Development of a carbon sequestration web tool for *Eucalyptus fastigata*

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CLIENT REPORT (Confidential)
Development of a carbon sequestration web tool for *Eucalyptus fastigata*

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REPORT INFORMATION SHEET

REPORT TITLE	DEVELOPMENT OF A CARBON SEQUESTRATION WEB TOOL FOR EUCALYPTUS FASTIGATA
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EXECUTIVE SUMMARY

Objective

The aim of this study was to provide robust tools and models for predicting carbon sequestration for *Eucalyptus fastigata*. This was achieved by addressing four specific objectives. First, determine if stand growth varies by site and region. Second, identify environmental factors that influence any variation in stand growth. Third, determine if wood density varies by site, region, and age. And finally, develop a website-ready relationship or relationships that link the above objectives to determine a site's ability to sequester carbon with *E. fastigata*.

Key Results

1. *Eucalyptus fastigata* stand growth varied regionally, with the most productive sites located in Northland and the least productive site in Southland.

2. Eight environmental variables were found to be the optimal number to explain the variability (R^2=0.80) of mean top height (MTH) at age 11 between sites. These were: mean annual temperature (MAT); mean annual precipitation; fractional available root-zone water storage; Bray-2 extractable phosphorus (P) - first extraction; Total extractable Bray-2 P; soil order; sodium hydroxide extractable P; and land environments of New Zealand. Due to the complexity of obtaining most of these variables, only MAT (R^2 = 0.39) was selected to predict MTH at age 11 for the web tool.

3. Neither site productivity nor region influenced wood core density. Stand age was the only important variable (p=0.003) with wood density increasing over time.

4. The MTH and MAT linear relationship were used to predict site productivity. A mean basal area (BA) per tree power equation relationship was developed to compare BA between sites at different ages and stockings. These were used to constrain the series of stand growth scenarios developed with an empirical growth model. The model underestimated stand volume at age 30 of the sites by approximately 7%.

5. Output of the growth model was used in the modified version of C_Change to predict *E. fastigata* carbon sequestration. These models were used to develop a series of carbon sequestration scenarios for new and existing stands, which were developed into an easy-to-use web tool.

Implications of Results/Conclusions

The study provided a robust prediction of wood core and whole tree density. A number of climatic and soil factors were identified as influencing *E. fastigata* growth. Mean annual temperature was selected to predict MTH (and thus productivity) for the web tool because it was the only variable that was easily obtainable by web tool users. This study should be seen as a foundation of current knowledge about *E. fastigata's* potential to sequester carbon. As new information becomes available, it can be added to this study to provide more precise predictions of *E. fastigata's* carbon sequestration potential at a more localised scale.

Further Work

In view of the questions raised by some of the data presented in this report, the following is recommended:

1. Future biomass harvesting studies will be required to develop a more complete picture of biomass partitioning at different stockings and stand ages.

2. The environmental factors identified in this study (Table 4) should be the focus of any future research on *E. fastigata* productivity and siting. The effect of frost intensity, not considered in this study, should also be included.

3. The current empirical model needs to be improved to provide better simulations of *E. fastigata* productivity outside the Central North Island. This could be achieved by either including more data from sites from throughout the country or developing a model that excludes sites from the Central North Island. Either approach will be possible as more sites are planted in *E. fastigata* outside the Central North Island.

4. Due to the lack of permanent sample plots currently available, process-based modelling should be considered as an alternative method to identify sites that are suitable for *E. fastigata*. Process-based modelling is currently being investigated by Scion for species alternatives to *Pinus radiata* to identify suitable sites and to simulate stand growth under current and future climatic conditions.

5. There are a number of other species currently being considered for carbon farming. Application of this approach to these species would benefit those considering investment in this area. Species of importance would include *E. regnans, E. saligna,* Coast Redwood (*Sequoia sempervirens)* and cypresses, particularly *Cupressus lusitanica.*

Development of a carbon sequestration web tool for *Eucalyptus fastigata*

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Scion[1]

February 2010

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Introduction

Carbon sequestration in plantation forests can be used to off-set greenhouse gas emissions to meet international climate change obligations in the first commitment period of the Kyoto protocol (2008-2012) (IPCC 2003). Although *Pinus radiata* (D. Don) grows quickly, species with higher wood density are likely to be more suitable for plantations aimed at carbon sequestration. One such species is *Eucalyptus fastigata* (Deane and Maiden; brown barrel). Robust information about its growth and wood density characteristics throughout New Zealand is required for government agencies and landowners to evaluate *E. fastigata* carbon sequestration potential.

Eucalyptus fastigata is in the Monocalypt sub-group of eucalypts, from south-eastern Australia. *Eucalyptus fastigata* occupies a narrow zone that runs parallel to the coast from northern New South Wales (30°30' S) to northern Victoria (37°20' S) between 700 m and 1,200 m above sea level (Eldridge et al., 1993). The species was first introduced to New Zealand in the 1880s and was successful on a number of farm sites in the North Island (Barr, 1996; Miller et al., 2000). Provenance trials have identified the suitability of *E. fastigata* for New Zealand conditions (Harris, 1975; Wilcox, 1980; Menzies et al., 1981; Wilcox et al., 1985; Hathaway and King, 1986; Cannon and Shelbourne, 1991; Shelbourne et al., 2000 and 2002).

Although *E. fastigata* was initially a slow growing species, its growth rate can rapidly increase after age 10 (Poole, 2009).The species was investigated for its suitability as a short-fibre pulp and sawlogs (Revell, 1981; Cannon, 1993; Kibblewhite and McKenzie, 1999; McKenzie et al., 2000; Jones and Richardson, 2001).

Several small studies have examined *E. fastigata* nutrients and responses to fertilisation (Knight, 1984, 1985, 1986a, 1986b). However, these studies are too limited in size and location to provide information on the species nutrient limitations throughout New Zealand. In the 1980s and early 1990s, studies showed that *E. fastigata's* growth rate was initially slower than other eucalypts such as *E. regnans* and *E. nitens*. *Eucalyptus fastigata* was dropped in favour of these faster growing species with more favourable pulping characteristics, thus research on *E. fastigata* is limited.

Inappropriate siting combined with recent pathogen introductions from Australia have led to poor growth or severe dieback of *E. regnans* and *E. nitens* in the 1990s (Berndt et al., 2008; Poole, 2009). The decline of these eucalypts led to a re-assessment of *E. fastigata* as it appears to be resistant to the pathogens that afflict other eucalypts in New Zealand (Berndt et al., 2008). Recently, there has been renewed interest in *E. fastigata* for short fibre pulp and sawlog production (Berrill and Hay 2005), as well as carbon sequestration.

