO
EUREG	BF,BO			LO	MO			PI	RO,RT		WO		ZO
PCTOT	BA,BO				MO	NO		PI	RF,RO	UY		XO	
PO-all			GO					PJ,PX					ZO
PSMEN	BA,BF BL,BM BO	EO	GO	LO	MI,MO	NO		PI,PJ PP,PX	RF,RO RT	UY	WH		ZO,ZP ZX
SQSEM	BF,BL BO	EO	GO	LO	MO			PI,PX	RF,RO RT		WH		ZP

4.8 WOOD DENSITY

Beets et al. (2008a) found significant regional differences in wood density for some species, including *P. menziesii*, *C. macrocarpa*, and *C. lusitanica* for which the differences were highly significant. Because no significant correlation was found between region means and the corresponding means based on the provenance trial, the study concluded that regional differences appeared to be related to local differences in site fertility, rather than to broad geographic differences in mean annual air temperature. Mean whole stem wood density (including bark) and mean outerwood basic density at breast height are given by species in Tables 6 and 7. Large differences were observed between species, and these are shown in Table 8, by region. Regional gaps are clearly evident.

Table 6. Whole stem density of wood plus bark (WSD). Source: Beets et al. 2008a.

						Age regression		
Species	**Mean WSD**	**No. regions**	**No. studies**	**No. trees**	**Region P-value**	**Intercept**	**Slope**	**P-value**
SQSEM	310	6	12	36	0.7826	276	0.7	0.5827
CULUS	336	9	24	283	0.0261	316	1.2	0.0225
PODEL	357	1	1	4	.			
POEUG	357	1	3	9	.			
CUMAC	370	9	24	141	0.0008	342	0.7	0.0537
CULEY	370	3	12	50	0.1124	404.2	-1.7	0.3097
EUREG	389	6	28	120	0.0368	363	1.5	<.0001
CUARZ	393	1	1	3	.			
EUNIT	408	4	15	117	0.0414	373	4.3	<.0001
PSMEN	411	7	82	3321	0.0003	401	0.3	0.5647
EUFAS	420	2	6	22	0.5433	363	2.2	0.0003
PCTOT	370	2	3	19	0.6108	.	.	.
AGAUS	435	4	7	49	0.4367	.	.	.

Table 7. Breast height outerwood basic density (BHBD). Source: Beets et al. 2008a.

						Age regression		
Species	Mean BHBD	No. regions	No. studies	No. trees	Region P-value	Intercept	Slope	P-value
SQSEM	333	6	12	36	0.7826	296	0.7	0.5827
CULUS	361	9	24	283	0.0261	339	1.3	0.0225
PODEL	383	1	1	4	.			
POEUG	383	1	3	9	.			
CUMAC	396	9	24	141	0.0008	367	0.8	0.0537
CULEY	397	3	12	50	0.1124	433.6	-1.8	0.3097
EUREG	406	6	28	159	0.0643	380	1.7	<.0001
CUARZ	422	1	1	3	.			
EUNIT	437	4	15	117	0.0414	400	4.7	<.0001
PSMEN	441	7	82	3330	0.0003	429	0.3	0.5095
EUFAS	450	2	6	22	0.5433	389	2.4	0.0003
PCTOT	384	2	3	19	0.6599	.	.	.
AGAUS	460	4	7	49	0.2621	.	.	.

Table 8. Whole stem (wood and bark) density by species and region (defined in Table 3). Source: Beets et al. 2008a.

Species	NT	AK	BP	WK	GS	HB	TR	WM	WN	NN	MB	WC	CY	OT	SD
SQSEM	.	353	313	317	341	.	.	270	.	.	.	210	.	.	.
CULUS	372	321	356	357	328	340	337	327	.	386	.	.	.	.	.
PODEL	.	.	357	.	.	.	.	.	.	.	.	.	.	.	.
POEUG	.	.	357	.	.	.	.	.	.	.	.	.	.	.	.
CUMAC	413	.	353	.	331	376	356	391	369	.	.	380	418	.	.
CULEY	.	.	357	399	375										
EUREG	.	.	381	414	429	369	.	.	.	.	.	378	.	462	.
CUARZ	.	.	393	.	.	.	.	.	.	.	.	.	.	.	.
EUNIT	.	.	396	420	.	.	.	.	.	.	.	426	496	.	.
PSMEN	.	.	396	422	.	.	.	419	.	437	.	.	427	455	409
EUFAS	.	.	413	449	.	.	.	.	.	.	.	.	.	.	.
PCTOT	.	.	364	385	.	.	.	.	.	.	.	.	.	.	.
AGAUS	446	459	.	403	.	.	414	.	.	.	.	.	.	.	.

4.9 IMPROVING LOOK-UP TABLES FOR OTHER PLANTED SPECIES - REVIEW GAPS BY SPECIES

Results of the literature review and gap analysis for each of the species under consideration, beginning with Douglas-fir the most prevalent of alternative species, follows.

4.9.1 Douglas-fir [PSMEN]

Douglas-fir, the most abundant of the alternative species (refer Fig.4), is associated with PSPs in 13 of the 15 regions of New Zealand (refer Table 3), and is the most well represented species in terms of productivity indices (site index and the 500 Index) , volume, taper, growth and yield models. A Douglas-fir calculator, that enables carbon estimation, has also been developed

However, development of a productivity map at the national level for Douglas-fir has not been successful. Watt et al. (2009b) determined that it was not possible to produce a national-level map because the productivity indices were only weakly correlated (R^2 <0.1) with mean annual air temperature, annual rainfall and other environmental variables. They speculated that the low correlations could be due to either Swiss needle cast infestation, and/or to the provenance of the material, and concluded that examination of productivity at the regional, rather than national level may be worthwhile. Another important point to note is that the variables tested in the study were based on averaged climatic values (e.g. mean annual temperature, total annual rainfall) rather seasonal variations or climatic extremes, which have been demonstrated to being important to productivity.

Waring et al. (2008), on questioning why New Zealand grown Douglas-fir produces up to 40% more wood volume annually than that recorded on the best sites in the Pacific Northwest (PNW) of the United States (Ledgard and Belton, 1985), and on determining that mean annual values of temperature, precipitation, and solar irradiance were similar at sites examined within NZ and within the PNW, concluded that the higher NZ yields could be attributed to differences in temperature extremes recorded in the PNW during the summer growing season. The higher temperature extremes caused greater deficits in daytime air humidity, resulting in reduced stomatal conductance and photosynthesis.

The current state of knowledge for Douglas-fir is given below.

Douglas-fir 500 Index

This productivity index combines site index and basal area ‘level’ (as represented by site basal area potential, SBAP), and can be used to compare yields across a range of sites. The index has been standardised to a specific regime, involving thinning to waste by 15m MTH to 500 stems/ha, and then growing the stand to age 40 yrs. Hence it has been named the ‘500 Index’ (Knowles 2005).

Douglas-fir calculator

The calculator (Knowles 2008, Knowles et al. 2003a, 2003b, 2004, available from Future Forest Research Ltd) can be used to analyse growth and log quality, to determine the average BA increment for a fully stocked stand to age 40, and to estimate biomass and carbon stocks in Douglas-fir stands growing in New Zealand. Carbon estimates are made using a series of stand-level functions (Knowles et al. 2010), and developed through algebraic manipulation of the equations presented by Ponette et al. (2001) and Ranger and Gelhaye (2001).

A recent upgrade to the calculator (Version 4.0, Dungey et al. 2011) has removed bias in the growth model which caused under-prediction following thinning. Furthermore, validation exercises have indicated that overall, results are unbiased (Kimberley and van der Colff 2010).

Growth and yield models

Growth and yield models for Douglas-fir growing in four regions of the South Island (Nelson, Westland, Canterbury, Southland) are also available online (Lee 2012). Van der Colff and Shula (2006) developed a distance-independent tree growth model for Douglas-fir. The model predicts the growth and yield of a stand of trees at an individual tree level, using a list of trees obtained from inventory, and predicts diameter at breast height and total tree height growth and the probability of mortality to project the stand into the future. Typical information contained for each tree in a tree list includes individual tree breast-height diameters, heights, and the weighting of each individual (the number of trees per hectare represented by the individual). This is in contrast to a stand growth model that requires stand level statistics only to predict growth, before predicting a diameter distribution at the desired future age. The advantage of an individual tree model is that in projecting inventory information, the data collected on individual trees (e.g., on stem quality) is not lost by any amalgamation to stand level averages.

Reduced growth due to Swiss needle cast disease

Kimberley et al. (2011b) analysed the effect of Swiss needle-cast on growth increment using PSP data based on Douglas-fir trees aged between 15 and 60 years and plots located between 38-46º latitude, from Southland to Bay of Plenty. Climatic variables (mean temperature, mean minimum temperature, annual rainfall, and mean monthly rainfall) were extracted for each PSP from biophysical geographic information system (GIS) surfaces developed for New Zealand (Leathwick et al. 2002). A steady decline in growth rate over a 30-year period from the first appearance of *P. gaeumannii* (the cause of the disease) to a point when it stabilized at a lower increment level 14-20 years later was found. The cumulative mean reduction was 25% for mean top height, 27% for basal area, and 32% for stem volume. Volume growth rate decline was greater in the North Island (35%) than the South Island (23%) of New Zealand. Mortality did not increase as a result of infection by *P. gaeumannii*. The disease had less effect on cooler sites, especially those with low spring minimum temperatures ($p<0.001$). Negligible growth decline occurred on sites with daily minimum October temperatures averaging below 3.2ºC. Rates of reduced growth are given in Table 9.

Table 9. Estimates of the percentage reduction in growth increments attributable to Phaeocryptopus gaeumannii. Source: Kimberley et al. (2011b)

	Reduction in growth (%)		
	Volume CAI	**Mean top height CAI**	**Basal area CAI**
All New Zealand	31.9	25.4	27.3
North Island	34.6	27.0	35.5
South Island	22.9	22.8	19.5

CAI = current annual increment.

Watt et al. (2011) used a process-based niche model (CLIMEX) to project the potential habitat suitable for Douglas-fir and to predict abundance of the *P. gaeumannii* pathogen and severity of Swiss needle cast. The climate change scenarios used for the 2080s indicated that the land area suitable for Douglas-fir production in the North Island would reduce from the current level of near 100% to 36-64% of the total land area by 2080s. In the North Island, four of the six climate change scenarios predicted substantial increases in

disease severity that would make the affected regions marginal for Douglas-fir by the 2080s. In contrast, most regions in the South Island were projected to sustain relatively low levels of disease, and remain suitable for Douglas-fir.
Under current climate, Watt et al. (2011) found the entire North Island to be suitable for Douglas-fir and for the pathogen. However the effect of the pathogen on sites north of the Bay of Plenty has yet to be quantified. Given the greater reduction in growth rates for the northern dataset used by Kimberley et al. (2011b), a reduction in excess of the values presented in Table 9 for the North Island could be expected.

Volume and taper functions

A number of volume and taper functions have been developed for Douglas-fir. The functions have diameter, rather than age, as the major variable. The diameter range of trees within a stand is used to select sample trees, and this data, when combined with that from other forests within the same region, forms the basis from which the model can be derived. In general tree volume and taper equations are used to determine the stem volume of trees given measurements such as breast height diameter and tree height. They can also be used to predict volume, diameters and taper of arbitrary stem sections. The equations are basic components of stand inventory, growth and yield, forest planning and production simulation systems. One such system developed at Scion that incorporates volume and taper equations is Atlas Forecaster . This software tool provides the ability to predict the impacts of site, silviculture and genetics on tree and branch growth and wood properties, and hence on wood value, internal rate of return and net present value. Equations relevant to Douglas-fir and included within Atlas Forecaster are listed in Table 10. To ensure reliable estimates, the equations used should be appropriate to the age, location, and silviculture of the stands to which they are applied,

Table 10. Douglas-fir volume/taper equations available within Atlas Forecaster software

Vol/Taper	Number	District	Created	Treatment*	Forest
Vol	120	ASHY	1973	U	ASHY
Vol&Taper	136	ALL NZ	1977	UT	ALL NZ
Vol&Taper	228	LONG age 33-37	1986	U	Longwood
Vol&Taper	273	NN	1990	T	G. Downs
Vol&Taper	274	SD	1990	T	Southland
Vol&Taper	275	CA	1990	T	Canterbury
Vol	438	Kaingaroa	2002	T	FCF KANG

*T = thinned; U = unthinned

Biomass

Keyes and Grier (1981) estimated the above- and below-ground biomass of 40-year-old Douglas-fir stands on both low and high productivity sites. Above-ground biomass was estimated using logarithmic regressions of tree dry weight on stem diameter (Dice 1970). An individual tree equation that estimates above-ground biomass from total tree height and breast height diameter was developed by Moore et al. (2011).
Biomass data of New Zealand-grown Douglas-fir were collected by Nordmeyer and Ledgard (1993) who sampled five 15-year-old trees growing at a site in the Craigieburn Range (lat. 41°10’S, long. 171°45’E, elev.1040 m). Additional data were also collected from the same site 13 years later when the trees were 28 years old and from two other sites in the South Island high country (Alan Nordmeyer, unpublished data).
More recently Oliver et al. (2011) examined above- and below-ground biomass of a 28-year-old stand in Kaingaroa and above-ground biomass of a 31-year-old stand in Whakarewarewa. Above-ground biomass was 318 t/ha at Kaingaroa and 273 t/ha at

Whakarewarewa, with the percentage of stem wood plus bark amounting to 77% in each stand. Below-ground biomass at Kaingaroa totalled 57.5 t/ha with 68% found in roots above 10 cm diameter including the bole (root stock). The root/shoot ratio of the Kaingaroa stand was 0.19.

In addition to the above past research, current research includes biomass studies in Southland and Canterbury, wood density studies of biomass trees, and a national wood density survey. As part of this research, Mark Kimberley, in conjunction with Stuart Kennedy, is working on an improved wood density model which is integrated with the 500 Index model and C_Change, a model for predicting plantation tree carbon stocks in above and below ground biomass and litter pools. Further information on the new model should be available later this year.

4.9.2 Eucalypts [EUFAS, EUNIT, EUREG]

As each of the three eucalypt species (*E. fastigata, E. nitens, E. regnans)* are substantially different, they are reviewed separately, rather than as a combined group. Growth and productivity are reviewed below, while a more general background into the species can be found in publications such as Miller et al. (1992, 2000).

The growth rate of eucalypts can be at least as fast as *P. radiata* on favourable sites (Maclaren 2004). The average site index for *E. fastigata* at age 20 is 31.2m with a range of 23.7-37.3m while the range for *E. regnans* is higher at 25.8-45.2m. However *E. nitens* is highly susceptible to paroplysis, and infection by this disease will have a negative effect on productivity.

Locations of eucalypt PSPs also differ by species and region. *E. regnans* is associated with the most plots (404), followed closely by *E. nitens* with 356 plots. *E. fastigata*, however, has been established with only about half that number of plots (174). Only six (of the 15) regions for which PSP data are held, comprise all three species (refer Table 3).

E. regnans appears to be sited in warmer climes than either *E.nitens* or *E. fastigata* (refer to both the global data presented in Table 1 and to the statistics shown in Fig. 6), however this does not necessarily imply that *E. regnans* cannot grow in colder regions. Weston (1957) reported that *E. regnans* appears extremely tolerant to climate and will tolerate very severe frosts of up to -6°C. Ashton (1958) conducted experiments, both in the field and in refrigerators, and found that *E. regnans* seedlings were sensitive to frost, and under artificial frost, softened seedlings were killed at about -3°C and well-hardened seedlings at -6°C. In the field the lethal frost temperature was some degrees lower. *E. regnans*, however, is sensitive to salt winds (Weston 1957).

E. fastigata is a fast growing species that is disease resistant and can tolerate a wide range of New Zealand environments. It has high potential as a plantation species for pulp and paper, timber, and for carbon forestry. However, insufficient PSPs exist to develop a robust empirical growth and yield model for the entire country. To circumvent this issue, a process-based model 3-PG_2S (physiological processes for predicting growth spatially), was parameterised for *E. fastigata* for New Zealand conditions, and used to simulate a series of management scenarios for decision makers to assess the suitability of this species throughout the country (Meason et al. 2011).

Meason et al. (2010) developed a carbon sequestration web tool for *E. fastigata*. In the process, they found that stand growth varied regionally, with the most productive sites located in Northland and the least productive site in Southland. They also found that wood core density was not influenced by site productivity, nor by region.

Austin et al. (1984) developed response surfaces (shown below) for *E. fastigata* and other eucalypt species grown in Australia using mean annual temperature, mean annual rainfall, radiation index and geology. The analysis indicated curvilinear response curves for temperature and rainfall, and linear for radiation index with higher probability of occurrence on granite (Fig. 8). The model predicted the highest probability (0.70 on sediments) of finding *E. fastigata* being under environmental conditions of mean annual temperature approximately 11 °C and mean annual rainfall of 1 200 mm on steep, very protected (gully) southern slopes. Under similar conditions, but on exposed northern slopes the probability fell to 0.22. The relative importance of the environmental variables in predicting the occurrence of *E. fastigata* was temperature (68.3 change in deviance), rainfall (26.1), radiation index (15.3), and geology (7.8). In contrast, environmental drivers considered by Meason and colleagues (Meason and Dungey 2009, Meason et al. 2011) *for E. fastigata* grown in New Zealand included temperature, rainfall, frost, soil depth, and plant available soil phosphorus.

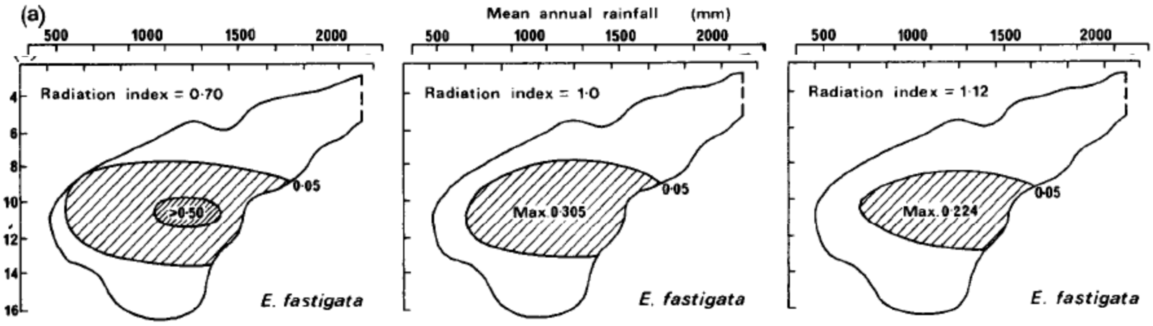


Fig. 8. Predicted response surfaces of probability of occurrence for selected eucalypt species in relation to mean annual temperature and mean annual rainfall at different levels of radiation index on sediments. The predicted surfaces are based on continuous quadratic (or

Figure 8. Response surfaces for *Eucalyptus fastigata* in Australia. Source: Austin et al. (1984).

Growth and yield

Growth models have been developed for *E. nitens*, *E. fastigata,* and *E. regnans*.

E. regnans model No. 1

The *E. regnans* growth model (Hayward 1988) was developed from data from over 220 plots, located in Kinleith Forest. Thus the model is geographically limited to the volcanic plateau. Furthermore, the trees were relatively young (3-15 years old) and stocking ranged from 2500 to 600 stems/ha. The model, which excludes a thinning function, was validated in 1990 (McKenzie 1990). Validation showed the model was adequate for unthinned stands less than 15 years of age.

E. regnans model No. 2

A new model (MacLean and van Zyl 1997) was subsequently developed to address some of the limitations of *E. regnans* No. 1. It included thinning functions and incorporated an extended range of sites and ages, with over 900 measurements from 138 plots. The majority of data were from the central North Island area but there was also data from Northland and Southland, were used to construct the No. 2 growth model. A thinning function was included in the model. Tree age was still relatively young with a range of 3.2 to 32.2 years. Stocking ranged from 50 to 2900 stems/ha, and MAI from 0.77 to 51.04 (m^3/ha/yr), Table 11. These MAI seem relatively low, as Miller et al. (2000) report that MAI for volume is typically 20-30 m3/ha/yr. Subsequent validation indicated that the model was adequate for stands under 20 years of age

Table 11. Summary of data used in development of E. regnans No. 2 growth model.

	Age (years)	Site Index	MTH (m)	Stems/ha	BA (m^2/ha)	MAI (m^3/ha/yr)	Vol (m^3/ha)
Mean	9.7	35.9	20.2	612	14.6	10.93	119.5
Min	3.2	25.8	m5.8	50	1.1	0.77	3.6
Max	32.2	48.2	55.7	2900	76.4	51.04	1226.2

E. nitens

Candy (1997) developed a growth model for *E. nitens* with data sourced from plantations in Tasmania and New Zealand. The combined data set was aged 2 to 34 years (mean 7 years), MAI 0.4 to 32.4 m^3/ha/yr (mean 10.7 m^3/ha/yr), site index at age 15 ranging from 13.8 to 38.9 (mean 26.2), and initial stocking of 100 to 2600 stems/ha (mean 1142 stems/ha). An independent data set from Otago (FR 137/7 Garden regime trial site) was used to compare with growth predictions from the Candy growth model.The model was found to consistently underestimate basal area growth for the Garden regime trial site (Berrill 1999).

E. fastigata

A stand growth model for *E. fastigata* was developed using a combination of PSP and Carter Holt Harvey Forests (CHHF), (van der Colff and Kimberley 2005). The latter plots were mainly located mainly in Kinleith Forest estate in the Central North Island. The combined dataset had a mean age of 16.8 years (range: 10-66 years), MTH of 29.5m (range 10.7-58.4m), and a mean final stocking of 1259 stems/ha (range 220-4400 stems/ha).
A growth and yield model for *E. fastigata* was developed by Berrill and Hay (2005) using data from a combination of 66 PSPs and 45 other plots obtained using the "Method for the Assessment of Recoverable Volume by Log Type", more commonly known as MARVL The data were predominantly from the North Island (Northland, Bay of Plenty, Central North Island, Wanganui/Manawatu) but four plots (2 PSP and 2 MARVL) were located in the Nelson/Marlborough region. Tree age ranged from 2 to 66 years (mean 12 years), and stocking from 21 to 5000 stems/ha (mean 1111 stems/ha).

Volume and taper functions

Two national equations for *E. nitens*, have been developed. Equation T256 was developed in by Gordon et al. (1990) and can be applied to trees ranging in DBH from 6 to 56 cm and in height from 4 to 33 m. Equation T435 was developed in 2000 and can be applied to trees ranging in DBH from 3 to 64 cm and in height from 4 to 39 m. A further function, 201, was developed by E. Baalmann in 2011. Comments on a draft of this FEA volume and taper function are reported in Goulding (2009).
Equation T276 was developed for *E. fastigata* in 1992 (Smart 1992). It is based on sectional measurements of 90 trees growing in the Central North Island and can be applied to trees ranging in DBH from 10 to 100 cm and in height from 13 to 55 m. There are also two older volume equations; number 34 developed in 1959 and based on data from Oakura Forest, Taranaki; and number 38, created in 1961.
Chikumbo and Nicholas (2011) used stand volume models, together with models for stand basal area and average stand height, to determine efficient thinning regimes for E. fastigata that provided a balance between volume and value production.
Equation T247 was developed for *E. regnans* by Hayward (1987). It is applicable to trees ranging in DBH from 8 to 50 cm and in height from 8 to 50 m, and is based on sectional measurements of 364 trees growing in former NZFP forests in the Central North Island. The original data was held by Carter Holt Harvey Forests Ltd. and appears to be

unavailable for use in any volume and taper equation revision. The taper function was also undefined at the tip of the tree.

