Alternative Species Site Mapping

Review and Analysis

Authors:

Dean Meason, Pierre Bellè, Barbara Höck,

Stefanie Lumnitz, and Christine Todoroki

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EXECUTIVE SUMMARY

Background
Commercial forestry in New Zealand is dominated by the site insensitive species *Pinus radiata* (radiata pine). The commercial planting of non-radiata pine (alternative) forestry species over the last century has largely been small and fragmented. Although alternative species could potentially be commercially successful at larger scales, the tools for predicting where to grow such species and the potential yield of different sites are not at their full potential. The dominance of radiata pine in the last 40 years in the forestry sector and the stop-start support for a number of species has at times created a piecemeal approach in the development of productivity models for alternative species. Robust and accurate productivity model tools are now required to give certainty for landowners and investors to grow alternative species at a large scale.

This report investigates the state of knowledge of seven alternative species: *Eucalyptus fastigata, E. nitens, E. regnans*, *Sequoia sempervirens (*coast redwood), *Pseudotsuga menziesii* (Douglas-fir), *Cupressus lusitanica*, and *C. macrocarpa*. The report recommends what can be done to improve current models to more accurately predict species productivity at the national, regional, and local scale.

Project objective
The objectives of this report are four-fold. The first objective is to review the permanent sample plots (PSPs) for each species as the primary source of data for predicting productivity. Second is a literature review on the productivity models of each species and evaluate their ability to predict productivity throughout New Zealand. Third is to evaluate existing national spatial information in regard to each species' modelling basis (the PSPs for the species) to determine the locations where the models are robust predictors of growth. The fourth objective is to provide recommendations to the SWP program on the steps needed to improve the accuracy and precision of the models.

Key results
The literature review revealed that model developments for alternative species were largely sporadic with no overall strategic direction until the Future Forests Research program was started.

Empirical productivity models use statistical relationships to predict growth and yield for a stand and/or geographic region. For these models to produce robust results, data from a large number of plots over a wide environmental range are required. Process-based productivity models require fewer plots than empirical models to be robust as they are based on a species' physiological processes and limitations. However, this type of modelling does require data across the environment range. For the species in this report, the amount of PSPs available numbered in the low hundreds – at best. There was also an uneven geographical distribution of the species' PSPs with the majority of them concentrated in central North Island. Only the *P. menziesii* PSPs had a wide geographic spread, however even they were not located in every region. Growth and yield models generally performed well in the central North Island and less so in other regions. Arguably, the regions outside the central North Island may be where alternative species could have the best productivity rates.

The literature review of the spatial productivity models showed that on a nationwide scale there were strong statistical relationships of species productivity with mean annual temperature and to a lesser extent other environmental factors. However, mean annual temperature only gives an indication of regions in New Zealand that are more or less suitable for each species. It did not give a finer scale prediction of productivity below the regional scale. Indeed, the spatial maps only showed that productivity was higher when a site was closer to the coast. These productivity maps are inadequate for locating optimal sites for alternative species.

The current productivity models were used in previous projects to produce spatial productivity surfaces for *E. fastigata*, *E. regnans*, *S. sempervirens*, and *C. lusitanica*. These surfaces were used in this report were used for objective three to analyse the robustness of the models' prediction of productivity and to provide an indication of the strength of the alternative species productivity models in general. This analysis used environmental factors that exist at each species PSPs to give a measure of confidence of the productivity spatial maps. The range of two climatic (mean annual temperature and rainfall) and soil data (soil group and soil C:N ratio) were extracted from PSP locations and two confidence intervals were developed per species. Areas between the 25^{th} and 75^{th} percentile of each of the four environmental factors were classified as having high confidence. Areas between the 5^{th} and 95^{th} percentile were classified as having medium confidence. Overlaying these confidence intervals revealed for the *C. lusitanica* surface that only 9.3% fitted the high confidence category, *S. sempervirens* only 4.6%, and only 1.1% for both *Eucalyptus* species. For the moderate confidence interval, the fits were 49.6% of the original surface for *C lusitanica,* 25.5% for *S. sempervirens*, and *E. fastigata* and *E. regnans were* 16.8% and 8%, respectively.

This report highlights that the models developed for the alternative species were based on a limited number of PSPs unevenly distributed throughout the country and with differing ages, stocking, and silviculture. Several of the empirical models heavily relied on PSP data from the central North Island region – which is not ideal environments for all the species. Spatial productivity maps are a good approach for identifying areas of New Zealand most suitable for an alternative species and comparing different species. These should be developed for all alternative species. However, the productivity models for all alternative species need to be improved for the spatial precision of the models to robustly predict productivity at the regional and local level. Recommendations to improve the productivity models for alternative species are below:

	Option	Positives	Negatives	Costs and Timeline
1	Install a series of species trials in a number of different environments to determine the best species and collect growth data to improve growth models	• Lots of quality data for modelling • Direct comparison of species performance	• Very expensive • Time consuming to establish • Long time horizon (>7 yrs) before trees are old enough to provide data	• Very high cost • Eight to 20 years timeline
2	Create new statistical models to improve existing models by including latest PSP data	• Cheap • Quick turnaround • Potential to include differences between regions	• Small amount of new PSP data • Unlikely to significantly improve models	• Low cost • One year timeline
3	Locate new stands to install new PSPs to collect data to improve models	• Cheaper than option 1 • Relatively simple and straight forward approach	• Unlikely to locate enough new stands to significantly improve models • Potentially time consuming in locating and installing new PSPs	• Medium to high cost • Two to three year timeline. Longer to collect several measurements from new PSPs
4	Statistical modelling using radiata pine as a proxy for site productivity for alternative species	• Uses existing data in PSP database • Quick turnaround	• Radiata pine is not as site sensitive as alternative species • Unlikely to provide the sensitivity below the regional level	• Low cost • One year timeline
5	Improve models by determining drivers of productivity to between and within sites with combination of remote sensing, drones, digital elevation models (DEM), soil moisture, slope, aspect, soil fertility, etc.	• Will directly measure microsite and local variation of growth • With enough plots will be able to extrapolate productivity more robustly • Shorter timeline than option 1	• Very expensive to collect measurements • Relies on existing PSP network • Extrapolation will be difficult in regions & districts where few PSPs exist • Potentially local effect bias	• Very high cost • Three to five year timeline
6	Use process-based modelling to predict productivity. Improve existing process-based models with collection of additional data from PSPs	• Improve productivity models with existing PSPs • Able to extrapolate more robustly with existing PSPs than statistical models • Potential to lean on current research under the Growing Confidence in Forestry's Future program	• Will not be able to predict microsite effects (< 1 ha)	• Medium cost • Two to three year timeline
7	Consider the above recommendations specifically for creating or improving productivity surfaces	• Ability for surface-based comparisons • Ability to quickly demonstrate species' suitability, potentially at a finer scale	• New data requirements • Regression may not be significant	• Aligns with items 1 & 3 above

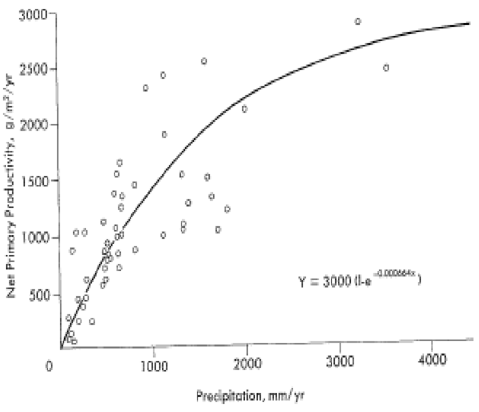
INTRODUCTION

Tree growth is the rate at which energy is bound and organic matter created by photosynthesis, per unit of the earth's surface, per unit time (Whittaker, 1975). The productivity of a tree or a forest stand over time can be expressed in a number of ways: biomass produced, energy captured, rate of height growth, rate of stem or basal area growth, or rate of volume growth. Generally in forestry, the average annual commercial stem volume fraction of a forest stand grown over a rotation is counted as the forest productivity, and is referred as the mean annual increment (MAI) and is expressed in $m^3/ha/yr^{-1}$. Other measurements typically used in forestry to assess the growth and yield of a forest stand include basal area (BA), mean stem diameter at breast height (DBH), stand leaf area index, stand density index, and stand mean tree height; these measurements are correlated with site productivity.

Site index (SI) is a commonly used method for indicating productivity of a range of tree species throughout the world. This is defined as the mean top height (MTH) of the 100 largest-diameter (dominant) trees per hectare at a particular age. For *Pinus radiata*, the base age for SI is 20 years. Site indices assumes that stands with the same MTH will have the same yield/productivity. While this is not always true, SI does provide a standardised estimation of productivity that can be compared over a range of sites.

Productivity differs between species and between sites, and is influenced primarily by moisture and temperature, and secondarily by nutrients and succession (Watt et al. 2009a). Productivity for tree species generally increases with increasing precipitation (Fig. 1a) and increasing temperature (Fig. 1b), although this does not hold for all species. Other factors that influence productivity include tree density/spacing (i.e. the number of trees per unit area (Evans 1992)), soil, genetics, competition, disease, pests, drought, exposure, aspect, fire, and mortality.

In the late 18th and early 19th century, with the reduced availability of native timber, plantation forests were seen as a way to respond for the demand for wood resources. This was also true for New Zealand which saw a dwindling supply of wood resources from indigenous forests in the late 19th century. Species like *Sequoia sempervirens* ((D. Don) Endl), coast redwood) and *Pseudotsuga menziesii* ((Mirb.) Franco, Douglas-fir) were introduced to New Zealand as plantation species but with varying levels of success (Brown et al. 2008). Some species that were introduced to New Zealand by settlers (Nicholas et al. 2007), for example for shelterbelts, firewood, landscaping and scenic beauty, are only found in minor, scattered stands. A number of tree species introduced to New Zealand are sensitive to site factors such as frost, soil nutrients, soil depth, and wind exposure. Such species nevertheless have the potential to be a commercially successful forestry species in the sites that do suite them. However the success of the site insensitive species *Pinus radiata* (D. Don radiata pine) meant that the forestry sector as a whole moved to growing radiata pine almost exclusively. This emphasis led to consequences such as only piecemeal research on other, non-radiata pine (alternative) species, over the last 40 years.



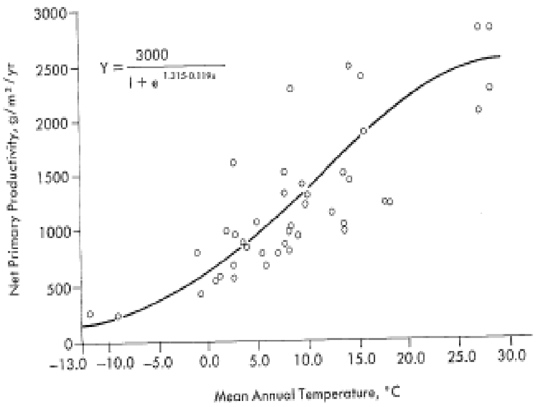


Figure 1a. Net primary productivity, above & below ground, in relation to mean annual precipitation.
Source: Lieth (1973).

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

This report focuses on the six alternative tree species that had been identified by the Speciality Wood Products (SWP) program to have the greatest potential for commercial success on a large scale in New Zealand. The species are *Pseudotsuga menziesii* (Douglas-fir), *Eucalyptus fastigata* (Deane & Maiden), *E. nitens* (Deane & Maiden), *E. regnans* (F.Muell.), *Cupressus lusitanica* (Mill.), and *C. macrocarpa* (Hartw.). *Sequoia sempervirens* (coast redwood) was also included in this report as it is also known for its commercial potential, raising the total to seven species. (For consistency the report standardises on the Latin names).

The objectives of this report are four-fold. The first objective is to review the distribution and number of permanent sample plots (PSPs) for each species as this is the primary source of data for predicting productivity. Second is to complete a literature review on the productivity models developed for each species and evaluate their ability to predict productivity throughout New Zealand. Third is to evaluate existing national spatial information in regard to each species' modelling basis (the PSPs for the species) to determine the locations where the models are robust predictors of growth national, regional, or at the local level. The fourth objective is to provide recommendations to the SWP program on the steps needed to improve and accuracy and precision of the models.

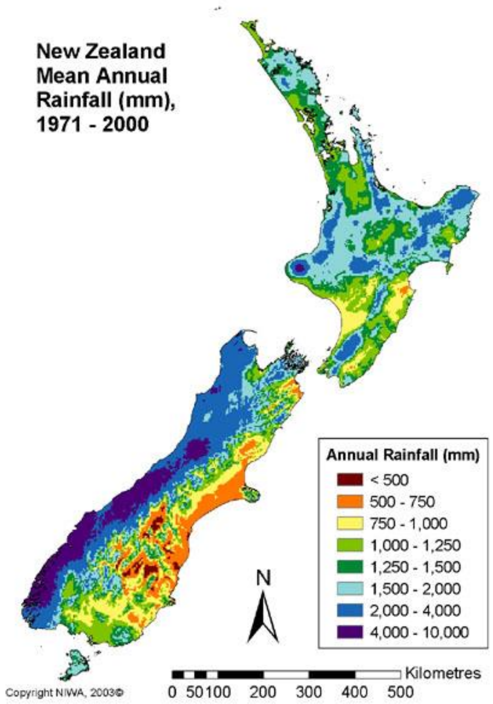
OVERVIEW OF NEW ZEALAND'S CLIMATE, ALTERNATIVE SPECIES PLOT NETWORK, AND DISTRIBUTION OF ENVIRONMENTAL FACTORS

New Zealand's climate and potential 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". The mean annual rainfall varies considerably between regions (Fig. 2a) as does mean annual temperature which ranges from approximately 2°C to 18°C, although the dominant range is much less at 10°C in the south to 16°C in the north (Fig 2b).