The most comprehensive study on *E. fastigata* growth rates, wood densities, and biomass partitioning was from a bioenergy study that compared the growth rates of four year-old *E. nitens* with *E. fastigata* (Madgwick et al., 1981 and 1991). This study could not be used to predict biomass partitioning and wood density beyond four years.

Another study examined wood density from three sites in the Central North Island for nine species over a range of ages (McKinley et al., 2000). The majority of the trees sampled were from Kaingaroa and Kinleith forests. Tree disk samples were taken at 0.15 m, 1.5 m, 5.5 m, then at 5 m intervals to a minimum diameter of 100 mm. *Eucalyptus fastigata's* basic wood density increased with age; from 385 kg/m^3 at the youngest age (<7 years) to 501 kg/m^3 at the oldest age (> age 30) (McKinley et al., 2000). An earlier study on the wood density of 43-year-old E. fastigata from Kaingaroa Forest was found to be 501 kg/m^3 (Harris, 1975). A recent study of saw log density from 25-year old *E. fastigata* from Rotoehu forest in the Central North Island had a similar density to McKinley et al. (2000) (Jones et al., 2009). Although these three studies provided on *E. fastigata* density over a large age range, it is unknown if wood density changes by region or by site productivity.

Two studies in 2005 examined growth and yield of *E. fastigata*. The first study developed growth and yield models from 111 plots with ages ranging from <9 years to 60 years (Berrill and Hay, 2005). The majority of the plots were from the Central North Island. Equations developed by Berrill and Hay (2005) included height, volume growth, and volume yield. The second study used a larger *E. fastigata* dataset that included the same data plus Carter Holt Harvey Forests data from Tokoroa and Kinleith Forests in the Central North Island (van der Colff and Kimberley, 2005). The equations developed for the second study were height, site index, basal area, mortality, thinning, and diameter distribution (van der Colff and Kimberley, 2005). The approach used to predict stand growth differed between the two studies; Berrill and Hay (2005) directly modelled stand volume growth while van der Colff and Kimberley (2005) modelled basal area growth. The latter study was used to develop the empirical *E. fastigata* Growth Model in 2007. These two studies provided detailed growth and yield equations for *E. fastigata* in the Central North Island. However, it is unlikely that these equations would be appropriate to predict *E. fastigata* productivity throughout the rest of New Zealand. Indeed, future plantings of *E. fastigata* are most likely to occur on marginal agricultural land outside the Central North Island.

The objectives of this study are four-fold. First, determine if *E. fastigata's* stand growth varies by site and region. Second, identify the environmental factors that influence stand growth. Third, determine if wood density varies by site, region, and age. And finally, develop a website-ready relationship or relationships that link the above objectives to determine a sites ability to sequester carbon with *E. fastigata*. This study was done in conjunction with another study that examined *E. fastigata* biomass partitioning and wood density of the entire tree (Oliver et al., 2009). The results of that study were incorporated into this study to calculate carbon sequestration by *E. fastigata*.

Materials and Methods

Site selection

A total of 53 plots from 15 sites were used in this study. Sites were selected to ensure the widest possible geographical range of *E. fastigata* grown in New Zealand and preference was given to older sites. Also, priority was given to sites outside the Central North Island. Three sites were located in Northland, three sites in the East Coast, four sites in Bay of Plenty, one site in Waikato, one site in Taranaki, two sites in Marlborough, and one site in Southland. The age range of stands was from 8 to 32 with a mean age of 20 (Table 1). A total of nine environmental variables were collected for each site from various geographic information system (GIS) layers (Appendix A) developed by Scion (Palmer et al., 2009a and 2009b).

Table 1: Site descriptions and locations of *E. fastigata* stands

Site	Region	Plots	Age	Latitude	Longitude
Davis-Colley	Northland	2	13	-35.8022	173.9934
Carnation	Northland	3	21	-35.5664	173.7677
Karaka	Northland	6	21	-35.7227	173.9054
RossD	East Coast	2	13	-38.6959	177.8649
Tolaga	East Coast	2	19	-38.3245	178.1876
Manutahi	East Coast	2	32	-37.9099	178.3269
Kapenga	Waikato	1	8	-38.2199	176.2237
Ohauiti	BOP	2	9	-37.7990	176.1878
Waerenga	BOP	15	11	-38.0196	176.2975
Omataroa	BOP	2	17	-38.0427	176.8506
Kaingaroa	BOP	1 Nelder[a]	30	-38.4586	176.6672
Howe	Taranaki	2	24	-39.0174	174.5736
Drummond	Marlbourgh	2	25	-41.2672	172.8884
Millen	Marlbourgh	2	15 & 25	-41.2915	173.8160
Milligan	Southland	1	13	-45.8788	168.3994

[a] The Nelder plot has 15 arcs with each arc having a different initial stocking which ranged from 4356 to 91 stems per hectare. At age 30, only 9 arcs had trees at the correct spacing.

Stand measurements

Permanent sample plots (PSP) that were not measured in 2008 were measured in 2009. All non-PSP or inactive PSPs were also measured in 2009. All live *E. fastigata* trees greater than 1cm were measured for diameter at breast height (DBH), and a subset of trees measured for height. From these measurements, the following variables were determined: live stems per hectare (SPH); mean DBH; height; stand basal area (BA); and mean tree BA. Volume was calculated from *E. fastigata* equations developed by Smart (1992).

Wood density

At each plot, individual trees were randomly selected and double sided 5mm stem wood cores were sampled at DBH. The number of trees sampled per plot was three, although this did vary for some plots. At the laboratory, wood core samples were frozen until analysis at Scion. Increment cores were sectioned into two radii which were cut into 50mm segments starting at the cambium and analysed for basic wood density using the maximum moisture content method (Smith, 1954). The outer 50mm of the core (outerwood) and the mean density of the entire core were used in the analysis.

Soil samples

Soil was randomly sampled between rows from the top 5cm of the mineral soil with a Hoffer tube sampler. Five random samples were sampled and bulked per plot except for Karaka and Waerenga. For Karaka, three of the six plots were randomly selected for sampling, For Waerenga, two of the three blocks were randomly selected for sampling and samples were bulked by block. For Kaingaroa, spokes were randomly selected around the Nelder and soils were systematically sampled between every fifth arc from the centre to the edge. Within each location, samples were randomly collected along the arc's length and were bulked into one bag.