E. fastigata calculator and web-based tools

A web-based calculator for evaluating the economics of growing *E. fastigata* is available on the Future Forests Research (FFR) website (Hansen 2011). The calculator uses the *E. fastigata* growth model (van der Colff and Kimberley 2005).
Other research, culminating in a web-based calculator for carbon forestry (Meason et al. 2010) has also been developed and has shown that site productivity for *E. fastigata* is influenced by extractable phosphorus and soil order.

Biomass and density

Moore et al. (2011) developed a generalised above-ground biomass equation, derived from168 *Eucalyptus* trees of a variety of species (*E. nitens*, *E. fastigata*, *E. saligna*, *E. regnans* and *E. maidenii*). A number of other biomass studies have been performed (Madgwick et al. (1981) for *E. fastigata* and *E. nitens*; Frederick et al. (1982a and 1985) for *E. regnans*). Frederick et al. (1982b) also analysed wood density of young *E. regnans* and McKinley et al. (2000) analysed that of *E. fastigata, E. nitens, E. regnans,* and other species.

4.9.3 Poplars [PODEL, POEUG, POMIX, POREG, POROB, POSER]

Research related to the poplar species is somewhat limited, with the least number of PSP plots established (just 13), and with these being geographically scattered (refer Fig 5fF). However, volume and taper functions have been developed for the species, and growth and yield reported.
Poplars are commonly planted on moist, unstable pastoral hill country to combat soil erosion. However they have also been identified as promising for production forestry. In particular, *P. trichocarpa* was identified by Shelbourne and Wilkinson (1997) as a promising species for both production forestry and soil conservation.

Poplars offer other advantages including (Maclaren 2004):

1. The ability to grow in wetter areas than radiata pine, provided that the water is not stagnant.
2. Poplar can be planted out of reach of livestock, in the form of poles, without the need to either fence the plantings or to forgo grazing for several years.
3. The foliage can provide valuable stock feed during droughts, but only at the considerable cost of pollarding, or by scheduling normal clearwood pruning to coincide with a feed shortage.

Recent trials of poplar clones bred for soil stabilisation (McIvor et al. 2011) showed favourable results, with the experimental clones demonstrating similar survival to commercial clones, and showing a high tolerance to wind. *P. maximowiczii* × *P. nigra* clones were considered particularly suitable for colder sites subject to severe winter frosts and to warmer sites with regular rainfall, but less suited to sites prone to salt spray and to summer drought.

Growth and yield

Wilkinson (2000) reported that poplars are fast-growing trees in their natural habitats, commonly exceeding 30 m in height and 90 cm in diameter when mature. *P. deltoids*, the fastest growing commercial forest species in North America, and planted at 2700 stems/ha without irrigation yielded 140 m^3/ha total volume at age four, while *P. trichocarpa* has

been at 500 m^3/ha in 24 years. In NZ, at age 12 and with a stocking of 500 s/ha, the volume of seven families of *P. deltoides* at Brookfield Arboretum at Napier, ranged between 283 and 442 m^3/ha; equivalent to 20-37 m^3/ha/yr (Wilkinson 2000).
Poplar yield tables for predicting mean top and volume were developed by MacLean (1997) based on 34 MARVL inventories. After the addition of supplementary data, the height and volume functions were re-estimated (McElwee and Knowles 1998). Using this model to achieve maximum growth rates (optimal site, no pruning, very high stocking) enables a productivity of about 53.5 m^3/ha/yr at age 15 – a figure close to the maximum theorised for radiata pine (Maclaren 2004).

Volume and taper functions

Volume equation 113 (RO, WN) was created for poplar in 1972, and a national volume and taper equation, 394, was created in 1998.

Wood density

McElwee and Knowles (1998) reported a density range of 330 to 450 kg/m^3 for the outer 10 rings at age 15 of *P. trichocarpa,* i.e. approaching that of Douglas-fir. Mean breast height outer wood density values for *P. deltoids* and *P. eugenei* of 383 kg/m^3 (refer Table 7) also falls within this range.
McElwee and Knowles (1998) concluded:

1. The past introduction and breeding of poplars has neither effectively explored the genetic variability among and within the 30-40 species of the genus nor provided adequate genetic base populations of any species for further breeding for soil conservation and for production forestry.
2. It is strongly contended that the genus has great unrealised potential for production forestry in New Zealand which has never been explored, and that the identification of valuable species could provide needed diversity in products, markets and genetic material for an industry that is dependent on very few species.

4.9.4 Cypresses [CULEY, CULUS, CUMAC]

The cypresses are established throughout New Zealand. Though there are about 20 species of the genus *Cupressus* (Miller and Knowles 1996), the majority of PSPs are planted with either *C. macrocarpa* (419 plots) or *C. lusitanica* (239 plots). For this reason, model development has been largely restricted to these two species. With relatively young crops (*C. lusitannica* averaged 12.7 years, and *C. macrocarpa* 17.1 years) from which measurements were obtained, the models for growth and yield were biased towards younger trees.
A productivity profile was developed for *C. lusitanica* (Watt et al. 2009a) from PSPs that covered most of the North Island, but limited to Nelson and northern regions of the West Coast in the South Island. Sites that were either very cold (mean annual temperature 8.5 - 10.5 C) or dry (mean annual rainfall 600 - 972 mm) were not represented. While *C. lusitanica* is susceptible to damage by salt winds, *C. macrocarpa* is not (Weston 1957).
Recent silvicultural trials (Low and Andersen 2011) suggest that *C. lusitanica* grows best when planted at 1100 stems/ha, pruned and thinned to a final stocking of 400 stems/ha at age eight (or ten metres in height), and harvested at age 30, with the production of 800 m^3 on good sites. Results for *C. macrocarpa* were similar, though less aggressive thinning was recommended to account for mortality due to canker.

Growth and yield

Preliminary growth and yield models, with a base age of 30 years for site index, were developed for *C. lusitanica* and *C. macrocarpa* by Berrill (2004). A wide range of height growth rates, ranging from 15 to 35 m mean top height at age 30 was observed. Berrill (2004) also developed basal area, mortality, and volume models. However data used in model development were biased towards younger trees (Table 12).

Table 12. Cupressus lusitanica and C. macrocarpa sample plot count, maximum age, and mean annual volume increment (MAI) by geographic region. Source: Berrill (2004)

	Region	*C. lusitanica*			*C. macrocarpa*		
		No. Plots	Max age	Max MAI (m^3/ha)	No. Plots	Max age	Max MAI (m^3/ha)
North Island	Northland	34	41	19.3	4	42	17.2
	Auckland	6	8	11.0	-	-	-
	Bay of Plenty	47	41	24.6	20	39	15.5
	Waikato	33	67	19.8	23	61	22.6
	Gisborne	20	31	20.3	3	4	6.3
	Hawke's Bay	10	28	26.0	-	-	-
	Taranaki	1	32	19.6	1	33	29.0
	Wanganui/Manawatu	3	31	17.5	10	34	20.0
	Wellington	3	13	18.5	6	51	22.9
	All regions	157	67	26.0	67	61	29.0
South Island	Nelson	1	13	11.4	8	36	4.7
	West Coast	8	14	9.2	7	16	18.9
	Canterbury	-	-	-	21	55	16.9
	Otago	-	-	-	53	72	36.1
	Southland	-	-	-	7	18	16.4
	All regions	9	4	11.4	96	72	36.1

4.9.5 Coast redwood [SQSEM]

Coast redwood, though intolerant of strong prevailing winds, salt-laden coastal winds and vulnerable to out-of-season frosts (Weston 1957), can grow well in New Zealand. When young, coast redwood is very sensitive to climate and site factors, and retarded or checked early growth is common when conditions are less than ideal (Knowles and Miller 1993).

The majority of the coast redwood PSPs are located in the North Island. However there are also a number of plots established in the South Island, extending down to Southland. Despite this, a number of growth and yield models and productivity indices have been developed. Coast redwood site index has been found to range between 17 and 49 m, and the newly developed 400 Index from 6 to 50 m^3/ha/yr (Palmer et al. 2009).

Productivity models and maps of New Zealand coast redwood were developed by Palmer et al. (2009). They were based on data (23 plots) derived from the PSP database subject to the coast redwood trees being at least 15 years old and with screening for coppicing. The PSP data was used to develop multiple regression models of S. sempervirens site index and 400 Index using independent variables obtained from interpolated climate surfaces and a national ancillary soil phosphorus map. Palmer et al. (2009) found that temperature was important to productivity, accounting for 55 and 71% of the variance in 400 index and site index respectively. Furthermore, the final 400 index model accounted for 76% of the variance in the data. Independent model variables for the 400 index included mean spring air temperature, subsoil acid soluble phosphorus, and mean summer vapour pressure deficit, with these variables respectively accounting for 55, 16, and 5% of the variance. The final site index model explained 82% of the data variance using mean annual daily temperature and mean summer vapour pressure deficit, with the variables accounting for 71, and 11% of the variance, respectively. Although the productivity models and surfaces related PSP data to environmental conditions (i.e. climate and soil), data from drier (e.g. Canterbury, Otago, Northland) or wetter regions (e.g. West Coast) were not represented. Thus the model is suited to temperate climatic conditions (i.e. a mild climate, free from extremes), and limitations of the model cannot be immediately addressed.

Site Index

Palmer et al. (2009) defined site index for coastal redwood as the height of the 100 largest diameter trees per hectare at breast height age 40 years (i.e. 40 years after attaining a MTH of 1.4 m, which typically occurs at about age 3 years). Site index was derived from measurements of age and mean top height (MTH, mean height of the 100 largest diameter trees per hectare). Spatial datasets used to model site index included climatic data; namely mean annual daily air temperature and mean summer vapour pressure deficit. Mean annual daily temperature was limited to a lower value of 10.6°C and mean summer vapour pressure deficit constrained between 0.42 and 0.77 kPa. Site index values ranged from 17 to 49 m.

Basal area growth

An index of basal area growth, BA40/400 was derived from measurements of age, stocking and BA using the BA model. BA40/400 is defined as the BA at BH age 40 years for a stand growing at 400 stems ha-1.

400-index

The 400 index (Palmer et al. 2009) is defined as the stem volume mean annual increment at breast height age 40 years for a reference regime of 400 stems ha-1. The index was derived from spatial datasets that included mean spring temperature, mean summer vapour pressure deficit, and subsoil acid soluble phosphorus, and combined both site index and basal area growth. For the PSP data used in the model, the 400 index ranged from 6 to 50 m3/ha/yr.

Redwood calculator

The redwood calculator described by the New Zealand Redwood Company (2012) and upgraded by van der Colff and Kimberley (2011) applies site index at age 40 and a “400 Index Basal Area”. It was originally based on coast redwood data collated from 14 stands (Lismore, Wenita, Akatarawa, Te Wera Forest, Wilson, Ngongotaha, New Plymouth, Totara Grove Farm, Mangatu Cpt 98, Mangatu Cpt 11, Urenui, Patunamu, Ruatoria Cpt 303, and Brann). The Excel-based calculator incorporates a growth model (Kimberley et al. 2011a). The calculator requires input of initial stocking, site index, mortality, basal area, diameter at breast height, stem volume, mean top height, and crown height, and other variables. Stem volume under bark is calculated using the T458/F458 tree volume/taper functions (van der Colff 2005).

Growth and yield models

A growth model that predicts basal area (BA) and mean top height (MTH, mean height of the 100 largest diameter trees per hectare) and a stem volume function, have also been developed by Scion. The growth model was constructed using data from stem analysis of trees from eight 20 to 30 year old stands supplemented with data from a national series of 32 permanent sample plots (PSPs). The project was initiated by NZ Forestry Limited (NZF) and was jointly funded by NZF and The New Zealand Redwood Company (TNZRC), the New Zealand based subsidiary of the Soper Wheeler Company of California. The model uses a common-asymptote Chapman-Richards function (Richards, 1959) to predict MTH, and for predicting BA uses an anamorphic Schumacher function (Schumacher, 1939) with the asymptote parameter varying as a function of stocking.

A review of the effects of silvicultural practices was recently conducted however there was insufficient data to develop a stand level model for predicting the response to thinning and pruning (Grace and Meason 2011).

Volume and taper functions

NZ Coast redwood volume and taper functions (T458/F458 functions) were developed by van der Colff (2005). The functions were reviewed by Meason (2010) who recommended the development of separate volume and taper equations for slow growing/low productivity sites whilst also recommending clear specifications for distinguishing between these site types. About the same time, new equations (T472/F472) were developed (van der Colff 2010) as the former functions (T458/F458) were considered unsatisfactory for estimating volumes/taper of smaller trees. The new equations were fitted to tree sectional measurement data collected in 2005 and 2009, and covered a range of ages and densities. The 2005 data was collected from trees aged from 6 to 68 years. The 2009 data comprised two stands, one stocked at 625 stems/ha, the other at 1675 stems/ha, and both aged seven years.

Biomass

Biomass data was collected for young 3 and 4-year old coast redwood trees and below-ground observations were published by Phillips et al. (2012). In the US, Jenkins et al. (2003, 2004) developed generalised allometric equations for predicting total aboveground (oven-dry) biomass for individual stems given DBH. Coast redwoods were classified as cedar/larch softwoods. The biomass equation was of the form:

$$BM = Exp(b0 + b1\ln DBH)$$

where BM = total aboveground biomass (kg) for trees 2.5 cm and larger in DBH (cm), and, for b0 = -2.0336 and b1 = 2.2592. The equation was based on a sample size of 196 stems, with RMSE = 0.2946 and R2 = 0.981.

Density

Basic density of 45-year old coast redwoods growing near Tauranga was found to be 356 kg/m3 (Colbert and McConchie 1983). This is less than the 380 kg/m3 for US old growth trees but more than the 340 kg/m3 for young growth trees (US FPL 1974). Density varies with height up stem and with distance from pith. Basic density also appears to be subject to regional variation (Colbert and McConchie 1983, Young 1983, Table 13). One coast redwood growing in Hokitika, recorded with a productivity of 19.74 m3 at 0.31 m3/annum had an exceptionally low basic density of just 225 kg/m3 (Young 1983).

Table 13. Basic density by location. Source (Young 1983).

Sample Source	No. trees	Age (years)	Basic density (kg/m^3)
Taumaruni	2	29	348
Helensville	1	~60	380
Whakarewarewa SF Cpt 2	7	50	289
FRI Arboretum	1	~50	397
Waitapu SF Cpt 2	2	63	460
Whakarewarewa Cpt 2	7	69	327
Mangakino	4	-	336
Gisborne	2	40	365
East Cape	2	49	367
Tauranga	5	45	353
Hokitika	1	64	225
Mean	36	52	332

4.9.6 Totara [PCTOT]

Totara permanent sample plots are located in the North Island, with 75% of these being located in Northland. Because of this, the variation in environmental gradients (refer Figs 6 & 7 for annual rainfall and temperature, respectively) for this species is small. However totara has also been established as planted stands in many other parts of the North Island, as small woodlots or shelter belts. Furthermore, it has been suggested by Bergin and Pardy (1987) that totara could be grown successfully as a plantation species for timber production. To this end, a long-term genetics trial has been established (Bergin, 2001). These trials were used to examine the population genetics of totara as well as growth and form (Alderson-Wallace et al. 2010).
Though there are some limitations in the models (described below), diameter and height growth have been studied, and models of volume and basal area developed.

Diameter and height growth

Bergin and Kimberley (2009) examined diameter and height growth of two totara stands, one aged 100 years, the other 21 years, and the response to thinning. For the 21-year old stand, mean stem diameter varied from 8.6-21.5 cm for the thinned plots and 9.3-18.6 cm for the unthinned plots. Diameter growth averaged across all plots showed a 3-fold increase in response to thinning.

Volume and basal area

Bergin and Kimberley (2003) derived growth curves for totara, aged 10-94 years. Both basal area and volume growth curves, while indicating slow growth over the first 20-30 years, demonstrated an exponential form. At age 80 years, basal area was 110 m^2/ha, and volume 800 m^3/ha. Mean annual increment for totara stocked at 1000 stems/ha was estimated at 10 m^3/ha at 60 years. Note that the model ignored mortality, thus estimates of volume and basal area would be expected to be over-estimated, particularly at higher ages.

Wood density

Bergin and Kimberley (2009) also examined heartwood and sapwood densities. The former ranged from low of 402 kg/m^3 to 558kg/m^3, and the latter from 407 kg/m^3 to 608 kg/m^3, giving an overall disc weighted value of 476 kg/m^3.

Biomass

To develop new regression equations for biomass and above-ground carbon estimation, Beets et al (2008b) assessed totara trees in the Whirinaki region and found a range in breast height (1.4m) basic density of 250 to 432 kg/m^3 (at 0-5 cm), and 353 to 474 kg/m^3 (at 5-15 cm).

4.9.7 Kauri [AGAUS]

Kauri, like totara, with all PSPs established in the North Island, has little variation in environmental gradients (refer Figs 6 and 7). Unlike totara, more is known about its growth and yield. Furthermore, a kauri calculator has recently been developed (in conjunction with Scion and Tane's Tree Trust, with funding from the Sustainable Farming Fund) and is available through membership of FFR.

Height and diameter growth

Observations of growth in natural stands indicate mean annual increment of 2.5–6.0 mm in diameter and 0.3 m in height (Steward and Beveridge 2010). In planted stands, mean annual growth of kauri has been reported at 7.0 mm in diameter and 0.36 m in height (Pardy et al., 1992). Steward (2011a) found a similar height increment of 0.4 m/yr for planted kauri for periods of up to 30 years. At age 50, planted kauri was predicted to be 20 m in height, over twice the height of kauri in natural stands, and to be 28.1 m by 100 years.

Growth and yield

A preliminary stand productivity model, based on data from two 60-year-old unthinned kauri stands in New Plymouth, predicted tree height of 25 m and diameter of 34 cm at age 80 years (Herbert et al., 1996). At 80 years, total wood volume in stands containing 1300 stems/ha was predicted to be 1103 m^3/ha.

Basal area

A stand basal area model, valid for stand density within the range of 300-1400 stems/ha, was developed from data from thirteen planted kauri stands (Chikumbo and Steward, 2007). Predicted basal area values were similar to those of Herbert et al. (1996) until age 60. From age 60 the extrapolated values were considerably larger (22% at age 80).
Steward (2011a) developed models of growth and productivity, valid for stands from 320-2000 stems/ha, for three stand types (planted, second-growth unthinned and thinned), and for a combined data set of the three stands. Planted kauri data was derived from 31 PSPs located in 25 planted stands and ranging in age from 14-83 years at the last assessment. Kauri in all stand types were found to be slow to establish with little height growth in planted stands for the first five years after planting, and for the first 25 years in natural stands. Similar trends were observed for basal area and whole-tree volume. Productivity in planted stands was better than that in second-growth stands. Basal area at age 50 averaged 64.9 m^2/ha for all planted stands, and was predicted to be 98.2 m^2/ha at age 100. Whole-tree volume was predicted to increase by11.7 m^3/ha/annum for all stands, but was as high as 20.6 m^3/ha/yr in one 70 year old stand. The maximum productivity of kauri was observed in one high-performing young kauri planted stand where whole-tree volume increment in excess of 30 m^3/ha/yr were predicted for a period from age 15-30.

Kauri calculator

A kauri calculator is available on FFR website to members. The calculator incorporates models developed for MTH, volume and basal area of unmanaged, unimproved stands.

Biomass

Beets et al (2008b) assessed the biomass of stems, branches and foliage of felled kauri trees located in Hunua and Taranaki in order to develop new regression equations for biomass and above-ground carbon estimation. Trees from Hunua were 130 years old, while those from Taranaki were 69 years old.

Wood quality

Work is currently in progress (Steward 2011b) to develop an understanding of the wood quality and characteristics of plantation-grown New Zealand kauri based on standing tree measurements and increment cores from stands within and outside the current natural range of the species, and with comparisons made with kauri of similar diameter in natural stands.

Summary and conclusions

The models identified in this review are the best available for predicting productivity, however none (including those for Douglas-fir) can accurately predict growth for the combination of all environmental (temperature, rainfall, soil, altitude, wind) gradients. The geographic spread of the PSPs is heavily weighted to the North Island with a porosity of plots associated with *E. fastigata* and *C. lusitanica*.

Our current knowledge of species productivity in terms of climate, soil, geographic coverage, and density studies is summarised in Table 14 below. The colour-coded cells indicate the total number of regions or soil orders associated with each species. The maximum number for each is 15 (refer Table 3 for the regions, and Table 4 for the soil orders). Gaps in knowledge, for all species, are clearly evident. Less apparent are other knowledge gaps caused by bias in the underlying data. For example, models developed for *C. lusitanica* (CULUS) and *C. macrocarpa* (CUMAC) are biased towards younger trees. Growth models for *E. fastigata* are based on data that is predominantly from the Central North Island, and due to the limited amount of data, the model (incorporated in the *E. fastigata* calculator) has not been subjected to validation with independent data. There is no calculator for totara, though growth curves for the species have been developed. However growth curves (for the basal area and volume) ignore mortality, thus estimates would be expected to be over-estimated, particularly at higher ages.
Note that in those cases where productivity is defined using environmental (climate, soil) data, mortality caused by disease or other abiotic factors has, in general, not been integrated within the models.

Table 14: Summary of current state of knowledge of selected alternative species

Species	Productivity index	Productivity defined by climate & soil	Calculator	Soils supporting PSPs	PSP geographic coverage	Density studies
				#Soil orders (of 15)	#Regions (of 15)	#Regions (of 15)
Douglas-fir	✓		✓	11	14	7
Cypresses	✓	CULUS	✓	10 CULUS/CUMAC	15	9
E. fastigata			✓	9	10	2
E. nitens				9	9	4
E. regnans				7	11	6
Redwood	✓	✓	✓	9	10	6
Poplar				3	3	1
Totara				7	6	2
Kauri			✓	4	6	4

Key:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

SI = Site Index; SBAP=Site Basal Area Potential

In conclusion, the current information available for alternative species is not adequate to predict productivity and carbon sequestration accurately throughout New Zealand. In view of the gaps identified in this review, further sample plots should be established; particularly for the poplars, totara, and kauri. To improve the imbalance in the current geographic distribution of PSPs, additional plots should be established in regions currently underrepresented – notably the South Island and Northland. To improve and/or validate current models, further measurements of the reviewed tree species are also require, particularly for *E. fastigata*. These recommendations will improve and PSP database and the models over the long term. To improve predictions in productivity in the short term, it is recommended that other methods are investigated including pair plots with *P. radiata*, process-based modelling, and an improved understanding of drivers of growth for alternative species.

4.10 NEW PLOTS TO FILL GAPS

A total of 421 plots were used to in the analysis of alternative species productivity (Table 15). A total of 80 new plots across 12 sites were strategically located and installed for key alternative species to increase the distribution of plots throughout the country with wood density data and growth data, to address geographically deficiencies. The following sections on wood density of other species incorporate both existing and new data.
Three of these other species were used in the paired plot growth analysis in section 8; *Eucalyptus fastigata*, *Cupressus lusitanica*, and *Sequoia sempervirens*. These species are most suitable for carbon sequestration and had the best geographic spread to determine if alternative species productivity could be robustly predicted from radiata pine productivity.