The rainfall and temperature ranges are equivalent to a range in net primary productivity (NPP) of 990-1960 $g/m^2/yr$ and 1410-1930 $g/m^2/yr$ according to the graphs in Figure 1a and b. This NPP range overlaps almost completely with 1000-2000 $g/m^2/yr$ which is regarded as the normal range of NPP for most forest communities (Whittaker 1975).

The more elevated parts of New Zealand however experience a drop in temperature of 0.7°C 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 decrease for higher elevations as illustrated in Fig. 3.



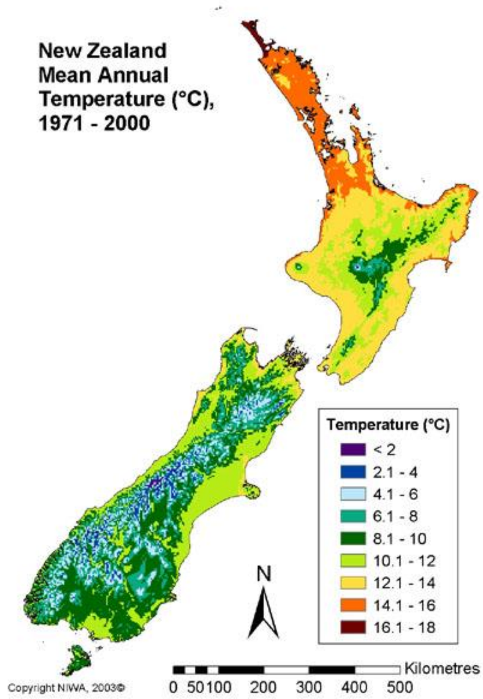


Figure 2a. Mean annual rainfall **Figure 2b.** Mean annual temperature

Source: NIWA (2012)

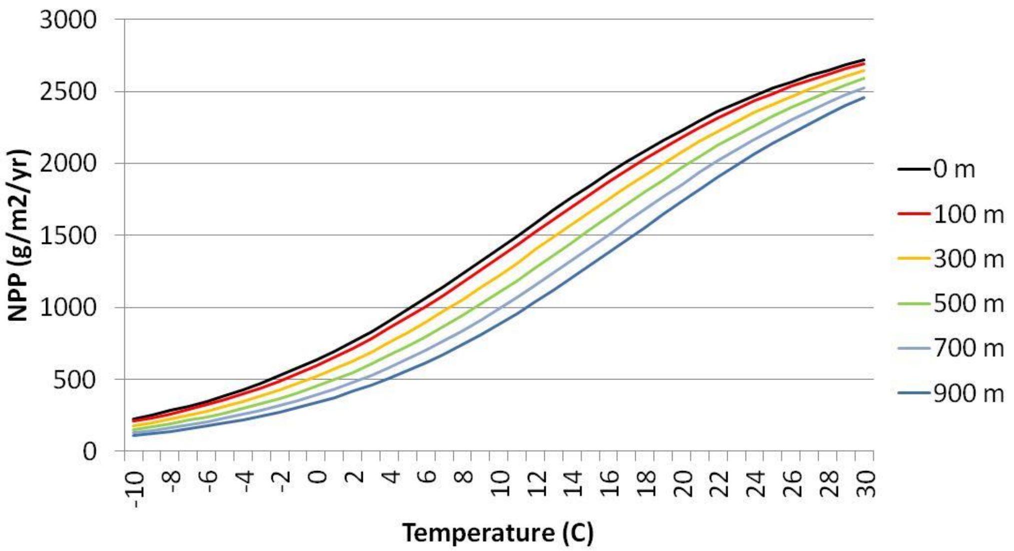


Figure 3. Net primary productivity above & below ground, in relation to mean annual temperature at altitudes ranging from sea level to the maximum considered suitable for commercial planting. The lies represent the general trend and do not indicate the response of an individual species' productivity.
Source: Todoroki and Meason, (2012).

Alternative species plot network

There are 3718 plots associated with *P. menziesii*, *E. fastigata*, *E. nitens*, *E. regnans*, *C. lusitanica*, *C. macrocarpa*, and *S. sempervirens* in the Scion PSP Database (Table 1). Nearly half (1823 plots) are associated with *P. menziesii* (Douglas-fir), and a further quarter (1004 plots) with the three *Eucalyptus* species.

The breakdown of the plots by individual species and region is given in Table 1. The number of plots for each species in each region varies dramatically with some regions having no PSPs. Overall, the Bay of Plenty and Waikato regions have the most number of PSPs for the seven species. This represents the concentration of trials established by Rotorua-based scientists at Scion in the central North Island (CNI).

Table 1. Number of plots, by region for which measurements are held in the Scion Permanent Sample Plot database.

Species/Region	NT	AK	WK	BP	GS	HB	TR	WM	WN	NN	MB	CY	WC	OT	SD	Total
CULUS	34	6	43	155	22	10	1	3	3	3		4	14			298
CUMAC	175		23	62	5	8	1	10	6	10	7	44	9	55	10	425
EUFAS	21		58	78	11	2	4	12	3	1						190
EUNIT	68		56	133		2				5		4	6	38	71	383
EUREG	6		158	183	2	47	6	7	2	3	4				13	431
PSMEN			101	482	8	156	3	26	23	267	15	355	45	247	95	1823
SQSEM			17	28	27	30	7	9	1			18	1	8		146
Total	310	6	457	1125	76	258	24	69	39	289	26	427	75	348	189	3718

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
CULUS=*C. lusitanica* CUMAC=*C. macrocarpa* EUFAS=*E. fastigata* EUNIT=*E. nitens*
EUREG=*E. regnans* PSMEN= *P. menziesii* (Douglas-fir)
SQSEM=*S. sempervirens* (coast redwood)

The distribution of climatic and soil environmental factors for alternative species

Mean annual rainfall at the PSP plot locations ranged from 480 to 4380 mm. Figure 4 summarises the mean annual rainfall by species. The cypresses were located on plots with the greatest mean annual rainfall, while *E. nitens*, with the largest interquartile range, grew on plots with wide variability in rainfall.

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. Figure 5 summarises the mean annual temperature by species. Again, *E. nitens* demonstrated the greatest range in climatic conditions, as shown by the interquartile range*. S. sempervirens* also had a large interquartile temperature range.

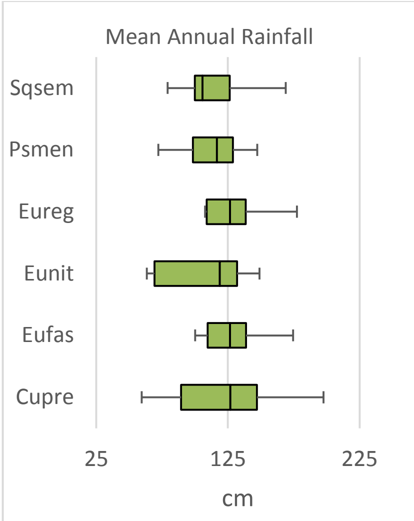


Figure 4. Box and whisker plots of mean total annual daily rainfall at sites held in Scion's Permanent Sample Plot system by species; *Sequoia sempervirens* (Sqsem), *Pseudotsuga menziesii* (Psmen, Douglas-fir), *Eucalyptus regnans* (Eureg), *E. nitens* (Eunit), *E. fastigata* (Eufas), and for *Cupressus lusitanica* & *C. macrocarpa* (Cupres). The box represents the 25th and 75th percentiles of the data distribution, the whiskers represent the 5th and 95th percentiles, and the line is the median value.

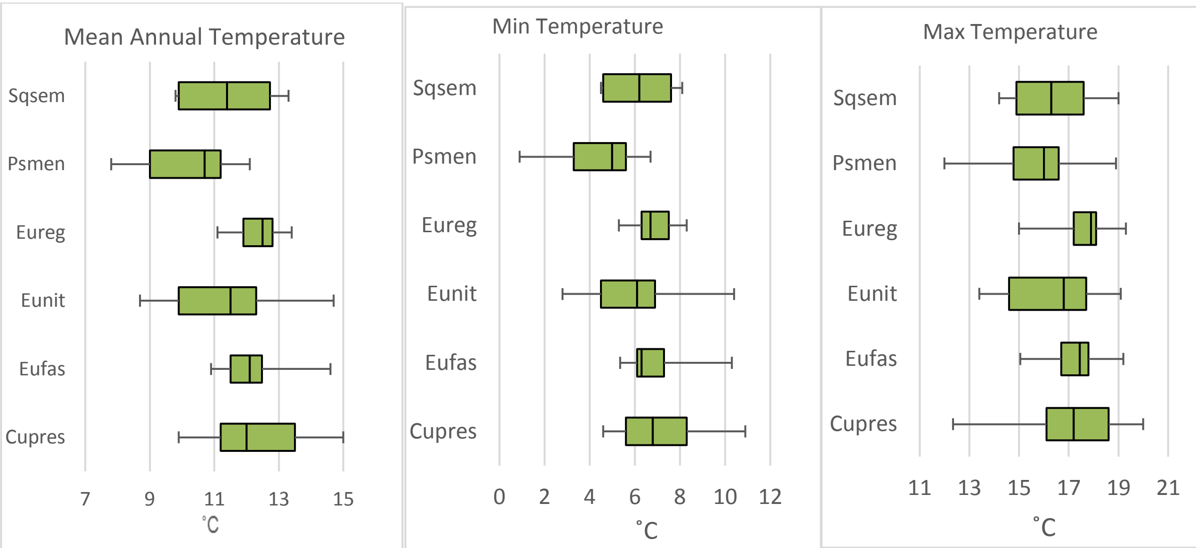


Figure 5. Box and whisker plots of mean annual daily temperature, mean annual daily minimum temperature, and mean annual daily maximum temperature at sites held in Scion's Permanent Sample Plot Database by species; *Sequoia sempervirens* (Sqsem), *Pseudotsuga menziesii* (Psmen, Douglas-fir), *Eucalyptus regnans* (Eureg), *E. nitens* (Eunit), *E. fastigata* (Eufas), and for *Cupressus lusitanica* & *C. macrocarpa* (Cupres). The box represents the 25th and 75th percentiles of the data distribution, the whiskers represent the 5th and 95th percentiles, and the line is the median value.

For each PSP, the New Zealand Soil Classification (NZSC) soil order and group were extracted. NZSC comprises 15 soil orders, of which Brown soils are the most extensive soil order covering 43% of New Zealand. Brown soils are typically found in places where summer drought is uncommon, and they are not waterlogged in winter (Hewitt 2010). Many of the PSPs are established on Brown soils. Two of the least common soil orders, Anthropic and Semiarid, were absent from the PSPs. The NZSC soil classification for soil groups where PSPs are established is shown in Table 2. The soil orders underlying each species in the PSP plots is given in Table 3.

Table 2. New Zealand soil classifications associated with the species of this study held in Scion's Permanent Sample Plot Database. Anthropic and Semiarid soils are intentionally omitted.

Soil Order	Soil 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 3. New Zealand soil group classifications by species where PSPs are located; *Sequoia sempervirens* (SQSEM), *Pseudotsuga menziesii* (PSMEN), *Eucalyptus regnans* (EUREG), *E. nitens* (EUNIT), *E. fastigata* (EUFAS), *C. lusitanica* (CULUS), and *C. macrocarpa* (CUMAC).

	NZSC Classification Key for Soil Groups (defined in Table 2)												
Species	**B**	**E**	**G**	**L**	**M**	**N**	**O**	**P**	**R**	**U**	**W**	**X**	**Z**
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 PI,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
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

The C:N ratio of the upper 10cm of the soil is a common measure to assess soil fertility. C:N ratios have been identified for New Zealand soils, and were extracted for each PSP. For each species, the range in C:N ratios sampled by the species' PSPs is shown in Figure 6.

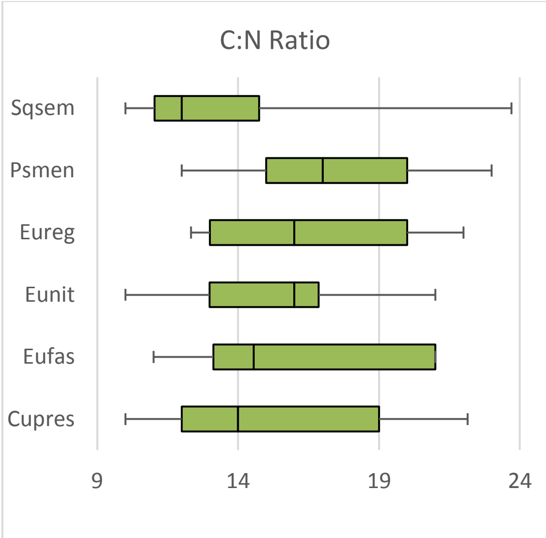


Figure 6. Soil C:N ratio (upper 10cm) range relation on soils underling the alternative species' PSP by species; coast redwood (Sqsem), *P. menziesii* (Psmen), *Eucalyptus regnans* (Eureg), *E. nitens* (Eunit), *E. fastigata* (Eufas), and for *C. lusitanica* & *C. macrocarpa* (Cupres).