Soil samples were transported back to the laboratory, airdried, then sieved with a 2mm mesh, and sent to Veritec Laboratories (Scion) for analysis. Briefly, total nitrogen (N) and carbon (C) were determined by a LECO carbon, nitrogen, and sulphur analyser. Phosphorus (P) was extracted by the Bray-2 method (Bray and Kurtz, 1945) and concentrations determined by colorimetery with flow-injection analysis. Bray-2 was used to extract calcium (Ca), magnesium (Mg), and potassium (K). It was assumed that the nutrients extracted were available for plant uptake. Concentrations were determined with inductively coupled plasma atomic emission spectroscopy. Sodium hydroxide (NaOH) extractable P provided a measure of plant available P in both the organic and inorganic P pools (Hedley et al., 1982). The P extracted by 0.1M NaOH was analysed by colorimetric flow-injection analysis.

Modelling stand growth and carbon sequestration

Scion's *E. fastigata* Growth Model was used to simulate stand growth and productivity. This empirical model was developed for the Eucalypt Cooperative in 2007 and is based on sites located in the Central North Island (Van der Colff and Kimberley, 2005). The model's growth projections were adjusted by using age 11 BA and height relationships developed from the sites measured in this study. The growth model's mortality equation was used to simulate live stems as there was insufficient information from this study to develop an independent mortality curve. Once the growth model was constrained, simulations were run until age 30. The growth model's live stems and stand volume output was subsequently used as input for the carbon sequestration model, C_Change.

C_Change was developed by Scion to simulate carbon sequestration in *Pinus radiata* stands (Beets et al., 1999). Carbon stock predictions from C_Change were therefore adjusted for *E. fastigata* using the following steps: 1) Inputting estimates of whole stemwood density into C_Change – these were calculated from the outerwood density surveys described above, after multiplying by a conversion factor from the biomass study (0.96); 2) Scaling the resulting above ground carbon stock predictions – the scale factor was applied to adjust for crown/stem ratio derived from the biomass data obtained by Oliver et al. (2009); 3) Applying the root/shoot ratio from the biomass study (Oliver et al., 2009) to the adjusted above ground carbon stocks from C_Change These steps provided carbon sequestration estimates for the above and below ground live biomass pools.

Statistical analysis

Simple regression was performed with Microsoft Excel 2003 (Microsoft Corporation, Redwood, Washington, USA). Other analyses were carried out with the statistical software SAS, version 9.1 (SAS Institute Inc., Cary, North Carolina, USA). Analysis of variance of the effects of stand growth on woodcore density was performed using the general linear model (GLM) procedure. Individual means were tested using Tukey's multiple comparison test. The PROC REG procedure was used to develop multiple linear regression models to predict *E. fastigata* productivity from environmental variables. Four model-selection methods were used to manually select the optimal number of parameters.

The coefficient of determination (R^2) provided the percentage of variation explained by the dependent variables. Typically, the more variables in the model, the higher the R^2. Mallow's Cp statistic provides a method to balance reducing the sum of squares error with additional variables without over parameterisation (Daniel and Wood, 1980). The best model is one where the value for Cp is approximately equal to the number of parameters in the model. Akaike Information Criteria (AIC) uses maximum likelihood to minimise the error sum of squares with the minimum number of parameters (Gill, 2002). Adding more parameters to the model to improve the goodness of fit does not necessarily decrease the AIC value, since there is an increasing penalty for each additional parameter. Sawa Bayes Criteria (SBC) applies a Bayesian modification to AIC to eliminate over parameterisation by using a more complex penalty function as well as maximising explained variance of the theoretical "complete" model (Gill, 2002).

Results

Wood core density

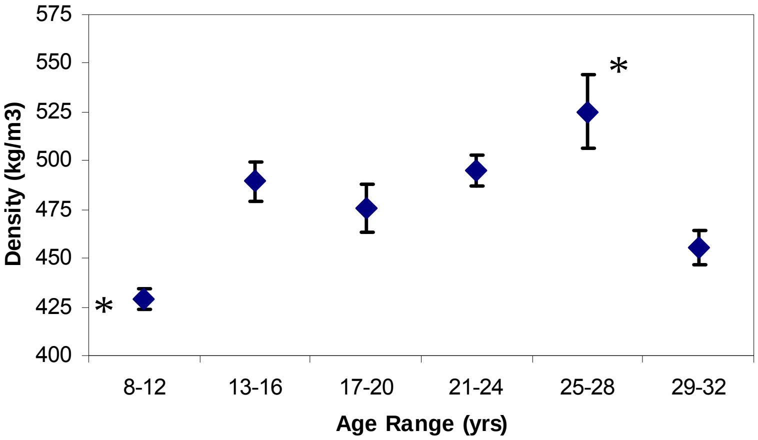
The outer 5cm (outerwood) of the wood core was found to be denser and less variable than the rest of the core (Table 2). These outerwood values were converted to whole tree density using an equation given in Oliver et al. (2009), who found a strong correlation in outerwood density and whole stemwood density. Sources of variation in breast height outerwood density were examined below.

Table 2: Wood core outerwood (outer 5cm) and whole core density by site. Cores sampled from stem at 1.4 m. Standard error in parentheses.

Site	No. cores	Outerwood Core Density (kg /m^3)	Whole Core Density (kg/m^3)
Davis-Colley	6	481 (17)	456 (15)
Carnation	9	492 (16)	473 (18)
Karaka	15	493 (12)	455 (8)
RossD	6	532 (17)	464 (16)
Tolaga	6	489 (24)	447 (16)
Manutahi	6	492 (12)	448 (8)
Kapenga	32	430 (5)	431 (5)
Ohauiti	5	406 (14)	408 (16)
Waerenga	18	434 (12)	411 (7)
Omataroa	6	462 (6)	425 (5)
Kaingaroa	21	456 (9)	440 (7)
Howe	6	506 (12)	456 (8)
Drummond	6	516 (23)	470 (16)
Millen Age 15	3	435 (11)	431 (6)
Millen Age 25	2	554 (38)	482 (17)
Milligan	6	483 (9)	471 (8)

Stand age was the only variable to have a significant effect (p value = 0.003) on outerwood density. Stands under age 13 generally had a lower outerwood density than older stands (Fig. 1). Density was highest for stands aged 25-28 (Fig 1). Variation in stem volume growth rate at the stand level had little effect on wood density.