Table 15: Alternative species used in this study by plot type

Species	Number of existing plots	Number of new plots
Cupressus lusitanica	161	
Eucalyptus fastigata	65	7
Eucalyptus nitens		11
Eucalyptus regnans		17
Eucalyptus saligna		15
Sequoia sempervirens	115	30

5 Improving wood density and growth of eucalyptus using data for Northland

C.L. Todoroki and D.F. Meason

5.1 INTRODUCTION

This report compares the survival, growth, wood density, basal area, and biomass of four eucalypt species, E. *fastigata*, *E. nitens, E.regnans*, and *E. saligna*, growing on two sites in Northland. Comparisons are made with existing growth models and with other allometric relationships, e.g. for estimating above-ground tree biomass. A correction is made to the *E. fastigata* model developed by Van der Colff and Kimberley (2005). Data from this study has been forwarded to augment the Atlas Permanent Sample Plot system.

The four species, E. *fastigata*, *E. nitens*, *E.regnans*, and *E. saligna*, (FAS, NIT, REG, SAL respectively) grew on two sites in Northland (one on Carnation Road, the other on Karaka Road). Each site comprised a series of eucalypt establishment trials, established at 2500 stems per hectare (sph) and thinned to a stocking of 1250 sph at age two. Tree measurements were made when the trees were 24 years of age. Wood density cores were obtained at 21 years for *E. fastigata*, and at 24 years for the other species. The survival, growth, wood density, basal area, and biomass were examined and compared by species.

Main findings:

1) SAL exhibited the greatest survival rate and NIT the least.
2) Forking was more pronounced with FAS, particularly on the CARN site.
3) REG recorded the greatest mean diameter and SAL the least.
4) Tree volume ranking (m^3): REG > FAS > NIT > SAL
5) Core density ranking (kg/m^3): (FAS = SAL) > NIT > REG
6) Stand volume ranking (m^3/ha): (FAS=REG) > SAL > NIT
7) Basal area ranking (m^2/ha): (FAS = REG) > (SAL = NIT)
8) Stem mass ranking (kg/ha): REG = FAS ≥ NIT ≥ SAL

Overall REG and FAS performed well in terms of diameter, volume, basal area, and biomass. FAS and SAL performed well in terms of wood density. However, NIT did not achieve top rankings for any of the measured and calculated factors.

Of the height-diameter models evaluated, the log-transformed diameter models performed best. The Patterson function for FAS provided similar height results based on quadratic mean diameter. However, the Candy model appeared to under-predict NIT Northland growth.

The density-age relationship developed by Meason et al. (2010), while demonstrating a good fit to that derived from the Northland FAS cores, needs to be interpreted with care, as the former study relates to density of the outer 5 cm of cores, while the latter study presented here relates to pith to bark density. Further research is required to develop a relationship linking the two.

5.2 BACKGROUND

Northland sites

The sites were located in Northland, one on Carnation Road, known hereafter as CARN, (35° 34' N, 173° 46.5' W, altitude 195 m), the other on KRKA Road, known hereafter as KRKA, (35° 34' N, 173° 54.5' W, altitude 135 m). The CARN site had a mean annual rainfall of 1917 mm, mean annual temperature of 14.24°C, and gentle slope, while the KRKA site had lower rainfall of 1623 mm, and a slightly greater mean annual temperature of 14.40°C, and a flat slope. Both sites were described as sheltered (Shelbourne et al. 2000), and when established on plots measuring 16 m x 16 m, were planted with 64 trees per plot, 2500 stems per hectare. Tree species included: *E. fastigata* (FAS), *E. nitens* (NIT), *E. regnans* (REG), and *E. saligna* (SAL). At age two, trees on both sites were thinned to a stocking of 1250 sph. The experimental design used in the trials was randomised complete blocks with replications which were generally balanced, except where poor survival necessitated rejection of a few plots.

Study variables

Tree diameter (D) was measured at breast height (cm) and tree top height (H) from the ground to apex (m) when the trees were 24 years old. As heights were not recorded for all trees, estimates of tree heights were derived from diameter-height relationships for each site and species.

Height-diameter models

Three model forms which have been used by various authors (e.g. Ker and Smith, 1955; Curtis 1967), were evaluated for goodness of fit:

1) $H=a+bD$
2) $H=a+bD+cD^2$
3) $H=a+b\ln(D)$

Relationships developed for FAS were subsequently compared with earlier relationships developed for two FAS stands (Oliver et al. 2009) growing in the central North Island (Kaingaroa Nelder and Kapenga). The Kaingaroa Nelder stand was 30 years of age while the Kapenga stand was 8 years of age.

<u>Patterson equation for Fastigata</u>

The height-diameter curve given by the Patterson equation to predict heights across the range of diameters within a stand (Goulding & Shirley, 1979) was also compared. The equation had the form:

$$h = 1.4 + \left(a + \frac{b}{d}\right)^{-2.5}$$

where h is mean top height (m), d is mean top diameter (the quadratic mean diameter of the 100 largest stems per hectare in cm), and a and b are coefficients.

Coefficients *a* and *b* were obtained from a Eucalypt Cooperative report (van der Colff and Kimberley, 2005). They were however transposed in this study, as the coefficients given in the report were inconsistent with a figure showing the relationship. The figure was first used to derive approximate values for the coefficients, and then it was obvious that the coefficients given should be swapped. Coefficients used in this study were:

a = 0.154
b = 4.330

The Patterson function for FAS was based a sample of 854 measurements from 118 plots held in the Permanent Sample Plot (PSP) system. The trees ranged in age from 10 to 66 years, with a mean of nearly 17 years.

Mean top diameter

To derive mean top diameter, the number of stems required to achieve 100 stems per hectare was calculated for both sites using ratios, and then the quadratic mean diameter calculated. The procedure was repeated for trees (i.e. forked stems counted as one tree).

Eucalypt tree volume model

Tree volume (V) was calculated from diameter and height using the general volume equation for eucalypts developed from PSP data (volume table 38). The equation was of the form:

$$V = D^{b1} * (H^2/(H-1.4))^{b2} * e^{b3} + b_4$$

With coefficients $b_1 = 2.009$, $b_2 = 0.757$, $b_3 = -9.703557$, and $b_4 = 0$.

Basal area

Tree basal area was calculated as $\pi*(D/200)^2$ (m^2), plot basal area as the sum of tree basal areas divided by the plot area (generally 0.0256 ha but somewhat less for FAS plots on the KRKA site), and stand basal area (BA, m^2/ha) for each species and site calculated as the mean plot basal area.

Wood density

Wood density was determined from one-sided, pith-to-bark, core samples. The core samples were extracted from NIT, REG, and SAL when trees were 24 years old, whereas density cores of FAS were 21 years old. An estimate of the density of whole stem plus bark thickness was obtained using a conversion factor of 0.905 following Beets et al. (2008).

Mean wood density for the 21 year-old FAS cores were also compared to the age-density equation developed by Meason et al. (2010).

Stem biomass

Stem biomass (SB, kg) was calculated as the product of whole stem density (calculated as 0.905 x core density) and volume:

$$SB = 0.905 \times \text{core density} \times V$$

Aboveground biomass

Aboveground biomass, AGB (kg), was estimated using the general equation of Williams et al. (2005):

$$\ln(AGB) = -2.0596 + 2.1561 \ln(D) + 0.1362 (\ln(H))^2$$

from which carbon content can be calculated as half the aboveground biomass:

$$\text{i.e. } C = ½ \times AGB$$

Statistical analysis

A graphical approach, with box plots, was first applied as a useful visual check for normality, skewness, homogeneity of variance, and detection of outliers (Quinn and Keough 2002) within sites. Comparisons were made using analysis of variance (ANOVA) and were followed by post hoc testing, using the Tukey Honestly Significant Difference (HSD) for pairwise comparisons. An alpha value of 0.05 was used throughout.

5.3 RESULTS AND DISCUSSION

Of the four Eucalypt species, SAL had the most surviving trees, while NIT appeared to have the highest mortality rate, with the lowest number of surviving trees (Table 1). FAS had the greatest percentage of forked trees, particularly on the CARN site.

Table 1. Number of trees of each species assessed on the Northland sites. Trees were 24 years of age when assessed for height and diameter. Core density samples were from 21-year–old FAS and 24 year-old NIT, REG, and SAL trees.

Site	Species	#plots	#trees	#trees/ hectare	#forked trees	%forked	#core samples
CARN	FAS	6	144	938	33	23	9
	NIT	6	58	378	3	5	24
	REG	6	85	553	3	4	24
	SAL	6	160	1042	7	4	25
KRKA	FAS	9	90	391	7	8	15
	NIT	5	42	328	2	5	19
	REG	6	97	632	2	2	27
	SAL	6	149	970	9	6	25
Combined	FAS	15	234	609	40	17	24
	NIT	11	100	355	5	5	43
	REG	12	182	592	5	3	51
	SAL	12	309	1006	16	5	50

Given that there were 938 fastigata trees per hectare at CARN, and 391 at KRKA, the quadratic mean diameter, QMD, was based on the 15 largest trees/stems on the former site and 23 on the latter. QMD at CARN was 59 cm for stems (i.e. forks treated as separate stems) and 64 cm for trees (i.e. with forks combined). The equivalent values for KRKA were 50 and 53 cm respectively.

Diameter and height (actual measurements only) distributions of the eucalypt samples are shown, by site, in box plots of Figure 1.

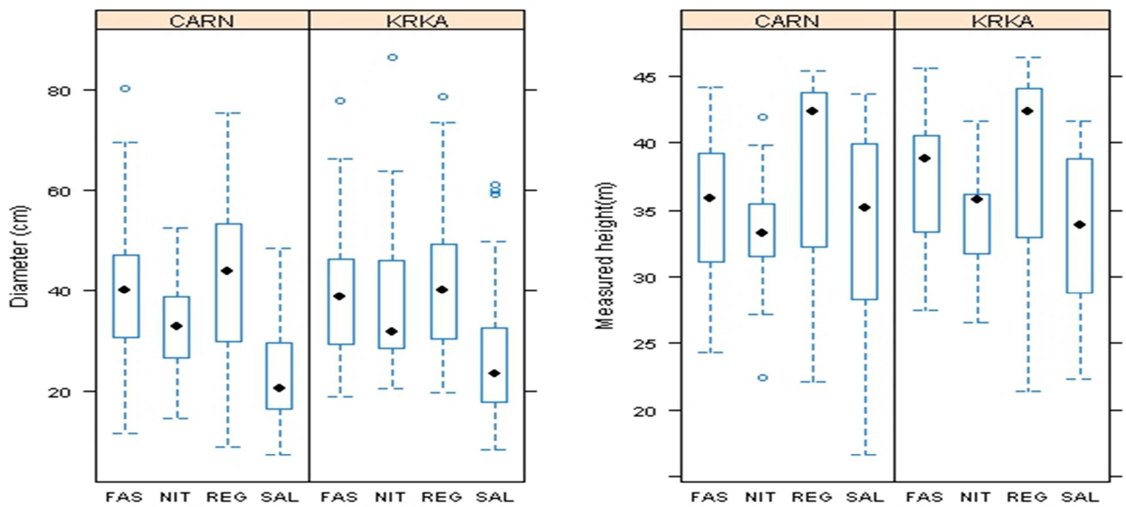


Figure 1. Summary of data collected from the two Northland sites of Eucalypts.

Mean tree diameter was greatest for REG, followed closely by FAS and NIT, and least for SAL (Table 2). Analysis of variance indicated that differences in diameter between species, as assessed on all stems, was highly significant ($p < 0.001$). There was also strong evidence to suggest statistically significant differences between sites ($p = 0.02$). However when forked stems were treated as single trees and diameters of forked trees calculated to give the same combined cross-sectional area at breast height (i.e. $D = \text{sqrt}(D_1^2+D_2^2+D_3^2)$ differences between sites were no longer significant ($p=0.16$).

Hereafter, all diameters, estimated heights, volumes, and other variables refer to those obtained from single trees using the equivalent diameter as defined above.

Table 2. Mean diameter (± standard deviation) of measured stems, trees, and height-assessed subsamples.

	All stems		All trees		Height-assessed subsample	
Species	N	D (cm)	N	D (cm)	N	D (cm)
CARN						
FAS	178	36.2±11.5 b	144	40.3±12.7a	44	39.4±9.3
NIT	61	32.3±7.3 c	58	33.1±7.9b	46	34.6±7.7
REG	87	41.4±14.7 a	85	41.9±14.7a	38	44.1±14.0
SAL	169	22.3±9.7 d	160	23.2±9.4c	42	29.9±10.3
KRKA						
FAS	94	37.1±9.4 ab	90	38.8±10.8a	36	39.8±9.9
NIT	44	36.2±12.0 b	42	37.4±13.2a	15	35.6±11.6
REG	99	41.0±13.0 a	97	41.5±13.0a	19	43.6±11.7
SAL	158	25.4±10.7 c	149	26.2±10.8b	20	30.6±7.1
Combined sites						
FAS	272	36.5±10.8 b	234	39.7±12.0a	80	36.2±5.2
NIT	105	34.0±9.7 b	100	34.9±10.6b	61	33.6±3.7
REG	186	41.2±13.8 a	182	41.7±13.8a	57	38.5±7.1
SAL	327	23.8±10.3 c	309	24.6±10.2c	62	33.5±6.9

Height-diameter relationships

Parameters for the three height-diameter models, by species and site, are shown in Table 3. The third model form H=a+bln(D) provided the best overall-result, being appropriate to all species across both sites. Greater height-growth, for the same diameter, was particularly pronounced for FAS growing on KRKA (Table 4, Figure 1).

Table 3. Parameters of models predicting height, H, from breast-height diameter D.

Equation	Site	Species	a	b	c	SE(a)	SE(b)	SE(c)	R^2
H=a+bD	CARN	FAS	18.5	0.425		2.4	0.059		0.55
		NIT	26.1	0.212		2.3	0.064		0.20
		REG	20.0	0.422		2.1	0.045		0.71
		SAL	16.1	0.579		2.1	0.066		0.66
	KRKA	FAS	22.5	0.374		2.1	0.053		0.59
		NIT	25.5	0.244		2.2	0.059		0.57
		REG	14.9	0.537		3.9	0.087		0.69
		SAL	12.8	0.677		3.3	0.107		0.69
	Combined	FAS	20.3	0.403		1.7	0.041		0.55
		NIT	25.7	0.227		1.7	0.046		0.29
		REG	18.7	0.451		1.9	0.041		0.69
		SAL	15.5	0.596		1.7	0.055		0.66
$H=a+bD+cD^2$	CARN	FAS	-7.19	1.72	-0.0155	7.99	0.39	0.0046	0.65
		NIT	-2.95	1.89	-0.0232	8.64	0.49	0.0067	0.37
		REG	-1.79	1.51	-0.0122	3.55	0.16	0.0018	0.87
	Combined	FAS	5.09	1.17	-0.0092	5.64	0.28	0.0033	0.59
		REG	-2.00	1.49	-0.0118	3.79	0.18	0.0020	0.81
H=a+bln(D)	CARN	FAS	-29.14	17.66		8.07	2.21		0.60
		NIT	4.85	8.12		7.62	2.16		0.24
		REG	-28.6	18.03		5.50	1.47		0.81
		SAL	-21.1	16.34		6.09	1.82		0.67
	KRKA	FAS	-16.9	14.85		7.50	2.05		0.61
		NIT	1.01	9.40		8.06	2.28		0.57
		REG	-41.6	21.4		12.1	3.24		0.72
		SAL	-38.6	21.2		10.5	3.10		0.72
	Combined	FAS	-23.4	16.3		5.76	1.57		0.58
		NIT	3.31	8.60		5.76	1.63		0.32
		REG	-32.0	18.9		5.21	1.39		0.77
		SAL	-23.5	17.0		5.19	1.54		0.67

Table 4. Parameters and fit statistics of a mixed-effects model, based on the relationship H = a +bln(D), developed by grouping trees within plots within sites.

Equation	Site	Species	a	b	SE(a)	SE(b)	RMSE	MAPE
	Combined	FAS	-22.6	16.1	5.54	1.49	3.33	7.29
		NIT	2.35	8.87	5.43	1.53	2.99	6.72
		REG	-32.2	19.0	4.72	1.25	3.39	7.57
		SAL	-23.5	17.0	5.19	1.54	3.91	9.91

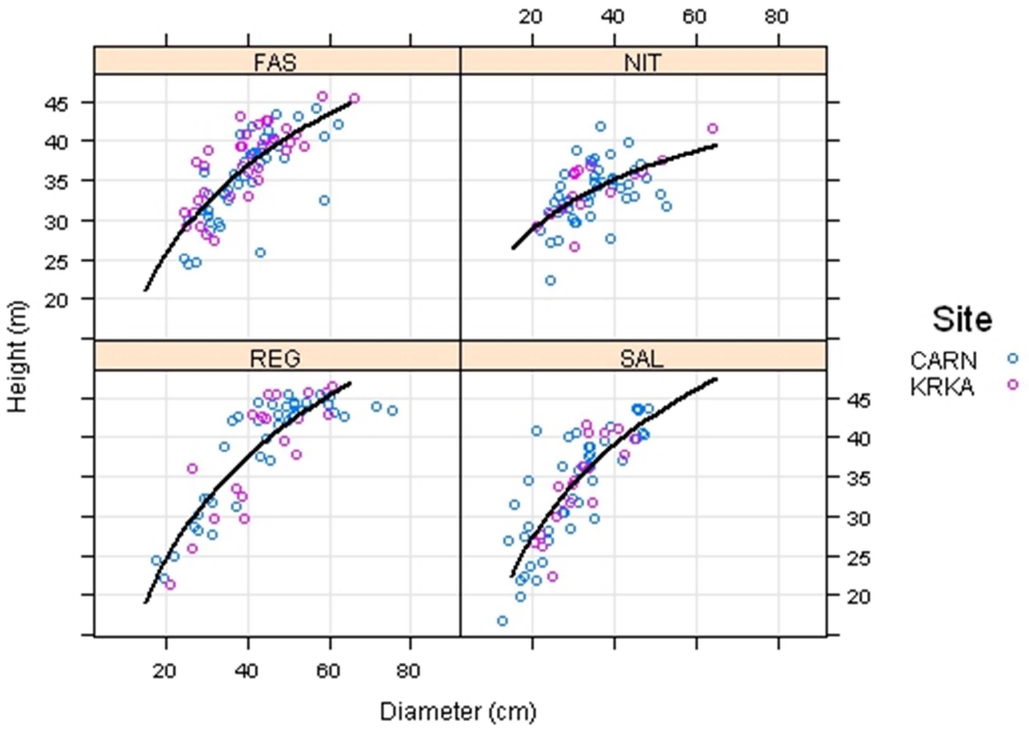


Figure 2. Diameter-height relationships given by the form y = a + b ln (x). Model coefficients are given in Table 4.

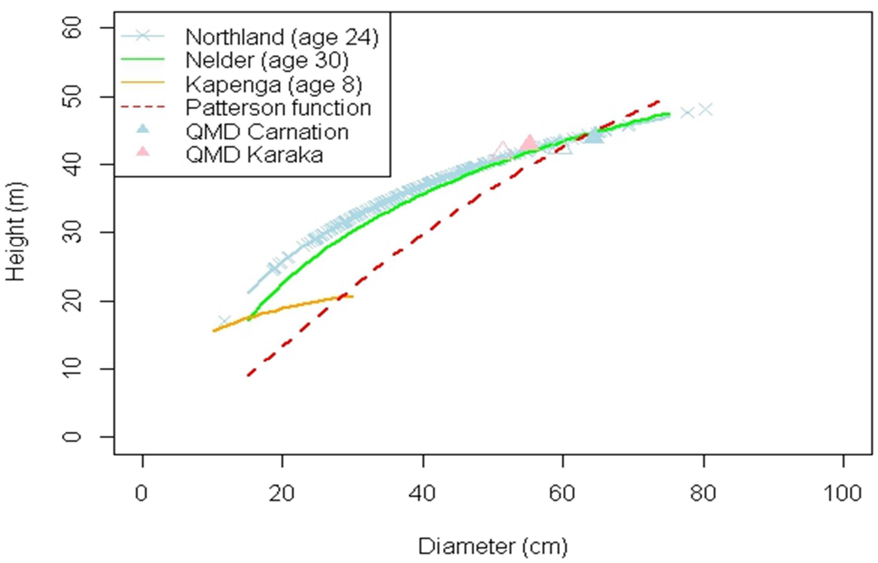


Figure 3. Comparison of Northland FAS growth with an older Nelder stand, a younger Kapenga stand, and the Patterson function. Quadratic mean diameter (QMD) is shown for both Northland sites for trees (forks combined – filled triangles) and stems (hollow triangles).

Table 5. General statistics of measured and estimated tree heights and volumes.

Site	Height of measured trees (m)	Estimated Height (m)	Estimated Volume (m^3)	Core density (kg/m^3)
		CARN		
FAS	35.3±5.3	35.4±5.8	1.83±1.32	492±48
NIT	33.4±3.6	33.1±2.4	1.09±0.57	431±30
REG	38.8±7.0	37.1±7.4	2.15±1.52	382±34
SAL	33.4±7.4	28.5±6.5	0.58±0.57	473±55
		KRKA		
FAS	37.4±4.8	36.6±4.1	1.68±1.13	493±47
NIT	34.2±3.8	34.0±2.5	1.54±1.42	441±47
REG	38.3±7.6	37.4±6.7	2.03±1.51	388±102
SAL	33.5±5.8	30.5±9.2	0.78±0.80	499±56
		Combined sites		
FAS	36.2 a	35.9 a	1.78 b	493 a
NIT	33.6 b	33.5 b	1.28 c	435 b
REG	38.5 a	37.3 a	2.08 a	385 c
SAL	33.4 c	29.5 c	0.68 d	486 a

Tree volume

Estimated tree volumes (Table 5) did not differ significantly between sites (p=0.135). Within species, differences in means were statistically significant:
Tree volume ranking (combined sites): REG > FAS > NIT > SAL

Density

Core density distributions are shown in Figure 4. There appears to be slightly less variation within species on the CARN site. However, on both sites, the lowest median density is associated with the REG cores, followed by the NIT cores. FAS and SAL have higher wood density, on average, than either NIT or REG. Of note are two very low density core readings on the KRKA site for Regnans. The median shown on the plot corresponds to a value of 405 kg/m^3 while the mean value is 17 less at 388 kg/m^3.

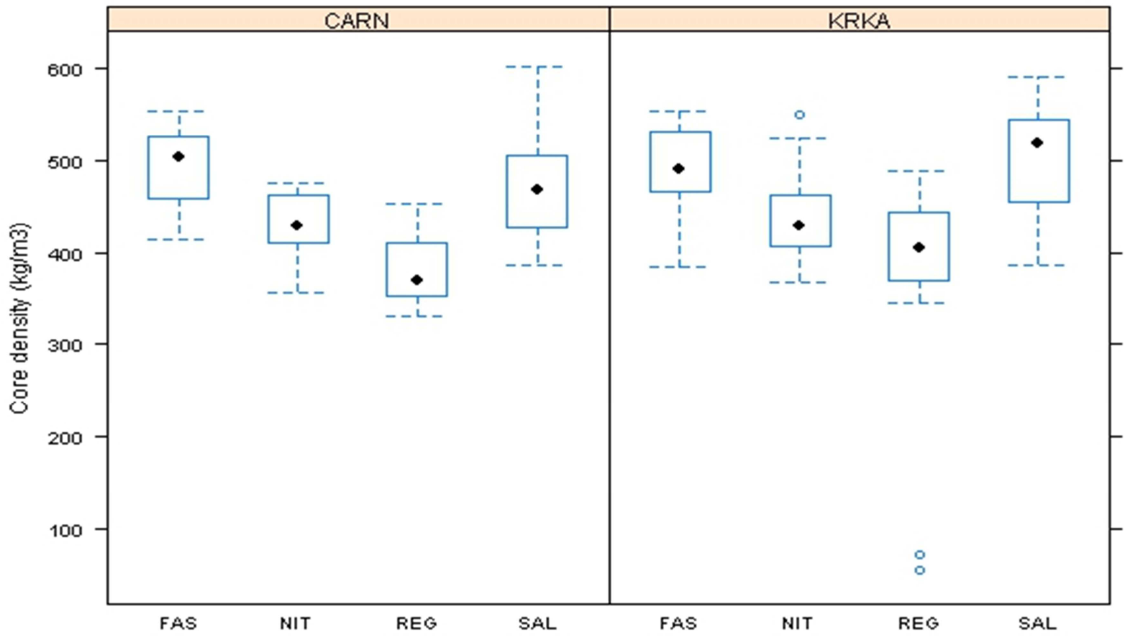


Figure 4. Eucalypt wood density collected from breast height core density samples.