LITERATURE REVIEW BY SPECIES

Eucalyptus fastigata

Eucalyptus fastigata is a fast growing species that is disease resistant and can tolerate a wide range of New Zealand environments. It has good potential as a plantation species for pulp and paper, timber, and for carbon forestry. Two growth and yield model have been developed for the species; van der Colff (2005) and Berrill and Hay (2005). The van de Colff model used data from the existing PSP and Carter Holt Harvey Forest's plots in the Kinleith Forest estate in the Central North Island. The plots locations can be seen in Figure 7. This combined dataset ranged in age from 10 to 66 years with a mean of 17 years, mean top height average of 29.5m (ranging from 10.7 to 58.4 m), mean top diameter of 39.6 cm (ranging from 14.4 to 100 cm) and a final stocking of 1259 stems per ha (SPH) (ranging from 220 to 4400 SPH) (Todoroki and Meason 2012).

The second growth and yield model constructed by Berrill and Hay (2005) used data from a combination of 66 PSPs and 45 other plots obtained using the "Method for the assessment of Recoverable Volume by Log Type" (MARVL) method. The data were predominantly from the North Island; Northland, Bay of Plenty, central North Island, Wanganui/Manawatu, and four plots from the Nelson/Marlborough region. However, the majority of the data for the model was from plots from the Central North Island. Tree age ranged from 2 to 66 years old with a mean of 12 years, mean top height average of 19.4 m (ranging from 2.6 to 58.4 m), an average basal area of 29.3m^2 ha^{-1} (ranging from 0.06 to 138m^2 ha^{-1}), and a mean stocking of 1111 SPH (ranging from 21 to 5000 SPH).

These two growth and yield models provided accurate predictions for *E. fastigata* in the Central North Island. However, these models under-predicted *E. fastigata* productivity for the rest of New Zealand (Meason and Dungey 2009). Indeed, future plantings *of E. fastigata* are most likely to occur on marginal agricultural land outside the Central North Island (Meason et al. 2010).

Meason et al. (2010) developed a carbon sequestration model for *E. fastigata* using the data from 15 sites, with an average age of 16 years old (ranging from 8 to 32 years old) and stocking from 103 to 1633 SPH with an average of 649 stems per hectare, an average basal area of 49.6 m^2 ha^{-1} (ranging from 24 to 94m^2 ha^{-1}). The mean annual increment was on average 21.8m^3 $ha^{-1}yr^{-1}$ (ranging from 8.4 to 49.1m^3 ha^{-1} yr^{-1}). This work used the van der Colff and Kimberley (2005) growth model with a modification value to correct a perceived underestimation of the mean top height prediction outside the Central North Island. An adjustment in the input values was derived from an age 11 basal area (BA) and height relationship, which was generated using climatic and site data from locations outside the central North Island, so as to fit the model to the actual growth data behaviour.

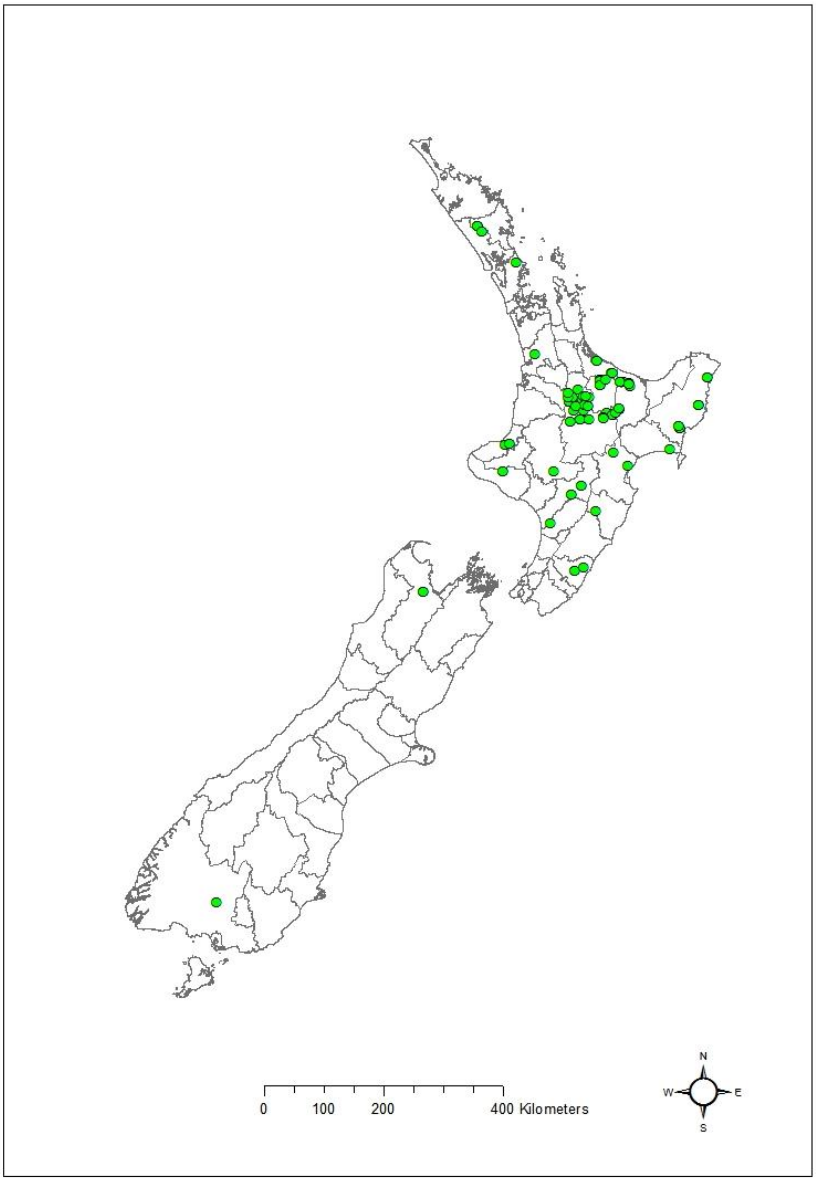


Figure 7. Distribution of *Eucalyptus fastigata* sites held in Scion's PSP database.

As seen for growth and yield models other than for radiata pine, insufficient PSPs exist for the development of a robust empirical growth and yield model for the entire country (Todoroki and Meason 2012). To circumvent this issue, a process-based model 3-PGS$_2$ (physiological processes for predicting growth spatially), was parameterised for *E. fastigata* under 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). This approach involves the simulation of stand growth by the underlying physiological processes or mechanisms that regulate tree growth, subject to the effect of site conditions on these processes. This allows process-based models to be applied to sites, ages and situations beyond the original data sets (Meason and Dungey 2009). The parameterisation of this model used data from seven sites throughout New Zealand including Marlborough and Southland, seeking to provide the greatest range of sites and productivities, with ages ranging from 8 to 25 years old and initial stocking from 625 to 2500 SPH.

A validation dataset was used to access model quality. The dataset was comprised of thinned and unthinned stands, at 9 sites distributed across 6 regions, with initial stocking from 650 to 1200 SPH and ages ranging from 7 to 31 years old. The output of this model generates a spatial productivity surface which can be simulate different management options.

Eucalyptus regnans

A growth model was developed by Hayward (1988) from data representing 220 plots on the Kinleith volcanic plateau (Fig. 8) for relatively young trees (3-15 years old) and stocking from 600 to 2500 SPH. Validation showed that this model is suited for stands younger than 15 years old. Because of the geographically restricted origin of the dataset, this model is only accurate for the central North Island (Todoroki and Meason 2012).

A second model was devloped by MacLean and Lawrence (1997) which includes data from 138 plots. Again the majority of the plots were from the central North Island, but plots from Northland and Southland were also included based on the national *E. regnans* program commenced in 1983. Trees ages ranged from 3 to 32 years old, with a mean of 9 years, with the majority of its distribution between 4 and 16 years old. Stocking averaged 612 SPH ranging from 50 to 2900 SPH. Plot data presented MTH values from 5.8 to 55.7m with a mean of 20.2m. Basal area ranged from 1.1 to 76.4 m^2 ha^{-1} with a mean of 14.6 m^2 ha^{-1}, and Mean Annual Increment (MAI) had a mean of 10.93 m^3 ha^{-1} yr^{-1} and ranged from 0.77 to 51.04 m^3 ha^{-1} yr^{-}1. Subsequent validation showed that this model is adequate for stands younger than 20 years old (Todoroki and Meason 2012).

As mentioned by MacLean and Lawrence (1997), the Hayward model lacks mortality and thinning functions, therefore does not adequately account for changes in stocking over time*. E. regnans*' growth in New Zealand does not fully support this assumption and as a result, volume and basal area predictions may be overestimated, especially in its use for solid wood regimes. As indicated, the model was based predominantly on data from a limited geographical area (the Kinleith region), and was never expected to model growth elsewhere in New Zealand.

A computer program was developed for the FRI/Industry Eucalypt Management Cooperative by MacLean and Van Zyl (1997) incorporating the MacLean and Lawrence (1997) model. This program requires inputs such as age, initial stocking, MTH and BA, and allows multiple thinning simulations, and generates graphical and tabulated results.

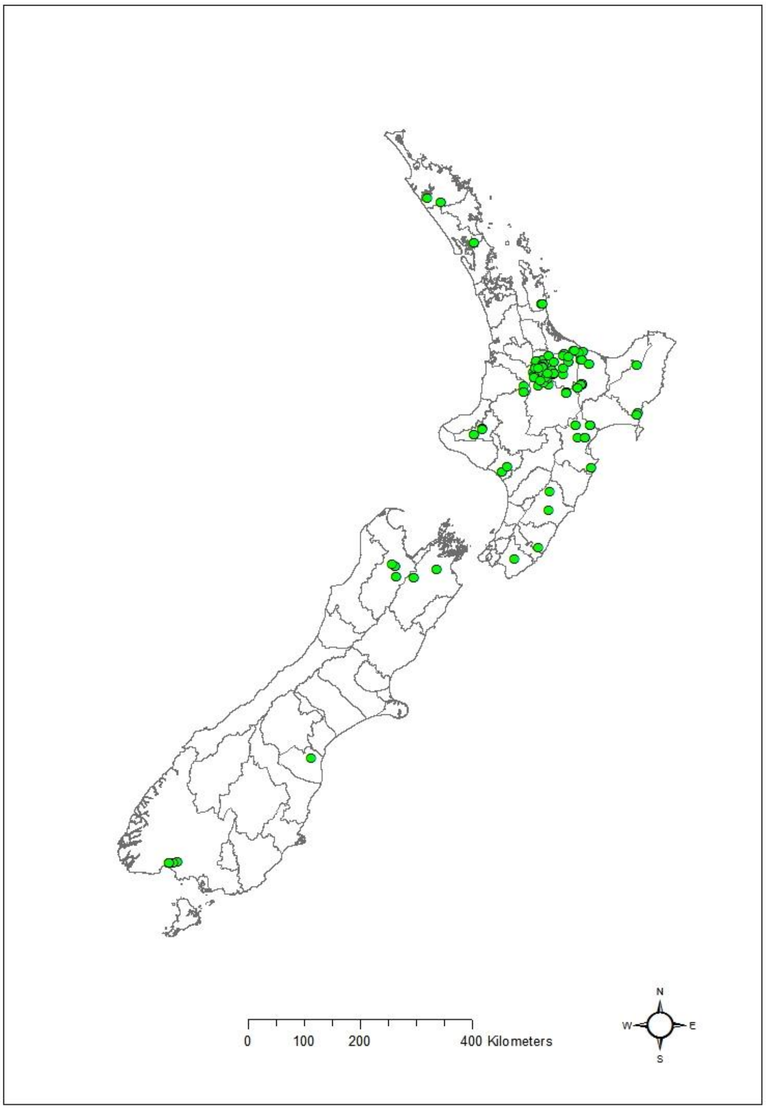


Figure 8. Distribution of the *Eucalyptus regnans* sites held in Scion's Permanent Sample Plot database.

A process based model developed by Meason (2015) used data from 12 sites across New Zealand including Tasman and Marlborough on the South Island, with stands ages between 10 and 47 years old. The 3-PGS$_2$ model used three layers of special data, including geographical, climatic and edaphic proprieties, like soil water, depth and fertility. The model's spatial productivity surface can be created following different management options, e.g. carbon farming on a complete stocking regime and timber production through thinnings.

Eucalyptus nitens

Candy (1997) developed a growth model with data from plantations in Tasmania and New Zealand based on 96 plots. The combined data set was aged 2 to 34 years (mean 7.4 years), SI at age 15 years ranging from 13.8 to 38.9 (mean 26.2 years), and initial stocking from 100 to 2600 SPH (mean 1142 SPH) and MTH of 14.7m ranging from 1.8 to 35.5m. The total standing volume of the samples had a mean of 90.4 m^3 ha^{-1} with a range from 0.7 to 742.9 m^3 ha^{-1}.

A second model for *E. nitens* in New Zealand was devolved by Candy (2002) using updated data from the PSP network and enhanced with a thinning option. The location of the actual PSPs can be seen in Figure 9. From the 42 trials distributed across both North and South islands, 266 PSPs were measured. This new dataset covered ages from 2 to 24 years old, with a mean of 8.1 years. The average MTH was 30.4m, with a range from 15.9 to 38.8m. This model gave an accurate prediction, but as the author mentions, the lack of older age measurements available for model calibration, especially for mortality and one of the most difficult stand characteristics to model satisfactorily, results in a lack of confidence in predictions at ages greater than 20 years old.

MacLean and Van Zyl (1997) created a computer program for the FRI/Industry Eucalypt Management Cooperative that incorporates the Candy (1997) model. This program needs inputs such as age, initial stocking, MTH and BA; and allows only one thinning simulation for which age and stock remaining must be stated. Outputs from the model are generated as graphical and tabulated results.