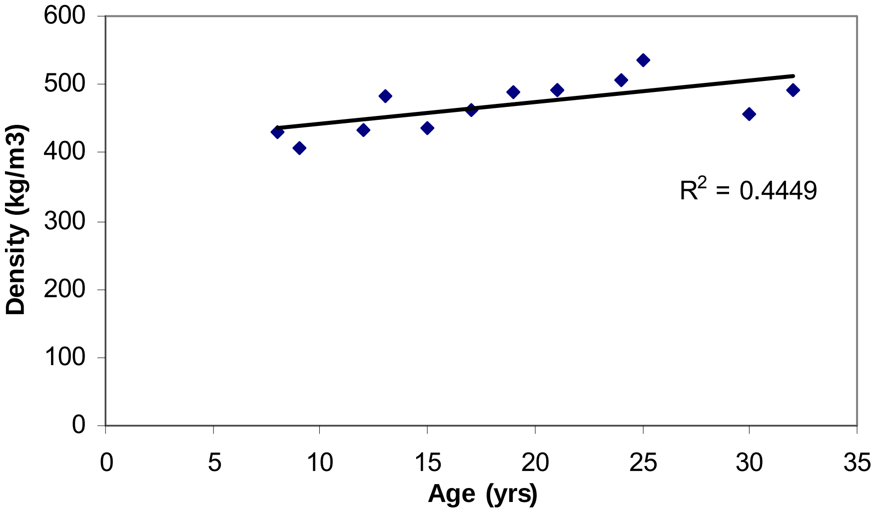
Figure 1: Mean woodcore density by age class; 8-12 (n=55), 13-16 (n=21), 17-20 (n=12), 21-24 (n=30), 25-28 (n=8), and 29-32 (n=21). Standard error bars are shown. * significant at p=0.05 level.



Stand growth had no significant effect on wood core density, age was used to predict density over time. When outerwood core density for each site and sites with the same age were averaged, a positive linear regression line was fitted with an R^2 of 0.45 (Fig. 2). The ratio between outerwood core density and whole tree density for *E. fastigata* was 0.96 (Oliver et al., 2009), which was used to calculate whole stemwood density (Density_{wt}) from the breast height outerwood density:

$$\text{Density}_{wt} = 0.96 * (3.2209 \times \text{Age} + 409.13) \qquad [1]$$

Figure 2: Outerwood (outer 5 cm) wood core density by age



Soil properties

The measured soil properties varied between sites due to the differences in soil type and geographic location. The C:N ratio ranged from 11:1 to 26:1 with a mean ratio of 16:1 (Appendix B). Extractable Bray P and NaOH P were higher than expected. For total P extracted by Bray-2, mean extractable P was 91.2 mg P/kg (Appendix C). For all the properties measured, only Bray extractable K (0.3 cmolC/kg) were low.

Stand growth

Stand growth varied by geographic location, age, and stocking. The Southland site, Milligan, was the slowest growing site with a volume of 109 m^3/ha at age 13. The fastest growing site was Carnation in Northland with a volume of 1032 m^3/ha at age 21 (Appendix D). The overall mean annual increment (MAI) of stem volume for all sites was 21.8 m^3/ha/yr (Appendix D). Due to the differences in stocking and age, the traditional measures of stand growth and productivity could not be used to compare sites. This was further hampered by the fact that a number of sites were not measured until well after establishment. Thus, few sites had stand growth measured at a similar age. To compare stand growth between sites (site productivity), nonlinear regression was used to extrapolate mean top height (MTH) to a uniform age. Mean top height was selected as it is assumed that stands with taller trees at the same age are more productive and is independent of stand density for most species (Clutter et al., 1992).

Age 11 was selected to compare site productivity with MTHs as that was the age where the maximum number of sites could be included in the analysis. The Manutahi and Tolaga sites were excluded. It was found that age 11 MTH was significantly different between sites at the α level of 0.05 (data not shown). Site differences in climate and site conditions were able to explain the differences in MTH. The single most important site variable was minimum mean annual temperature, followed by annual mean temperature, total soil nitrogen, latitude, and soil C:N ratio (Table 3). Annual mean temperature was then selected as the primary environmental variable to compare sites over minimum mean annual temperature as the former was easier to apply operationally as a web tool.

Table 3: Environmental variables that had the highest individual R^2 values for explaining mean top height variability

Variable	**R^2**
Minimum mean temperature	0.50
Annual mean temperature	0.36
Total nitrogen	0.25
Latitude	0.24
C:N ratio	0.21

While mean annual mean temperature (MAT) was the primary variable, further analysis showed that more factors are involved, with the optimal number of eight environmental variables found to be influencing MTH. This more complex model explained 80% of the variability (Table 4), but was considered too complex to apply operationally for the web tool. Precipitation and mean annual fractional available root zone water storage capacity (RZWS) were the second and third most important variables, respectively, followed by extractable soil P, soil order, and land environments of New Zealand (LENZ) (Table 4). RZWS is the proportion of available soil water in the rooting zone to the soil's potential water storage capacity in that zone (Palmer et al., 2009b). LENZ classifies New Zealand into different environmental types based on a number of different criteria (Leathwick et al., 2002 and 2003).

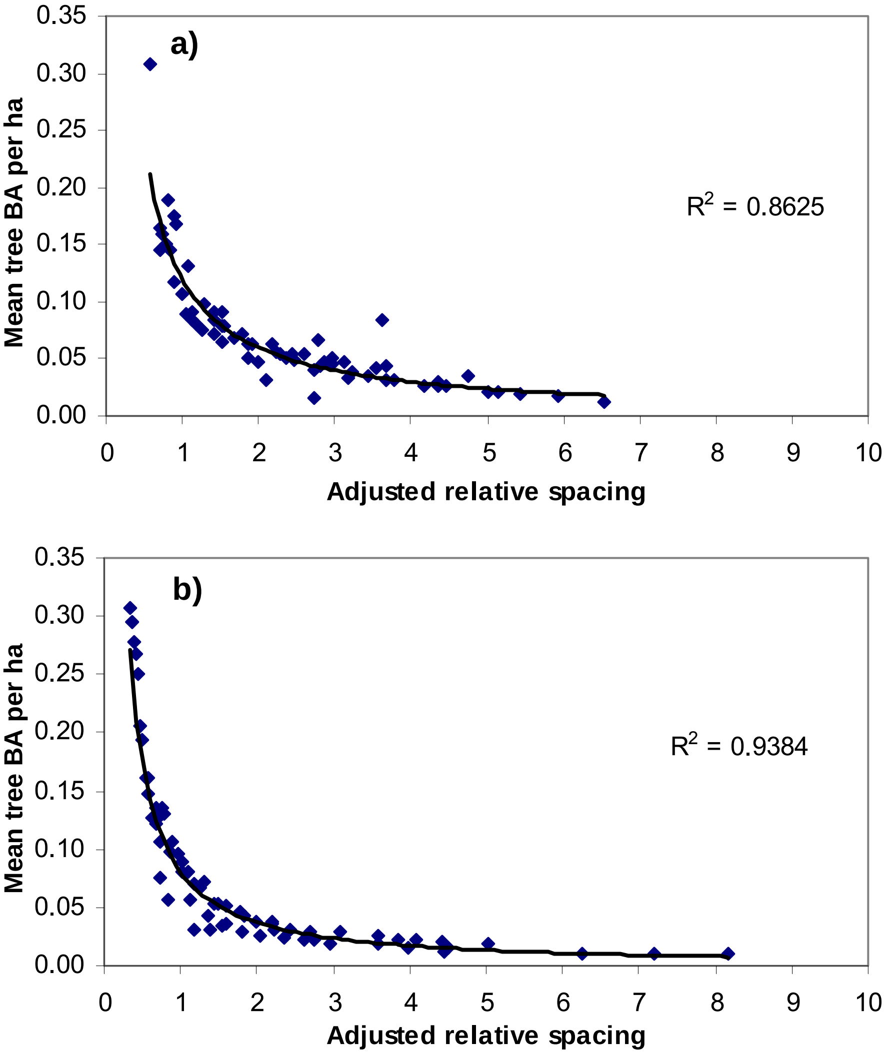
Table 4: Multiple linear regression models of indicators of mean top height productivity at age 11 using four selection methods; C(P) = Mallow's CP, AIC = Akaike information criteria, and SBC = Sawa bayes criteria. RZWS =fractional available root zone water storage, LENZ = Land environments of New Zealand.