Density of the corewood samples did not differ significantly between sites ($p = 0.178$), however there were significant differences between species. With data grouped by species results of ANOVA followed by Tukey's HSD test gave the following density rankings:
FAS = SAL > NIT > REG
However, since FAS samples were younger, it would be reasonable to assume FAS > SAL > NIT > REG
There was no apparent relationship between density and diameter (Figure 5) for FAS, NIT, and REG. However, for SAL density tended to increase with increasing diameter ($R^2 = 0.34$).

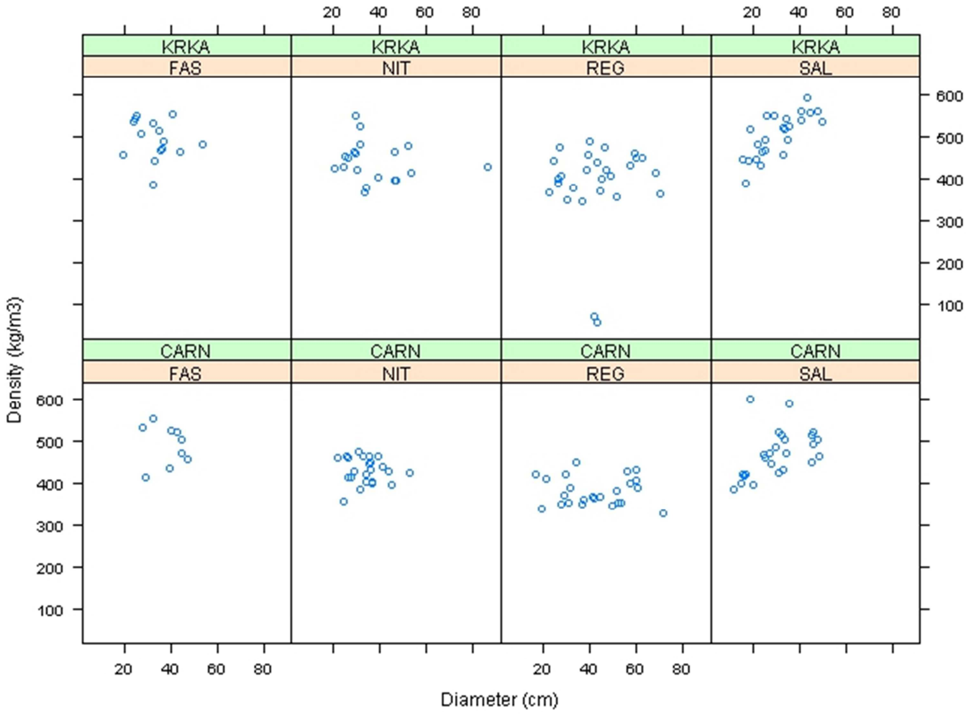


Figure 5. Relationship between diameter and density of breast height core samples.

The mean density of the cores from the combined FAS stands, at age 21 years, at 493 kg/m^2 (Table 3), demonstrated a good fit to the density-age relationship developed by Meason et al. (2010), Figure 6.

Stand-level results

Figure 6 shows the range, upper and lower quartiles, and median of total tree volume and basal area on a per hectare basis as calculated for the eucalypt plots. Basal area trends were similar to volume trends.

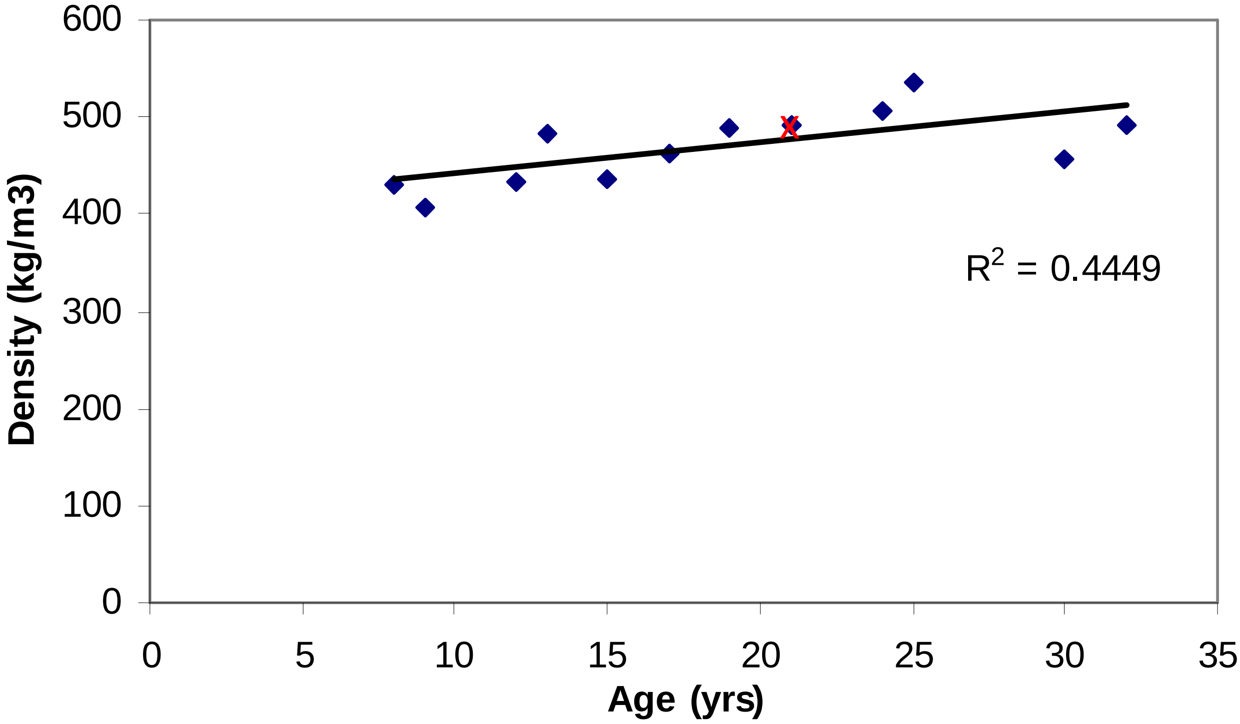


Figure 6. Relationship between E. fastigata outerwood (outer 5 cm) wood core density and age (Meason et al., 2010) with mean density of the Northland cores superimposed at age 21.

Volume and basal area

Two of the six FAS plots on CARN exhibited plot volumes and basal areas that were considerably greater than the mean values. Mean plot volume of FAS on CARN was 1719 m^3/ha. In comparison, plots, A2 and C7, had plot volumes of 2519 and 2545 m^3/ha respectively. Both plots comprised forked trees (7 forked trees on A2 and 6 on C7) however the largest trees on each of the plots were single leaders. One tree on A2 (Tree 21) had a diameter of just over 80 cm, while on C7 the largest single leader tree had a diameter of nearly 70 cm (Tree 28).

NIT plots were of low volume and basal area. Neither site had NIT volume exceeding 1000 kg/m^3. The maximum volume, associated with a plot on KRKA, was 853 m^3/ha.

Ranking total volume across both sites (Table 6) gives: (FAS=REG) > SAL> NIT.

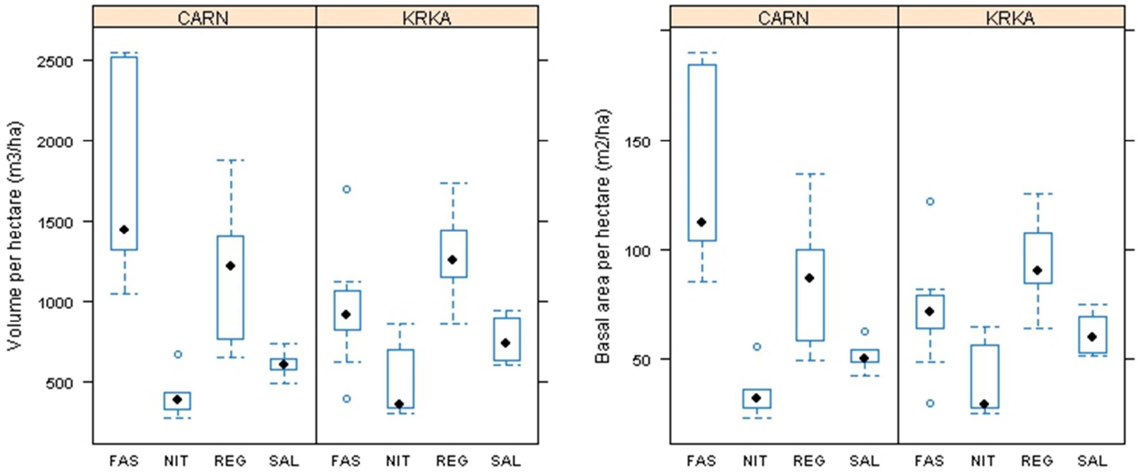


Figure 6. Distributions of volume and basal area per hectare by site and species.

Table 6. Stand level statistics on a per hectare basis and ratio of stem to estimated aboveground biomass (AGB).

Site	Species	Total volume (m^3/ha)	Basal area (m^2/ha)	Stem biomass (M kg/ha)	AGB (M kg/ha)	Stem:AGB
CARN	FAS	1719 a	131 a	0.756 a	2.397 a	0.323 ab
	NIT	411 c	34 c	0.161 c	0.533 c	0.302 b
	REG	1187 ab	86 b	0.406 b	1.707 ab	0.242 c
	SAL	604 bc	51 bc	0.258 bc	0.766 bc	0.338 a
KRKA	FAS	939 ab	71 ab	0.478 a	1.302 ab	0.329 a
	NIT	507 b	41 b	0.197 b	0.691 b	0.300 ab
	REG	1281 a	94 a	0.467 a	1.827 a	0.250 b
	SAL	758 b	61 ab	0.342 ab	0.996 b	0.346 a
Combined	FAS	1251 a	95 a	0.571 a	1.740 a	0.327 ab
	NIT	454 c	37 b	0.177 c	0.604 b	0.301 b
	REG	1234 a	90 a	0.437 ab	1.767 a	0.246 c
	SAL	681 b	56 b	0.300 bc	0.881 b	0.342 a

Basal area per hectare was greatest for REG and least for NIT on both sites. On the combined sites FAS was found to be equivalent to REG, and SAL equivalent to NIT. Thus the rank order for basal area on the combined sites is:
(FAS=REG) > (SAL=NIT).

Based on the Candy (1997) models, NIT at age 24 years and with a volume of about 450 m^3/ha, corresponds to growth on a site with a site index of 24 (Figure 8b). This in turn corresponds to a basal area of about 27 m^2/ha (Figure 8a), a lower result than that found for the Northlands NIT (37 m^2/ha).

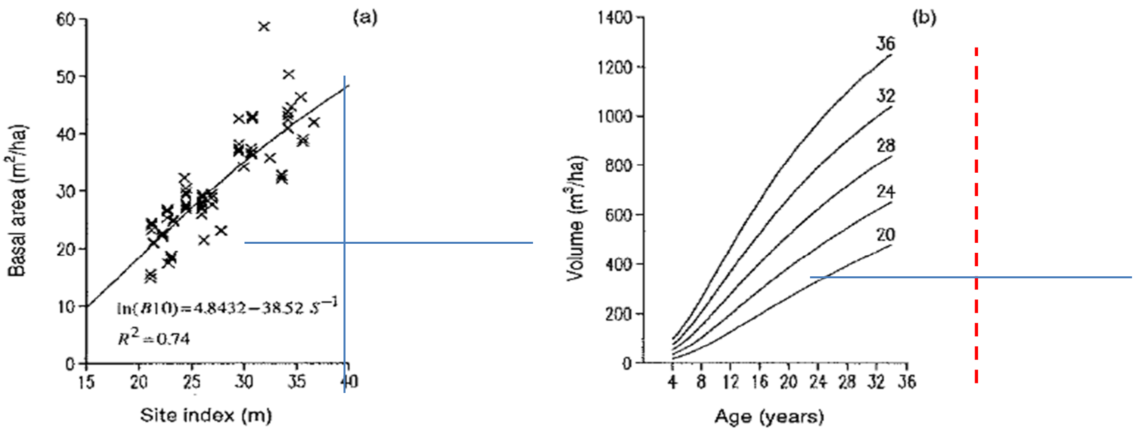


Figure 8. Comparsion of Northland NIT results with the Candy growth model. Source: Candy (1997).

Stem and aboveground biomass

Figure 9 shows boxplots of stem and aboveground biomass, estimated using mean plot density times volume times 0.905, and the equation of Williams (2005) respectively. Trends for stem biomass and aboveground biomass are similar. NIT clearly demonstrates the least mass and REG has considerably greater mass (which is statistically significantly different) than NIT. SAL's mass lies between those for these two species. However, results for FAS differ between sites. Overall, the stem biomass ranking is REG = SAL > NIT, which is consistent for both sites.

While trends were similar, the ratio of stem mass to AGB (Table 4) was about 25-35%. This contrasts with that found for 8-year old FAS by Oliver et al. (2009) at Kapenga (64%) and 30 year-old FAS in the Nelder trial at Kaingaroa (78%), suggesting that the general equation for predicting AGB (Williams 2005), developed from 11 sites across the Northern Territory, Queensland and New South Wales, may not be suitable for these Northland Eucalypts.

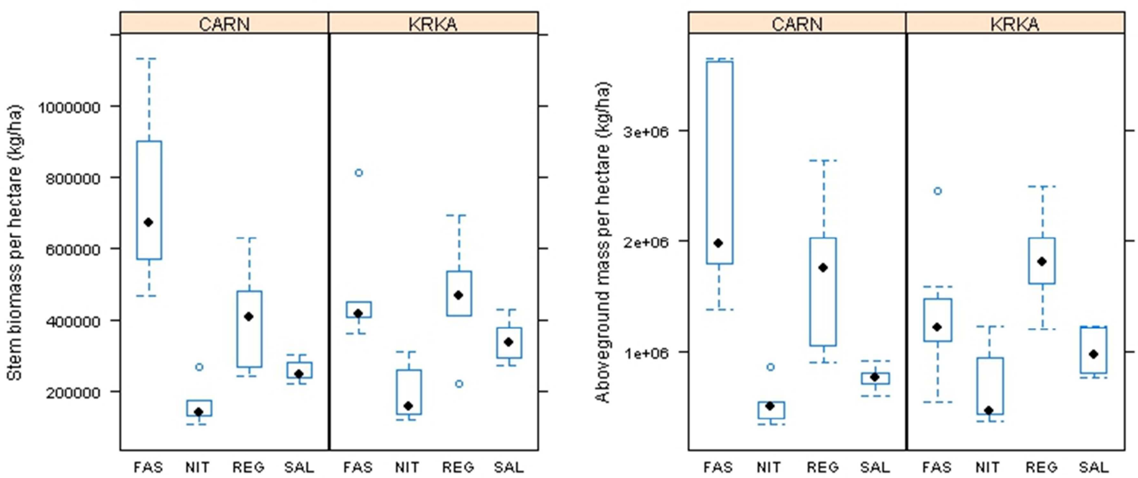


Figure 9. Distributions of stem and estimated aboveground biomass (following Williams 2005) per hectare by site and species.

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6 Improving wood density of cypress

C.L. Todoroki and D.F. Meason

<u>Overview</u>

The purpose of this study was to determine whether sufficient data exist to develop wood density by age profiles for two cypress species, *Cupresses lusitanica* and *C. macrocarpa,* across a range of regions and growth environments.

Wood density data collated for analysis included: 1) Studies contained in Scion’s wood density database following an update by Beets et al. (2008); 2) Cores estimated by Silviscan and discs cut at 3 m intervals from 21 year-old trees grown on the Scion campus grounds (Low et al. 2005); 3) Density data from progeny trials at Gwavas (Hawkes Bay) and Strathallan (in Southland), courtesy of Charlie Low. Reports on Scion's science information database (SiDNEY) and data available on the Atlas Permanent Sample Plot (PSP) database were also investigated, to fill gaps.

Gaps in knowledge, in terms of tree age and regions were identified. Relationships between age and density were developed with existing data.

6.1 WOOD DENSITY DATABASE

The wood density database (Beets et al. 2008) provides the most comprehensive review of wood density surveys conducted in New Zealand on cypresses, and other species. Density measurements were obtained from a variety of studies; some captured whole stem wood basic density, some breast height outerwood (resin-extracted and unextracted – at a range of depths) basic density, and others whole stem wood plus bark density. For each study, the location, tree species, stand age, number of trees, merchantable log basic density (mean, minimum, maximum), whole stem wood and bark density, breast height outerwood (0-50mm depth or in some cases the outer 5 rings) basic density (mean, minimum, maximum), breast height (50-150mm depth) basic density (mean, minimum, maximum), and reference to data source, if available, were entered in the database.

Using the database, Beets et al. (2008) found regional differences in wood density for *C. lusitanica* and *C. macrocarpa*. Beets et al also found that tree age significantly influenced whole stem density of *C. lusitanica*. The authors further noted "The lack of information on the effects of tree age probably does not matter for carbon stock estimation purposes for trees in natural forest plots, because the bulk of the carbon is likely to be contained in large trees in mature stands. The lack of data at young ages may, however, be an issue for young stands that are included in Emissions Trading Scheme (ETS) and in Kyoto compliant Land Use and Carbon Analysis System (LUCAS) plots, particularly those from the more common species such as *Pseudotsuga menziesii*, cypress, eucalyptus, and redwood."

Results are summarised in Table 1 and Table 2. In Table 1, linear regressions with stand age are given (intercept, slope and p-value) to indicate if age information is important, while Table 2 summaries wood density by region.

Table 1. Wood density averaged across all studies compiled by Beets et al. (2008). The upper half of the table gives whole stem density of wood plus bark (WSD), and the lower half gives breast height outerwood basic density (BHBD). Note that both sets of values were from the same studies. P-values for region and age are also given.

	Whole stem wood plus bark studies					Age regression		
Species	Mean WSD	No. regions	No. studies	No. trees	Region P-value	Intercept	Slope	P-value
C. lusitanica	336	9	24	283	0.0261	316	1.2	0.0225
C. macrocarpa	370	9	24	141	0.0008	342	0.7	0.0537
	Breast height outerwood studies					Age regression		
	Mean BHBD	No. regions	No. studies	No. trees	Region P-value	Intercept	Slope	P-value
C. lusitanica	361	9	24	283	0.0261	339	1.3	0.0225
C. macrocarpa	396	9	24	141	0.0008	367	0.8	0.0537

Table 2. Whole stem (wood and bark) density and breast height outerwood basic density by species and region. Source: Beets et al. (2008).

Region	*C. lusitanica*		*C. macrocarpa*	
	Whole stem	Breast height	Whole stem	Breast height
Northland	372	399	413	443
Auckland	321	344	.	.
Bay of Plenty	356	382	353	379
Waikato	357	383	.	.
Gisborne	328	352	331	355
Hawkes Bay	340	365	376	403
Taranaki	337	361	356	382
Wanganui/ Manawatu	327	351	391	419
Wellington	.	.	369	396
Nelson	386	415	.	.
Marlborough	.	.	.	.
Westcoast	.	.	380	408
Canterbury	.	.	418	448
Otago	.	.	.	.
Southland	.	.	.	.

Regional gaps apparent in Table 2 are illustrated in Figure 1. Canterbury, Marlborough, Otago, Southland, West Coast, and Wellington are not represented in the *C. lusitanica* wood density studies, while Auckland, Marlborough, Nelson, Otago, Southland, Waikato are not represented in the *C. macrocarpa* wood density studies. Note that density data from the Strathallan progeny trial in Southland (discussed later in this report) provides some new information that addresses this regional gap for 11 year-old *C. macrocarpa*.

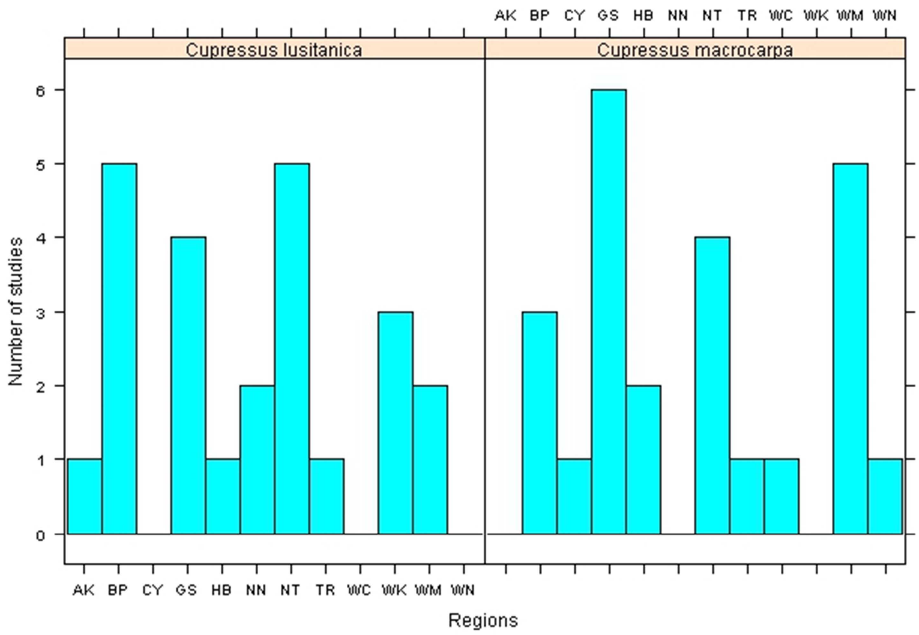


Figure 1. Regional distributions of *C. lusitanica* & *C. macrocarpa* trees in the wood density database. Regional codes are provided in Table 3.

Current PSP stands could be utilised to fill some of the gaps (Table 3). For *C. lusitanica*, PSP stands currently exist in Canterbury, West Coast, and Wellington, but not in

Marlborough, Otago, and Southland. For *C. macrocarpa*, PSP stands currently exist in Marlborough, Otago, Southland, and Waikato, but not in Auckland or Nelson.

Table 3. Current PSP stand age statistics: min-max; mean.