It must be highlighted that the incidence in *E. nitens* of leaf spotting by *Phaeophleospora eucalypti* and *Mycosphaerella cryptica* causing severe foliage blight became widespread in young stands, and is especially destructive at warmer sites; hence it is regarded as a serious pathogen in New Zealand (Hood et al. 2002). Growth reduction due to these pathogens can be considerable in warmer areas prone to their occurrence, so the use of growth and yield models should be used with caution, preferably for areas free or with only a slight occurrence of this disease.

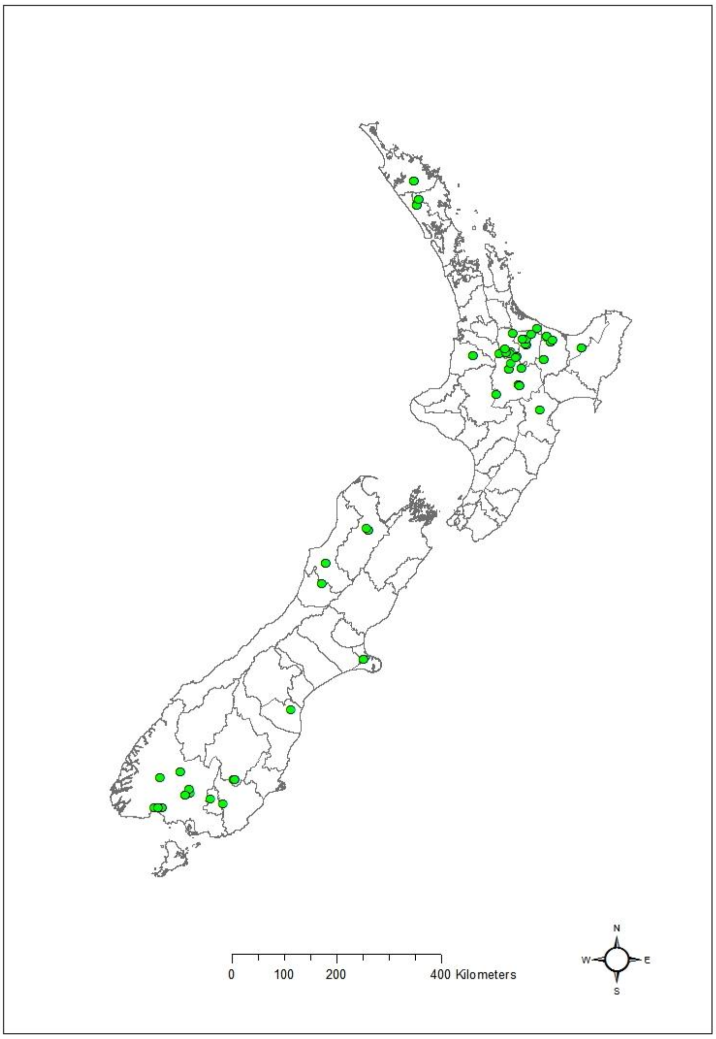


Figure 9. Distribution of the *Eucalyptus nitens* sites held in Scion's Permanent Sample Plot database.

Sequoia sempervirens (coast redwood)

Collaboration between Scion and industry before and after the establishment of FFR led to the development of several productivity models.

The first empirical growth and yield model that predicts basal area (BA), mean top height, and stand volume was developed by industry and improved by Scion. The Interim Growth Model (IGM) 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 PSPs (Fig. 10). The project was initiated by NZ Forestry Limited (NZF) and was jointly funded by NZF and The New Zealand Redwood Company (Meason et al. 2012a).

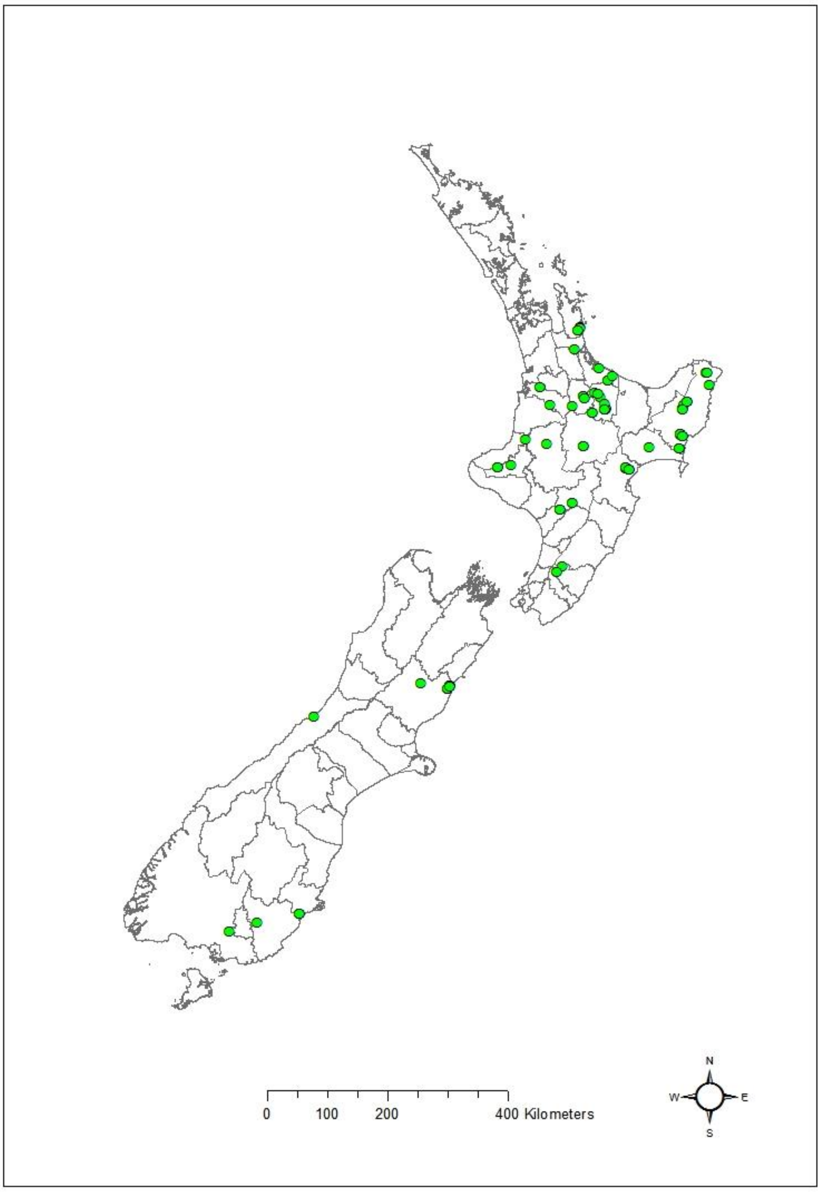


Figure 10. Distribution of the *Sequoia sempervirens* sites held in Scion's Permanent Sample Plot database.

This model was later converted into an Excel-based growth calculator (Kimberley et al. 2011a) that has initial stocking, BA, MTH and desired rotation length as inputs; and projects stand volume, DBH and its distribution.

In turn, this growth calculator model was used to develop a site productivity index for *S. sempervirens*. This index was defined as the height of the 100 largest DBH trees per hectare, 40 years after reaching a breast height of 1.4m (Palmer et al. 2012). This definition was necessary as poor weed control can dramatically slow seedling growth until trees overtop the weeds. With proper weed control, seedlings typically reach 1.4 m at three years. The growth calculator model was also used to develop an index of stand basal area (BA) growth, and referred to as the 40/400 index or the 400 Index. It was defined as the BA at breast height age 40 years for a stand growing at 400 stems ha^{-1}.

In turn, the 400 Index was modelled using climatic and soil properties to generate a volume productivity surface across New Zealand (Palmer et al. 2012). This allowed the ability to predict *S. sempervirens* volume productivity between sites. Despite the relatively small and geographically restricted dataset used to develop the IGM, the model has performed well in predicting growth at sites added to the PSP network since its initial development (Meason et al. 2012b).

Watt, Kirschbaum et al. (2012) parameterised 3-PGS_2 to simulate *S. sempervirens* productivity under current climate conditions in New Zealand and develop potential productivity surfaces under a range of climate change scenarios. Data was acquired from 12 sites across New Zealand from stands with ages ranging from 3 to 86 years old, and stocking from 133 and 1660 SPH. Climatic and edaphic layers were used, as input variables, combined with physiological data from the PSPs. After the model was fully calibrated, simulations were perform resulting in different climate change scenarios.

Results showed that increasing temperature and fewer frost days were the most important climatic factors impacting growth in the climate change scenarios. The decrease in precipitation in some regions reduced the size of productivity gains. Reductions in precipitation were not large enough to adversely affect productivity in many areas in New Zealand. However, there were indications that the productivity increase was not at its maximum potential in some areas (Watt et al. 2012).

***Pseudotsuga menziesii* (Douglas-fir)**

A growth model for *P. menziesii* was developed for the central North Island by Xu (1989) with characterisations of three localities, presence of Swiss needle cast disease, and thinning history. The data originated from stands aged between 9 and 82 years old, with a mean age of 35 years; an average DBH of 32.5cm, with a range from 5.8 to 66.8cm; and MTH ranging between 9 and 46m. Initial stand stockings were between 1376 and 6944 SPH, which would be considered high, however after thinning and mortality, the average stocking was 638 SPH, with range of 170 to 4941 SPH.

A validation of this model was done by Kimberley and Knowles (1996), with data from seven locations on the central North Island. The validation stands were aged between 10 and 85 years old, and SI varied from 22.4 to 33.3m. Results included over-estimation of MTH on higher SI sites, and under-estimation on low quality sites, and colder and flat regions. Mortality was under-estimated in high-stocked, unthinned mature stands.

Lee (1998) developed growth and yield models adaptable for four regions in the South Island – such models rely on a prediction of MTH depending on locality and altitude to project stand growth through time. The data was acquired from 366 PSP in Canterbury, Nelson, Southland and Westland. Stand ages ranged from 5 to 78 years, stocking ranged from 73 to 4025 SPH; and MTH ranged from 1.9 to 46.6m with means of 19.8, 22.9, 21.0 and 16.6m, respectively.

A web-based platform is available online that uses the Lee (1998) model with inputs such as age, MTH, BA, initial stocking, region, and altitude of the location to be simulated. An output table is then generated showing the evolution of MTH, BA, mean DBH, volume and stocking (Lee 2012). The program is able to provide estimates under multiple thinning regimes.

The Douglas-fir Calculator was created as a ‘calculator’ running under Microsoft EXCEL, after its original development as Decision Support Software. The first version of the Douglas-fir Calculator, estimates the Equivalent Farming Gross Margin of crops of *P. radiata* and *P. menziesii*, compared to the livestock previously grazing the land. It also allows the identification of the most profitable silvicultural regime for the tree crop, and generates yield tables (Halliday and Knowles 2003). Over the years the programme was improved with more complex and complete models, resulting in better precision and amplitude.

In the second version of the Douglas-fir Calculator, some of the functions were embedded in the EXCEL code, however most of the calculations were estimated from regressions fitted to a database of output generated from STANDPAK runs (Knowles et al. 2004). In later versions, all functions are embedded directly in the EXCEL code.

The second version of the Douglas-fir Calculator relied, among others thing, on an age / height model, developed by Van der Colff et al. (2004). Data from sample plots throughout New Zealand were extracted from the PSP database. The plots were located in stands ranging in age from 4 to 130 years. MTH varied between 2.0 and 57.8m, with a mean of 23.4m; and SI (MTH at age 40 years) had a mean value of 32.1m, ranging from 12.9 to 45.5m.

This model also accounts for latitude as a predictor of MTH, as there can be different growth rates for different latitudes even though the SI curve is the same. Figure 11 shows the behaviour of SI curves located at different latitudes. At low latitudes, the initial growth is better than at high latitudes, but this reverses after year 40. Hence for *P. menziesii,* productivity does not necessarily increase with increasing temperature. It has been observed that *P. menziesii* and species other than radiata pine tend to have more specific microsite requirements (Ledgard et al. 2005).

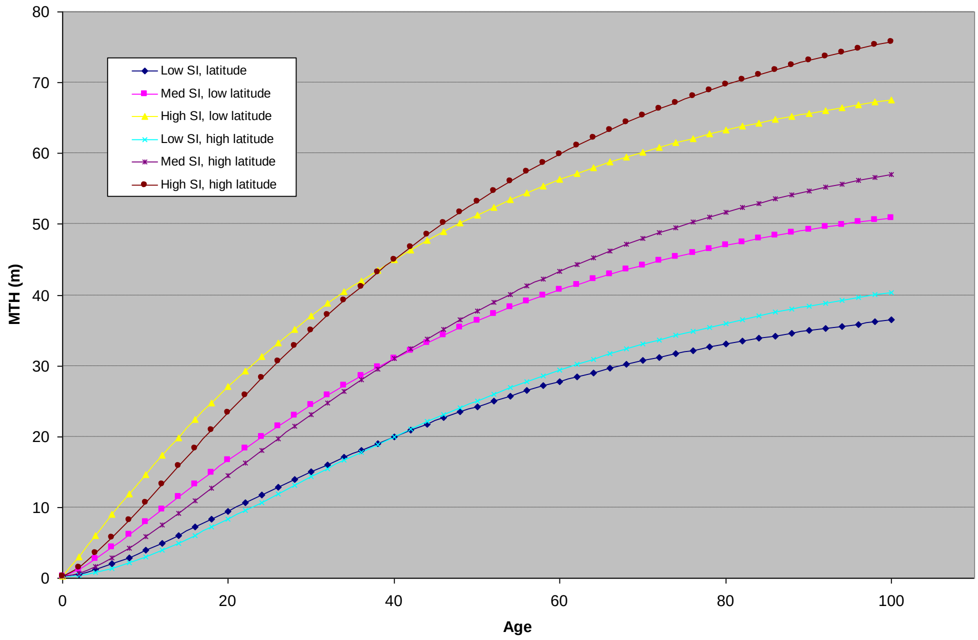


Figure 11. National h eight/age curves *for Pseudotsuga menziesii* for variations of site index and latitude (VanDerColff and Kimberley 2003).