Variable Number	Variable Added	R^2	C(P)	AIC	BIC	SBC
1	Mean annual temperature	0.36	89.5	123.8	122.5	127.7
2	Mean annual precipitation	0.44	73.7	118.7	116.6	124.5
3	Mean annual RZWS	0.58	47.2	106.7	104.8	114.4
4	Bray-2 P1	0.62	40.1	103.3	101.3	112.9
5	Total Bray-2 P	0.68	28.6	96.0	94.9	107.6
6	Soil Order	0.76	15.1	84.7	86.4	98.2
7	NaOH P	0.78	12.3	81.8	85.0	97.2
8	LENZ	0.80	10.1	79.0	84.3	96.4

Basal area

Mean top height and stand BA is required as inputs for the *E. fastigata* Growth Model. Linear regression cannot be used to model stand BA to a uniform age as it is density dependent. The stand basal area needed to be adjusted for stem density and age to be compared directly. Using techniques described by Clutter et al. (1992) and Gordon and Lawrence (1994), Basal area per tree was calculated and adjusted by relative spacing and age. Relative spacing (RS) was defined in this study as the square root of the number of live stems per hectare. This created a power relationship for all sites except Kaingaroa, with an R^2 of 0.86 (Fig. 3a; equation 2). At Kaingaroa, the growth of *E. fastigata* seemed to be lagging behind the other sites. This lag could not be explained by the environmental variables measured in this study. A separate power relationship was developed for Kaingaroa, which had a R^2 of 0.94 (Fig. 3b; equation 3). Either relationship could be used to predict mean tree BA for a particular age and stocking for their data set. These equations could be used to constrain the range of stand BA for a particular age.

Figure 3: Mean tree basal area (BA) by relative spacing adjusted for stand age. a) All sites except Kaingaroa. b) Kaingaroa only.



Predicting mean tree basal area (Tree_{ba}) BA from age and live stems for all sites except Kaingaroa

$$\text{Tree}_{\text{ba}} = 0.1195 \text{ RS}^{-1.0007} \qquad [2]$$

Predicting mean tree basal area (Tree_{ba}) from age and live stems for Kaingaroa only

$$\text{Tree}_{\text{ba}} = 0.0805 \text{ RS}^{-1.1181} \qquad [3]$$

Modelling *Eucalyptus fastigata* growth and carbon sequestration

To test the validity of Scion's *E. fastigata* growth model, actual site data was used as model inputs at a younger age and the model outputs were compared to the oldest age at each site. Data from Carnation was not used because stand BA at age nine was extremely high (133 m^2/ha). Waerenga, Kapenga, and Ohauiti were not used as the oldest stand age was less than 12 years. Stand BA and MTH between ages 9 to 15 were used as model inputs. On average, the growth model underestimated stand basal area and stand volume by 9.0 % and 6.7%, respectively (Table 5).

Table 5: Difference in actual and modelled stand basal area (BA) and volume by site

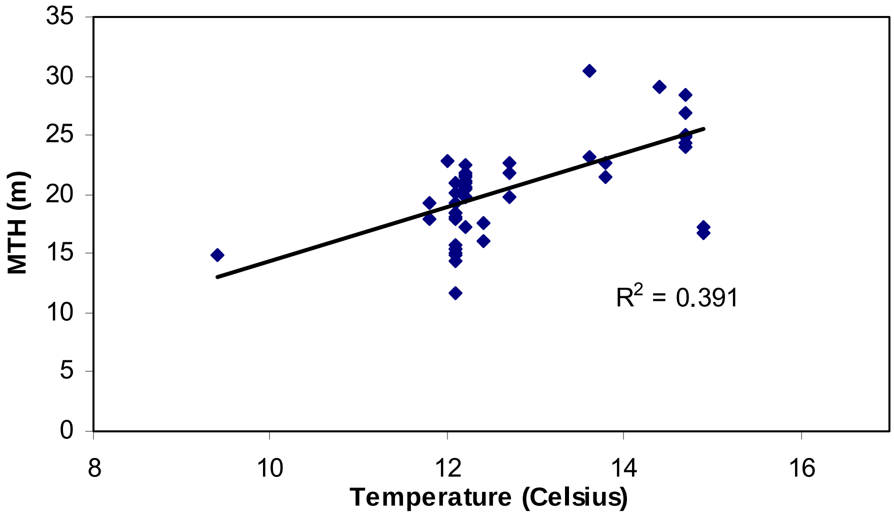
Site	Age of Actual BA & MTH inputs	Stems per hectare at input age	Age of BA & volume comparison	Difference in stand BA (%)	Difference in stand volume (%)
Davis-Colley	9	638	13	4.2	-6.3
Karaka	9	1100	21	22.2	19.0
RossD	10	345	13	-3.1	-2.4
Tolaga	16	405	19	-5.4	21.9
Manutahi	29	575	32	-0.2	-7.0
Omataroa	11	1067	17	3.2	-0.7
Kaingaroa 3	13	2500	30	29.8	22.5
Kaingaroa 4	13	1265	16	-16.1	-22.2
Kaingaroa 5	13	1230	16	-4.9	-3.1
Kaingaroa 6	13	1012	28	-14.6	-4.4
Kaingaroa 7	13	818	28	-27.3	-4.2
Kaingaroa 8	13	564	30	6.8	21.7
Kaingaroa 9	13	438	30	-38.8	-33.3
Kaingaroa 10	13	356	30	-31.2	-35.1
Howe	15	380	24	-32.6	-35.4
Drummond	13	673	21	-6.9	-6.7
Millen	15	450	25	-11.4	-13.2
Milligan	10	750	13	-35.3	-30.8