Region		*C. lusitanica*		*C. macrocarpa*	
		Min-max	mean	Min-max	mean
Northland	NT	22-29	23	21-33	22
Auckland	AK	17-21	18	.	.
Bay of Plenty	BP	10-44	21	17-23	17
Waikato	WK	18-82	25	19-77	23
Gisborne	GS	12-37	24	11-12	12
Hawkes Bay	HB	28-45	31	25	25
Taranaki	TR	46	46	47	47
Wanganui/Manawatu	WM	27	27	52	52
Wellington	WN	20-27	24	25-65	38
Nelson	NN	14	14	.	.
Marlborough	MB	.	.	20-31	22
Westcoast	WC	16-29	21	26-31	28
Canterbury	CY	3-52	30	14-38	22
Otago	OT	.	.	18-66	29
Southland	SD	.	.	25-31	27

Within the wood density database, stand age ranged from 9 to 65 for *C. lusitanica* and from 12 to 70 for *C. macrocarpa*, with mean ages of 27 and 29 years, respectively. However age classes were often represented by single trees or stands and some age classes were not represented (Figure 2).

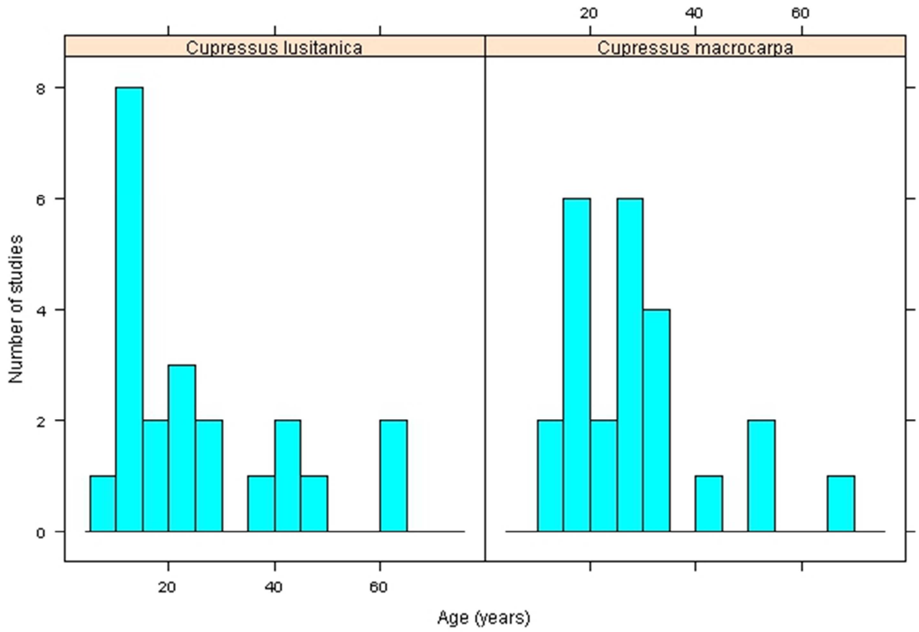


Figure 2. Age distribution of *C. lusitanica* and *C. macrocarpa* stands in wood density database.

The relationship between age and mean log density was stronger for *C. lusitanica* than *C. macrocarpa* (Figure 3). The logarithmic transform of age provided a better relationship than a simple linear relationship for *C. lusitanica*, however for *C. macrocarpa* there was little difference in terms of R^2 values and residual plots. Figure 3 also shows the linear relationships between age and breast height outerwood density (refer Table 1).
The uppermost *C. lusitanica* outlier (age 14, density 431 kg/m^3) was for a Northland stand (Figure 3) while the lowermost outlier was an 11 year-old stand from Gisborne. The two lowermost *C. macrocarpa* densities were 332 kg/m^3 for a 28 year old stand in Hawkes Bay and 334 kg/m^3 for a 19 year old stand in Gisborne.

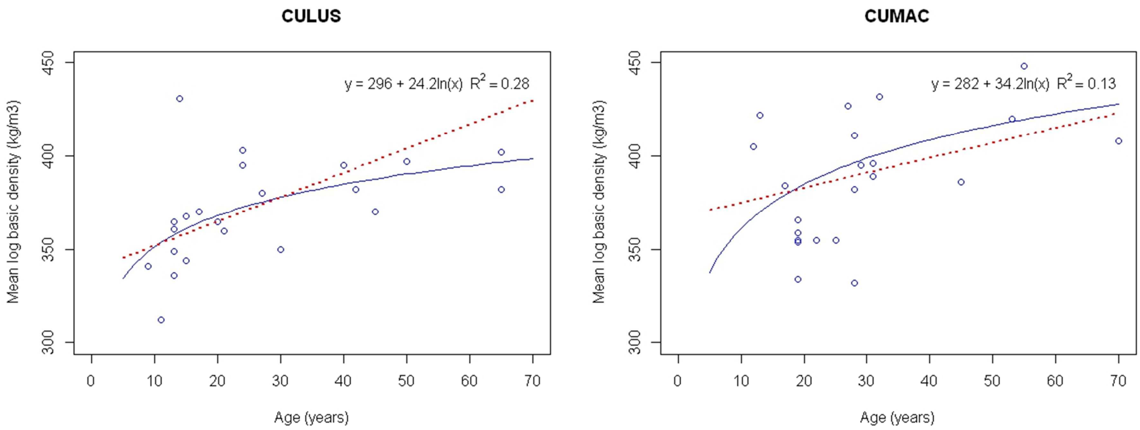


Figure 3. Relationship between stand age and mean log density for *C. lusitanica* and *C. macrocarpa* stands. Linear relationships between age and mean breast height outerwood density (after Beets et al. 2008) are also shown.

6.1.1 Young Cypress Trial

<u>Siliviscan density data from Scion campus trees</u>

Density derived from the 21 year-old trees (18 *C. lusitanica* and 17 *C. macrocarpa*) via Silviscan of 10 mm pith-to-bark increment cores extracted at breast height are shown in Figure 4. Mean values for each species are shown in Figure 5. Note that only 15 rings are shown due to data beyond ring 15 being unreliable. While the most vigorous trees had 19 rings at 1.4 metres, the rest had 17 or 18 rings. However, there was difficulty in apportioning true ring boundaries as the cypresses are known to produce false rings. Therefore, as the density data does not reflect the true value for a 21 year-old tree, tree age is approximated to 19 years.

Density trends from pith to bark, as assessed by Silviscan, are similar for both species. The mean density of *C. macrocarpa*, when averaged from pith-to-bark is about 12% higher than that of *C. lusitanica*.

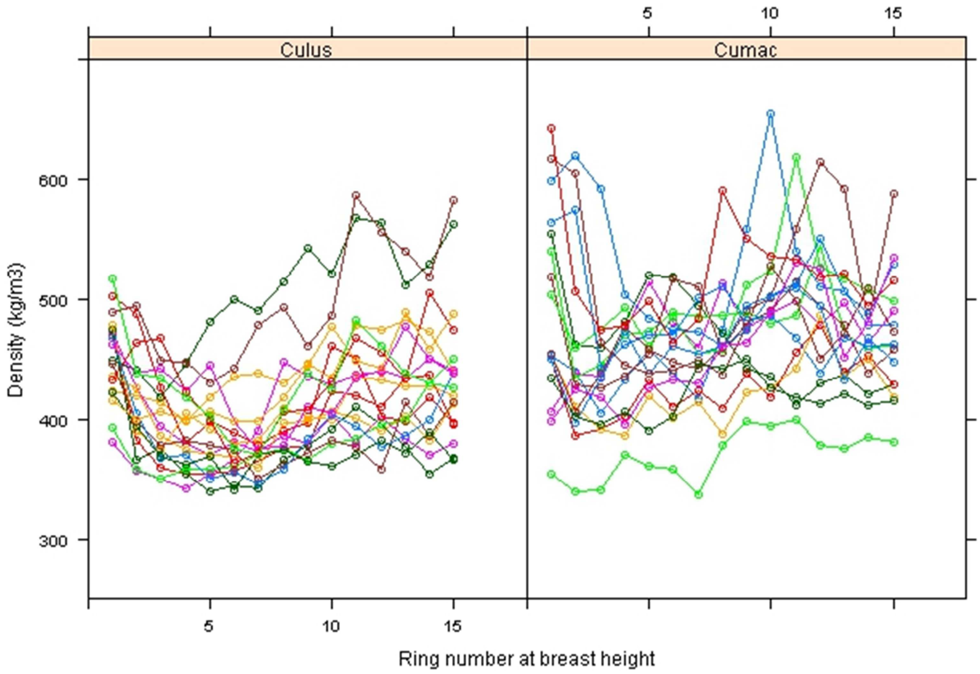


Figure 4. Silviscan density data by ring number from pith derived from breast height cores.

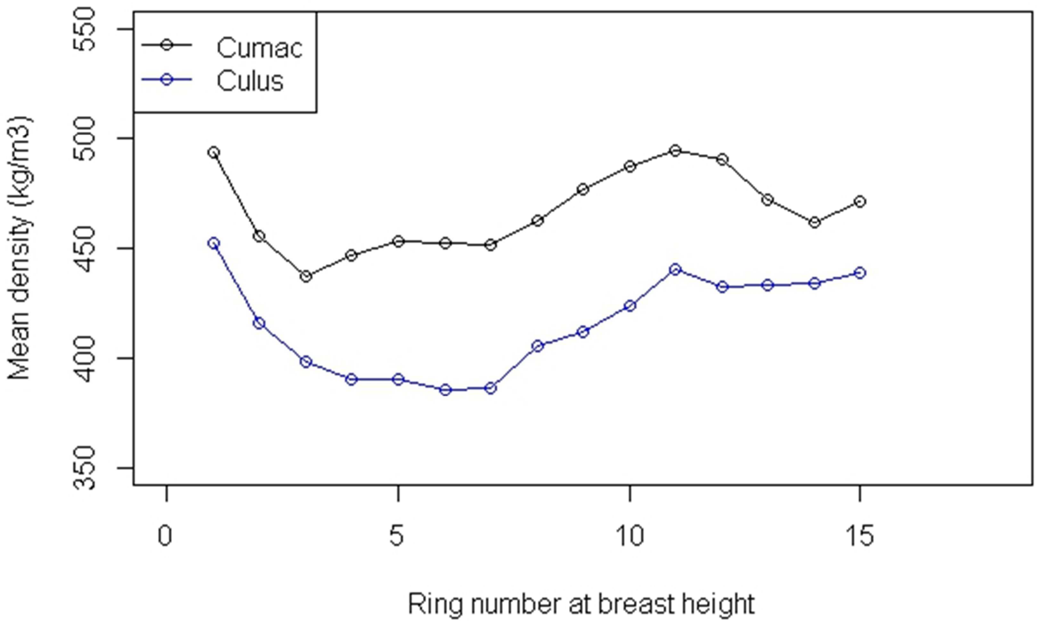


Figure 5. Mean density derived from Silviscan data, measured by ring number in the pith to bark direction, of 18 *C. lusitanica* (bottom line) and 17 *C. macrocarpa* (top line) breast height cores.

Mean weighted density for each breast height core sample was calculated using ring width, (Figure 6). Mean weighted density was 408 kg/m^3 for *C. lusitanica* and 457 kg/m^3 for *C. macrocarpa*. The rather high density values reflect that Silviscan estimates air-dry density (typically 12-15% moisture content) rather than basic density. To estimate basic density for *C. lusitanica* and *C. macrocarpa* from air-dry density data from Silviscan, conversion factors were derived from *C. lusitanica* data extracted from a report by McConchie and Young (1976), and from algebraic rearrangement of the equation derived by Young (1983) for *C. macrocarpa* (refer below for further details), to give 341 and 387 kg/m^3, respectively.

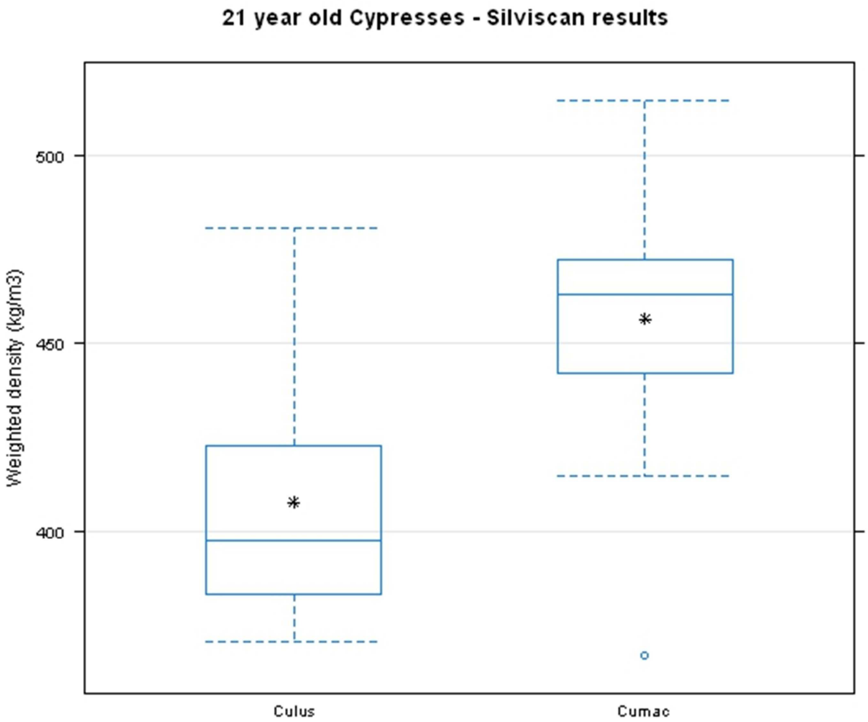


Figure 6. Weighted mean air-dry density derived from Silviscan breast height cores. Box plot whiskers extend to the most extreme data points, provided they are no more than 1.5 times the interquartile range from the box. Outliers, i.e. points outside the whiskers, are denoted as circles. The horizontal line within the box denotes the median, and the asterisk denotes the mean.

Variation in basic density of discs sampled at 3 m height intervals is shown in the left panel of Figure 7. While the majority of trees show an initial drop in density with increased height, this trend is not consistent between all trees. The right panel shows estimates of mean tree basic density derived from the discs. The higher density of *C. macrocarpa* is clearly evident.

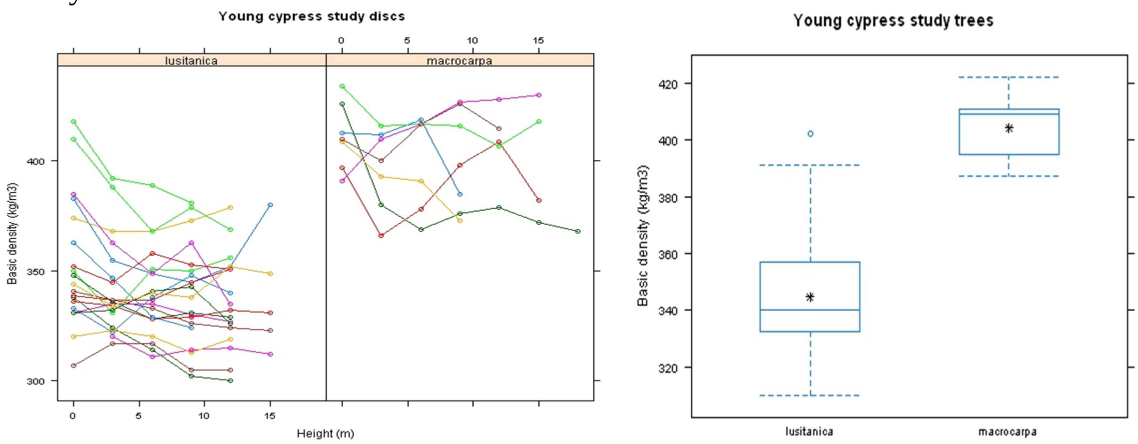


Figure 7. Basic density of discs at 3 m height intervals (left) and mean tree density derived from weighted means of the discs, (right) of 21-year old cypress trees. Symbols are as described for Fig. 6.

An alternative estimate of basic density at breast height was obtained by calculating the average of the discs at 0 and 3 m. The results are shown in Figure 8. Overall, mean breast height basic density of *C. lusitanica* was about 350 kg/m^3 and *C. macrocarpa* 404 kg/m^3, which are slightly higher than breast height basic density estimates derived from Silviscan. Overall, mean tree density was 345 and 405 kg/m^3 for *C. lusitanica* and *C. macrocarpa* respectively.

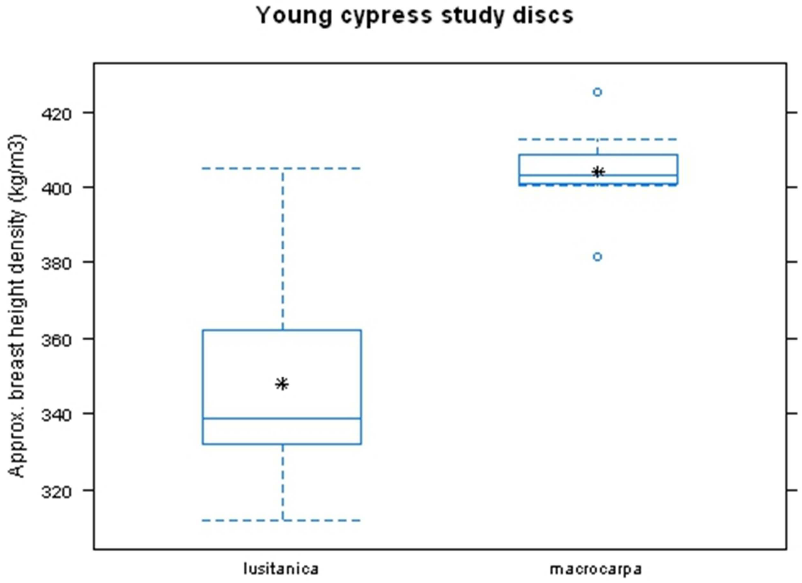


Figure 8. Estimated breast height basic density of 21-year old cypress trees grown on campus at Scion. Symbols are as described for Fig. 6.

6.1.2 Strathallan macrocarpa and Gwavas lusitanica progeny trials

The trial design of the Gwavas *C. lusitanica* progeny trial is a single-tree plot, sets-in replications layout with just over 100 families, divided into six sets of 19 trees plus a control seedlot from the Tairua seed stand. The parent trees were mainly selected as outstanding individuals in New Zealand stands, with some families coming from breeding programs in Kenya and some families from Colombia.

One tree of each family was assigned to each replicate, so each family had 30 trees in the trial. The 30 or so families were selected on the basis of above average growth rate, good branching and low levels of malformation and the 5-6 trees within each family selected for sampling were chosen on the basis that they were the best of the 30 trees available per family.

The trees, though not a random sample of a stand of that age, can be considered as representative of stands established from seed collected from these individuals (2 seedlots in 1999 / 2000) or more recent stands established from seed collected in PROSEED's seed orchard of the best phenotype from these families that were grafted into their Amberley seed orchard.

The Strathallan *C. macrocarpa* trial is the same layout as the Gwavas *C. lusitanica* progeny trial, with the families originating from outstanding trees in New Zealand stands. The best growing families were selected for density core sampling. Resistance to cypress canker (*Seiridium* species) was an additional selection criterion.

When assessed for density, *C. lusitanica* stands at Gwavas were 12 and 13 years old. *C. macrocarpa* stands were 12 years old at Gwavas and 11 years old at Strathallan. Mean density of *C. macrocarpa* at Gwavas was 386 kg/m^3 while that at Strathallan was 364 kg/m^3. However, the difference in means was not significantly different ($\alpha = 0.05$). Density at breast height obtained from sample cores is shown by site, species, and age in Figure 9.

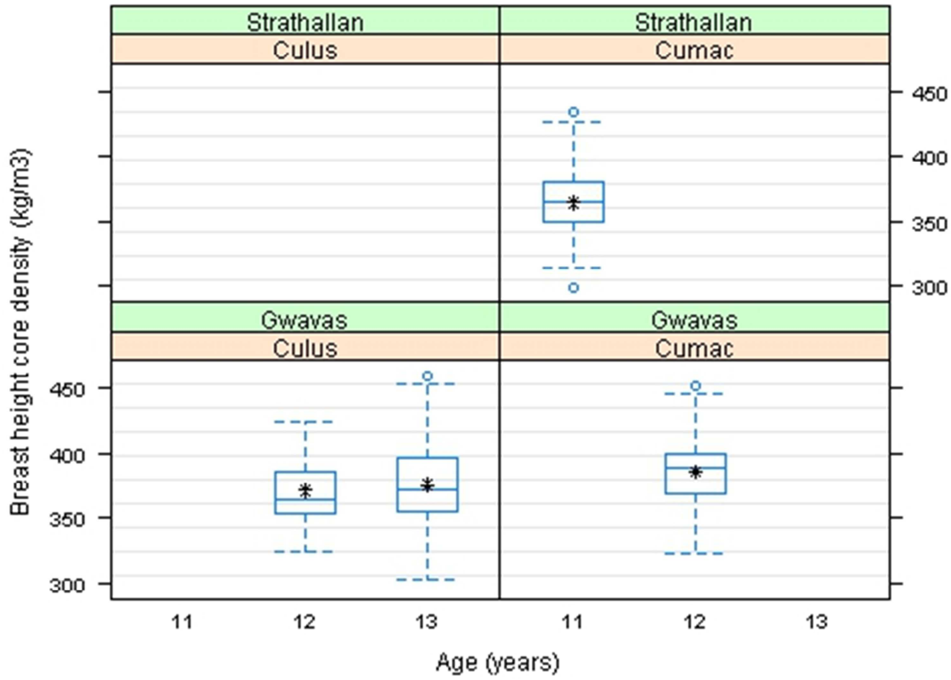


Figure 9. Mean breast height basic density of *C. lusitanica* and *C. macrocarpa* at progeny trials at Gwavas and Strathallan. Symbols are as described for Fig. 6.

6.1.3 Other Literature (SiDNEY)

McConchie and Young (1976) examined wood density of 155 discs obtained from felled *C. lusitanica* trees when first thinned at a provenance trial in Mangatu Forest (Gisborne). Green, air-dry, and basic density (D_{green}, $D_{air\text{-}dry}$, D_{basic}) were assessed on all discs, each containing 10 growth rings. Mean density was 1069, 416, and 361 kg/m^3 with standard deviations of 41, 40, and 34 kg/m^3, respectively. The relationship between green density and basic density (equation 1), after removal of two outliers, with an R^2 of 0.99, was:

[1] ***C. lusitanica*** $\mathbf{D_{air\text{-}dry} = 1.197 x D_{basic} - 0.992}$

Equation 2 shows the algebraic rearrangement of equation 1 to calculate basic density from air-dry density for *C. lusitanica*:

[2] ***C. lusitanica*** $\mathbf{D_{basic} = 0.835 x D_{air\text{-}dry} + 0.829}$

The relationship between green and air-dry density was poor.