The development of the Douglas-fir National Growth Model used all available sample plots in Scion's PSP Database (Fig. 12) with the objective of calibrating the model for multiple sites. The results were aggregated into general look-up tables which provided regional productivity levels with modifiers for site characteristics, such as elevation. This allowed growth and yield simulations of specific forest to be matched to the most appropriate productivity estimations (Knowles and Hansen 2005).

Site index as the MTH at age 40 was estimated using the height age curves that include latitude as a parameter (Van der Colff, 2004), and the most recent measurement of MTH for each sample plot. Latitude for each forest was taken from the plot locations stored in the PSP Database. The mean stand age for the measurements was 37 years and the mean MTH was 28.7m.

Knowles and Wichmann-Hansen (2007) validated this growth model with data originating from a series of re-measured plots/trials in the PSP Database. They used a total of 3291 measurements of stand conditions from 242 different sample plots located on 16 different sites around New Zealand. The plots ranged in age from 11 to 73 years on sites where MTH ranged from 25 to 40 m, and SBAP (site basal area potential) from 0.5 to 3.6 m^2ha^{-1} yr^{-1}.

A distance-independent tree-level growth model was developed by Van der Colff and Shula (2006), using 436 PSPs distributed throughout New Zealand. Ages ranged from 15 to 62 years with a mean of 30 years for the North Island stands, while the South Island sites ranged from 15 to 55 years with a mean age of 21 years. Mean top height ranged from 8.3 to 45.1m, DBH from 6.6 to 81cm, and stocking from 360 to 2283 SPH. Average values for MTH, DBH and SPH were for the North Island, respectively 25.8 m, 34.4 cm, and 568 SPH; and for the South Island, respectively 17m, 16.2 cm, and 800 SPH. The model predicts the growth and yield of a stand of trees (without thinning interventions) at an individual tree level of detail. It makes use of starting data from an initial individual tree list, predicts annual tree growth in DBH and total height, and the annual probability of a tree dying. Stand statistics are accumulated from a tree list (starting age, then iterative annual predictions). For over 80% of the trees, annual growth of tree DBH and total tree height was predicted within ±0.5 cm and ±0.5 m, respectively. Tree-level survival was predicted with an acceptable level of reliability to adequately account for changes in stand-level stocking over time.

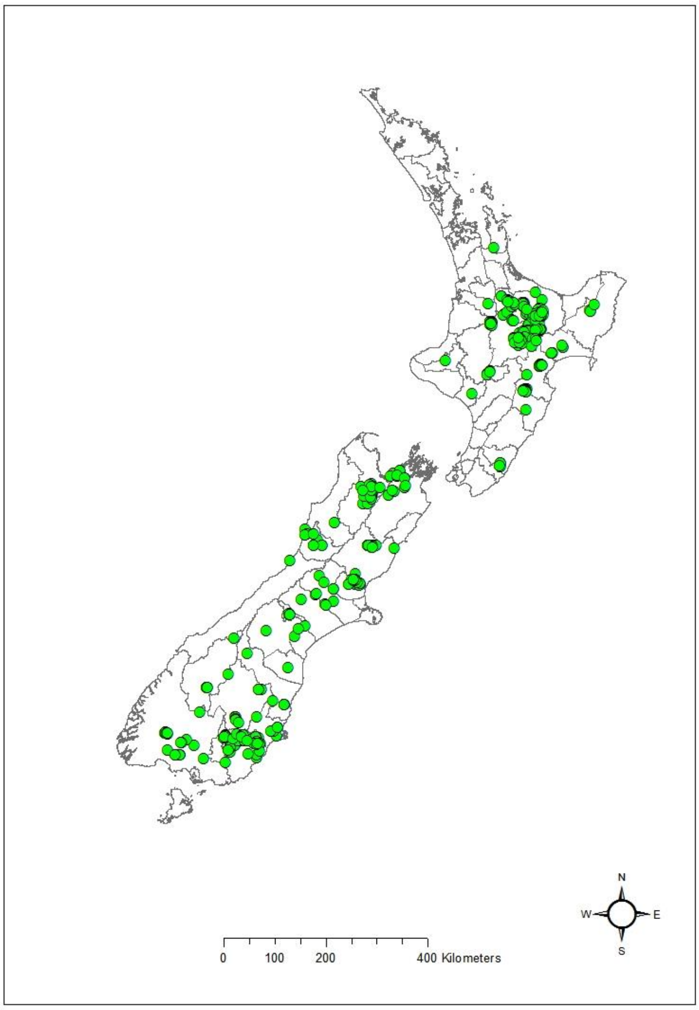


Figure 12. Distribution of the *Pseudotsuga menziesii* sites held in Scion's Permanent Sample Plot database.

Forecaster, the decision support system developed by Scion and owned by FFR, is used to predict the growth and yield of stands, schedule silvicultural operations, and generate yield tables. It allows users to simulate impacts of site, silviculture, and genetics on tree growth and form, branching and wood properties. In addition to its use as an operational tool, Forecaster is also a means of delivering new science to the forestry industry. Such outputs provided through Forecaster include the individual stem-level implementations of the 500 Index. This system is also based on the same growth model as the Douglas-fir Calculator. Although they share the same model, differences in stand volume and carbon quantities, especially after thinning, are occurring. The difference is mainly due to different versions of the carbon sequestration model for trees, C_Change, and stand and stem-level approaches to under bark volume (Narayan et al. 2013).

Attention also needs to be given to the effect of Swiss needle cast (SNC) disease (caused by *Phaeocryptopus gaeumannii*) on the growth of *P. menziesii*, as recent work confirms that the disease has a substantial impact on growth rate. SNC was first recorded in the Central North Island in 1959 and spread throughout most of the North Island in the following decade. It was first observed in the northern South Island in 1969, and spread throughout the remainder of the island in the following two decades (Kimberley and VanDerColff 2010).

A spatial model was produced by Watt, Palmer et al (2009b) to predict the direct and indirect impacts of climate change on the distribution of *P. menziesii* in New Zealand and the effect of Swiss needle cast intensity of infection. The model used climatic variables to estimate foliage retention in different climate change scenarios.

The spatial distribution of abundance and defoliation due to Swiss needle cast disease in New Zealand conforms very well with predictions based on long term winter temperature patterns. In general, greater colonisation and less foliage retention were found in sites characterized by warmer winter temperatures in the central and eastern North Island. The Karioi site in the central North Island is a higher elevation site (800m), characterized by much colder winter temperatures, than the other North Island sites. This site had colonisation levels and needle retention more comparable to sites in the South Island (Watt et al. 2011).

Kimberley, Hood et al. (2011b) found reductions of 34 and 22% in volume increment, and 27 and 22% in MTH increment due to the Swiss needle cast pathogen on the North and South Island, respectively. These losses tend to increase and then stabilize 10 to 15 years after infection.

An attempt to model the environmental effects on the productivity of *P. menziesii* was done by Watt et al. (2009b) using data posterior to 1955 to ensure that data was unbiased by the effect of SNC on growth. Multiple regression was attempted using climatic, environmental and terrain attributes related to site and the 500 Index, however no significant relationship could be established.

The authors discussed the effect of the provenances and the possibility of a local model being more effective, although with such work it would not be possible to determine the primary driver of changes in *P. menziesii* productivity. The hypothesis was also raised that Swiss needle cast throughout the country is concealing relationships between productivity and the environment.

Cupressus macrocarpa and C. lusitanica

Growth models for *C. macrocarpa* and *C. lusitanica* was constructed by Lawrence and MacLean (1995) using 208 plots throughout the country with a concentration of measurements in the Rotorua and Auckland regions. Stocking ranged between 231 and 2212 SPH with an average of 1054 SPH. Mean age of the data was 19 years with stands ranging from 3 to 42 years old. The SI curves included MTH from 10 to 25m at age 20 years. This work also provides models for BA increment, stand BA, and volume.

Contrary to the previous model, Baalman (1998) created models for *C. macrocarpa* and *C. lusitanica* separately, with data from 200 *C. macrocarpa* plots and 128 *C. lusitanica* plots. The plots were split in half to comprise the fitting and validation dataset. Geographical distribution for *C. macrocarpa* was wider over the entire country, while for *C. lusitanica,* the plots were predominantly in the North Island (Figs. 13 and 14). Stand age of the fitting dataset ranged between 1 and 65 years with a mean of 15 years. Mean stocking was 676 SPH with stands from 32 to 4950 SPH; and MTH was on average 12.8m varying between 1.6 and 37m. The validation dataset had similar DBH values to the calibration data. According to the author, who compared this new model to the previous Lawrence and MacLean (1995) model, reduced bias was achieved in basal area, height growth and stand volume.

Berrill (2000) compared these two previous models to several older cypress stands selected to represent a range of sites and stockings for *C. lusitanica* and *C. macrocarpa* around New Zealand. Very similar predictions were obtained by growing the same young stand data in the two models. The estimation of MTH was not biased up to age 14 years with only a slight over prediction.

As the author mentioned, later-age height growth may be over-predicted for many cypress stands, as many stands will not reach the MTH of which they are biologically capable (theoretical upper height asymptote) due to the vulnerability of the tree tops to pest and wind damage. Berrill concluded that the model's height asymptotes do not reflect the effect of cypress canker and the effect of weeds on growth.

Basal area and volume predictions were being influenced by the inaccurate prediction of mortality, especially for *C. macrocarpa*. The variation in cypress stand health and mortality between sites is large, making the rate of mortality for a given stand particularly difficult to predict. A growth rate or mortality modifier that accounts for the regional/user's canker data (as a model input) would be useful.

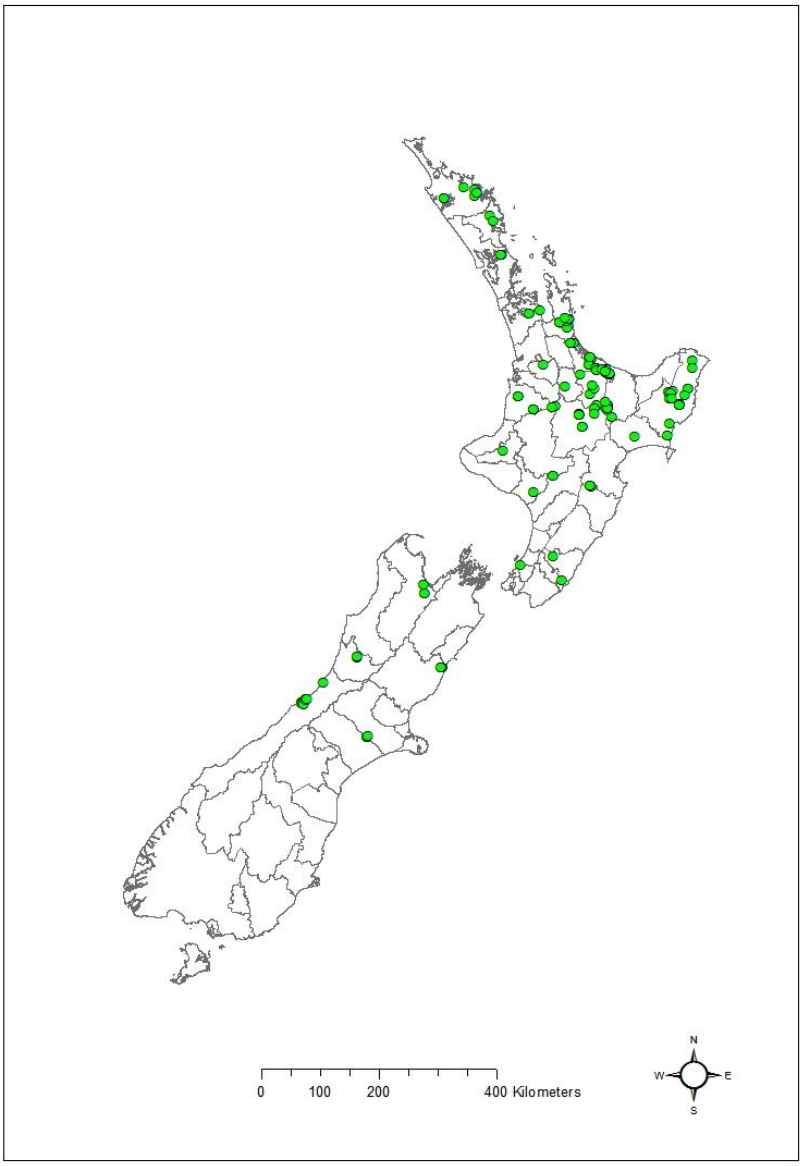


Figure 13. Distribution of the *Cupressus lusitanica* sites held in Scion's Permanent Sample Plot database.

Berrill (2004) developed growth and yield models using 1897 plot measurements from 166 *C. lusitanica* and 163 *C. macrocarpa* sample plots. Data for the *C. lusitanica* modelling had an average age of 12 years, ranging from 3 to 70 years old; and stocking density from 72 and 2566 SPH with an average of 687 SPH. Average MTH was 12.3m, ranging from 3.6 to 35.5m.