Mean annual temperature was selected as the variable to predict mean top height (MTH) using actual MTH data at age 11 (Fig. 4):

$$\mathrm{MTH} = 2.2622\ \mathrm{MAT} - 8.2275 \qquad [4]$$

The mean tree basal area power equation was used to generate a range of stand BA at age 11. Mean top height and stand BA were used as inputs for the growth model to simulate stand growth from establishment to age 30. The output from the growth model was then entered into the carbon model C_Change to predict carbon sequestration rates of live stems. Output from C_Change was modified for *E. fastigata* carbon sequestration by using equation 4.

Figure 4: Stand mean top height (MTH) by mean annual temperature



Discussion

Wood density

This study found there was no difference in wood core density between regions. The only factor that was found important was age. There was some large variability in wood core density between some regions at the same age, which may indicate that a more intensive study may find some regional differences. The study did clearly show that the fastest growing stands did not have the lowest wood core density and vice versa for the slowest growing stands. Thus, it is unlikely that highly productive sites will have a large negative effect on wood density. The results from this study were similar to earlier studies in the Central North Island (Harris, 1975; McKinley et al, 2000; Jones et al., 2009). This is further evidence of the lack of regional effects on wood density.

This study developed a density/age relationship that increased over time. This finding was despite the 15% decrease in wood core density between age 25 and 30, due primarily to the low density values of the Kaingaroa site. It is unknown if the lower wood density was due to the inferior genetics of the seedlings planted at this site (pers. comm., C. Low), the tough growing conditions of the Kaingaroa plateau, or another factor. Whatever the cause, it is unlikely that the decrease in density was solely due to age. One factor not controlled in this study was the genetic resource. It is plausible that the other old stand at Manutahi was planted with inferior seedlings. Provenance trials would have identified families with better growth and wood density characteristics. It is impossible to isolate the effects of genetics in this study and including the two oldest sites ensures a conservative estimate of wood density with stand development. Removing Kaingaroa would have little impact on the wood density equation. At age 30 mean tree wood density would only increase by 3.4%.

Soil fertility

Not surprisingly, there was a large range in total soil C and N between the sites. However, the C:N ratio indicated that soil fertility between sites were closer than expected. The C:N ratio ranged between 11:1 to 25:1, but almost all sites had ratios less than 20:1. All sites except Kaingaroa were most likely to have been farmland before they were planted with *E. fastigata*. Thus, these sites have higher fertility than sites that were converted directly from indigenous forests to plantations. Plant available P was the second most limiting soil nutrient for many forests around the world (Fisher and Binkley, 2000). The high Bray-2 and NaOH extractable P values indicate that not only were the sites fertile, but it was unlikely that *E. fastigata's* growth was limited by plant available P. Indeed, the youngest site Kapenga was converted from farmland eight years earlier and still had livestock present and the highest levels of extractable P by far. The high N and P fertility from the former farm sites (ex-pasture) makes it difficult to detect the potential effects of different soil series on *E. fastigata* growth.

Bray-2 extractable cations were low across all the sites, which may indicate that these nutrients were not added as fertiliser in the past. Despite these low levels, it is unlikely that *E. fastigata* was suffering from Ca or Mg deficiency. Only extractable K was low enough to be potentially deficient at some sites. Foliar analysis would be required to determine if *E. fastigata* was limited by this or other nutrients at these sites.

Stand growth

The wide variety of initial stockings and stand ages made it impossible to directly compare stand basal area and volume between sites. Most sites were also not fully stocked. Only the comparison of MTH at a uniform age enabled a comparison of stand growth and potential site productivity. Due to the ages when stand measurements were taken, the MTH of several sites had to be extrapolated to age 11. Despite this extrapolation, MTH at this age appeared to provide a robust measure of productivity.

To model stand growth and carbon sequestration, MTH and stand BA were required as model inputs. Equation 2 was used to constrain the stand basal area and stocking – this applied across all sites except Kaingaroa (Equation 3), which was not used. It appeared that Kaingaroa growth rates lagged behind the other sites, even when compared to sites in the Central North Island. This difference could be attributed to the tougher growing conditions on the Kaingaroa plateau. The environmental variables measured did not identify any factor that could explain this slow growth. However, the temperature variables used in this study do not provide a measure of the extreme frosts that occur on a regular basis on the plateau. The results indicate that if growth and yield data are used from plots located on the Kaingaroa Plateau, these could underestimate productivity in most sites considered for planting *E. fastigata* in New Zealand.

Environmental variables affecting stand growth

Eucalyptus fastigata stand growth was influenced by a range of environmental factors. Mean top height was taller for sites that had higher rainfall, warmer annual mean temperatures, warmer minimum mean temperatures, and higher soil N and plant available P. Multiple linear-regression analysis revealed that eight was the optimal number of environmental variables to predict *E. fastigata* productivity. However, the interpretation of these results must be treated with caution. Although the variables explained 80% of the variability in MTH, the range of data for most variables was limited (Appendix A to C). Thus, it is difficult to extrapolate effects of most variables beyond the current set of data. The only variables that had a wide enough range to extrapolate beyond the current data set were mean annual temperature (9.4 to 14.9^{o}C), mean minimum annual temperature (4.6 to 9.8^{o}C), and total soil N (0.2 to 0.8%).

The combination of mean annual temperature and total soil N (R^2=0.51) or mean minimum annual temperature and total soil N (R^2=0.51) were able to explain a majority of the variability in *E. fastigata* productivity. However, mean minimum temperature and soil N were dropped as predictors of productivity as they were deemed to be too technical for the average web tool user to obtain. Total soil N was further confounded by the fact that all sites except Kaingaroa were ex-pasture. This left mean annual temperature as the only variable to predict MTH, and thus productivity, throughout New Zealand.