Young (1983) examined wood properties of 26 trees in a 45-year-old *C. macrocarpa* stand in Whakarewarewa Forest and found a significant relationship between basic and air-dry density:

[3] *C. macrocarpa* $\mathbf{D_{air\text{-}dry} = 1.214xD_{basic} - 12.7}$

Equation 4 shows the algebraic rearrangement of the above relationship to calculate basic density from air-dry density for *C. macrocarpa*:

[4] *C. macrocarpa* $\mathbf{D_{basic} = 0.824xD_{air\text{-}dry} + 10.5}$

Green density of *C. macrocarpa* was also found to correlate well with basic density (kg/m^3):

[5] *C. macrocarpa* $\mathbf{D_{green} = 1.576xD_{basic} + 230}$

The relationship between breast height diameter, DBH (mm) and whole tree weighted basic density, D_{tree}, (equation 6) for *C. macrocarpa* was:

[6] *C. macrocarpa* $\mathbf{D_{tree} = 451 - 0.14xDBH}$ (correlation coefficient, r = -0.54)

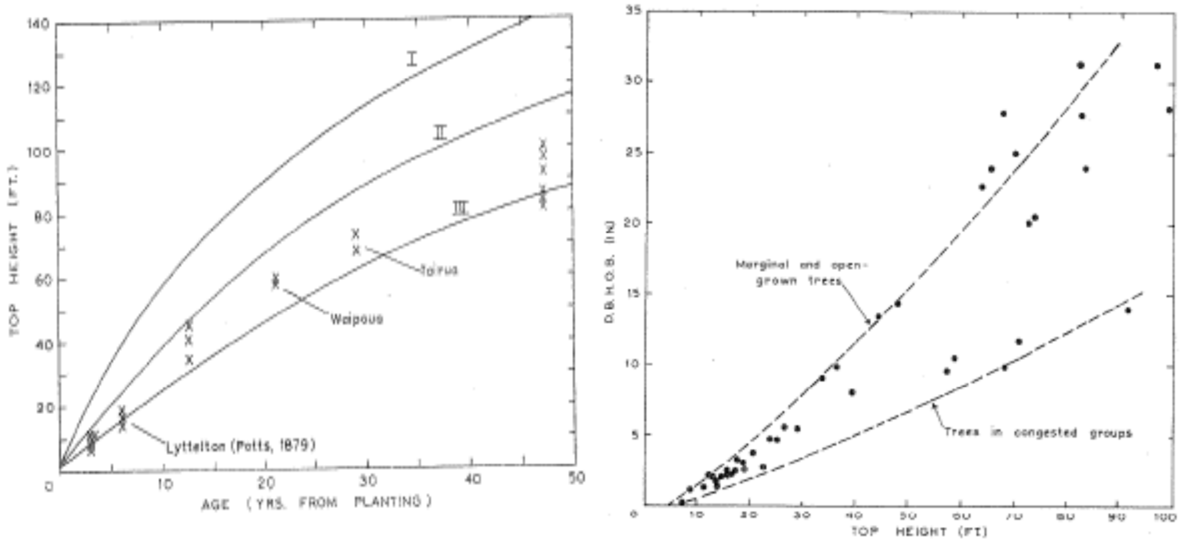
Density data from the above studies, and another study conducted in a 70 year-old *C. macrocarpa* stand on the West Coast (Colbert and McConchie 1981), are included in the wood density database.

Haslett (1986) provided an overview of wood properties for *C. lusitanica*, *C. macrocarpa*, and hybrids, and reported that there was very little variation in density between and within trees. However no specific information, such as age and number of trees, or location(s) was provided. Green, air-dry, and basic densities reported by Haslett are provided in Table 4.

Table 4. Density (kg/m3) of C. lusitanica and C. macrocarpa. Source Haslett (1986).

Species	Green	Air-dry (12% mc)	Basic
C. lusitanica	910	460	385
C. macrocarpa	820		405

Bannister and Orman (1960) reported air-dry density and basic specific gravity of *C. lusitanica.* The study was based on seven trees; three 21-year old trees from Waipoua (Northland), two29-year old trees from Tairua (Waikato), and two 45 year-old trees from the Whakarewarewa arboretum (BP). Air-dry densities were 449, 416, and 449 kg/m^3 at the three sites respectively, while basic specific gravity was 360, 350, and 370 kg/m^3, respectively. Using Equation 1, basic density for *C. lusitanica* is thus estimated to be 375, 347, and 375 kg/m^3 respectively, which are close to the measured values. The authors also presented height-age and diameter-height curves for the species, with comparisons to data from Kenya (Figures 10a and 10b respectively).



a) Crosses represent trees at Whakarewarewa, unless otherwise indicated. Curves I, II, and III represent mean height-age data for the 3 site-quality classes in Kenya (Griffith 1958).

b) Relationship between diameter and height. Dotted lines show approximately how spacing affects stem growth.

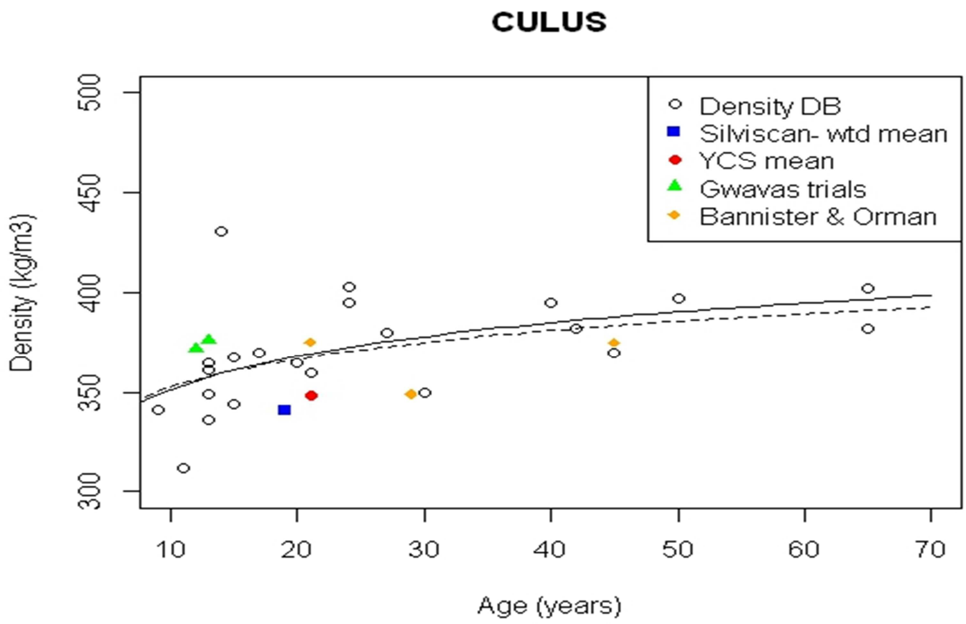
Figure 10. *C. lusitanica* growth relationships. Source Bannister and Orman (1960).

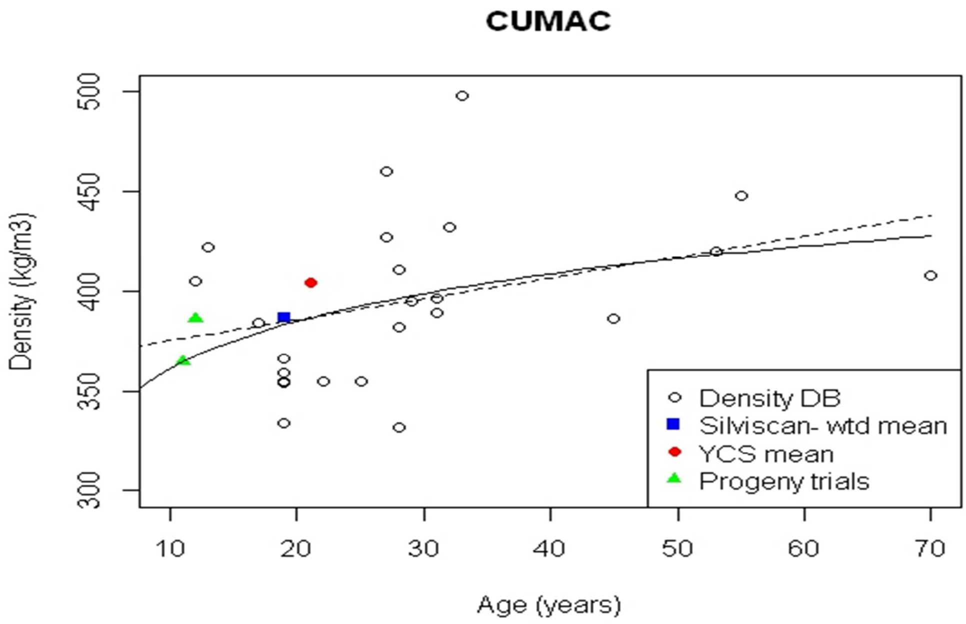
McKinley *et al*. (2000) reported whole-tree basic wood density for four cypress species that were amalgamated into one group due to insufficient data. The species were*:* *Chamaecyparis lawsoniana* (Murray) Parl.*, Ch. nootkatensis* (D.Don) Spach x □*Cupressus macrocarpa, C. lusitanica* Miller, and *C. macrocarpa* Gordon. The group ranged in age from 13 to 52 years and comprised 119 trees of which the majority (85 trees) were *Ch. Lawsoniana* which spanned the age range, and 30 *C. lusitanica* trees (all aged 43 years and with density averaging 413 kg/m^3). No information was provided regarding the species breakdown of the remaining four trees. No relationship between age and density was found for the grouped species.

6.2 SUMMARY

There appears to be a reasonably strong relationship between density and age for *C. lusitanica* and, although weaker, also for *C. macrocarpa* (Figure 11). Outliers from Northland in particular, but also Hawkes Bay, appear to have influenced this result (i.e. the weaker relationship). Additional data obtained from the progeny trials, the young cypress study (YCS), and for, *C. lusitanica* Bannister and Orman (1960), had little effect on relationships developed using only data currently available in the wood density database (Figure 11).

Density derived from Silviscan assessment of pith-to-bark increment cores of 21 year-old trees, suggests that, on average, density of *C. macrocarpa* is about 12 % higher than that of *C. lusitanica*. In the direction pith-bark, density appears to initially decrease until about ring 4, and then increase to a level slightly higher than the level at the pith at about ring 15. Young (1983) found a decreasing trend in density that extended slightly beyond ring 5 (to about ring 7), but then also increased until about ring 20 before declining again. As some trees bucked this trend, while others increased in density before ring 5, when averaged over a sample of trees, this will give a relatively flat density trend as has been observed in past studies.


CULUS
Density DB
Silviscan- wtd mean
YCS mean
Gwavas trials
Bannister & Orman
Density (kg/m3)
Age (years)
300
350
400
450
500
10
20
30
40
50
60
70


CUMAC
Density DB
Silviscan- wtd mean
YCS mean
Progeny trials
Density (kg/m3)
Age (years)
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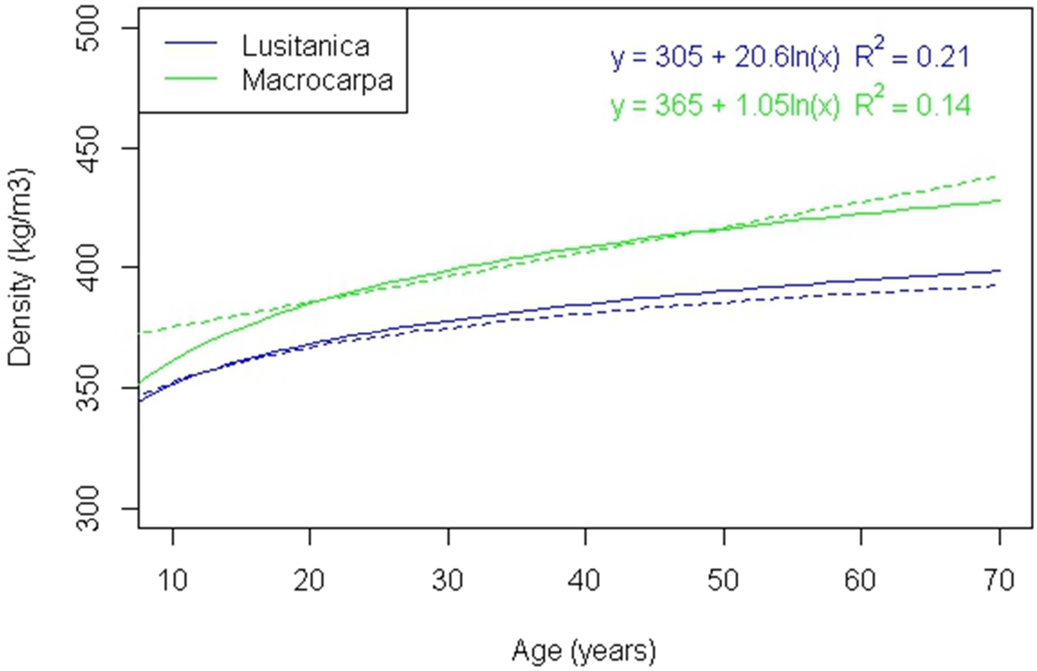

Figure 11. Relationship between breast height basic density and age for *Cupresses lusitanica* (CULUS) and *C. macrocarpa* (CUMAC). Solid lines represent regressions developed from the Density DataBase (DB) only (Figure 3), while dashed lines, and equations of corresponding colour, include all other points. Equations 2 and 4 are applied to Silviscan and Bannister & Orman (1960) data to estimate basic density from air-dry density. YCS = Young Cypress Study.

There are gaps in regional data for both species. For *C. lusitanica* current PSP's in stands in Canterbury, West Coast, and Wellington could be sampled to assist with filling gaps. For *C. macrocarpa*, regions with stands that could be sampled include Marlborough, Otago, Southland, and Waikato. Regions where density data exists (even if limited to one tree) are shown in Figure 12. Apart from the Bay of Plenty and, for *C. macrocarpa*, the Wanaganui/Manawatu region, the range in tree age is generally limited to 20 years or less.

Also lacking from current surveys, possibly due to the small sample sizes, are data relating to tree spacing. This is likely to influence tree growth (refer Figure 10) and hence wood density. For *C. macrocarpa*, presence and severity of cypress canker is likely to also influence wood density.

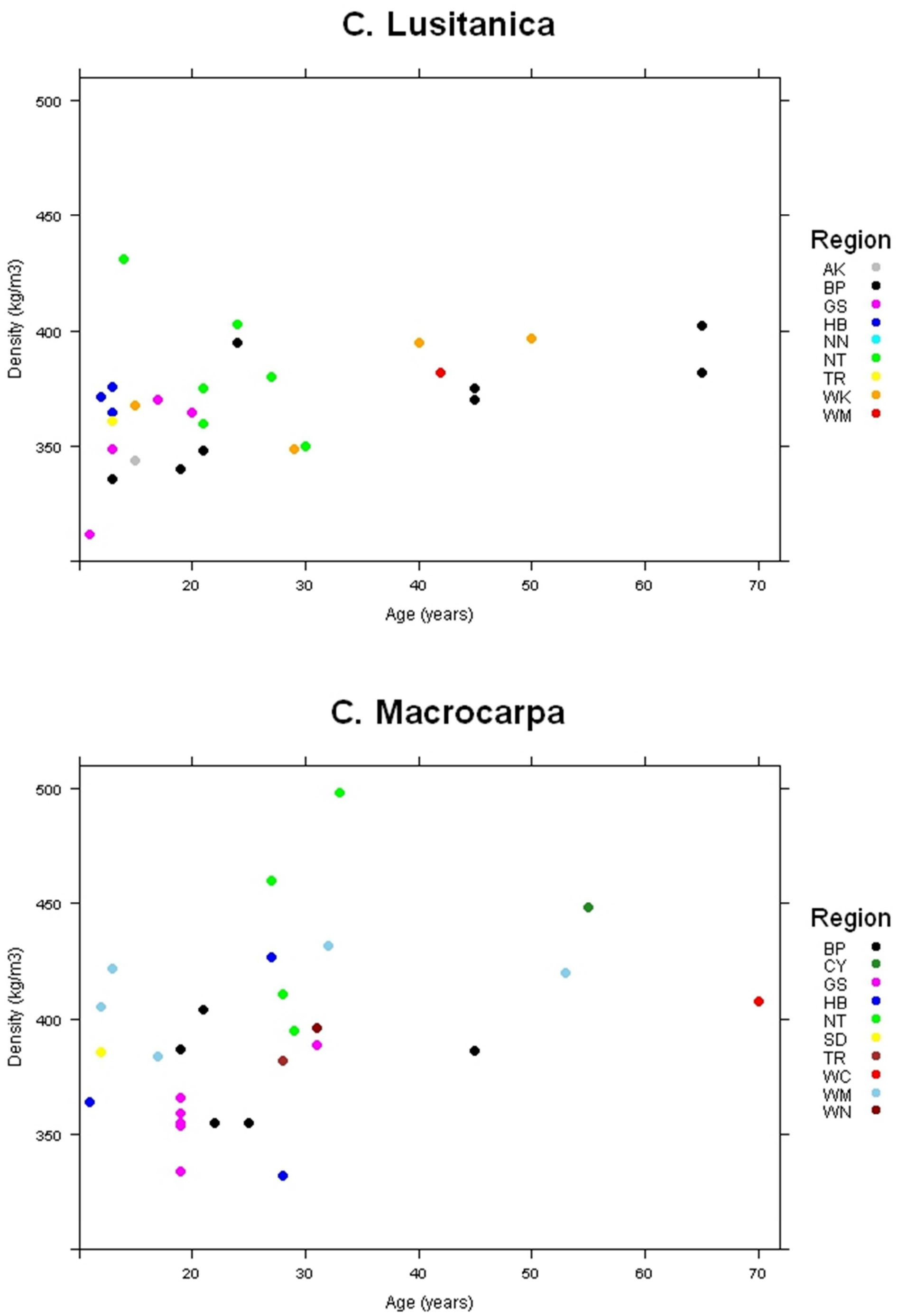

Figure 12. Summary of cypress density data by age and region.

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7 Improving wood density of Sequoia sempervirens

C.L. Todoroki and D.F. Meason

Overview

The purpose of this study was to determine whether sufficient data exist to develop wood density by age profiles for the redwoods, *Sequoia sempervirens*, across a range of regions and growth environments.

Wood density data collated for analysis included: 1) Studies contained in Scion's wood density database following an update by Beets et al. (2008); 2) 10 year-old density data from two of the Kuser young provenance trials located on the East Coast and in Taranaki (courtesy of D. Meason), and from a further 10 year-old stand in the King Country; 3) Density data from the Rotoehu redwood provenance trial (courtesy of C. Low); 4) Density data of 38-year-old Mangatu redwoods (courtesy of R. McKinley). Reports on Scion's Science Information Database (SiDNEY) and data available on the Atlas Permanent Sample Plot (PSP) database were also investigated.

Gaps in knowledge, in terms of tree age and regions are identified. The relationship between basic density and air-dry density is investigated and compared with an existing relationship. A preliminary relationship between stand age and density is developed.

7.1 WOOD DENSITY DATABASE

The wood density database (Beets et al. 2008) provides the most comprehensive review to date of wood density surveys conducted in New Zealand on redwoods and other species. Density measurements were obtained from a variety of studies; some captured whole stem wood basic density, some breast height outerwood (resin-extracted and unextracted -range of depths) basic density, and others whole stem wood plus bark density. For each study, the location, tree species, stand age, number of trees, merchantable log basic density (mean, minimum, maximum), whole stem wood and bark density, breast height outerwood (0-50mm depth or in some cases the outer 5 rings) basic density (mean, minimum, maximum), breast height (50-150mm depth) basic density (mean, minimum, maximum), and reference to data source, if available, were entered in the database.

Summary data from Beets et al. (2008) are provided in Tables 1 and 2. In Table 1, linear regressions with stand age are given (intercept, slope and p-value) to indicate if age information is important, while Table 2 summaries wood density by region. With the available stand data, neither relationship was found to be significant.

Table 1. Wood density of S. sempervirens averaged across all studies compiled by Beets et al. P-values for region and age are also given. Source: Beets et al. (2008).

Density study	Mean density	No. regions	No. studies	No. trees	Region P-value	Age regression Intercept	Age regression Slope	Age regression P-value
Whole stem wood plus bark	310	6	12	36	0.7826	276	0.7	0.5827
Breast height outerwood	333	6	12	36	0.7826	296	0.7	0.5827

Table 2. Whole stem (wood and bark) density and breast height outerwood basic density of S. sempervirens by region. Source: Beets et al. (2008).

Region	Whole stem	Breast height	No. studies	No. trees*	Tree age
Northland	.	.			
Auckland	354	380	1	1	60
Bay of Plenty	313	336	5	5,1,7,2,7	45,50,50,63,69
Waikato	317	340	1	4	45
Gisborne	341	366	2	2,2	40,49
Hawkes Bay	.	.	.	.	.
Taranaki	.	.	.	.	.
Wanganui/Manawatu	270	290	2	2,2	28,29
Wellington	.	.	.	.	.
Nelson	.	.	.	.	.
Marlborough	.	.	.	.	.
West Coast	210	225	1	1	64
Canterbury	.	.	.	.	.
Otago	.	.	.	.	.
Southland	.	.	.	.	.

*individual trees from which one or more logs, boards, discs, or increment core was obtained

Regional gaps are apparent in Table 2. In the North Island, *S. sempervirens* density data is not available for Northland, Hawkes Bay, Taranaki, and Wellington, while the only region that is represented in the South Island is the West Coast. However, the solitary tree sampled in that West Coast study (Young 1983, refer below for further details) was not sourced from a managed stand, and therefore should not be considered to be representative of South Island *S. sempervirens* trees.

The number of studies conducted by region is illustrated in Figure 1. Note that within regions, though density studies have been conducted, gaps still exist. For example, for the Auckland region, density data was based on only two boards sawn from a single 60-year-old tree. The Wanganui/Manawatu studies were also based on a limited sample size (two boards for the study of 28 year-old trees, and a total of six boards for the 29 year-old study).

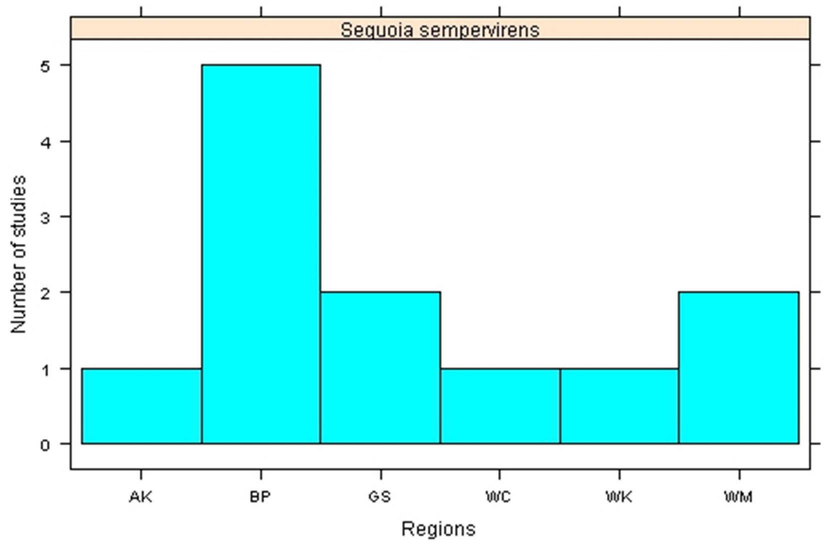

Figure 1. Regional distributions of *S. sempervirens* trees in the wood density database. (AK = Auckland, BP = Bay of Plenty, GS = Gisborne, WC = West Coast, WK = Waikato, WM = Wanganui/Manawatu).

Within the wood density database, stand age for the 12 studies ranged from 28 to 69 years, but within these limits, gaps still exist (Figure 2).

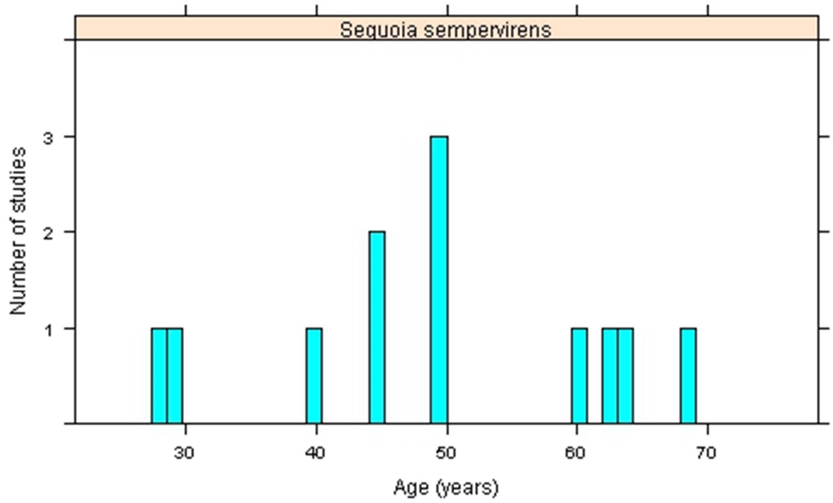

Figure 2. Age distribution of *S. sempervirens* stands in wood density database.