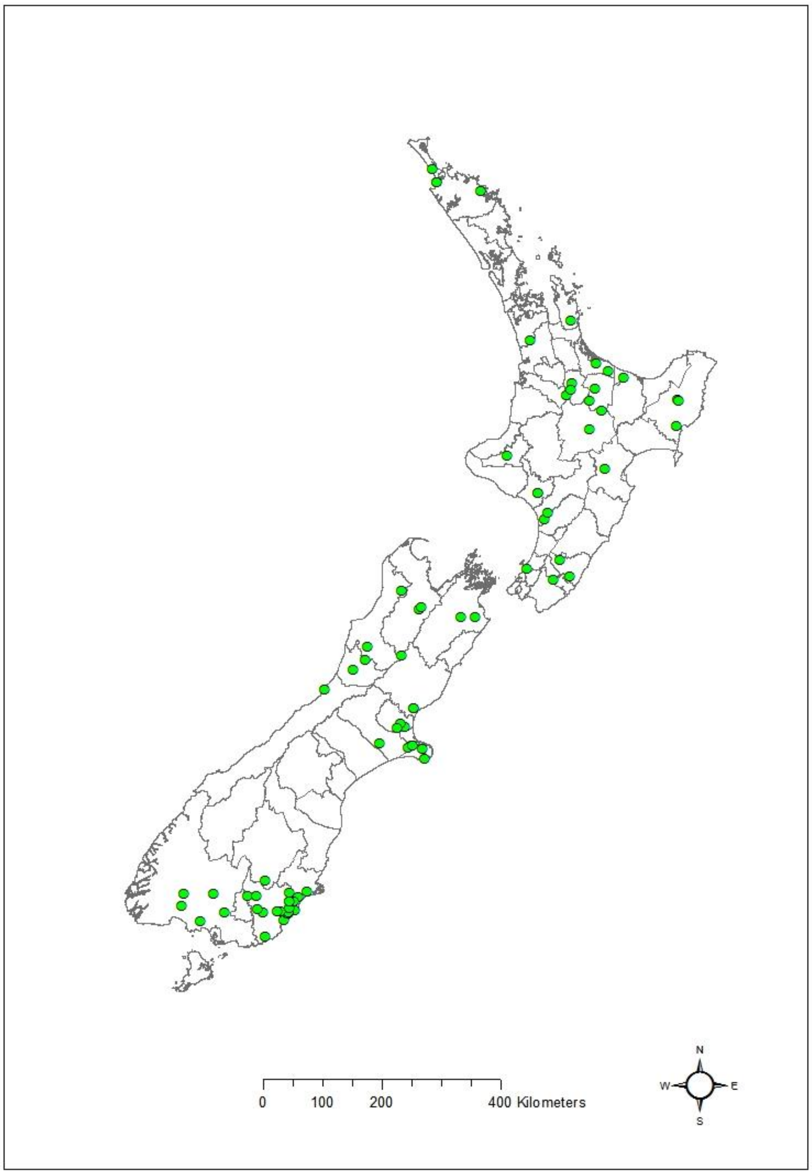


Figure 14. Distribution of the *Cupressus macrocarpa* sites held in Scion's Permanent Sample Plot database.

For *C. macrocarpa,* mean age was 17 years, with stands from 3 to 74 years old. Stocking values ranged from 32 to 4950 SPH with an average of 821 SPH. Mean top height ranged from 2.3 to 37.8m with a mean of 13.6m. The geographical locations of the *C. macrocarpa* plots covered all regions of the South Island with the majority of data coming from Otago and Canterbury. In the North Island, the distribution of *C. macrocarpa* plots was across almost all regions with the only exceptions being Auckland and Hawk's Bay, however more than half of the samples were from the Bay of Plenty and Waikato regions.

The distribution of *C. lusitanica* was heavily concentrated in the North Island, especially in the northern areas, such as Bay of Plenty, Northland and Waikato; and only on the West Coast and Nelson regions in the South Island. The height growth model is the same for both species, and has a root mean square error of 0.22m for both species combined; and 1.19 and 1.45m for *C. lusitanica* and *C. macrocarpa,* respectively.

A spatial model of productivity for *C. lusitanica* in New Zealand was made by Watt et al. (2009) who found significant correlations of SI to the establishment date, mean minimal temperature, soil depth, degree of summer frosts, and previous land cover. Multiple regression was used to estimate site index on the national scale, and as the historic record showed, sites planted on ex-pasture/cropland had a MTH that was 1.9m higher, on average, than the ones established on previously exotic/native forest sites. This research also found that the date of establishment of the stand has a significant impact on the productivity, as the older stands have significantly lower SI compared to younger stands. This fact may be attributed to genetic improvement, as well as better silvicultural techniques, such as herbicides for weed control; another factor may be changes in climate. These surfaces are shown in Appendix 1, and demonstrate the effects that different dates of planting and previous land uses have on the geographical distribution of site index.

The Berrill (2004) model was used by Lars Hansen for developing a web-based cypress growth calculator in 2008 (Dungey, 2010). The calculator (available only to FFR) provides profitability comparisons between growing cypresses and a variety of other land uses. Mean top height, age, stocking and basal area are input data for the model. The calculator can predict the stand growth and yield evolution according to desired thinning regimes. It also offers financial analysis using fixed costs, and estimates the internal return rate and net present value.

CONFIDENCE INTERVAL ANALYSIS OF EXISTING PRODUCTIVITY SURFACES

The productivity models discussed in the previous literature review section were used to develop productivity spatial surfaces for some of the species, namely *E. fastigata*, *E. regnans*, *S. sempervirens*, and *C. lusitanica*. However, as shown in Figures 7, 8, 10, and 13, the PSP distribution for each species only represents a certain range of the total distribution of New Zealand's climatic (Fig. 2) and site environmental factors (Fig. 6, Tables 2 and 3) . Hence, the spatial productivity surfaces represent a statistical extrapolation of the range of environmental factors influencing growth at existing PSP sites for each species. Extrapolating beyond the known data ranges means that those model predictions of productivity are not as strong as the models' predictions within the PSP environmental range. This is especially a concern when the empirical models are used, as their development relies on a large number of PSP's to give the model robustness.

In order to provide an indication of the robustness of the spatial surfaces, we performed an analysis on existing spatial productivity maps that were produced for previous projects to determine the robustness of the extrapolations. We assumed that if a particular location (500m^2) had the same environmental site factors as the PSP data that was used to create the spatial model, then there would be strong confidence that the model would give a robust estimate of productivity. Conversely, if a particular location did not fall into the range of the environmental site factors, then there would be weaker confidence that the model would give a robust estimate of productivity. The environmental factors we used for this analysis was mean annual temperature, mean annual rainfall, soil C:N ratio, and soil group classification.

The PSP's for each of the four species had a different range of values for the four environmental factors – as shown in Figures 4 to 6. We used the box-and-whiskers classification of the distribution of values for each environmental factor as a way to classify the level of confidence when a particular location's environmental factors fell within the range of the PSPs. It was assumed that locations of the spatial map within the 25th to 75th percentile (the box) of all four environmental factors infer the model had the highest confidence; areas that were within the 5th

and 95th percentile (the whiskers) had moderate model confidence, and locations outside these percentiles had the lowest confidence. The last category does not infer that the model's prediction for productivity is wrong for these areas, rather that there is no direct supporting PSP data in how the species will perform.

The approach used for this analysis was to clip the productivity surfaces of each species at the 25-75th percentile and 5-95th percentile of each environmental surface. A scheme of the steps is shown in Figure 15. The resulting maps, as described below, represent areas of New Zealand where all four environmental factors occurred within "the box" range and "the whiskers" range. For an example of the process described in Figure 15 applied to a productivity map, see Appendix 2.

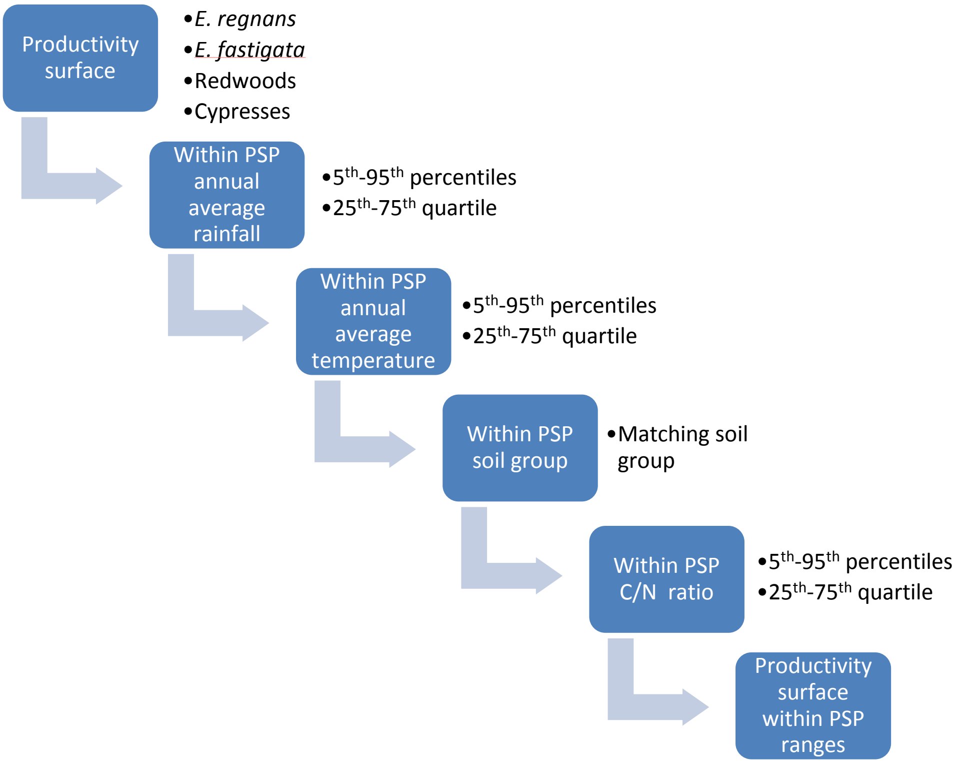


Figure 15: Schematic process for producing the confidence level spatial map representing each species range of values for the four environmental factors across the PSP sites. See Appendix 2 for an example.

Eucalyptus fastigata

Figure 16 represents the original surface productivity for *E. fastigata,* at left, and on the right is the productivity surface that is within the box and whisker's range of each of the four environmental factors. The productivity map covers 1.1% of the most confident category and 16.8% of the moderately confident category (Fig. 16). These two categories are concentrated in the central North Island, Whanganui, Wairarapa, Hawke's Bay, Gisborne, Wellington, Nelson, and Marlborough regions (Fig. 16).

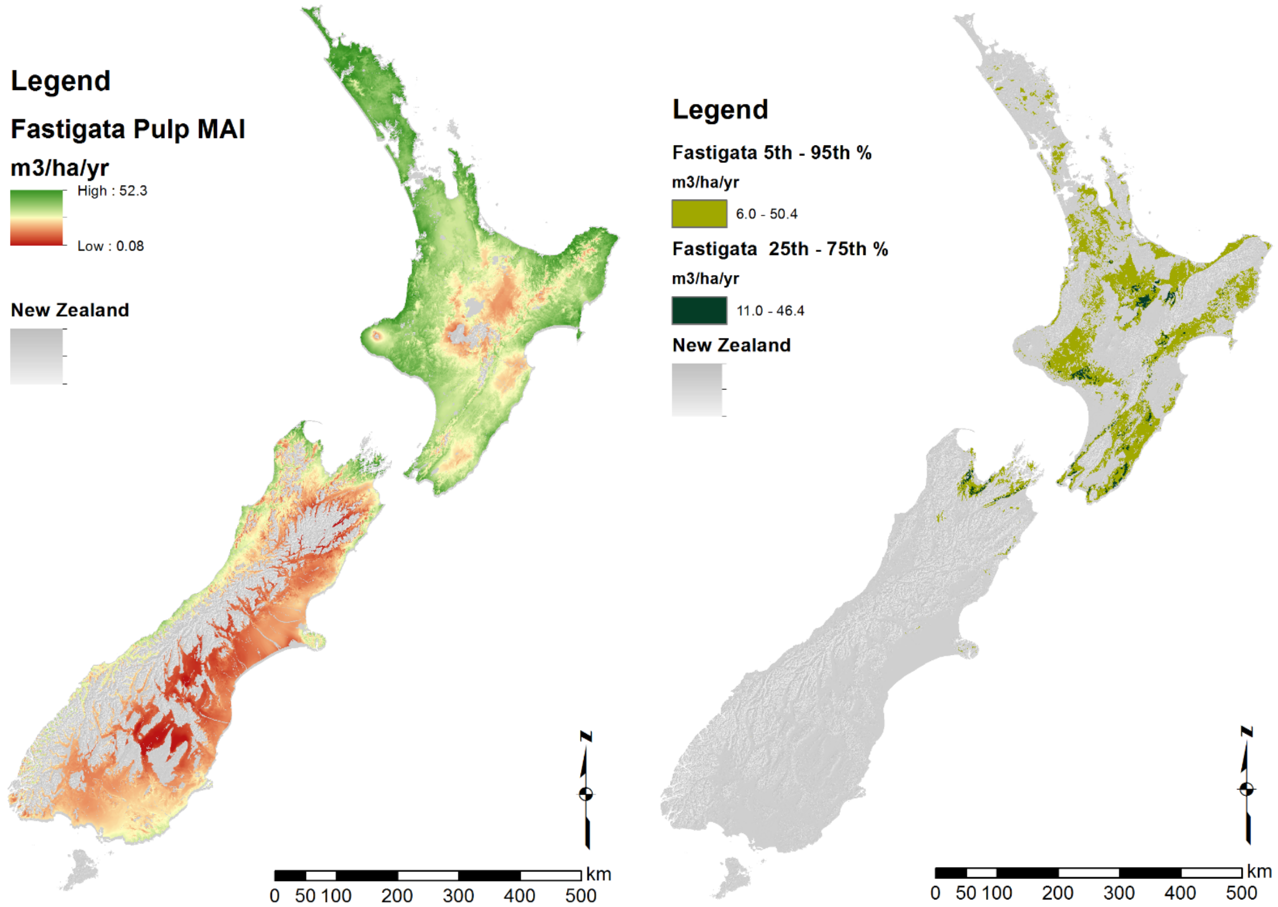


Figure 16: *Eucalyptus fastigata* spatial productivity map, mean annual increment (m^3 ha^{-1} yr^{-1}), for the entire country (on left), and areas that are within the most confident (25th – 75th percentile), and moderately confident (5th – 95th percentile) categories – based on four environmental factors (on right).