Growth model robustness and carbon sequestration

The sites' stand growth data were not enough to predict *E. fastigata's* growth and yield over a range of stockings and site productivity. The *E. fastigata* Growth Model provided a means to simulate stand growth while using site stand BA and MTH as the model's constraints. The growth model was adequate in predicting stand growth and yield for most of the sites measured. Overall, the growth model underestimated actual stand volume by 7%. There were several sites that the model either over- or under-predicted stand volume and basal area growth by over 20%. Most of the larger differences were from comparisons that were older than 10 years. This indicated that the growth model underestimated volume even when the model was constrained by actual stand data. A fuller evaluation of the growth model was not possible as most sites had stands younger than 24 years. The model even underestimated volume of the slow growing Kaingaroa site. For the arcs that reached age 28 or 30, volume was underestimated by 17% for six arcs and overestimated by 22% for two arcs. The growth model's predictions could be improved if the growth model was able to accept input of stand variables at two different ages. This would provide a better guide to simulate *E. fastigata* growth. The growth model could also be improved by incorporating data from sites outside the Central North Island region. Despite these problems, it was the best performing model for all the empirical models that are currently available. Importantly, the growth model did not over-predict stand biomass for most sites. Thus, the data used for the web tool can be seen as a conservative measure of stand growth over a range of sites.

The canopy is a large part of the total carbon sequestrated by young trees. The size of the canopy is affected by the tree density of a stand. Olivier et al. (2009) measured biomass partitioning, including foliage, from two sites that had a tree density of 1270 and 480 stems per hectare for Kapenga and Kaingaroa, respectively. This data were insufficient to calculate changes in the percentage of canopy with changes in stocking. Thus, the C_Change biomass partitioning function was used. As the default species for C_Change was *P. radiata*, the carbon sequestrated for the above ground tree was then adjusted downward using *E. fastigata* biomass measurements made by Olivier et al. (2009). Carbon sequestrated in the roots was estimated from the root:shoot ratio also developed by Olivier et al. (2009). These steps resulted in reasonable estimates of carbon sequestration by *E. fastigata* for a range of stockings and MTHs. Further research would be required to fully develop the relationship of canopy size with tree density.

Web tool

Two types of data were used to develop the web tool:

1. The first was for users to assess the carbon sequestration potential of a site that is being considered for planting *E. fastigata*. Equation 4 was used to calculate site productivity over a range mean annual temperatures and initial stockings. The stand BA at age 11 and the range of initial stockings was used to constrain the dataset. Type one provided annual growth data from establishment to age 30.

2. The second created a range of stand BA and predominant heights for the user to select that best represent the inventory measurements of their stand at age 11. Predominant height is a measure of the height of the dominant trees, which was defined as the tallest 20% of the trees in the stand. At this percentile, predominant height was similar to MTH. Predominant height was selected over MTH as the web tool interface as it was an easier concept for users without a forestry background to understand. Type two provided annual growth data from age 11 to 30.

For both types of data, stand BA and MTH were entered into the growth model, its output was entered into C_Change, and the modified output was used as carbon sequestration data for the web tool. Thus, 63 and 288 unique lookup tables were created for type one and two data, respectively. The web tool provides carbon stock and sequestration estimates for end-users who are either considering planting *E. fastigata*, or have an existing stand.

Summary and Conclusions

Neither site productivity nor geographic location had any impact on wood core density. Only age was relevant for wood density, which increased over time. Soil properties varied between sites, but almost all were relatively fertile ex-pasture sites. Mean top height at age 11 was the only approach to directly compare stand growth across sites. Eight environmental variables were found to be the optimal number to explain the variability in MTH between sites. Minimum and mean temperatures were found to be the most important. Mean annual temperature was selected to predict *E. fastigata* site productivity for three reasons. There was a wide distribution in values, it had the second highest individual R^2, and it was a simple measure for web tool users to obtain.

Due to the large differences in initial stockings and stand age between sites, an empirical growth model was required to simulate stand growth and development. The *E. fastigata* Growth Model was found to be the best model available, but it continues to underestimate actual stand volume by approximately 7%. The power relationship was able to predict mean tree BA over a range of ages and stockings for all sites except Kaingaroa. This relationship was used to constrain the growth model simulations over a range of site productivity and stand density scenarios. The growth model's output was entered into C_Change to calculate carbon sequestration rates, which were then modified for *E. fastigata* biomass partitioning and tree wood density.

The resulting data from C_Change was used to develop a range of scenarios for users who are either considering planting *E. fastigata* or have an existing stand. Using mean annual temperature to predict MTH provided a straightforward method to predict site productivity. Future research should build on the other environmental variables identified in this study to enable the prediction of site productivity at a more localised scale. The empirical growth model provided an adequate means to estimate stand growth. However, its output does not fully capture stand growth, especially for sites outside the Central North Island. Either more data from outside this region needs to be incorporated into current empirical models or an alternative approach is needed. One such approach is process-based modelling, which uses the tree physiology of a species and its growth limitations to predict a species stand growth. This approach is currently being investigated by Scion for species that are seen as alternatives to *P. radiata*. The first project is under Future Forests Research, under the Diversified Species Theme, which is using process-based modelling to simulate stand growth for at least one eucalypt species under current and future climatic conditions. The other project is under the MAF SLMACC project, Designing Optimal Future Forest Systems, which will use process-based modelling to locate sites on marginal agricultural land that are suitable for two alternative species.

In conclusion, the whole tree density equation will provide a robust and conservative prediction of *E. fastigata's* carbon sequestration ability throughout New Zealand. The lookup tables developed from the growth model and C_Change does provide a strong foundation for predicting *E. fastigata's* potential to sequester carbon in the developed web tool. This data can be improved upon as further research is undertaken with *E. fastigata* in the future.

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Appendix A

Relevant environmental variables by site; MTH = mean top height, LENZ = land environments of New Zealand, RZWS = fractional available root-zone water storage[1].

				Precipitation (cm)		RZWS		Temperature (^{o}C)		
Site	**MTH at age 11**	**Elevation (m)**	**LENZ**	**Annual Mean**	**Sum**	**Annual Mean**	**Jan Mean**	**Annual Mean**	**Mean Minimum**	**Soil Order**
Davis-Colley	17.1	35	19	121	98	91	84	14.9	9.7	Brown
Carnation	29.0	200	19	160	119	85	71	14.4	9.8	Granular
Karaka	25.6	90	20	127	100	87	62	14.7	9.8	Brown
RossD	22.1	60	20	90	75	66	38	13.8	9.0	Recent
Tolaga	n/a	60	21	127	99	86	76	14.1	8.8	Recent
Manutahi	n/a	370	20	182	136	94	84	12.8	9.1	Recent
Kapenga	22.8	370	1	123	112	93	92	12.0	7.2	Pumice
Ohauiti	20.8	320	1	184	146	93	88	12.7	8.8	Pumice
Waerenga	20.7	360	1	175	154	93	88	12.2	7.9	Pumice
Omataroa	26.8	65	1	126	113	79	72	13.6	8.1	Pumice
Kaingaroa	17.2	285	1	111	108	82	76	12.1	6	Allophanic
Howe	16.9	190	1	166	147	97	96	12.4	7.5	Allophanic
Drummond	18.6	50	11	108	80.5	77	61	11.8	6.4	Brown
Millen	22.7	50	6	135	102	89	88	12.7	8.9	Brown
Milligan	14.9	300	21	75	76	66	42	9.4	4.6	Brown

[1] Fractional available root-zone water storage: proportion of available soil water in the rooting zone to the soil's potential water storage capacity in that zone

Appendix B

General soil properties by site; total carbon (C), total nitrogen (N), carbon:nitrogen ratio (C:N), Bray-2 extractable calcium (Ca), magnesium (Mg), and potassium (K). Standard error in parentheses.