The relationship between age and density for *S. sempervirens* data held on the wood density database was poor (R^2 = 0.13), however after removal of the non-plantation West Coast tree, a stronger relationship based on the logarithmic transform of age was derived here (R^2 = 0.29), and is shown in Figure 3.

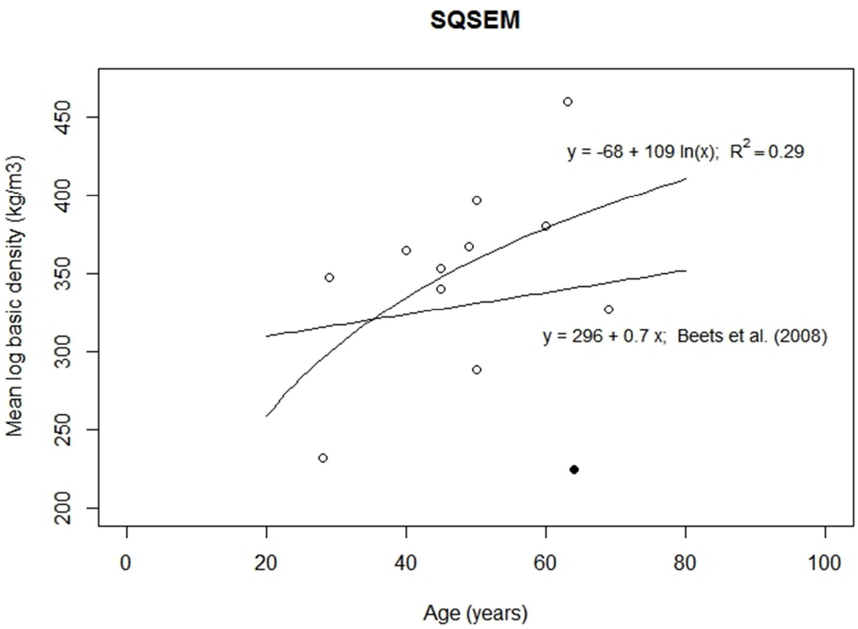

Figure 3. Relationship between stand age and mean log density for *S. sempervirens* stands in the wood density database. The linear relationship of Beets et al. (2008) includes all points, while the allometric relationship developed here excludes the unmanaged West Coast tree, denoted by a filled circle.

7.2 KUSER PROVENANCE TRIAL AND OTHER 10 YEAR-OLD DATA

Data from substantially younger, 10 year-old *S. sempervirens* trees have recently been obtained from the Kuser trial, named after the collection of cutting assembled by Professor John Kuser of Rutgers University. The collection comprises two random seedlings from 98 different stands located throughout the natural redwood range in America. From this collection, 35 clones were received in 1992, and a much more extensive collection of 182 clones of the original 198 Kuser clones were received in 2001. The latter were planted out in 11 complete trials across New Zealand from 2003 – 2006 (Table 3).

Table 3. Summary of the 11 Kuser clonal trials in New Zealand. Source: Saunders and McConnochie (2007).

Establishment Year	Location	Aspect	Altitude (m)	Latitude	Previous vegetation	Terrain	No. of Clones
2003	Kaikoura	South	100	42.35	Gorse,broom	Steep	174
2003	Taranaki	North	260	39.14	Farm pasture	Steep	174
2003	Wairoa	North	40	39.02	Farm pasture	Flat-Easy	174
2004	Kaitaia	North	170	35.13	P.radiata	Flat-Easy	136
2004	Blenheim	South	400	41.21	P.radiata, gorse	Moderate-Steep	136
2005	Turangi	NW	595	38.54	P.radiata	Flat-Easy	135
2005	Greymouth	West	236	42.24	Native, gorse	Flat	137
2005	Rangiora	West	227	43.13	Gorse	Undulating	135
2006	Winton	East	259	45.51	Heavy grass	Flat	160
2006	Huntly	East	100	37.38	Gorse	Easy-Steep	160
2006	Nelson	NW	426	41.28	P.radiata	Steep	160

Basic wood density data from two of these trials; one on the East Coast (established 2003) and one in the Taranaki (established 2003) have recently become available. A third site in the King Country (with an undocumented number of clones and establishment date) also comprised 10 year-old trees, from which a subset were selected as candidates for clonal propagation based on their growth rates, form and branching habits (McKinley and Cown, 2012).

For the East Coast trial at Awaho and Taranaki trial at Thompsons, 5 mm wood core samples were extracted at breast height as part of an FFR analysis of the 10 year-old provenance trial. More than one thousand cores were extracted across two sites, from four of the eight replicates.

Density distributions were approximately normally distributed, with mean values of 303 and 310 kg/m^3 at Awaho and Thompsons respectively (Figure 4). Density of the combined samples averaged 307 kg/m^3, with a standard deviation of 29 kg/m^3, and range of 232 to 418 kg/m^3.

A trend of decreasing density with breast height diameter (R^2 = 0.13) was noted for the 1183 density-diameter pairs (Figure 5, Equation 1).

Equation 1: $D_{basic} = -1.88xDBH + 350 \quad R^2 = 0.13$

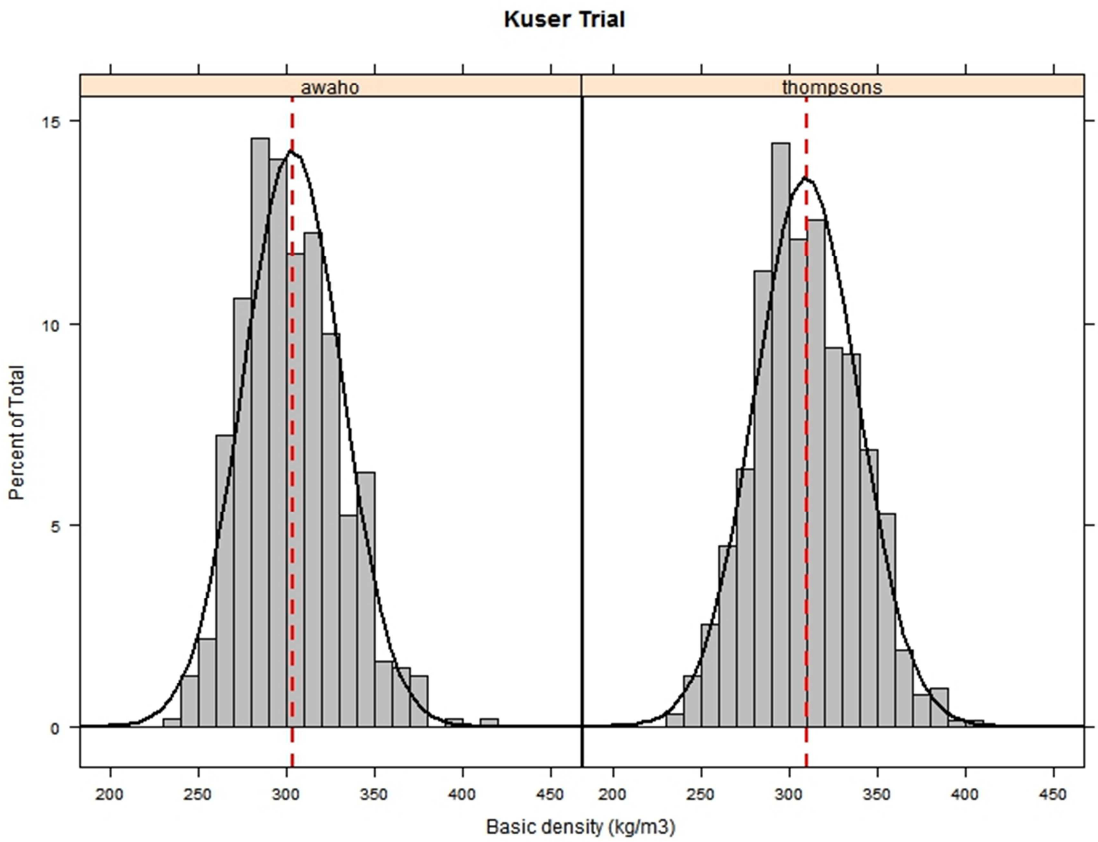

Figure 4. Basic density distributions derived from breast height cores extracted from the Kuser trial. Vertical dashed lines represent sample means.

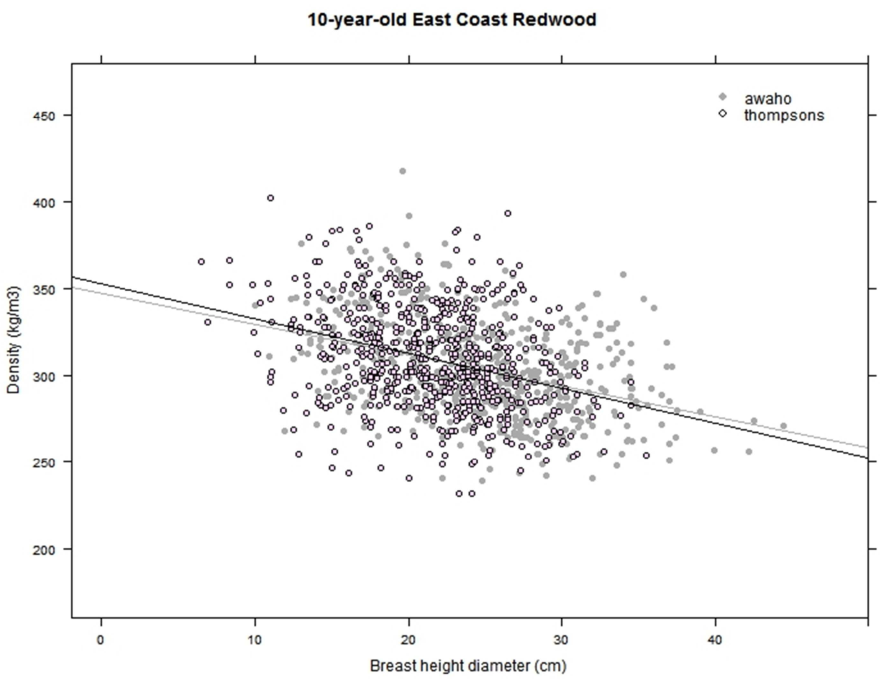

Figure 5. Relationship between breast height diameter and core density for 10 year-old *S. sempervirens*.

For the King Country trial, at Paraheka Station near Pio Pio, density data were obtained from breast height discs from four trees, and radial trends analysed in 5-ring and remaining 2 ring groups (McKinley and Cown 2012). Basic density averaged 263 kg/m^3 and ranged from 228 to 284 kg/m^3 (Table 4).

The mean density of the 10 year-old stand at Paraheka Station was 263 kg/m^3, which is lower than Awaho and Thompsons (303 and 310 kg/m^3, respectively). However, it should be noted that the Paraheka Station result is based on a sample size of four.

Table 4. Breast height disc properties of 10 year-old S. sempervirens at Paraheka Station, King Country. Source: McKinley and Cown (2012).

Tree no.	DOB*+ (mm)	DIB+ (mm)	Bark* (mm)	Heart+ wood (mm)	Heart+ wood (%)	Heart rings	Total rings	Growth rate (mm)	Density (kg/m^3) A-dry	Basic
500	300	280	10	170	37	5	7	21.6	276	228
510	240	220	10	120	30	5	7	17.7	342	284
520	380	330	25	210	40	5	7	24.6	312	255
530	210	190	10	95	25	5	7	15.4	343	284
Mean	**283**	**255**	**14**	**149**	**33**	**5**	**7**	**19.8**	**318**	**263**

+ Estimated from half disc
* Estimate of bark – discs had dried to varying degrees and some bark missing

7.3 ROTOEHU REDWOOD PROVENANCE TRIAL

The Rotoehu Coast redwood trial was planted in 1981. The trees initially struggled with possums and bracken, resulting in abandonment of the trial in 1987, but when revisited and measured in 1992 were found to have regained sufficient form to warrant further measurements. The trial was subsequently measured in 1992 and again in 2001 (Vincent 2001, Low & Shelbourne 2004). Density data from this trial was obtained by taking increment cores when trees were about 22 years of age.

Basic density statistics of breast height core samples are shown by provenance in Figure 6. The four outliers with density exceeding 400 kg/m^3 are speculated to contain compression wood which is virtually impossible to see in the similarly coloured heartwood. The extremely low density values of close to 250 kg/m^3 were from trees growing in gaps in the stand.

Overall, mean density for the sample of 92 cores was 314 kg/m^3 with a standard deviation of 30 kg/m^3, and range of 253 to 415 kg/m^3. Provenance 1972 had the lowest mean density, and also the least variation in density, but was based on only 4 samples. Provenance 1977 recorded the highest mean (327 kg/m^3, based on 14 cores), followed closely by provenances 1975 (324 kg/m^3, 14 cores) 18 (324 kg/m^3, 12 cores), and 1970 (320 kg/m^3, 12 cores).

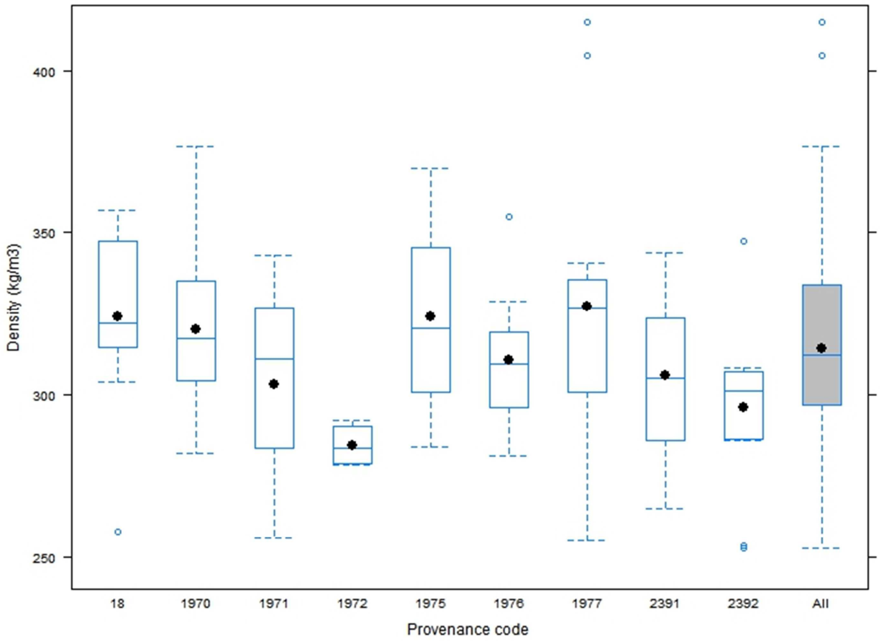

Figure 6. Basic density of breast height core samples from 22 year-old *S. sempervirens*, Rotoehu provenance trial Box plot whiskers extend to the most extreme data points, provided they are no more than 1.5 times the interquartile range from the box. Outliers, i.e. points outside the whiskers, are denoted as blue circles. Mean density is denoted by yellow circles.

7.4 MANGATU REDWOODS

Thirteen stems were randomly selected from a 38-year-old stand (Compartment 11) at Mangatu, Hawkes Bay. Stem diameter at breast height ranged from 39.0 to 84.2 cm, and height from 29 to 41 m. The stems were felled, crosscut into approximately 5 m long logs, and disc samples collected from each of the log ends for wood property measurements. Densities were measured in approximately 5-ring blocks. Results from the study, including results for heartwood content, wood density, and shrinkage, are discussed in McKinley and Cown (2008). A summarised version, which also contains the silvicultural history of the stand, is given in Cown and McKinley (2009). In general, (McKinley and Cown (2008) found density to increase with ring number from pith after the 15th ring. Although the authors concluded that "The wood density has again been shown to be relatively uniform within stems but highly variable between individual stems" their data suggests that differences between stems may, at least in part, be attributable to diameter growth. For example, the highest stem density of 380 kg/m^3 was associated with the tree of smallest diameter (380 mm over bark, OB) and the lowest density of 262 kg/m^3 with the largest diameter tree (842 mm OB). Wood density data derived from the study (courtesy of R. McKinley) were re-analysed here to glean further information from the data.

Outerwood increment core density of the 38 year-old trees ranged from 274 kg/m^3 to 420 kg/m^3 (Cown and McKinley 2009). The relationship between outerwood density and weighted stem density (i.e. whole tree density) was approximated by a strong linear relationship:

Equation 2: $$D_{wholetree} = 0.75xD_{outerwood} + 63.5 \qquad R^2 = 0.80$$

Density of the butt log (calculated as the weighted mean of the discs at the log ends) ranged from 263 to 400 kg/m^3 with a mean of 337 kg/m^3 while whole tree density (calculated as the mean of the weighted log densities) ranged from 262 to 380 kg/m^3 with a mean density of 323 kg/m^3.

Both whole tree density and outerwood density were negatively correlated with breast-height diameter (Figure 7). Regression lines are given by Equations 3 and 4, for the whole stem and outerwood respectively.

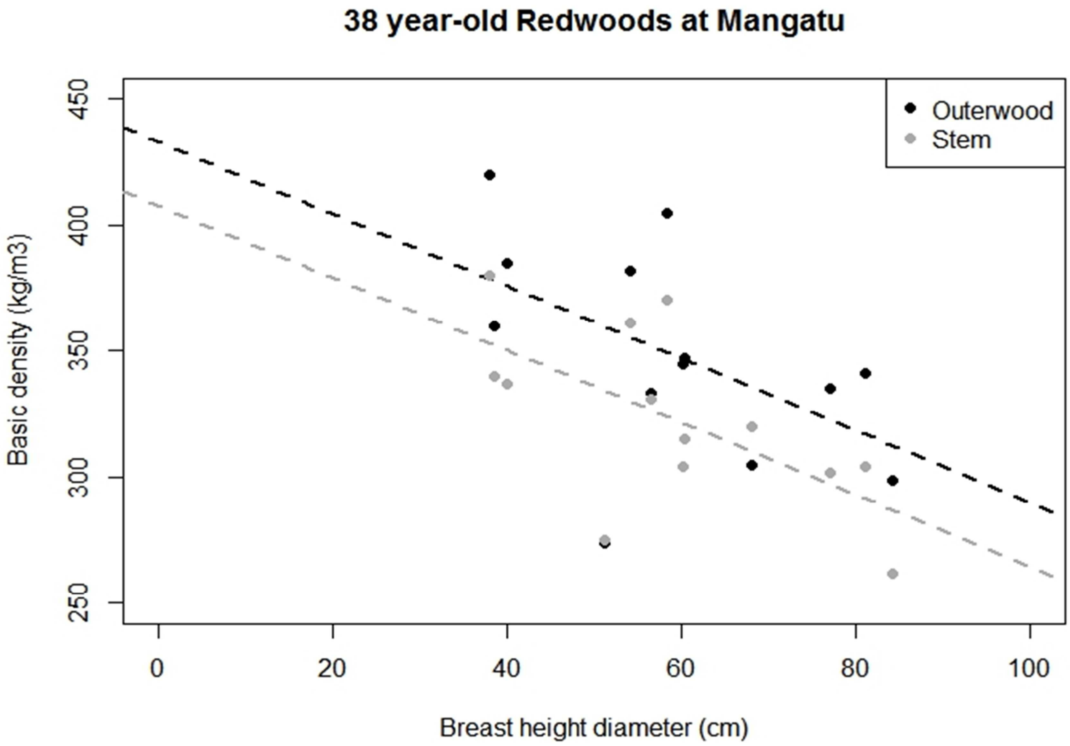

Figure 7. Relationship outerwood and whole stem density with diameter of 38 year-old *S. sempervirens*.

Equation 3: $D_{wholetree} = -1.43xDBH + 408$ **$R^2 = 0.40$**

Equation 4: $D_{outerwood} = -1.43xDBH + 433$ **$R^2 = 0.27$**

Wood density at the base tended to be higher than that of upper logs for the majority of individual trees (Figure 8) and, when averaged across all trees, was higher overall (refer Figure 3 of McKinley and Cown 2008). Mean basic density of discs at 0.2 m was 349 kg/m^3, while that for discs at 5.3 m was 314 kg/m^3. Trees 2 and 17, both of low density, were noted to contain rot (Figure 9). Some rot was also noted in the upper discs of Tree 11.

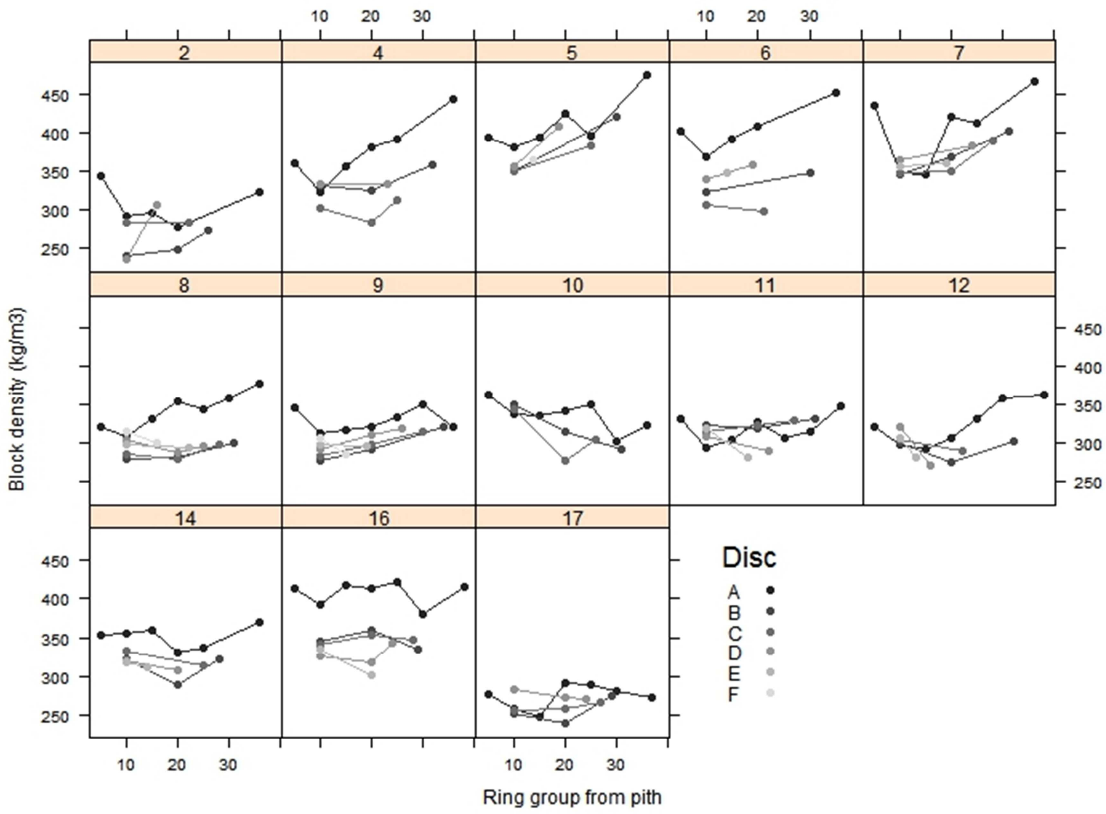

Figure 8. Radial wood density trends for individual 38-year-old trees *S. sempervirens*. Data courtesy of R. McKinley.