Eucalyptus regnans

Figure 17 shows that of the original productivity surface, only 1.1% of this area fits into in the most confident category and 8.0% of the moderately confident category. The “box” and “whiskers” categories are concentrated in the central North Island, Whanganui, Wairarapa, Hawke’s Bay, Nelson, and Marlborough regions (Fig. 17).

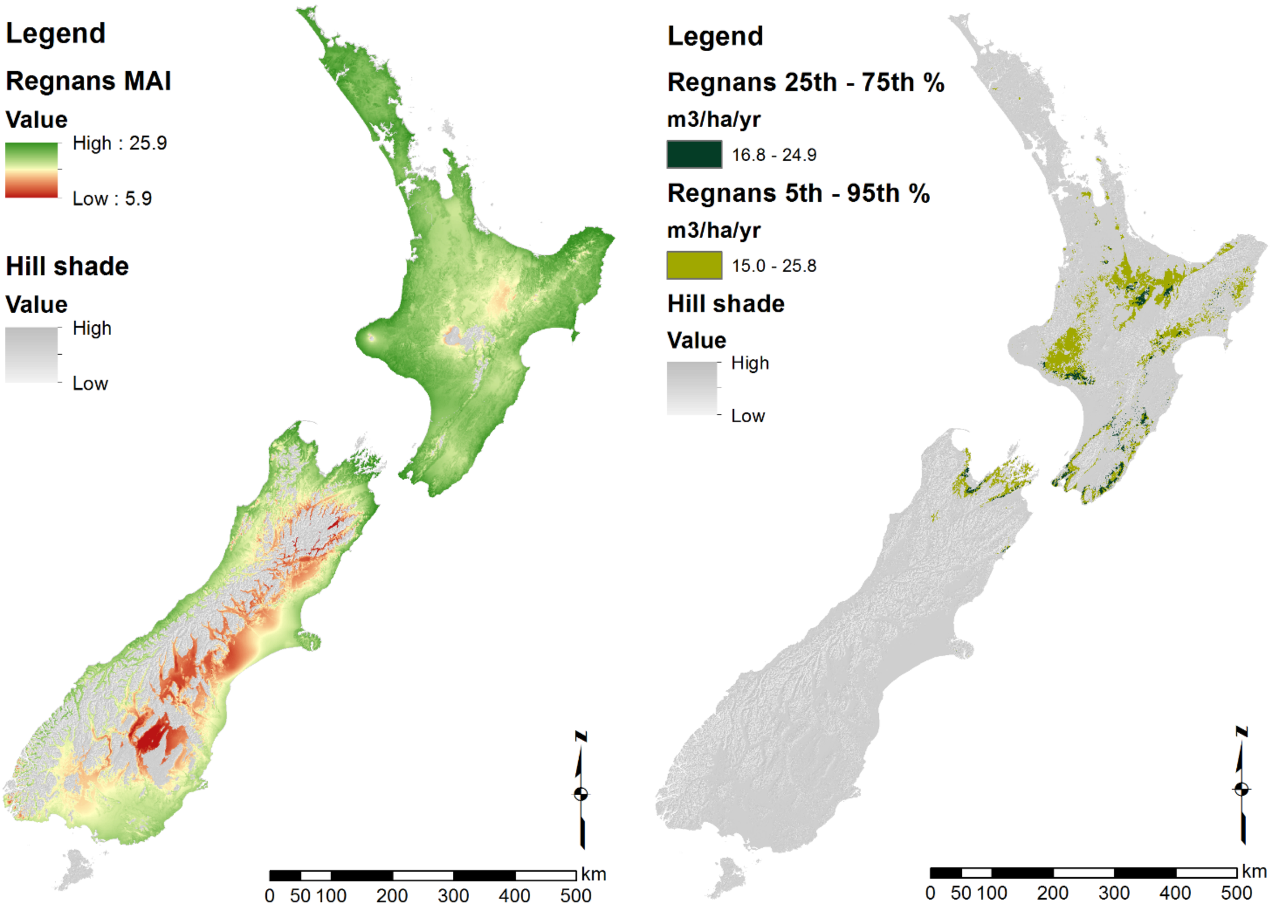
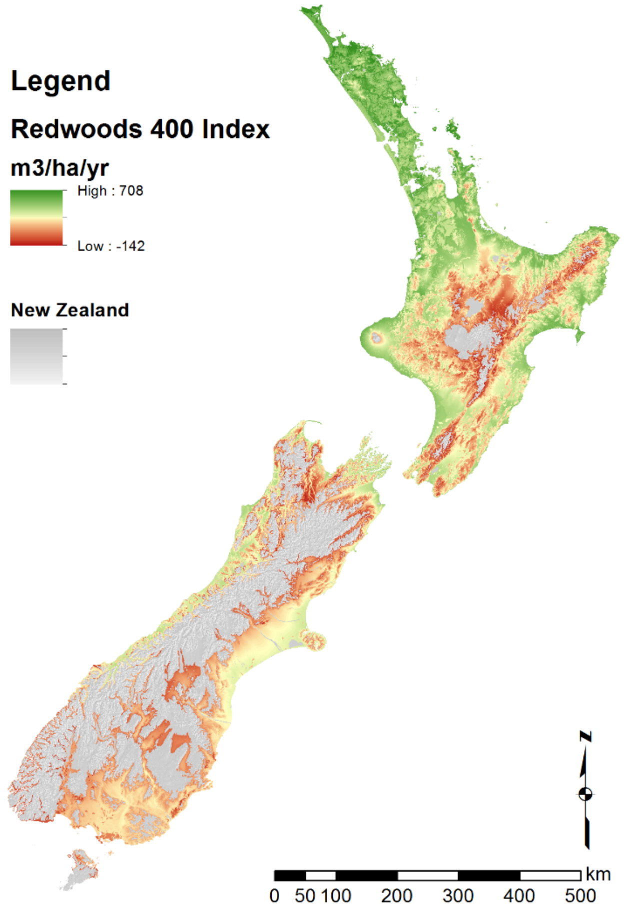


Figure 17: *Eucalyptus regnans* spatial productivity map, mean annual increment (m^3 ha^{-1} yr^{-1}), for the entire country (on left), and areas that are within the most confident (25th – 75th percentile), and moderately confident (5th – 95th percentile) categories – based on four environmental factors (on right).

Sequoia sempervirens

The productivity surface covered by the 400 Index productivity surface for coast redwood is shown in Figure 18. The areas that fit into the "box" and "whiskers" categories are greater than the *Eucalyptus* species. The map shows that 4.6% of the surface is in the most confident category and 25.5% of the moderately confident category (Fig. 18). These areas are concentrated in the lower part of the North Island, Nelson, the foothills of Marlborough and Canterbury, and in Southland.



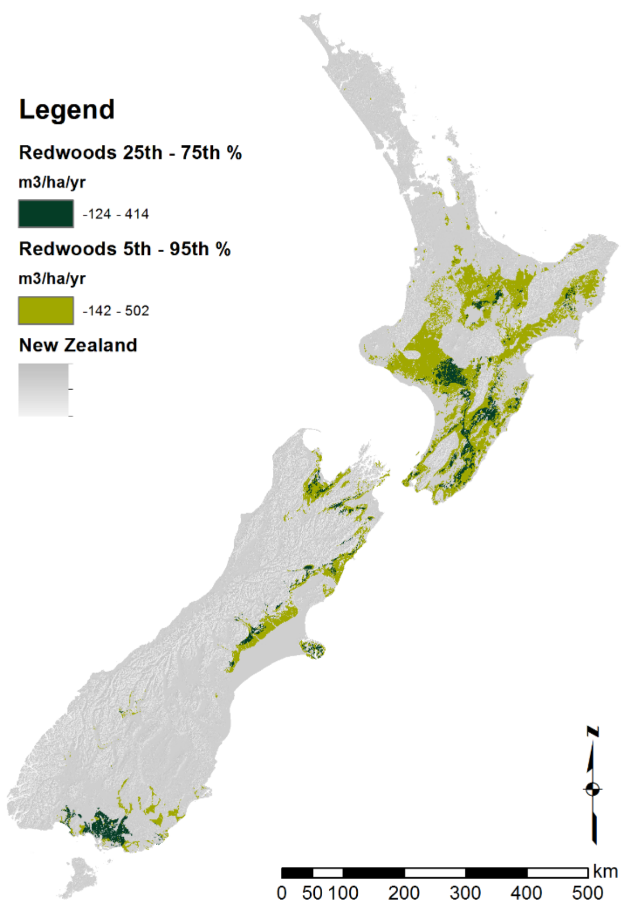


Figure 18: *Sequoia sempervirens* spatial productivity map, mean annual increment (m^3 ha^{-1} yr^{-1}), for the entire country (on left), and areas that are within the most confident (25th – 75th percentile), and moderately confident (5th – 95th percentile) categories – based on four environmental factors (on right).

Cupressus lusitanica

Among the alternative species, the *C. lusitanica* productivity surfaces encompass the largest area for the "box" and "whiskers" categories. For example, for the post-1999 establishment on previously scrub or forest land productivity surface (Fig. 19), 49.6% was in the moderate confidence category and 9.3% was in the high confidence category (Fig. 19) The values for the productivity surfaces for stands planted before 1965 and before 1931, as well as for stands planted on pasture post 1999 have the same percentage and distribution for each category as Figure 17. Therefore, model confidence maps for these other three maps are not shown. The moderate and high model confidence categories were concentrated in most regions of the North Island, Nelson, the foothills of Marlborough and Canterbury, and Southland (Fig. 19).

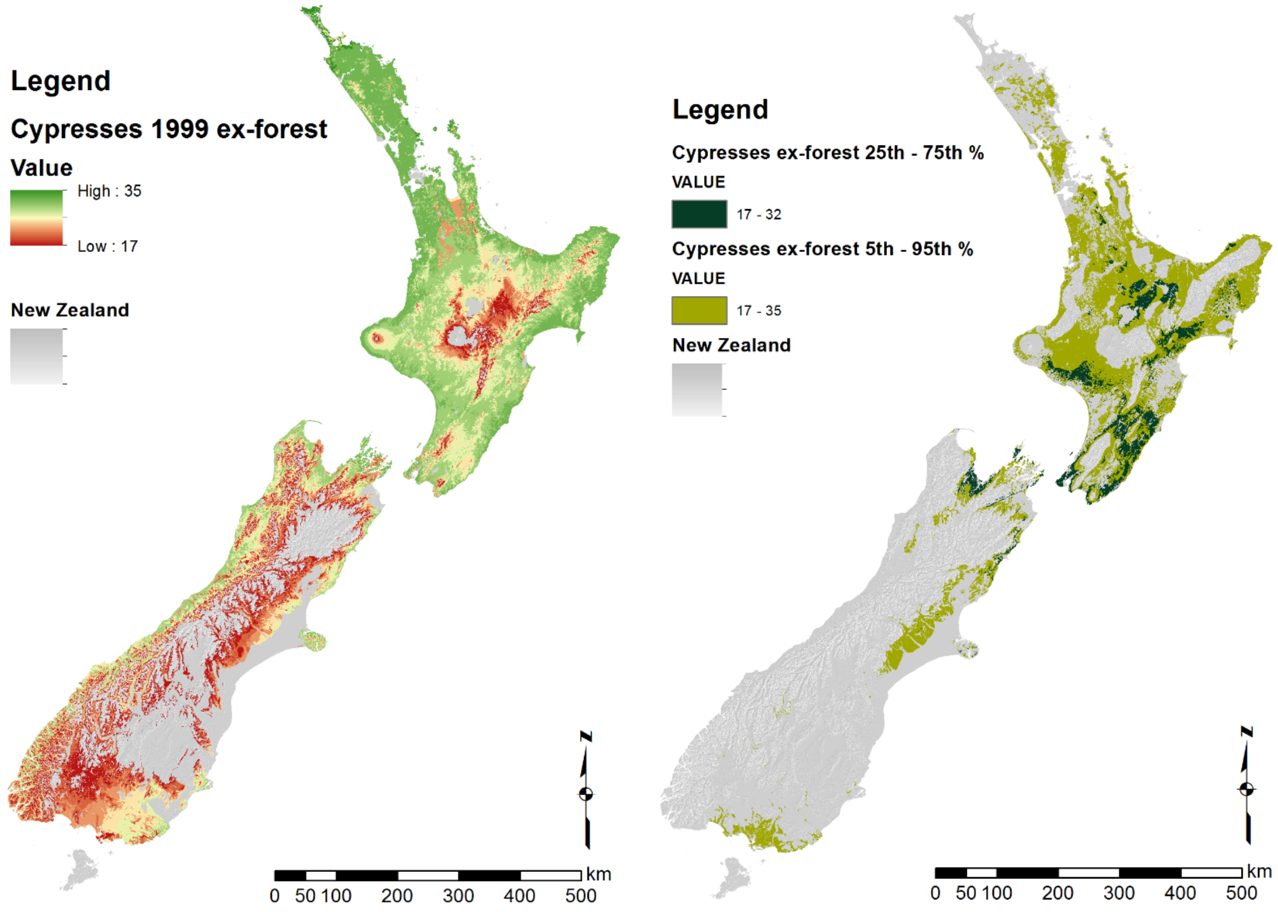


Figure 19: *Cupressus lusitanica* site index map for the post-1999 establishment on previously scrub or forest, (mean top height at age 30) for the entire country (on left), and areas that are within the most confident (25th – 75th percentile), and moderately confident (5th – 95th percentile) categories – based on four environmental factors (on right).