						Bray-2 Cations (cmolC/kg)		
Site	**n**	**pH**	**Total C (%)**	**Total N (%)**	**C:N**	**Ca**	**Mg**	**K**
Davis-Colley	2	5.1 (0.0)	4.8 (0.0)	0.3 (0.0)	16.0 (0.7)	4.8 (0.6)	2.8 (0.1)	0.3 (0.0)
Carnation	3	4.6 (0.1)	10.7 (0.5)	0.7 (0.0)	16.2 (0.4)	4.0 (1.0)	1.4 (0.1)	0.2 (0.0)
Karaka	3	4.9 (0.1)	7.4 (1.7)	0.5 (0.1)	14.3 (0.4)	2.8 (0.5)	1.7 (0.3)	0.2 (0.0)
RossD	2	5.6 (0.2)	5.1 (0.4)	0.5 (0.0)	11.0 (0.2)	6.3 (1.5)	1.7 (0.2)	0.6 (0.1)
Tolaga	2	5.2 (0.0)	5.6 (2.7)	0.4 (0.2)	13.2 (0.4)	5.2 (0.8)	2.5 (0.3)	0.5 (0.1)
Manutahi	2	4.8 (0.5)	13.0 (3.5)	0.7 (0.1)	19.1 (1.0)	7.7 (0.6)	3.6 (0.4)	0.4 (0.2)
Kapenga	1	4.5	10.2	0.8	12.5	0.5	0.1	0.2
Ohauiti	2	5.5 (0.2)	6.9 (1.2)	0.5 (0.1)	12.6 (0.6)	1.2 (0.5)	0.5 (0.2)	0.3 (0.0)
Waerenga	2	5.2 (0.3)	6.9 (1.0)	0.5 (0.1)	12.5 (0.1)	1.1 (0.2)	0.4 (0.1)	0.3 (0.0)
Omataroa	2	5.5 (0.1)	6.2 (0.9)	0.3 (0.0)	20.3 (2.0)	4.7 (1.1)	3.0 (0.3)	0.2 (0.0)
Kaingaroa	1	4.4	7.7	0.3	25.7	1.5	0.8	0.4
Howe	2	4.9 (0.0)	9.7 (0.3)	0.6 (0.0)	15.4 (0.1)	1.8 (0.6)	2.1 (0.1)	0.3 (0.0)
Drummond	2	4.6 (0.2)	3.9 (0.0)	0.2 (0.0)	18.6 (0.7)	1.2 (0.7)	0.4 (0.1)	0.1 (0.0)
Millen	2	6.3 (0.1)	8.3 (3.8)	0.5 (0.3)	15.3 (0.2)	8.2 (0.4)	3.7 (0.4)	1.1 (0.3)
Milligan	1	4.7	4.3	0.3	16.4	0.8	0.6	0.2

Appendix C

Soil phosphorus properties by site; Bray-2 extractable phosphorus (P) by number of extractions, and sodium hydroxide (NaOH) extractable P. Standard error in parentheses.

		Bray-2 P (mg/kg)				
Site	**n**	**1**	**2**	**3**	**Total**	**NaOH P (mg/kg)**
Davis-Colley	2	17 (3)	15 (2)	14 (3)	47 (7)	247 (11)
Carnation	3	16 (4)	15 (5)	15 (6)	45 (15)	422 (35)
Karaka	3	8 (1)	7 (1)	6 (0)	20 (2)	431 (67)
RossD	2	40 (12)	35 (11)	29 (7)	104 (29)	403 (159)
Tolaga	2	12 (2)	10 (4)	8 (4)	30 (10)	414 (203)
Manutahi	2	9 (3)	5 (2)	4 (1)	17 (5)	436 (103)
Kapenga	1	275	198	101	574	1412
Ohauiti	2	43 (8)	53 (10)	52 (11)	14 (29)	608 (61)
Waerenga	2	112 (38)	99 (30)	62 (24)	272 (91)	701 (110)
Omataroa	2	12 (1)	9 (2)	7 (2)	28 (5)	204 (27)
Kaingaroa	1	34	15	7	56	308
Howe	2	18 (0)	15 (0)	15 (1)	47 (1)	565 (4)
Drummond	2	9 (3)	6 (2)	4 (1)	18 (7)	167 (43)
Millen	2	33 (8)	20 (6)	12 (3)	66 (17)	445 (98)
Milligan	1	15	9	6	30	277

Appendix D

Stand growth and productivity by site.

Site	Age (yrs)	Stems per hectare	Basal area (m^2/ha)	Volume (m^3/ha)	MAI (m^3/ha/yr)
Davis-Colley	13	625	40	227	17.5
Carnation	21	1027	94	1032	49.1
Karaka	21	1013	80	853	40.6
RossD	13	345	29	187	14.4
Tolaga	19	405	36	290	15.3
Manutahi	32	525	87	950	16.4
Kapenga	8	1270	34	193	24.1
Ohauiti	9	625	42	242	26.9
Waerenga	11	608	34	212	19.3
	11	811	45	280	25.5
	11	1067	53	327	29.7
	11	1422	49	293	26.6
	11	1633	51	299	27.2
Omataroa	17	924	67	656	38.6
Kaingaroa	30	1648	70	778	25.9
	30	480	36	334	11.1
	30	459	59	573	19.1
	30	348	44	461	15.4
	30	263	42	424	14.1
	30	204	42	448	14.9
	30	158	42	427	14.2
	30	122	36	377	12.6
	30	103	32	323	10.8
Howe	24	380	72	704	29.3
Drummond	25	320	47	450	18.0
Millen	15	450	41	326	21.7
	25	200	62	619	24.8
Milligan	13	750	24	109	8.4