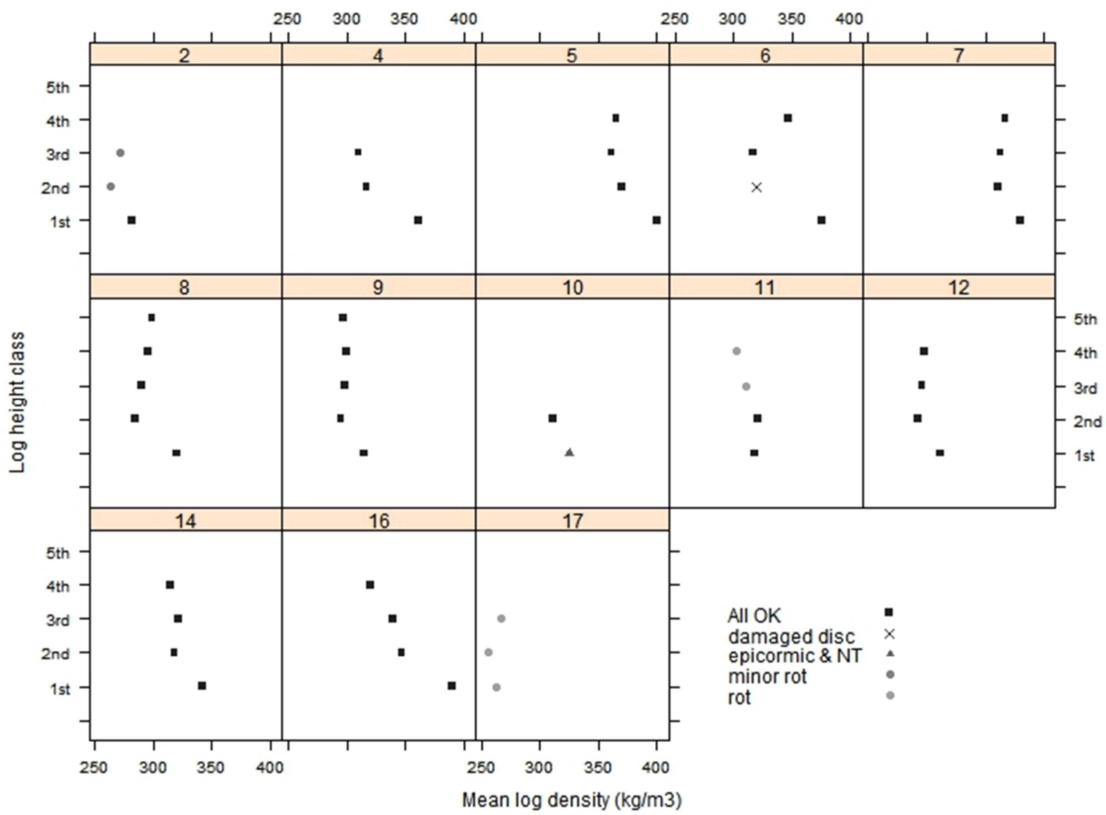

Figure 9. Mean log density, determined from weighted density of discs at the log ends, as a function of log height class. Data courtesy of R. McKinley.

In addition to density being higher at the base, density variation was greatest at the base and the variation decreased with increasing height (Figure 10). Note that Tree 7 discs at heights of 15.3 and 20.1 m, mislabelled as E and F respectively, were relabelled as D and E. Note also that the number of blocks within each disc decreases with height, from 83 discs at A to 5 discs at F (83, 37, 34, 28, 15, and 5 respectively).

Density variation of the 38 year-old trees grown at Mangatu, were also investigated by Jones et al. (2011) in a study that analysed sources of variation within trees, between trees, and between stands. In all, three stands were investigated: the 38 year-old Mangatu stand, a 22 year-old stand at Rotoehu, and a 71 year-old stand at Kinleith. Using variance components analysis, Jones et al. found that the greatest source of variation in basic density was within trees (64%) and between trees accounted for the remainder (36%). No variation was attributed to differences between the forest stands (Figure 11).

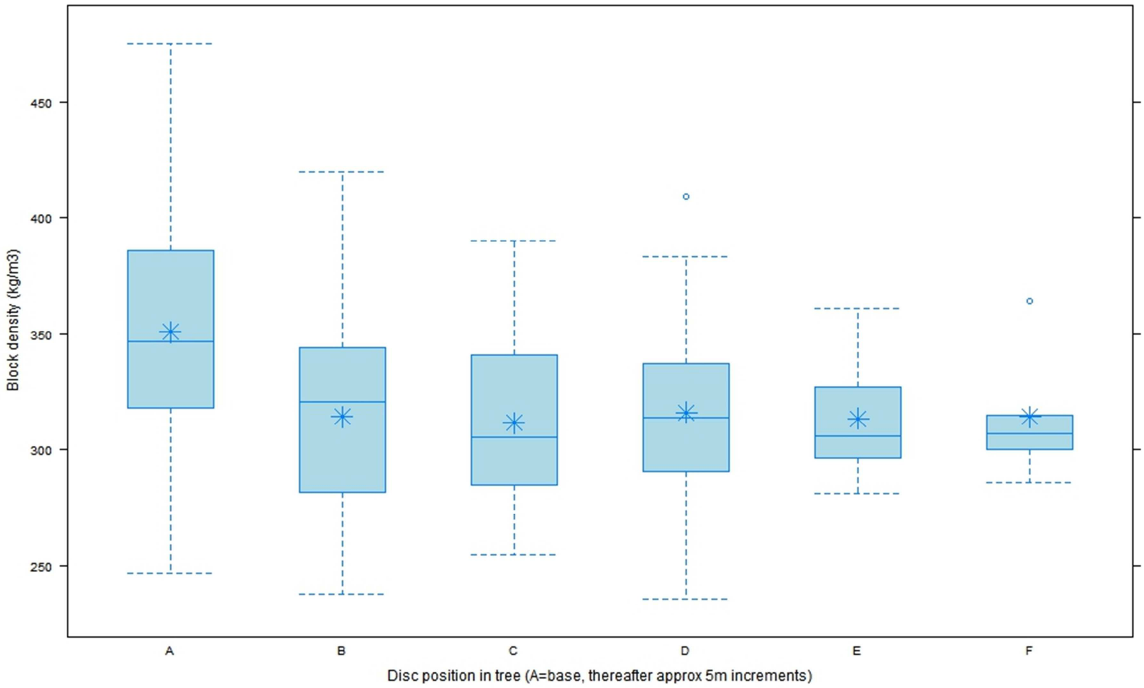

Figure 10. Density of (approximately) 5-ring blocks within 38-year-old *S. sempervirens* trees, at 5 m height intervals The horizontal bar within the boxes represents the median, while the mean is represented by "*".Data courtesy of R. McKinley.

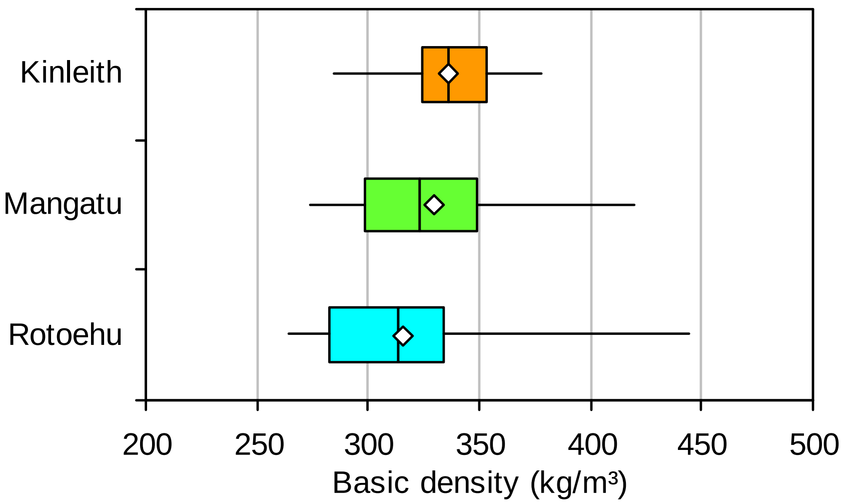

Figure 11. Basic density of discs at 6 m height for 71 year-old trees from Kinleith; at 0.2 m and 5 m heights of 38 year old trees from Mangatu, and at breast height for 22 year-old Rotoehu trees. Source: Jones et al. (2011).

These results need to be interpreted with caution because, not only are the stands of differing ages, but the underlying density data is also obtained from different heights. Through analysing all disc density data obtained from Mangatu, we have confirmed that Figure 11, Mangatu data, is obtained by the amalgamation of density data from discs at 0.2 m (A discs), and discs that are approximately 5 m higher (B discs). By amalgamating data from the two disk heights, the variability in density increased to include the high variability of wood density of the 0.2m disk (Figure 12). Thus, the variability of wood density within the butt log above 0.2m was exaggerated. The Kinleith results are also based on a combination of discs at 0 m and discs at 6 m (refer Jones 2011, Table 4).The Rotoehu data of Jones (2011) is reported to be derived from wood discs cut at breast height from 32 trees, however, at the time of writing this report, the raw data for KInleith had not been located.

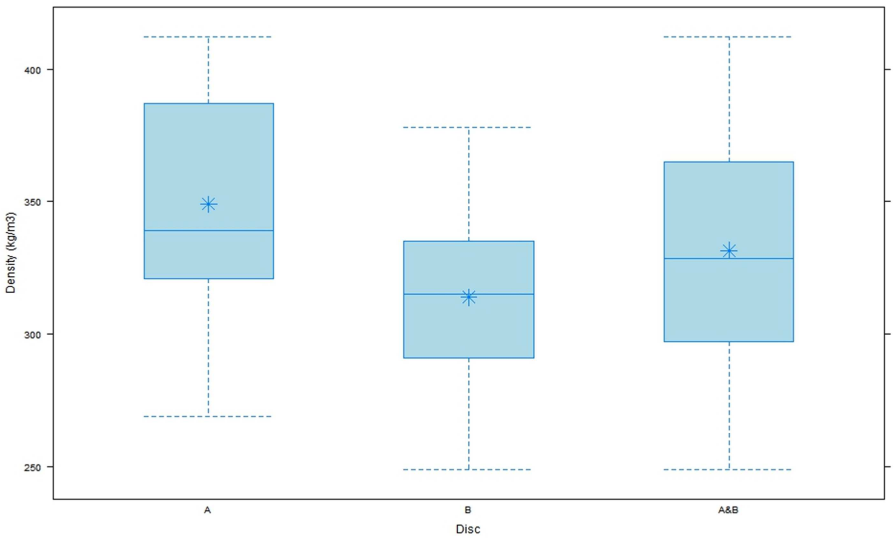

Figure 12. Comparison of density of density of 13 discs at 0.2 m (A), 12 approximately 5 m higher (B), and 26 A and B discs.

7.5 PERMANENT SAMPLE PLOTS

Current PSP stands are listed in Table 5. Clearly, some of these stands could be utilised to fill gaps identified in the wood density database, i.e. stands in Hawkes Bay, Taranaki, Canterbury, Otago, and Southland. The South Island stands would be particularly worthy of investigation due to the absence of any South Island data from managed stands.

Table 5. Current PSP stand age statistics for S. sempervirens: min-max; mean.

		Age	
Region		Min-max	mean
Northland	NT	.	.
Auckland	AK	.	.
Bay of Plenty	BP	13-112	35
Waikato	WK	18-91	44
Gisborne	GS	8-42	26
Hawkes Bay	HB	15-36	16
Taranaki	TR	50	50
Wanganui/Manawatu	WM	10-16	11
Wellington	WN	.	.
Nelson	NN	.	.
Marlborough	MB	.	.
Westcoast	WC	.	.
Canterbury	CY	3-83	6
Otago	OT	27	27
Southland	SD	13-48	27

7.6 OTHER LITERATURE AND DATA

Knowles and Miller (1993) provided an overview of coast redwood, and giant sequoia and other related ornamental genera (*Taxodium* and *Metasequoia*), and reported that the density of *S. sempervirens* at 50 years of age was about 80% of that of *P. radiata* at 35 years of age. However, it is difficult to evaluate the validity of this relationship as details specifying sample sizes and how the values were derived are not provided. Green, air-dry, and basic densities reported by Knowles and Miller (1983) are provided in Table 6.

Table 6. Density (kg/m3) of S. sempervirens. Source Knowles and Miller (1993).

Species	Green	Air-dry	Basic
S. sempervirens	910	380	335
P.radiata	955		420

The solitary West Coast sample tree (Young 1983), which is included in the wood density database, grew near Hokitika on a "typical open, farm-type planting; untended and with large open branching habit". Diameter at the base of the tree was 150 cm, with 64 rings. Basic density of 5-ring groups cut from cross-sectional slabs which were in turn cut from discs at various tree heights, ranged from 205-334 kg/m^3. This is a range of some 129 kg/m^3 in within-tree wood density variation. In general, density decreased in the direction pith to bark (Figure 13). This contrasts with the trend found by Cown and McKinley (2008).

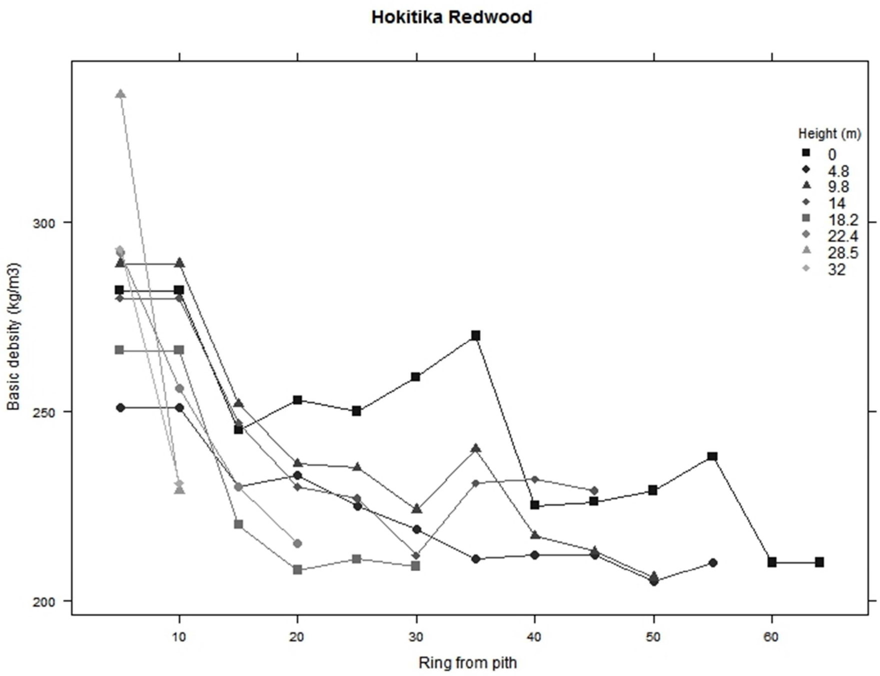

Figure 13. Variation in basic density from pith (ring 1) to bark at various heights for a 64 year-old *S. sempervirens* tree.

Young (1983) found a strong relationship (R^2 = 0.993) between air-dry density ($D_{air\text{-}dry}$) and basic density (D_{basic}). However, Young's equation (Equation 5a) differs to that derived from data obtained from McKinley and Cown (2012) for the 10 year-old Pio Pio data, Equation 5b (R^2 = 0.996). Equation 3a is based on a larger sample size (nearly 100 blocks, but all from the same tree), while Equation 3b is based on four disks, one from each of four trees. Basic density calculated using Equation 3b is higher than that calculated using Equation 3a.

Equation 5a: $D_{basic} = 0.852x\,D_{air\text{-}dry} + 0.179$ **64 year-old West Coast tree**
Equation 5b: $D_{basic} = 1.173x\,D_{air\text{-}dry} + 9.928$ **10 year-old King Country trees**

Another study included in the wood density database is that of 69-year old redwoods in the Bay of Plenty by Cown (1970). It is based on a sample of 11 discs, from seven trees. The discs were cut from the ends of seven 5m-length logs of various height classes (two butt logs, one second log, one third log, one fourth log, and a further three logs of unknown height class). A mean log basic density of 327 kg/m^3 is recorded in the wood density database. For the sample of 11 discs, we found a similar value for the mean, a standard deviation of 62 kg/m^3, and range 257 to 471 kg/m^3. Density variation for each of the 11 discs, grouped by tree, is shown in Figure 14. The greatest variation (of about 150 kg/m^3) is demonstrated in discs obtained from butt logs.

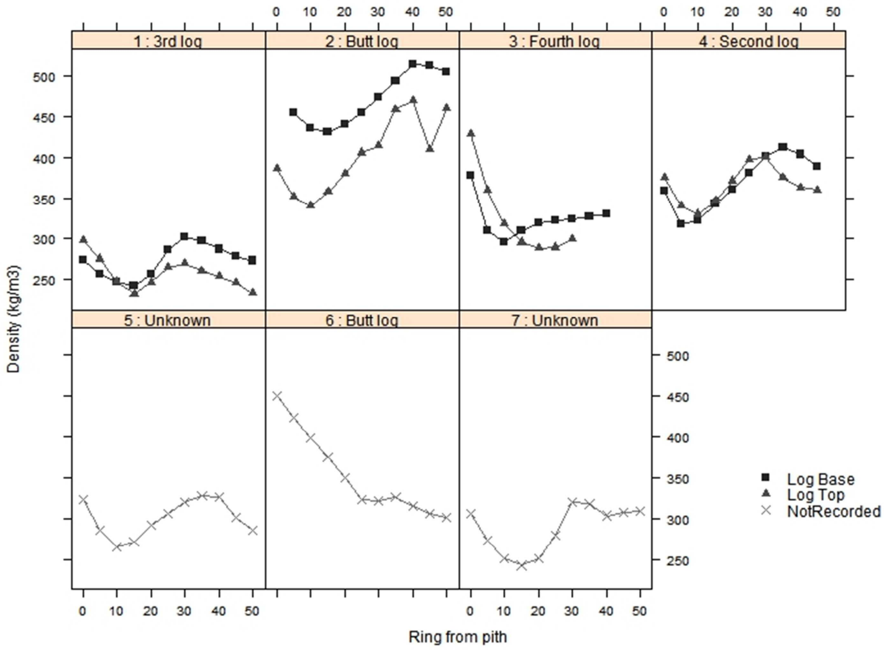

Figure 14. Density variation within discs cut from seven 69 year-old trees at various heights. Figure reconstructed from digitised data obtained from the report by Cown (1970).

7.7 SUMMARY

Various disk studies of wood density in New Zealand grown redwood have shown that redwood density increases from pith to bark in a generally constant manner. However, wood density at 0.2m can be highly variable near the pith. This variability could be due to rot, structural damage, or some other factor. This report shows that care must be taken in using disk study data to interpolate wood density variability of the entire tree. The wood disk studies also have shown that wood density generally decreases with tree.

A reasonably strong relationship ($R^2 = 0.39$, Equation 6, Figure 15) has been developed between mean log basic density of *S. sempervirens* and age. This was achieved after the removal of the non-plantation Hokitika tree and with the addition of data from two of the Kuser provenance trials (Awaho and Thompsons), data from a further 10 year-old stand (Paraheka), 22 year-old Rotoehu data and 38 year-old Mangatu data (refer Figure 15). Note that mean density of the breast height cores from Rotoehu and the three 10 year-old sampless were divided by a factor of 1.03 (following Beets et al 2008) to obtain mean merchantable log density.

Equation 6: $D_{basic} = 150 + 53x \ln(age)$

In the spreadsheet implementation of the New Zealand Redwood Growth Model (Snook 2013) a constant average density of 325 kg/m³ is used to convert predicted volume to biomass. Using the density-age relationship derived above, this equates to a 40-year old tree. However, if it is assumed that of 325 kg/m³ represents aboveground tree density then, following Beets et al. (2008) merchantable log density is determined by dividing by 0.93215 (0.905 x 1.03) giving a density of about 349 kg/m3. This equates to a 44 year-old tree. These values seem reasonable, but perhaps could be improved using the new age-based relationship developed here.

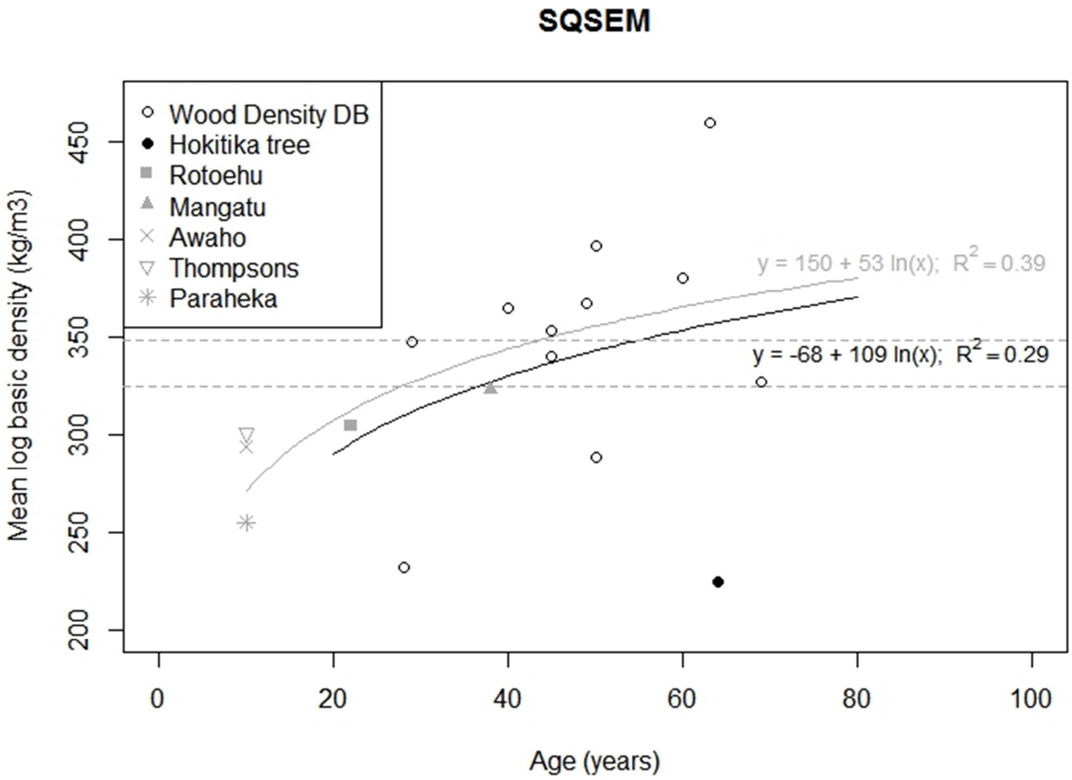

Figure 15. Relationship between log basic density and age for *S. sempervirens*. The upper curve includes all but the Hokitika tree (filled circle). The lower curve is the non-linear relationship developed from the Wood Density database (refer Figure 3). The lower horizontal line represents a density of 325 kg/m^3 , as assumed by the NZ Redwood growth model, and this value has been divided by a factor of 0.905x1.03 following Beets et la. (2008) to give the upper line at 349 kg/m^3.

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