RECOMMENDATIONS

A number of different productivity models have been produced for the seven species since the late 1980's with differing objectives and for different end users. The models developed for these species were all based on a limited number of PSPs that were unevenly distributed throughout the country, as well as differing in stand age, stocking, and silviculture. Several of the empirical models relied heavily on PSP data from the central North Island region. This region is not an ideal environment for all the species modelled except for *P. menziesii* (Douglas-fir). Productivity models for radiata pine were developed using measurements from over 5000 PSPs collected over many years. In contrast, the species in this report had data from PSPs numbering in the low hundreds – at best. Furthermore, a large number of alternative species PSPs have only a limited number of measurements, with many of these only in the more recently established PSPs, i.e. installed in the last 10 years, having only one or two measurements.

The weaknesses of alternative species productivity models were highlighted by using the model confidence analysis for the spatial surfaces of *E. fastigata, E. regnans, S. sempervirens,* and *C. lusitanica*. At the nationwide scale, there were strong statistical relationships of the species productivity with mean annual temperature and to a lesser extent other environmental factors. However, mean annual temperature only gives an indication of regions in New Zealand that are either more or are less suitable for each species. An analysis of the spatial productivity surfaces found that they all showed that productivity was higher in the North Island and productivity for both islands were highest near the respective coastlines. This is a particular contradiction for *Cupressus* species as they are sensitive to salt spray.

New data is required for developing improved surfaces for the productivity of each species. The improvements need to be aimed at better quality of predictions and also wider extent of the confidence of the predictions. Productivity surfaces provide additional capability for comparisons, i.e., comparing forestry returns against other land uses. Species where no productivity surface exists, such as *E. nitens* and *C. macrocarpa*, would benefit from data and analysis towards developing a productivity surface.

Even for the spatial surfaces produced by the process-based model 3-PGS_2, the productivity surface was primary driven by temperature. While process-based models use physiological based algorithms to predict tree growth, and hence require less data than empirical models; these models require more detailed species and site information to be effective. This report clearly shows that statistical and process-based models need to be improved in order to spatially predict productivity at the regional, local, or microsite level.

Table 4 presents to the Speciality Wood Products members a series of options to improve alternative species modelling. Each recommendation lists its positives, negatives, timeline, and relative level of costs. These recommendations will provide discussion material for members at one or more workshops in the second half of 2016, towards further decision-making and strategising for alternative species.

Table 4: Options to improve alternative species productivity models

	Option	Positives	Negatives	Costs and Timeline
1	Install a series of species trials in a number of different environments to determine the best species and collect growth data to improve growth models	• Lots of quality data for modelling • Direct comparison of species performance	• Very expensive • Time consuming to establish • Long time horizon (>7 yrs) before trees are old enough to provide data	• Very high cost • Eight to 20 years timeline
2	Create new statistical models to improve existing models by including latest PSP data	• Cheap • Quick turnaround • Potential to include differences between regions	• Small amount of new PSP data • Unlikely to significantly improve models	• Low cost • One year timeline
3	Locate new stands to install new PSPs to collect data to improve models	• Cheaper than option 1 • Relatively simple and straight forward approach	• Unlikely to locate enough new stands to significantly improve models • Potentially time consuming in locating and installing new PSPs	• Medium to high cost • Two to three year timeline. Longer to collect several measurements from new PSPs
4	Statistical modelling using radiata pine as a proxy for site productivity for alternative species	• Uses existing data in PSP database • Quick turnaround	• Radiata pine is not as site sensitive as alternative species • Unlikely to provide the sensitivity below the regional level	• Low cost • One year timeline
5	Improve models by determining drivers of productivity to between and within sites with combination of remote sensing, drones, digital elevation models (DEM), soil moisture, slope, aspect, soil fertility, etc.	• Will directly measure microsite and local variation of growth • With enough plots will be able to extrapolate productivity more robustly • Shorter timeline than option 1	• Very expensive to collect measurements • Relies on existing PSP network • Extrapolation will be difficult in regions & districts where few PSPs exist • Potentially local effect bias	• Very high cost • Three to five year timeline
6	Use process-based modelling to predict productivity. Improve existing process-based models with collection of additional data from PSPs	• Improve productivity models with existing PSPs • Able to extrapolate more robustly with existing PSPs than statistical models • Potential to lean on current research under the Growing Confidence in Forestry's Future program	• Will not be able to predict microsite effects (< 1 ha)	• Medium cost • Two to three year timeline
7	Consider the above recommendations to also create or improve productivity surfaces	• Ability for surface-based comparisons • Ability to quickly demonstrate species' suitability, potentially at a finer scale	• New data requirements • Regression may not be significant	• Aligns with items 1 & 3 above

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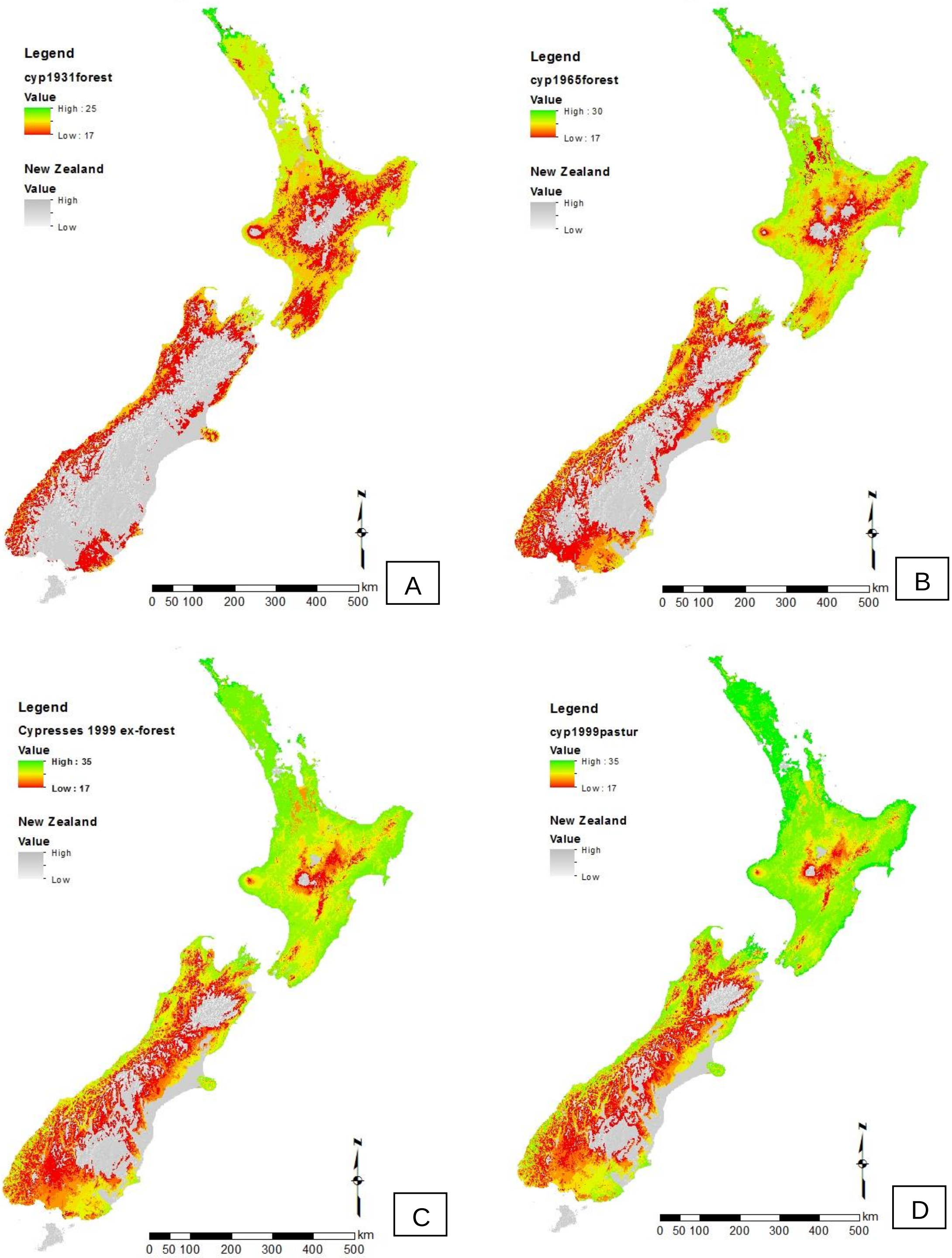
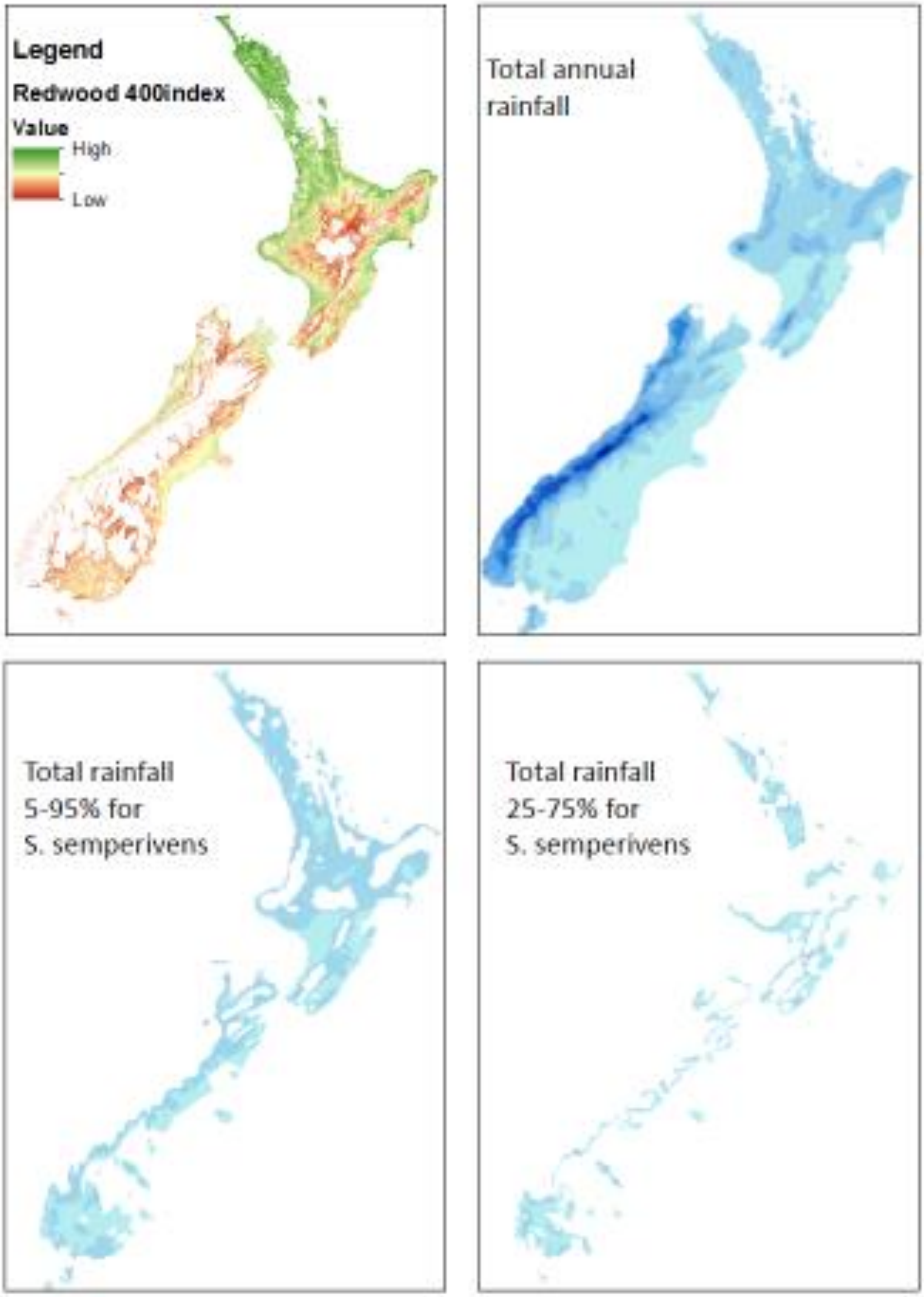
APPENDICES

Appendix 1. *Cupressus lusitanica* site index map for (A) the pre-1931establishment on previously scrub or forest, (B) pre-1965 establishment on previously scrub or forest,(C) post-1999 establishment on previously scrub or forest (D) post-1999 establishment on previously pasture or cropland and pasture.



Appendix 2. Example of the confidence interval analysis of an existing productivity spatial surface

Reference Figure 15 for the schematic process for producing the confidence level spatial map representing the range of four environmental factors of sites.



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